Comparison of Organic and Chemical Soil Amendments Used in the Reforestation of a Harsh Sierra Nevada Site

R. F. Walker

Abstract

A comparison of a composted organic amendment, a controlled-release fertilizer, and induced mycorrhizal inoculation as affecting the establishment and nutrition of bareroot Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) was conducted on a Sierra Nevada surface mine. The soil amendments were applied at outplanting to the backfill of augered planting holes, with a low rate of 8 g and a high rate of 16 g per seedling for the fertilizer, Gromax 21-6-2 + Minors, whereas a single rate of 2.0 L was used for organic matter. Colonization by *Pisolithus tinctorius* (Pers.) Coker & Couch was induced by coating the root systems with basidiospores suspended in a gel carrier. The organic amendment especially, but also mycorrhizal inoculation, caused substantial seedling mortality, whereas survival was unaffected by controlled-release fertilization. Gromax applied at the high rate produced a 74% increase in shoot volume after three growing seasons, whereas the organic amendment reduced volume by 28%. Growth was unaffected by mycorrhizal treatment. The growth response to the 16-g Gromax application probably reflected enhanced N, P, and K nutrition and decreased concentrations of potentially toxic metallic elements, including Mn and Al among others, as revealed through foliar analysis. Because they were accompanied by growth reduction, nutritional responses to the organic amendment, which involved both macronutrients and trace elements, were of little consequence. Impaired water relations may account for the poor response to this amendment. Likewise, nutritional responses to mycorrhizal inoculation produced no discernible benefit in terms of seedling performance. An inoculation procedure that failed to induce substantially greater *P. tinctorius* colonization in inoculated than uninoculated seedlings, and that may have also impaired water relations, likely explains this result. Overall, these findings indicate that further research is needed before either the organic amendment or the mycorrhizal inoculation procedure used here can be used in forest restoration efforts on dry sites.

Key words: **forest fertilization, forest nutrition, mine reclamation, mycorrhizal inoculation, organic soil amendments, *Pinus jeffreyi*, phytotoxicity, reforestation.**

Introduction

Because of the critical role of organic matter in nutrient cycling and soil water relations (Binkley 1986; Kozlowski et al. 1991; Kimmins 1997; Fisher & Binkley 2000), organic soil amendments are being increasingly examined for their potential as reforestation aids. This is especially true on harsh sites such as those disturbed by surface mining, which frequently results in exposed spoil materials that must suffice as plant growth media but which are severely lacking in organic matter content (Katzur & Haubold-Rosar 1996; Fisher & Binkley 2000). Sawdust, wood chips, tree bark, raw agricultural residues, and municipal biosolids have all been examined for this use (Berg & Vogel 1973; Plass 1978; Berry 1979; Vogel 1981; Moss et al. 1989; Schoenholtz et al. 1992).

The trials with these materials have largely been conducted in humid regions, however. On sites in dry climate zones, the feasibility of using such amendments rests upon the capacity of mine soils to sustain the mineralization rates needed for adequate nutrient release, without which there is little potential for organic amendments to replace chemical fertilizers in reforestation efforts other than as surface mulches to conserve soil moisture.

Largely as a result of their ready solubility, conventional chemical fertilizers can present an impediment to the reforestation of harsh sites, despite their capacity to supply scarce nutrients, because of a propensity to induce seedling mortality (Czapowskyj 1973; Vogel 1981; Walker et al. 1989). This is attributable either to a tendency to overstimulate herbaceous ground covers in mixed plantings or to cause disproportionate increases in the shoot growth of planted seedlings, both of which can lead to severe moisture stress. This problem has produced a hesitancy on the part of resource managers to incorporate conventional fertilization into reforestation programs. Alternatively, however, controlled-release fertilizers, which are characterized by a slow but prolonged nutrient release, have been shown to have far less impact on seedling survival while producing favorable growth responses. This was demonstrated

Knudtsen Renewable Natural Resource Center, University of Nevada, Reno, NV 89512, U.S.A., email walker@ers.unr.edu

initially in humid regions (Berry 1979, 1983; Marx & Artman 1979) and later in initial trials on dry sites (Walker 1999a,b), although the latter studies suggested a need for choosing carefully from among available controlled-release formulations and judicious calculation of application rates.

This article reports the results from a study that compared the growth and nutritional effects of an organic soil amendment with those of a controlled-release chemical amendment on bareroot Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) outplanted on a Sierra Nevada surface mine. A secondary objective entailed an examination of the interactions between these amendments and induced *Pisolithus tinctorius* (Pers.) Coker & Couch mycorrhization of the planting stock. This mycorrhizal fungus has been shown to improve the performance of conifer seedlings on harsh sites in the southern Appalachian Mountains attributable to increased uptake of critical nutrients, reduced uptake of potentially phytotoxic elements, and enhanced water relations (Marx & Artman 1979; Berry 1982; Walker et al. 1989). More recently, this mycobiont was also found to elevate survival of containerized Jeffrey pine in a reforestation trial on a similar site in the Sierra Nevada (Walker 1999b). The study reported here was undertaken as one of a series directed toward enhancing the success of forest restoration efforts in the Great Basin and other locales with similar climates.

