Initial Plant Growth in Sand Mine Spoil Amended with Peat Moss and Fertilizer Under Greenhouse Conditions: Potential Species for Use in Reclamation

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ABSTRACT

The Great Lakes Basin exhibits the largest collection of freshwater sand dunes in the world. Sand dunes are ecologically important and support a unique assemblage of flora and fauna. Sand dunes are also economically valuable. However, when sand dunes are mined, soil quality is drastically reduced. Therefore, soil quality improvements followed by revegetation maybe necessary for successful reclamation. This study evaluates the germination and initial growth of 2 legume species, sundial lupine (*Lupinus perennis*) and Illinois bundleflower (*Desmanthus illinoensis*), and 2 warm-season grass species, Indian grass (*Sorghastrum nutans*) and little bluestem (*Schizachyrium scoparium*), in the presence of 2 soil amendments (inorganic fertilizer and sphagnum peat moss) added to spoil from a local sand mine. We sowed species in pots and propagated them under greenhouse conditions. Results indicate that sundial lupine and Illinois bundleflower exhibited the greatest germination and growth among species. Peat moss had the greatest overall impact on germination and growth while the addition of fertilizer positively affected initial growth. Based on these results, sundial lupine is recognized as a primary candidate for sand mine reclamation, while Illinois bundleflower is also recommended as an appropriate species for revegetation efforts. We recommend using soil amendments that are functionally equivalent to peat in increasing soil water holding capacity. We further suggest that fertilization may be accomplished by including legumes in plant species mixes used for revegetation. Results presented here may help to identify appropriate species and soil amendments for the reclamation of former sand mines or restoration of freshwater sand dunes.

Keywords: *Desmanthus*, lupine, mine reclamation, sand dunes, soil amendments

The Great Lakes Basin exhibits the most extensive freshwater shoreline in the world, with Michigan containing the greatest amount at 4,912 km of the estimated 15,670 km total (U.S. Lake Survey 1952). Accordingly, the basin also exhibits the largest collection of freshwater dunes in the world (Albert 2000). Sand dunes in Michigan support a diverse flora and fauna including several rare, threatened, and endangered species such as Pitcher's thistle (*Cirsium pitcheri*), dwarf lake iris (*Iris lacustris*), Houghton's goldenrod (*Solidago houghtonii*), and piping plover (*Charadrius melodus*; Albert 2000, Kost et al. 2010).

Sand dunes are also economically important for providing sand used in glass production, foundry molds, and road construction and maintenance (Ayres, Lewis, Norris and May, Inc. and Chapman 1978). In the United States, sand and gravel mining constitutes 48% of all mining operations (USDHHS 2008); 805 million metric tons of sand and gravel were mined in 2009 at a value of $US6.8 billion (USGS 2010). Michigan is one of the leading sand and gravel producers in the nation, extracting 59 million metric tons in 2007 at a value of $US265 million (USGS 2007).

Sand mining drastically reduces biodiversity and soil quality in sand dune ecosystems (Bowles et al. 1990, Cummings et al. 2005). Removal of vegetation during mining leads to soil erosion, loss of pre-disturbance soil, decreased soil organic matter, nutrients, and water holding capacity, and increased soil surface temperatures which inhibit plant establishment (Gaffney and Dickerson 1987, Reeder and Sabey 1987, Enright and Lamont 1992, Prosser and Roseby 1995).

Sand processing also produces a waste product known as spoil which consists primarily of unwanted sand particle sizes with small amounts of

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impurities (e.g., soil organic matter). Spoil is typically spread over disturbed areas prior to revegetation efforts (A. Slater, Standard Sand Co., Fairmont Minerals, Grand Haven, MI, pers. comm.).

Although some dune species will colonize previously mined lands, rates of succession in these areas are incredibly slow (Maun and Krajnk 1989, Bowles et al. 1990). Therefore, reclamation efforts involving soil quality improvements and revegetation are necessary in order to assist the recovery of degraded sand dunes (Pichtel et al. 1994, Choi and Pavlovic 1998, Cummings et al. 2005).