Methods

Study Site

The study was conducted on spoils of an open-pit sulfur mine (38°42′30′′N, 119°39′15′′W) located at an elevation of 2,200 m on the east slope of the Sierra Nevada in Alpine County, California, U.S.A. Excavation, which ceased in 1962, and the indiscriminate dumping of the overburden as spoils outside the pit boundary resulted in a mine complex covering approximately 100 ha. Spoil materials are derived from hydrothermally altered volcanic rock, mostly andesites, and the mine soil is predominantly porous silica with small amounts of montmorillonite clays (Butterfield & Tueller 1980). There is presently little evidence of soil profile development in the spoil banks. Annual precipitation at the site averages 50 cm, primarily as snowfall. The composition of the forest stands immediately adjacent to the mine indicate that Jeffrey pine, California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.), and Sierra lodgepole pine (*Pinus contorta* var. *murrayana* [Grev. & Balf.] Engelm.) likely constituted the vegetative cover before the initiation of mining activity, but the elevation, aspect, soils, and especially the low precipitation suggest that Jeffrey pine was dominant (Potter 1994). Attempts to revegetate the mine since closure with both exotic and native herbaceous species have been unsuccessful, and presently the vegetative cover is exceedingly sparse and consists primarily of scattered Jeffrey pine near the periphery. Also colonizing the spoils, largely in symbiotic association with Jeffrey pine, is *P. tinctorius* introduced via wind-borne spores (Walker 1989). Sporocarps of this mycobiont were the source of the ectomycorrhizal inoculum used in the study.

Study Installation

This experiment was located on a bench with a slight 3% slope and a northwest aspect within the spoil bank area of the mine complex. At the outset of the study five soil subsamples were collected at a depth of 0 to 30 cm from each corner and from the center of the bench and combined into one composite sample per location for a total of five composite samples. The samples were air dried for 30 days, sieved to pass a No. 10 (2.0-mm opening) screen, and then analyzed as follows: texture by the hydrometer method; organic matter by loss on ignition; pH by glass electrode on a 1:1 mixture (by weight) of soil and distilled water; total N by macro-Kjeldahl digestion; P (Bray 1) colorimetrically after extraction with NH_4F and HCl; K, Ca, Mg, and S by inductively coupled plasma (ICP) spectroscopy after extraction with $NH_4C_2H_3O_2$; Fe, Mn, Zn, Cu, and B by ICP spectroscopy after extraction with HCl; Mo by ICP spectroscopy after extraction with $(NH_4)_2C_2O_4$ and $H_2C_2O_4$; and Al by ICP spectroscopy after extraction with KCl (Page et al. 1982; Klute 1986). These analyses revealed the following properties: 68% sand, 18% silt, and 14% clay (sandy loam textural class); organic matter, 0.2%; and pH 4.7. Elemental concentrations were (in μg/g): total N, 688; P (Bray 1), 32; K, 282; Ca, 3,841; Mg, 471; S, 301; Fe, 313; Mn, 84; Zn, 3.6; Cu, 26.7; B, 0.7; Mo, 1.8; and Al, 134. Poor water-holding capacity resulting from the coarse soil texture and near absence of organic matter, coupled with the paucity of precipitation, indicated that seedling moisture stress over a significant portion of the growing season is inevitable and exerts substantial influence on the success of cultural treatments. Furthermore, compared with routine eastern Sierra Nevada forest soils this mine soil is low in total N (Johnson et al. 1997), again reflecting the lack of organic matter, and severe foliar chlorosis in the Jeffrey pine that have colonized the mine periphery provide further evidence of N deficiency. The soil is also moderate in P but high in most of the other elements examined, including extremely high S and Cu concentrations (Walker 1999a), with the former largely accounting for its acidity.

The planting stock consisted of 2-0 (residence time of two growing seasons in the nursery bed) bareroot Jeffrey pine seedlings (Alpine County, CA seed source) produced through routine methods by the USDA Forest Service Placerville Nursery (Camino, CA). All seedlings were graded for height (≥12 cm), stem diameter (≥4 mm), and shoot and root system quality. Before outplanting the seedlings were transferred from cold storage to an acclimation tent for final processing. This consisted of dividing them into two equal lots, one to be inoculated with *P. tinctorius* while the other remained uninoculated. For inoculated seedlings the root systems were coated with Terra Sorb Root Dip Gel (Plant Health Care, Inc., Pittsburgh, PA, U.S.A.) that contained *P. tinctorius* basidiospores originating at the outplanting site. The spore mixing rate was 15.8 cm^3/L of prepared Terra Sorb, which was mixed at the rate of 7.9 g/L of water. Root systems of uninoculated seedlings were coated with Terra Sorb prepared in like manner except no spores were included. All seedlings were then jelly rolled in moist burlap (Wenger 1984) to prevent desiccation.

The seedlings were outplanted in early May 1997 in a completely randomized split-plot experimental design with each plot consisting of 20 seedlings divided equally between two rows and each plot divided into two subplots consisting of 10 seedlings, or one row, each. Spacing within rows was 1.0 m and that between rows was 2.0 m, which is typical for reforestation plantings on mine sites because tight spacings help to reduce erosion. Overall, 400 seedlings were planted in 20 plots and thus 40 subplots. One of four main treatments was applied to each of five randomly chosen plots, thus creating five replications of each main treatment, as follows: organic matter applied at a single rate of 2.0 L per seedling; Gromax 21-6-2 + Minors Forestry Dry Site Starter Pak controlled-release fertilizer (Salinas Gromax, Inc., Salinas, CA, U.S.A.) applied at a low rate of one packet (8 g) or high rate of two packets (16 g) per seedling; and an unfertilized control. The organic amendment consisted of shredded and composted plant materials derived from municipal landscape maintenance operations. The duration of composting was 10 weeks, and the materials were remixed when internal batch temperatures reached 65°C. Gromax is manufactured in prill form and prepackaged in a paper packet designed to quickly disintegrate when in contact with moist soil, thus placing the prills in direct soil contact. It has a release period of approximately 15 months at a constant 21°C, but on this field site the paper packets released their contents in approximately 3 weeks and the actual duration of nutrient released was at least three growing seasons (Walker 2002). Percent by weight of the macro- and micronutrients in this formulation are 21% N, 2.6% P, 1.7% K, 1% Ca, 0.3% Mg, 0.8% S, 0.3% Fe, 0.29% Mn, 0.014% Zn, 0.014% Cu, and 0.006% B. Both the organic matter and chemical fertilizer were applied to the backfill of augered planting holes that had dimensions of 13 × 38 cm. For the former this application was such that the amendment was uniformly distributed around the root systems. For the latter a single Gromax packet was placed at mid-depth for the low application rate or one each at mid-depth and at the base of the planting hole for the high rate. Subtreatments were randomly assigned to the subplots within each plot and consisted of inoculated or uninoculated seedlings.

Field Measurements

Initial measurements of seedling height and stem diameter were made at outplanting in May 1997, with subsequent dimension measurements plus assessments of seedling survival at the conclusions of the first, second, and third growing seasons in October 1997, 1998, and 1999. The height and diameter measurements were used to calculate an estimate of shoot volume, defined as the total volume of all aboveground woody and foliar tissues, by the formula of Ruehle et al. (1984). Also calculated for each growing season was relative growth in shoot volume on the basis of seedling size at the previous measurements (van den Driessche & van den Driessche 1991). This facilitates assessment of the extent to which growth responses to treatment at outplanting persist over time.

An evaluation of the effects of the inoculation treatment on ectomycorrhizal formation was conducted in 1998 at the conclusion of the second growing season. This was accomplished by harvesting the complete root systems of one randomly chosen seedling from every subplot within the unfertilized treatment, thus yielding five root systems of inoculated seedlings and five of uninoculated seedlings. After cleaning, the mycorrhizal development of each root system was quantified by determining the total number of short roots and the proportion bearing ectomycorrhizae as indicated by the characteristic monopodial, bifurcate, or coralloid short roots or those with an obvious fungal mantle. The number of colonized short roots was then expressed as a percentage of the total count (Grand & Harvey 1982).

Estimation of the residence time, and thus the mineralization rate, of the organic matter in this mine soil was accomplished by excavating the soil volumes surrounding the root systems of six seedlings that had received this amendment. Three each were randomly chosen from within the inoculated and uninoculated treatments, and the excavations were conducted at the conclusion of the final growing season. All organic matter particles that could be recognized as such were collected from each soil volume, dried to a constant weight, and weighed. These weights were then compared with the dry weight of the organic matter volume originally applied.

Foliar Analysis

Current-year needle subsamples of approximately equal size were collected from each surviving seedling in every subplot and combined into one composite sample per subplot during the fourth week of July 1997, a process repeated during the fourth week of July 1999. The needles were approximately 80% elongated when these samples were collected. All needle samples were dried at 75°C for 24 hr and then ground to pass a 20-mesh (850-μm opening) screen. The samples were analyzed for total N using a Leco Model FP428 N Analyzer (Leco Corp., St. Joseph, MI, U.S.A.) and for P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, Mo, and Al by ICP spectroscopy after wet ashing with HNO_3 and $HClO_4$ (Association of Official Analytical Chemists 1990).