Previous research has shown that the addition of soil amendments including paper de-inking sludge, compost, and inorganic fertilizer positively affect plant germination and growth due to increases in nutrient and soil water availability (Maun and Krajnyk 1989, Choi and Pavolic 1998, Fierro et al. 1999, Curtis and Classen 2007). Among plant functional groups, warm-season grasses and legumes are recommended for sand mine revegetation based on their ability to tolerate the hot, dry, and infertile conditions often found in former sand and gravel mines (Gaffney and Dickerson 1987, MacDonald et al. 2003). Legumes exhibit the added benefit of atmospheric nitrogen fixation (Gaffney and Dickerson 1987, Palmgren 2000).

This study evaluates the germination and initial growth of 2 native legumes, sundial lupine (*Lupinus perennis*) and Illinois bundleflower (*Desmanthus illinoensis*), and 2 native warm-season grasses, Indian grass (*Sorghastrum nutans*) and little bluestem (*Schizachyrium scoparium*). We evaluated germination and growth in pots under the influence of 2 soil amendments (inorganic fertilizer and sphagnum peat moss) added to spoil from a local sand mine and propagated under greenhouse conditions. We chose species based on their ability to limit soil erosion, increase soil nitrogen via nitrogen fixation, and reported success in previous mine revegetation efforts (Jefferies et al. 1981, Gaffney and Dickerson 1987, Palmgren 2000). We chose spoil amendments based on their ability to improve soil quality through nutrient additions (fertilizer) and soil water retention (peat moss). Soil nitrogen is particularly important in the reestablishment of degraded plant communities because it enhances the capacity of the ecosystem to support a more complex community (Tilman 1988, Callaway 1995, Callaway and Walker 1997). We also considered commercial availability when choosing these species and amendments.

Our objectives were to: 1) determine which of the evaluated species exhibit the greatest germination success and biomass accumulation; and 2) identify which spoil amendments, if any, positively affect seed germination and initial plant growth. Although reclamation of former sand mines is required by federal, state and provincial law throughout the Great Lakes Basin (e.g., United States Surface Mining Control and Reclamation Act of 1977; Chapter NR 135, Wisconsin Administrative Code; Michigan Natural Resources and Protection Act 451 of 1994; Ontario Mining Act of 1990), relatively little guidance is afforded in the literature. This study is useful in identifying plant species that may be appropriate for revegetation efforts at the regional scale while also providing insight into spoil amendments and plant functional groups (i.e. warm-season grasses, legumes) that may be appropriate for sand mine reclamation efforts at the global scale.

Methods

Study Species

We evaluated sundial lupine, Illinois bundleflower, Indian grass, and little bluestem for their potential use in sand mine reclamation. All species are native to the Great Lakes Basin and adapted for growth in well-drained, medium to dry, infertile soils including sands (USDA—NRCS 2011). Although little bluestem and sundial lupine are found locally in sand dunes or similar habitats (e.g., sand prairies), Illinois bundleflower and Indian grass are not characteristic species in these habitats (Kost et al. 2010). Therefore, it is important to note that the species used in this experiment are evaluated for their potential use in sand mine reclamation and would not satisfy restoration goals where only species that are characteristic of sand dune plant communities are acceptable.

Spoil

We obtained sand mine spoil from the Standard Sand Co., Fairmont Minerals, Grand Haven, MI. Spoil pH was determined from a 1:1 spoil/deionized water solution using a mini lab pH meter (IQ Scientific Instruments Inc., Carlsbad, CA). Mean spoil pH in non-amended spoil was 8.2 (H+ conc. = 6.3×10^{-9}; *N* = 7); mean spoil pH in spoil amended with peat was 6.2 (H+ conc. =6.3×10^{-7}; *N* = 7).

Spoil organic matter determination follows the Loss-On-Ignition method; samples were ignited in a muffle furnace for 5 h at 500°C (Nelson and Sommers 1996). Mean organic matter in non-amended spoil was 1.1% (*N* = 5); mean organic matter in spoil that contained peat was 5.2% (*N* = 5).