Statistical Analysis

The growth and nutritional data derived from this experiment were subjected to two-way analysis of variance

(ANOVA) using a split-plot ANOVA model with the four fertility treatments constituting main treatments, the two inoculation treatments constituting subtreatments, and five replications per treatment combination. Seedling survival percentages were subjected to arcsine transformation before analysis. Data collected at outplanting and during each of the three ensuing growing seasons were analyzed separately. Fertility main treatment and inoculation subtreatment effects and fertility × inoculation treatment interaction effects were considered significant when $p \leq 0.05$ according to the F test. Differences among means were evaluated using Tukey's studentized range test with $\alpha = 0.05$. All statistical analyses were accomplished using the Statistical Analysis System (SAS Institute, Inc., Cary, NC, U.S.A.). In the presentation of results that follows, p values are included in the text when either a main treatment, subtreatment, or treatment interaction effect proved significant as determined through ANOVA, whereas the interpretive information provided by mean separation analysis as embodied in the Tukey's studentized range test was considered supplementary in this regard.

Results

Mycorrhizal Development and Organic Matter Mineralization

The assessment of ectomycorrhizal formation conducted at the conclusion of the second growing season revealed that the only mycobiont on the roots of either the inoculated or uninoculated seedlings was *P. tinctorius*, which is easily identified by its unique pigmentation (Walker 1989). However, differences in colonization between these two treatments were marginal, as *P. tinctorius* had colonized 44% of the short roots in inoculated seedlings (range, 28–59%) and 41% of them in uninoculated seedlings (range, 23–52%).

The assessment of the organic amendment mineralization rate conducted at the conclusion of the third season indicated that only a small proportion of that applied had decomposed and that the amounts remaining differed only marginally between the inoculated and uninoculated treatments. Specifically, 82% of that from soil surrounding the root systems of inoculated seedlings remained after three seasons (range, 77–88%), whereas 84% remained of that from the soil around uninoculated seedlings (range, 79–91%).

Survival and Growth

ANOVA indicated that seedling survival was affected by the fertility main treatment ($p = 0.0001$) and the inoculation subtreatment ($p = 0.0017$) after the initial growing season (Table 1). Specifically, the organic amendment induced substantial mortality and to a somewhat lesser degree inoculation did also, with the latter effect particularly prominent within the organic matter and 16-g Gromax treatments according to mean separation analysis. Be-

Table 1. Survival and growth of bareroot Jeffrey pine seedlings at the conclusions of the first, second, and third growing seasons as influenced by an organic amendment, controlled-release fertilization, and mycorrhizal inoculation.

Fertility and Inoculation Treatment	*Survival (%) Season*			*Shoot Volume (cm^3) Season*			*Relative Shoot Volume Growth* Season*		
	1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
Organic matter									
Inoculated	34d	32d	32d	8.3a	11.7c	16.2d	0.36c	0.51c	0.34d
Uninoculated	58c	54c	50c	6.7a	12.8bc	21.2cd	0.38c	0.69bc	0.58cd
Mean	46	43	41	7.5	12.3	18.7	0.37	0.60	0.46
Gromax (8 g)									
Inoculated	70abc	70ab	70ab	9.0a	13.6abc	26.9b	0.78a	0.87ab	0.82bc
Uninoculated	82ab	80ab	78ab	7.4a	14.4abc	28.8b	0.61ab	0.78b	0.77c
Mean	76	75	74	8.2	14.0	27.9	0.70	0.83	0.80
Gromax (16 g)									
Inoculated	64bc	62bc	62bc	7.7a	18.8a	52.2a	0.57b	1.26a	1.38a
Uninoculated	86a	86a	86a	8.2a	16.1ab	38.3ab	0.65ab	1.06a	1.32a
Mean	75	74	74	8.0	17.5	45.3	0.61	1.16	1.35
Unfertilized									
Inoculated	82ab	80ab	78ab	8.3a	12.1c	25.0bc	0.59b	0.56c	0.96b
Uninoculated	82ab	80ab	80ab	7.8a	13.1bc	27.1b	0.54b	0.76b	0.76c
Mean	82	80	79	8.1	12.6	26.1	0.57	0.66	0.86
Inoculation									
Inoculated	63	61	61	8.3	14.1	30.1	0.58	0.80	0.88
Uninoculated	77	75	74	7.5	14.1	28.9	0.55	0.82	0.86

For each fertility × inoculation treatment combination, $n = 5$. Means sharing a common letter do not differ significantly at $\alpha = 0.05$ according to Tukey's studentized range test.
*Growth relative to shoot volume at the onset of each growing season.

cause the overwhelming majority of the mortality in this study occurred during the first season, the pattern of survival established initially remained virtually unchanged through the second ($p = 0.0001$ for fertility treatment and $p = 0.0092$ for inoculation treatment effects) and third seasons ($p = 0.0001$ and $p = 0.0115$ for the fertility and inoculation treatment effects, respectively).

Seedling volume was unaffected by treatment after the first season (Table 1). After two seasons, however, the fertility treatment effect proved significant ($p = 0.0274$), with seedlings that had received 16 g of Gromax the largest overall, those that had received organic matter and unfertilized seedlings generally the smallest, and those that had received the 8-g Gromax treatment largely of intermediate size. After three seasons the fertility treatment effect remained significant ($p = 0.0047$), and 16 g of Gromax again produced the largest seedlings overall whereas organic matter produced the smallest. However, seedlings fertilized with 8 g of Gromax and unfertilized seedlings were generally of comparable size after the final season. Ultimately, the high rate of Gromax produced a 74% increase in seedling volume in this study, but the organic amendment reduced volume by 28% in comparison with unfertilized seedlings.

Fertility treatment effects on relative volume growth, unlike those on volume itself, were significant ($p = 0.0382$) after one season (Table 1). This was most apparent in the poor growth exhibited by seedlings that had received the organic amendment. During the second season Gromax that had been applied at the high rate emerged as clearly superior among fertility treatments ($p = 0.0486$), whereas the organic treatment was generally poorest, although unfertilized seedlings also displayed comparatively little growth. During the final season the 16-g Gromax treatment again proved to be exceptional ($p = 0.0215$), with relative growth values that indicate an accelerated growth rate compared with that during the previous year. In contrast, a deceleration of growth rate was evident in the organic matter treatment, which generated the lowest overall relative growth values during the final season. The 8-g Gromax treatment exhibited relative growth that changed little from the second season and was generally comparable with that of unfertilized seedlings. With regard to both seedling volume and relative volume growth, neither the inoculation nor the fertility × inoculation treatment interaction effect proved to be significant during any of the three seasons of the study.

Nutrition

Foliar concentrations of the macronutrients N ($p = 0.0001$), P ($p = 0.0183$), K ($p = 0.0302$), and Mg ($p = 0.0404$) were significantly influenced by fertility treatment during the initial growing season (Table 2). For N both the organic and Gromax amendments produced increased concentrations, and the former also increased that of P and K, but the P and K responses were largely apparent in uninoculated seedlings only. Foliar Mg was somewhat higher overall in the 8-g Gromax treatment, but the differences among means for this nutrient were generally of limited magnitude. Inoculation treatment effects on macronutrients during the first season were confined to N ($p = 0.0034$) and Ca ($p = 0.0426$). For both, inoculation resulted in higher concentrations, most apparently within the unfertilized treatment for the former and within the organic matter treatment for the latter.

Fertility treatment effects on micronutrient concentrations were significant for Fe ($p = 0.0260$), Mn ($p = 0.0417$), and Cu ($p = 0.0359$) during the initial season (Table 2). For Fe and Mn this was apparent primarily in the lower concentrations found in the organic matter treatment and for the former in the higher concentration of the 8-g Gromax treatment, although these responses were most pronounced in uninoculated seedlings. Differences among treatments in Cu concentration were small, but nevertheless the 16-g Gromax treatment had somewhat less Cu overall. Foliar Mn was also influenced by inoculation ($p = 0.0473$), with higher concentrations generally found in inoculated than uninoculated seedlings, most apparently within the organic matter and unfertilized treatments. Concentrations of Zn, B, and Mo were unaffected by treatment during the first season but that of Al exhibited a fertility effect ($p = 0.0267$) that paralleled the Fe response in that the lowest concentration was found in the organic matter treatment and the highest in the 8-g Gromax treatment, again most apparently in uninoculated seedlings.

During the third growing season fertility treatment effects on the macronutrients N ($p = 0.0134$), P ($p = 0.0002$), K ($p = 0.0311$), Ca ($p = 0.0001$), and S ($p = 0.0132$) were significant (Table 2). For N the 16-g Gromax treatment had the highest concentration, unfertilized seedlings the lowest, and intermediate values were found in the organic matter and 8-g Gromax treatments. Similarly, P and K were also highest overall in the 16-g Gromax treatment and lowest in unfertilized seedlings, but although the 8-g Gromax treatment exhibited intermediate values for these two elements, concentrations in the organic matter treatment exceeded those in unfertilized seedlings only marginally. Foliar Ca and S responses diverged sharply from those of the other macronutrients in that the Gromax amendment produced substantially lower concentrations overall, most apparently with the high application rate. Inoculation did not influence any macronutrient concentration during the third season, but the fertility × inoculation treatment interaction produced a somewhat higher Mg concentration in inoculated than in uninoculated seedlings within the organic matter treatment but the reverse within the 8-g Gromax treatment ($p = 0.0402$).

Fertility treatment effects on micronutrient concentrations were significant for Fe ($p = 0.0094$), Mn ($p = 0.0006$), and B ($p = 0.0473$) during the final season (Table 2). For each of these elements the lowest concentrations were produced by the 16-g Gromax treatment, a result

Table 2. Foliar concentrations of nutrients and Al in bareroot Jeffrey pine seedlings during the first and third growing seasons as influenced by an organic amendment, controlled release fertilization, and mycorrhizal inoculation.