Spoil nitrate (NO_{3-}) was determined via ion chromatography (DIONEX DX 500 Chromatography System, Sunnyvale, CA) of an extraction from 15.0 g of spoil mixed with 100 ml of 2M KCl (Binkley and Vitousek 1991). Mean nitrate in non-amended spoil was 0.48 mg/L (range = 0.40–0.57 mg/L; *N* = 3); mean nitrate in spoil amended with fertilizer only was 1.15 mg/L (range = 1.11–1.22 mg/L; *N* = 3); mean nitrate in spoil amended with peat only was 0.52 mg/L (range = 0.39–0.77 mg/L; *N* = 3); mean nitrate in spoil amended with both peat and fertilizer was 1.31 mg/L (range = 1.28–1.34 mg/L; *N* = 3).

Experimental Design

Growth of each species from seed in sand mine spoil, with or without sphagnum peat moss and inorganic fertilizer, was evaluated using a 2 × 2 factorial array of spoil amendments which resulted in the following treatments: +peat/+fertilizer, +peat/-fertilizer, -peat/+fertilizer, -peat/-fertilizer (control). Spoil and amendments were mixed and added to sterilized 90 cm^2 × 8 cm-deep square pots. Total spoil and amendment volume was 400 ml. The +peat/+fertilizer treatment received 200 ml of spoil, 200 ml of sphagnum peat moss (Premier Horticulture Inc., Redhill, PA), and 0.6 g of 12-5-7 nitrogen-phosphorus-potassium (NPK) fertilizer (Ultra Vigoro Fertilizer, United Industries Corp, St. Louis, MO). The amount of fertilizer added corresponds to an application rate of 741 kg ha^{-1} (88.9 kg N, 16.3 kg P, and 43.0 kg K). The +peat/-fertilizer treatment consisted of 200 mL of spoil and 200 mL of peat. The -peat/+fertilizer treatment consisted of 400 mL of spoil and 0.6 g of fertilizer. The control treatment consisted of 400 mL of spoil only. Ten replicates of each treatment were used for each species for a total of 160 pots.

Growth/Harvest

Planting occurred on 19 January 2009. Seeds of sundial lupine and Illinois bundleflower were scarified with sandpaper and inoculated with *Rhizobium* spp. bacteria prior to planting. Sundial lupine seeds were cold-moist stratified for 3 d at 4°C in a 50/50 mix of damp sand/seed prior to planting. Seeds of Indian grass and little bluestem did not receive any treatment prior to planting. Seeds of all species were obtained from Prairie Moon Nursery, Winona, MN. Five seeds of each species were planted at a depth of 1 cm in each pot. Each pot contained a piece of shade cloth at the bottom to prevent spoil loss during watering. Pots were placed on tables in a greenhouse at Grand Valley State University, Allendale, MI.

Each pot received 29 mL water/d for the first 3 wks followed by 105 ml water/wk thereafter. Natural sunlight was supplemented with fluorescent grow lights to provide a total of 14 h of sunlight/day. The latter watering rate corresponds to the average weekly rainfall between April and August in Ottawa County, MI., while light exposure corresponds to the average day length between April and May in the area (Pregitzer 1972). The greenhouse was maintained at 22–24°C throughout the experiment, and we randomized the location of each pot throughout the greenhouse tables at each watering.

Plants were harvested on 23 March 2009. Extraction involved gently prying the plant and root ball from the spoil with the aid of a spoon. Roots were then rinsed with deionized water. After extraction, roots and shoots were separated, dried at 70°C for 48 h, and weighed.

Percent germination was calculated as the total number of seedlings per pot, including zeros, divided by the number of seeds planted. Mean root, shoot, and total weight were calculated as the total weight per pot divided by the number of seedlings within each pot. Chi-square analysis indicated that root, shoot, and total biomass were not significantly affected by seedling density (root: χ^2=0.0015, *df*=97, p>0.050; shoot: χ^2=0.0084, *df*=97, p>0.050; total: χ^2=0.0067, *df*=97, p>0.050). Differences in species germination and biomass accumulation among spoil amendments for all species combined and among spoil amendments within each species were analyzed with a GLM univariate two-way analysis of variance (ANOVA) with peat and fertilizer as fixed factors. Analyses among species were analyzed using a one-way ANOVA. Tukey's honest significant difference test (HSD) was used for post-hoc comparisons. Data were square root transformed where appropriate in order meet assumptions of parametric statistical analysis (Sokal and Rolf 1995). A non-parametric two-way analysis of variance (ANOVA; Schreirer-Ray-Hare) was used to examine differences in biomass among spoil amendments within each species for data that did not meet parametric assumptions despite transformations (Dytham 2003); a non-parametric Mann-Whitney *U* test was used to examine differences in total biomass among species. SPSS 14.0 for Windows was used for all statistical analyses.

Results

Germination differed significantly among species when all treatments are combined (F=15.942, *df*=3,156, p<0.001). Similarly, root, shoot, and total biomass also differed significantly (root: χ^2=34.351, *df*=3, p<0.001; shoot: F=28.140, *df*=3,94, p<0.001; total: χ^2=47.800, *df*=3, p<0.001). Comparisons among species show that mean germination was highest for Illinois bundleflower at 39% which was significantly greater than all other species (p<0.001; Table 1). Mean root, shoot and total biomass per plant for Illinois bundleflower was significantly greater than little bluestem (p<0.001); mean shoot biomass was significantly greater than Indian grass (p<0.050; Table 2).

Sundial lupine exhibited the second highest overall germination success at 21% (Table 1). Mean shoot biomass at 0.039 g and mean total biomass at 0.051 g were significantly greater than all other species (p<0.001); mean root biomass for sundial lupine was significantly greater than Illinois bundleflower and little bluestem (p<0.001; Table 2).

Comparisons among treatments across all species show that peat positively affected germination. Mean seed germination was 25.3% with peat compared to 18% without peat (F=4.478, *df*=1,156, p<0.050). The addition of peat or fertilizer positively affected root, shoot and total biomass. Mean root biomass per plant was 0.011 g in the presence of peat compared to 0.006 g in its absence (F=7.544, *df*=1,94, p<0.010). Mean

Table 1. Mean germination (% ± 1 SE) among species and spoil amendment treatments. Treatment codes: +P, +F = addition of peat or fertilizer, respectively; -P, -F = absence of peat or fertilizer, respectively.

Species	Overall	+P/+F	+P/-F	-P/+F	-P/-F
Lupinus perennis	21% ± 3.6	22% ± 3.6	42% ± 8.7	8% ± 5.3	12% ± 5.3
Desmanthus illinoensis	39% ± 3.4	52% ± 5.3	40% ± 6.7	28% ± 6.8	36% ± 7.2
Sorghastrum nutans	14% ± 2.5	16% ± 5.8	4% ± 2.7	18% ± 5.5	20% ± 4.2
Schizachyrium scoparium	12% ± 2.6	16% ± 7.2	10% ± 4.5	8% ± 4.4	14% ± 4.3

Table 2. Mean root, shoot, and total biomass per plant (g ± 1 SE) among species and spoil amendment treatments. Treatment codes: +P, +F = addition of peat or fertilizer, respectively; -P, -F = absence of peat or fertilizer, respectively.

Species	Overall	+P/+F	+P/-F	-P/+F	-P/-F
Lupinus perennis					
Root	0.012 ± 0.001	0.014 ± 0.002	0.010 ± 0.002	0.011 ± 0.007	0.012 ± 0.002
Shoot	0.039 ± 0.003	0.048 ± 0.003	0.034 ± 0.008	0.041 ± 0.001	0.030 ± 0.004
Total	0.051 ± 0.004	0.062 ± 0.004	0.045 ± 0.009	0.052 ± 0.008	0.041 ± 0.005
Desmanthus illinoensis					
Root	0.006 ± 0.001	0.007 ± 0.001	0.006 ± 0.001	0.005 ± 0.001	0.007 ± 0.001
Shoot	0.020 ± 0.001	0.028 ± 0.002	0.018 ± 0.002	0.016 ± 0.002	0.016 ± 0.002
Total	0.026 ± 0.002	0.035 ± 0.003	0.024 ± 0.003	0.021 ± 0.003	0.023 ± 0.003
Sorghastrum nutans					
Root	0.012 ± 0.005	0.032 ± 0.016	0.007 ± 0.005	0.008 ± 0.004	0.002± 0.001
Shoot	0.014 ± 0.004	0.031 ± 0.011	0.006 ± 0.004	0.012 ± 0.003	0.005 ± 0.001
Total	0.026 ± 0.009	0.061 ± 0.027	0.013 ± 0.009	0.020 ± 0.007	0.008 ± 0.001
Schizachyrium scoparium					
Root	0.003 ± 0.001	0.004 ± 0.001	0.003 ± 0.001	0.001 ± 0.001	0.003 ± 0.001
Shoot	0.009 ± 0.002	0.016 ± 0.003	0.008 ± 0.004	0.005 ± 0.003	0.006 ± 0.002
Total	0.012 ± 0.002	0.020 ± 0.003	0.011 ± 0.004	0.006 ± 0.004	0.009 ± 0.002