		Macronutrient Concentration (%)						Micronutrient Concentration (μg/g)						
Season	*Fertility and Inoculation Treatment*	*N*	*P*	*K*	*Ca*	*Mg*	*S*	*Fe*	*Mn*	*Zn*	*Cu*	*B*	*Mo*	*Al (μg/g)*
1	Organic matter													
	Inoculated	1.92a	0.14ab	0.54b	0.37a	0.10b	0.13a	611b	484b	70a	7.0a	29a	2.9a	1,389b
	Uninoculated	1.81ab	0.16a	0.79a	0.30b	0.10b	0.14a	411c	391c	59a	6.8a	29a	2.8a	867c
	Mean	1.87	0.15	0.67	0.34	0.10	0.14	511	438	65	6.9	29	2.9	1,128
	Gromax (8 g)													
	Inoculated	1.81ab	0.13ab	0.55b	0.37a	0.11ab	0.15a	630b	538a	80a	7.0a	34a	2.6a	1,491b
	Uninoculated	1.77b	0.11b	0.51b	0.37a	0.12a	0.12a	934a	518ab	72a	6.2ab	32a	2.9a	2,411a
	Mean	1.79	0.12	0.53	0.37	0.12	0.14	782	528	76	6.6	33	2.8	1,951
	Gromax (16 g)													
	Inoculated	1.93a	0.11b	0.53b	0.37a	0.11ab	0.15a	614b	556a	68a	5.0b	36a	2.2a	1,353b
	Uninoculated	1.82ab	0.11b	0.51b	0.36ab	0.10b	0.14a	658b	516ab	73a	5.0b	32a	2.2a	1,450b
	Mean	1.88	0.11	0.52	0.37	0.11	0.15	636	536	71	5.0	34	2.2	1,402
	Unfertilized													
	Inoculated	1.61c	0.12ab	0.52b	0.35ab	0.10b	0.13a	674b	530a	77a	5.2ab	35a	2.0a	1,564b
	Uninoculated	1.47d	0.10b	0.48b	0.34ab	0.09c	0.13a	544bc	488b	70a	6.0ab	34a	2.5a	1,255b
	Mean	1.54	0.11	0.50	0.35	0.10	0.13	609	509	74	5.6	35	2.3	1,410
	Inoculation													
	Inoculated	1.82	0.13	0.54	0.37	0.11	0.14	632	527	74	6.1	34	2.4	1,449
	Uninoculated	1.72	0.12	0.57	0.34	0.10	0.13	637	478	69	6.0	32	2.6	1,496
3	Organic matter													
	Inoculated	1.18b	0.10bc	0.72bc	0.42a	0.11a	0.32a	113ab	1,279a	38a	2.0c	88a	1.7a	353ab
	Uninoculated	1.10b	0.10bc	0.78bc	0.34ab	0.08b	0.31a	157ab	882b	35a	3.8bc	86a	1.8a	435a
	Mean	1.14	0.10	0.75	0.38	0.10	0.32	135	1,081	37	2.9	87	1.8	394
	Gromax (8 g)													
	Inoculated	1.21b	0.14ab	0.98ab	0.16c	0.08b	0.15c	76bc	500bc	26a	4.4b	51b	1.6a	230b
	Uninoculated	1.10b	0.13ab	0.83abc	0.30bc	0.11a	0.22bc	87bc	1,173ab	37a	2.4c	89a	1.6a	420a
	Mean	1.16	0.14	0.91	0.23	0.10	0.19	82	837	32	3.4	70	1.6	325
	Gromax (16 g)													
	Inoculated	1.42a	0.17a	1.02a	0.15c	0.09ab	0.15c	55c	403c	28a	4.4b	34c	1.4a	124c
	Uninoculated	1.40a	0.17a	1.10a	0.17c	0.10ab	0.19bc	67c	422c	26a	4.4b	34c	1.3a	155c
	Mean	1.41	0.17	1.06	0.16	0.10	0.17	61	413	27	4.4	34	1.4	140
	Unfertilized													
	Inoculated	0.93c	0.10bc	0.72bc	0.33ab	0.09ab	0.26b	125ab	1,260a	35a	3.2bc	84a	1.7a	386ab
	Uninoculated	0.87c	0.08c	0.62c	0.46a	0.10ab	0.27b	185a	1,198ab	38a	13.2a	71ab	1.8a	433a
	Mean	0.90	0.09	0.67	0.40	0.10	0.27	155	1,229	37	8.2	78	1.8	410
	Inoculation													
	Inoculated	1.19	0.13	0.86	0.27	0.09	0.22	92	861	32	3.5	64	1.6	273
	Uninoculated	1.12	0.12	0.83	0.32	0.10	0.25	124	919	34	6.0	70	1.6	361

For each fertility × inoculation treatment combination, $n = 5$. Means sharing a common letter do not differ significantly at $\alpha = 0.05$ according to Tukey's studentized range test.

that extended somewhat to the 8-g application as well, although the responses to the latter were confined to inoculated seedlings for Mn and B ($p = 0.0275$ and $p = 0.0488$ for the fertility × inoculation treatment interaction effects on Mn and B, respectively). The fertility × inoculation interaction was also significant for Cu ($p = 0.0270$), evident primarily in the high concentration found in uninoculated seedlings of the unfertilized treatment. Nevertheless, inoculation alone did not influence any micronutrient concentration during the third season, and as was true during the first season, Zn and Mo concentrations were unaffected by fertility treatment also. However, both the fertility ($p = 0.0099$) and inoculation ($p = 0.0307$) treatments influenced foliar Al, as the 16-g Gromax treatment again produced the lowest concentrations, whereas inoculated seedlings generally had lower concentrations than uninoculated seedlings, most apparently within the 8-g Gromax treatment.