shoot biomass was 0.028 g in the presence of peat and 0.026 g in the presence of fertilizer compared to 0.014 g and 0.017 g in the absence of peat or fertilizer, respectively (peat: F=19.762, df=1,94, p<0.001; fertilizer: F=5.763, df=1,94, p<0.050; Figure 1). Mean shoot:root ratio for plants growing in non-amended spoil was 2.70 (N = 26) and 3.66 for plants growing in spoil containing fertilizer (N = 48). Mean total biomass was 0.038 g in the presence of peat and 0.037 g in the presence of fertilizer compared to 0.019 g and 0.023 g in the absence of peat or fertilizer, respectively (peat: F=16.157, df=1,94, p<0.001; fertilizer: F=5.272, df=1,94, p<0.050; Figure 1).

Comparisons among treatments indicate that the germination of sundial lupine was positively affected by the addition of peat. Mean seed germination was 32% with peat and 10% without peat (F=18.651, df=1,36, p<0.001; Table 1). However, mean root, shoot, and total biomass per plant were not significantly affected by the addition of any spoil amendment.

Illinois bundleflower germination was positively affected by peat, while peat and fertilizer interacted to positively affect shoot and total biomass. Mean seed germination was 46% with peat and 32% without peat (F=4.594, df=1,36, p<0.050; Table 1). Mean shoot biomass per plant was 0.028 g in the presence of peat and fertilizer compared to 0.016 g and 0.017 g, respectively, in their absence (F=4.602, df=1,31, p<0.050). Mean shoot biomass in the control was 0.016 g. The presence of peat and fertilizer individually also had a positive effect on shoot biomass (+peat = 0.023 g vs. –peat = 0.016 g, F=11.842, df=1,31, p<0.010; +fert = 0.022 g vs. –fert = 0.017 g, F=4.728, df=1,31, p<0.050). Mean total biomass was 0.035 g in the presence of peat and fertilizer compared to 0.022 g and 0.023 g in the absence of peat or fertilizer, respectively (F=5.108, df=1,31, p<0.050). Mean total biomass in the control was 0.023 g for Illinois bundleflower. Peat alone increased mean total biomass (+peat = 0.030 g vs. –peat = 0.022 g, F=7.435, df=1,31, p<0.050; Table 2).

Germination was similarly low for both Indian grass and little bluestem, and spoil amendments did not significantly affect the germination of either species (Table 1). Growth of Indian grass was positively affected by the addition of fertilizer, with mean shoot biomass per plant at 0.021 g with fertilizer compared to 0.005 g without fertilizer (F=7.183, df=1,18, p<0.050; Table 2).

Little bluestem exhibited the lowest total biomass among species and was positively affected by the addition of peat. Mean shoot biomass was 0.012 g in the presence of peat compared to 0.006 g in its absence (F=4.823, df=1,13, p<0.050), while mean total biomass was 0.016 g in the presence of peat compared to 0.008 g in its absence (F=5.439, df=1,13, p<0.050; Table 2).