Discussion

Initial evaluation of reforestation practices must be based on the impacts of cultural treatments on seedling survival. Consequently, results reported here offer little evidence of the utility on dry sites of composted organic amendments incorporated into the soil, because this treatment induced substantial early mortality. Perhaps the retention capacity of organic matter as a counterbalance against water drainage out of the soil profile (Fisher & Binkley 2000) proved a disadvantage in this application, because this amendment may have bound the limited available water so tightly that access by the seedling roots was restricted. Alternatively, the organic matter additions may have increased soil aeration to such extent that desiccation of the root systems ensued. Both of these explanations imply severe consequences for seedlings on dry sites, particularly with regards to water relations.

The mycorrhizal inoculation treatment also reduced survival, although somewhat less so than the organic amendment, despite earlier findings that colonization by *P. tinctorius* enhanced survival of Jeffrey pine on this site (Walker 1999b). The difference between the results of the previous study and those presented here may be explained by the different approaches used to induce mycorrhizal formation, as the earlier study entailed the planting of seedlings previously colonized in the nursery with *P. tinctorius*. In contrast, the coating of the roots at outplanting with basidiospores in a gel carrier, the approach used here, may have impeded the movement of water from rhizosphere to root system, thus causing desiccation. Inherent in this explanation, however, is the stipulation that it was the spores and gel in combination that were debilitating, because the root systems of uninoculated seedlings were coated with the gel also. Nevertheless, limits on interpretation of this result imposed by the use of a single basidiospore application rate preclude a determination of whether this inoculation method, or the spore application rate used here, is unsuitable for dry sites, and further research in this regard is needed. Furthermore, inoculum purchased from a national company may not be adapted for all site-specific conditions. The lack of an impact by the Gromax amendment on survival in this study reinforces earlier findings (Walker 1999a,b, 2002) that controlled-release fertilization can be used at outplanting on dry sites without impairing seedling establishment.

Growth responses to the organic amendment reported here also indicated that this treatment was detrimental to surviving seedlings, because they were smaller than unfertilized seedlings at the conclusion of the study and exhibited the lowest relative volume growth among all treatments during the final season as well. The latter suggests that their growth rate would likely continue to lag for an extended time period, and again this may reflect impaired water relations as discussed above. The failure of *P. tinctorius* inoculation to stimulate seedling growth in this study, as it had in several previous studies on surface mines in humid regions (Marx & Artman 1979; Berry 1982; Walker et al. 1989), is probably explained by the near equal colonization levels of inoculated and uninoculated seedlings found after two growing seasons, reflecting the natural abundance of this mycobiont on these mine spoils. Growth stimulation by the Gromax amendment reported here largely paralleled that noted in a previous study (Walker 2002) and again indicated that to realize an appreciable growth enhancement with this controlled-release formulation, two rather than one fertilizer packet must be applied. However, the relative growth calculations of this study also revealed that the 16-g Gromax application became more stimulative as the study progressed, suggesting this stimulation would persist for additional seasons.

Interpretation of cultural treatment effects on elemental concentrations in seedling foliage is most meaningful when viewed within the context of appropriate nutritional standards. Among macronutrients the N concentrations during the first season exceeded the reference standard for western yellow pine (Jones et al. 1991) in all except unfertilized seedlings but declined well below the standard by the third season, particularly in unfertilized seedlings. Foliar P was well below the standard cited above in all treatments throughout the study, but least so within the organic matter treatment in the first season and the 16-g Gromax treatment in the last. Likewise, K was uniformly low initially, and only the Gromax treatments equaled or exceeded the standard in the last season. Conversely, Ca was initially above standard across all treatments but was low in the Gromax treatments during the final season, whereas Mg was low in all treatments during both seasons. No suitable reference standard currently exists for S, but based on that previously found in Jeffrey pine on a routine forest site (Walker 1999a), initial concentrations here were comparable but those in the organic matter and unfertilized treatments were elevated during the final season.