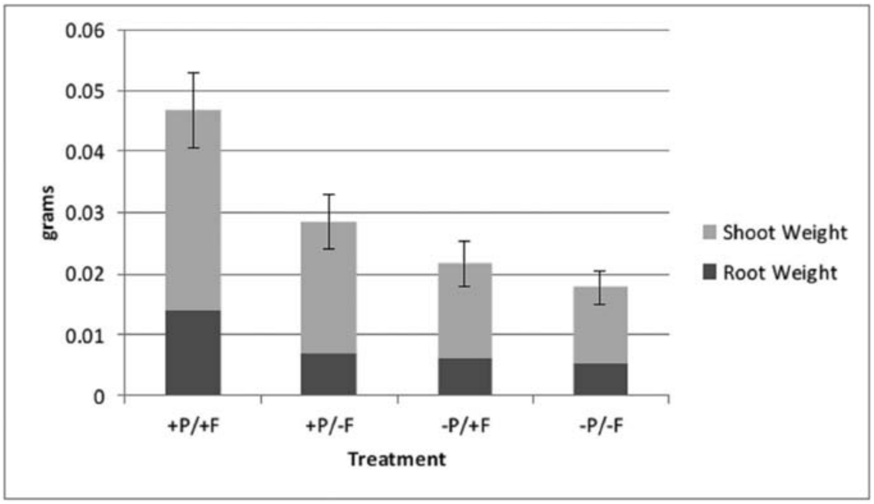

Figure 1. Mean root, shoot, and total biomass per plant (g ± 1 SE) among spoil amendment treatments for all species combined. Treatment codes: +P, +F = addition of peat or fertilizer, respectively; -P, -F = absence of peat or fertilizer, respectively.

Discussion

Results show that sundial lupine exhibited the greatest growth among species and was second only to Illinois bundleflower in germination success (21%), and therefore it should be considered a potential candidate for the reclamation of sand mines. Interestingly, this germination success is considerably lower than observations in field trials (~80%; St. Mary 2007, Pavlovic and Grundel 2009), suggesting that sundial lupine may exhibit better establishment under field conditions compared to greenhouse conditions.

Other practitioners have had success using sundial lupine for the revegetation of mine spoils due, in part, to its nitrogen fixing ability. The subsequent addition of plant-available nitrogen (NH_4+ and NO_3-) to the soil through leaf decomposition results in up to 295 kg/ha of additional soil nitrogen per yr and can facilitate the establishment of other species on mine spoils (Jefferies et al. 1981).

Another benefit of sundial lupine is its use as a larval food source for the federally endangered Karner blue butterfly (*Plebejus melissa samuelis*; Smallidge et al. 1996, Grundel et al. 1998), which has historically occupied the barrens and savannas of the Great Lakes region. Although habitat limitation is only one of several factors limiting the distribution of Karner blue butterfly populations (Andow et al. 1994), revegetating sand mine sites in the Great Lakes region with sundial lupine can ameliorate habitat loss and may ultimately contribute to Karner blue butterfly conservation and management efforts.

Although we recommend sundial lupine for sand mine reclamation, it is not without potential disadvantages. In low-light environments, sundial lupine exhibits lower abundance, growth, and survival (Smallidge et al. 1996, Grundel et al. 1998, Pavlovic and Grundel 2009). Under more hospitable growing conditions, congeners of sundial lupine [i.e. yellow bush lupine (*L. arboreus*)] have been shown to inhibit the growth of other species through shading. Therefore periodic burning or mowing may be required to reduce its competitive effect on other plants (Gosling 2005). Yellow bush lupine also elevates soil fertility; this coupled with its frequent death produces open, nitrogen enriched patches that are ideal sites for colonization by non-native grasses and forbs (Marons and Connors 1996). Therefore, given its ability to increase soil nitrogen, sundial lupine, and our other legume species Illinois bundleflower, could facilitate the establishment of undesirable plant species.

Illinois bundleflower should also be considered a candidate species for revegetation efforts based on its high average germination success (39%) and relatively high shoot growth. Other researchers have observed much higher germination success in laboratory settings (i.e. 96%; Call 1985), while others have found lower or similar germination success in field trials (i.e. 4–44%; Dovel 1990) suggesting that site-specific evaluation of germination success may be necessary prior to large scale revegetation efforts.

Another benefit to Illinois bundleflower is its ability to fix nitrogen, which can facilitate the establishment of other species in low nutrient environments where ecosystem development is dependent upon the accumulation of nitrogen to enable the growth of non-fixing species (Crocker and Major 1955). Soil nitrogen deficiency is a major factor limiting plant growth on spoils produced from the extraction of minerals. In nutrient poor soils, legumes have been shown to perform well when compared to non-legume species (Elias and Chadwick 1979, Imsande and Touraine 1994). In high soil nitrogen environments, legumes exhibit reduced nitrogen-fixing abilities (Lang et al. 1993, Rubio Arias et al.1999) which would limit the facilitative effect by legumes.

The 2 non-legume species evaluated in our study did not exhibit high levels of germination or growth. Despite low growth, however, results show that the addition of peat had a significantly positive impact on little bluestem growth. Indian grass also exhibited greater growth in the presence of peat compared to growth without peat, but these results were not statistically significant (Table 2). Results may be due, in part, to spoil pH. Soil pH of ≥5.5 is recommended for optimal growth of warm-season grasses (Dickerson et al. 1998). Spoil amended with peat exhibited a mean pH of 6.2 while unamended spoil had a pH of 8.2, suggesting that peat amended spoil provides a more favorable soil pH for the growth of these grasses.

Despite the poor results exhibited here, warm-season grasses can be an important component of sand mine reclamation. Gaffney and Dickerson (1987) found that warm-season grasses were the most successful in revegetating former sand mines over an 8 yr period, compared to legumes and cool-season grasses. Previous research also suggests that warm-season grasses may perform better than observed here. From a prescribed fire management perspective, a significant proportion of grasses are necessary for facilitating effective fires in plant community restoration projects (Packard and Mutel 1997). Furthermore, bunch grasses are effective barriers against soil erosion (Dabney et al. 1993, Dewald et al. 1996).

Among spoil amendments, peat exhibited the greatest positive effect on germination, root, shoot, and total biomass. Peat had a significant effect on sundial lupine and Illinois bundleflower germination and positively affected the growth of Illinois bundleflower and little bluestem. The positive impact of peat may be attributed to an increase in soil porosity and water holding capacity when peat is added to sandy soil (Sjors 1980, Ling et al. 2005). Peat also increased mean spoil acidity; however, the addition of peat did not change acidity beyond the tolerable range for most vascular plants (i.e. pH 3.5–8.5; Larcher 1995). While our study did not separate the individual effects of pH and water holding capacity on plant growth, our results indicate that any negative impact on growth that may have occurred from acidification by peat was apparently eclipsed by the overall positive impact by peat.

Although our results show that peat moss may promote initial growth and establishment of plant species used in sand mine revegetation efforts, we do not recommend peat as a spoil amendment due to negative environmental effects. Globally, the number of peat bogs has decreased substantially due to peat harvest which results in significant long term impacts on regional plant and animal diversity (Rochefort 2000, Mitchell et al. 2002, Suret et al. 2002). The loss of these ecosystems also results in the loss of important carbon sequestration sites. Peatlands are historic importers of CO_2 and represent a major global source of stored carbon (Gorham 1991). Peat mining decreases carbon sequestration capacity by up to 37% and effectively transforms these areas from carbon sinks to carbon sources (Heathwaite 1993, Cleary et al. 2005).

Rather than focusing on peat as a specific water holding soil amendment, we instead stress the importance of water retention in sandy mine spoils and suggest the use of alternative amendments to peat that are functionally equivalent. Alternatives include coconut fibers, green compost such as grass clippings, leaves, pumice, pine bark, sewage sludge, and de-inking sludge (Fierro et al. 1999, MacDonald et al. 2003, Larcher and Scariot 2010). Coconut coir dust ("cocopeat") is an abundant agricultural by-product that increases soil water availability when incorporated into xeric soils (Awang et al. 2009). Similarly, paper de-inking sludge positively impacts plant growth due to increases in soil water retention and bulk density (Fierro et al. 1999). Fertilizer did not significantly improve germination of any species; however, it did positively impact shoot and total biomass for Illinois bundleflower and Indian grass (both alone and in conjunction with peat for Illinois bundleflower). Further, an examination of shoot:root ratios indicate that the addition of fertilizer did not result in physiological drought which can be due to excessive fertilizer application. Shoot:root ratios typically decrease in response to deficiencies in nutrients or water (Wilson 1988). In comparing shoot:root ratios between non-amended spoil to spoil amended with fertilizer, we observed an increase in this ratio indicating an absence of drought and further illustrating the positive impact of fertilizer compared to non-amended spoil.