Apparent in data presented here is an incongruity regarding N. Higher concentrations were associated with an obvious growth stimulation in the 16-g Gromax treatment, but any relationship between foliar N and growth in the 8-g treatment had largely disappeared by the conclusion of the study. Furthermore, higher N in the organic matter treatment was apparently irrelevant given that these seedlings were ultimately smaller than unfertilized seedlings. Similarly, the higher P initially in seedlings of the organic matter treatment was obviously not stimulatory nor apparently was that in the 8-g Gromax treatment during the third season, but final concentrations in seedlings of the 16-g Gromax treatment ultimately correlated well with growth rate. As for K final year concentrations in the 16-g Gromax treatment correlated well with growth here also, but again those in the 8-g treatment did not. Other seeming incongruities involve Ca and S. High concentrations in the organic matter and unfertilized treatments were juxtaposed against low concentrations in the Gromax treatments, and especially with the high application rate, during the third season. Apparently, increased macronutrient levels in seedlings of the organic matter treatment reflected more of a concentration effect due to slow growth than an increase in uptake supplied by this amendment. Conversely, the low Ca and S concentrations in those of the 16-g Gromax treatment likely indicated a dilution effect resulting from the rapid growth (Timmer 1991) induced by greater availability of the more critical N, P, and K. Additional support for the latter assumption is provided by the macronutrient levels in the soil, as N and P were limiting whereas Ca and S were abundant. Inoculation effects on foliar macronutrient concentrations were largely confined to N and Ca, with both somewhat higher in inoculated seedlings during the first growing season. Increased N in pine on surface mine sites due to induced *P. tinctorius* infections has been frequently reported (Marx & Artman 1979; Berry 1982; Walker et al. 1989) and has typically been accompanied by growth stimulation. Nutritional responses to inoculation here, however, were not accompanied by added growth and, given the lack of success in inducing substantially greater *P. tinctorius* colonization in inoculated than uninoculated seedlings, may simply reflect random variation. Treatment effects on foliar Mg, although significant during both the first and third seasons, also produced only small variations in concentration that did not appear to be associated with notable growth responses.

Considerable variation in micronutrient concentrations over time was evident in this study, but common to most was that during either the initial or final growing season, if not both, they exceeded the reference standards (Jones et al. 1991), sometimes to an extreme degree. Foliar Fe in particular, but also Zn to an extent, was initially elevated but declined to a relatively low value by the third season, with the former especially low in the Gromax treatments. In contrast, Mn was initially elevated and became exceedingly so during the third year, although far less in the 16-g Gromax treatment. Average initial Cu concentrations declined to a low value later in all except seedlings that were both unfertilized and uninoculated, whereas average B concentrations became elevated later in all except the 16-g Gromax treatment. Foliar Mo was elevated initially and, although it declined somewhat, generally remained elevated nonetheless. A reference standard for Al is unavailable, but based on concentrations observed in a previous Jeffrey pine study on a routine site (Walker 1999a) those found here were exceedingly high during the first season, and although they decreased by the third they remained elevated in all except the Gromax treatments, especially with the 16-g application. Confined largely to the final season the overall micronutrient and Al responses to Gromax were nevertheless a reduction in foliar levels that was most pronounced at the high application rate. Possibly a result of the aforementioned dilution effect, the responses here generally coincide with earlier findings (Walker 2002) and suggest that controlled-release fertilization, intended as a remedy for deficiencies, may also deter potential toxicities sufficiently to contribute to improvements in survival and growth. Any evidence of a similar capability in the organic matter treatment was limited to Fe, Mn, and Al during the first season, most prominently as an interactive effect with the uninoculated mycorrhizal treatment, and was not sufficient to reduce the concentrations of these elements to normal levels or to elicit improvements in seedling performance. Unlike previous reports of *P. tinctorius* inoculation suppressing the uptake of potentially phytotoxic metals (Marx & Artman 1979; Berry 1982; Walker 1999b), the ultimately flawed approach used in this study induced exceedingly few, and generally conflicting, effects in this regard, again with no discernible enhancement of seedling performance.

In summary, this study entailed a comparison of a composted organic amendment, a controlled-release fertilizer, and induced mycorrhizal inoculation as they affected the performance of bareroot Jeffrey pine on a Sierra Nevada surface mine. The organic amendment, incorporated into the soil at outplanting using a 2.0-L rate, caused excessive mortality and depressed growth, whereas its nutritional impacts were irrelevant with regard to enhancing seedling performance. Impaired water relations may have contributed to the detrimental influences of this treatment. A flawed inoculation procedure that at minimum failed to stimulate colonization, and may have also impaired water relations, likely accounted for the unfavorable responses to induced *P. tinctorius* mycorrhization, which had much the same impacts as the organic amendment on survival and produced no discernible growth enhancement. Without impairing survival fertilization with 16 g of Gromax 21-6-2 produced substantial growth enhancement, likely attributable to improved N, P, and K nutrition and possible amelioration of phytotoxicities, but an 8-g application proved far less beneficial. These results indicate that further research is required before the organic amendment and mycorrhizal inoculation procedure used here can be relied on to facilitate reforestation of harsh sites in dry climate zones, but the controlled-release amendment appears to have considerable utility on such sites.

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