Fierro and others (1999) also found that fertilizer increased the growth of sand dune species, while other researchers have found that germination is only enhanced in the presence of fertilizer when used in conjunction with frequent irrigation (Lichter 2000). In contrast to our results, Masters and colleagues (1993) found that fertilization increased germination of Indian grass and little bluestem, while Van Auken and others (1992) found that little bluestem grew well under high levels of soil nitrogen. Gaffney and Dickerson (1987) found that legumes did not respond to fertilizer amendments whereas our results indicate that fertilizer increased Illinois bundleflower growth both alone and in combination with peat.

Identifying species that do not require spoil amendments for growth is an important practical consideration when restoring degraded habitats that may be large, inaccessible, or may lack the necessary resources for amendment purchase and incorporation. To this end, we strengthen our recommendation of sundial lupine as a primary candidate for sand mine revegetation efforts because it exhibits positive growth responses in the absence of fertilizer or peat amendments. While we recognize the positive impacts of inorganic fertilizer on initial species establishment of Indian grass and Illinois bundleflower, we do not recommend the use of this amendment. Instead, we recommend the use of sundial lupine or other legumes as a source of soil nutrient additions due to their nitrogen fixing ability (Jefferies et al. 1981). Nutrient additions beyond those provided by legumes may promote competitive dominance by a few species and result in decreased plant community diversity over time (Tilman 1982, 1988, Stevens et al. 2006).

Furthermore, considering increases in global nitrogen emissions, the addition of inorganic fertilizer may not be necessary for plant establishment.

Global nitrogen emissions have grown over the past 150 yr, primarily due to anthropogenic activity, from approximately 31 Tg N $^{-1}$ in the 1860s to a recent estimate of 124 Tg N $^{-1}$. Total nitrogen emissions are expected to continue increasing and reach 195 Tg N $^{-1}$ by 2050 (Fowler et al. 2004, Galloway et al. 2004). Therefore, additional nitrogen inputs via inorganic fertilizer should be carefully considered in areas that exhibit increased nitrogen deposition.

While our results elucidate the important role particular species and spoil amendments may play in sand mine reclamation efforts, recommendations should be viewed in light of the limitations of this experiment. Our experiment evaluates seedling establishment under greenhouse conditions. Results would likely have been vastly different given a longer period of growth or if our evaluation had been conducted under field conditions. For example, while our results indicate that legumes exhibited the greatest initial growth when compared to warm-season grasses, other researchers working with little bluestem and Indian grass under field conditions found that these species eventually become dominant components of the plant community (Dickerson et al. 1998). Our experiment also controlled for other important variables including water availability, seed density, seed predation, herbivory, intra- and interspecific competition. While these variables can be difficult to control in a field environment, a practitioner can help alleviate some of the potential problems associated with these factors. For example, a field application could incorporate artificial irrigation, transplanted seedlings, seedling protection from herbivores, and site preparation and management to help reduce interspecific competition.

Species selection should also be viewed with discretion considering Illinois bundleflower and Indian grass are not typically found in sand dune habitats (Kost et al. 2010). While these species would not satisfy restoration goals where only characteristic species of sand dune plant communities are acceptable, these species provide erosion control and soil nitrogen and organic matter additions which can facilitate future colonization of more characteristic species. Furthermore, the species evaluated here should not be viewed as the only possible candidate species for revegetation efforts nor do we recommend establishing monospecific stands of any of these species. Instead, these species should be considered as potential components of a diverse native species mix.

Despite these limitations, our results are helpful in determining which species and amendment combinations are potentially useful in revegetating former sand mines or similar habitats. Specifically, sundial lupine and Illinois bundleflower are recognized as potential candidate species for revegetation efforts in mine reclamation. We further recognize the importance of incorporating soil amendments into mine spoils that help to increase soil water holding capacity.

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