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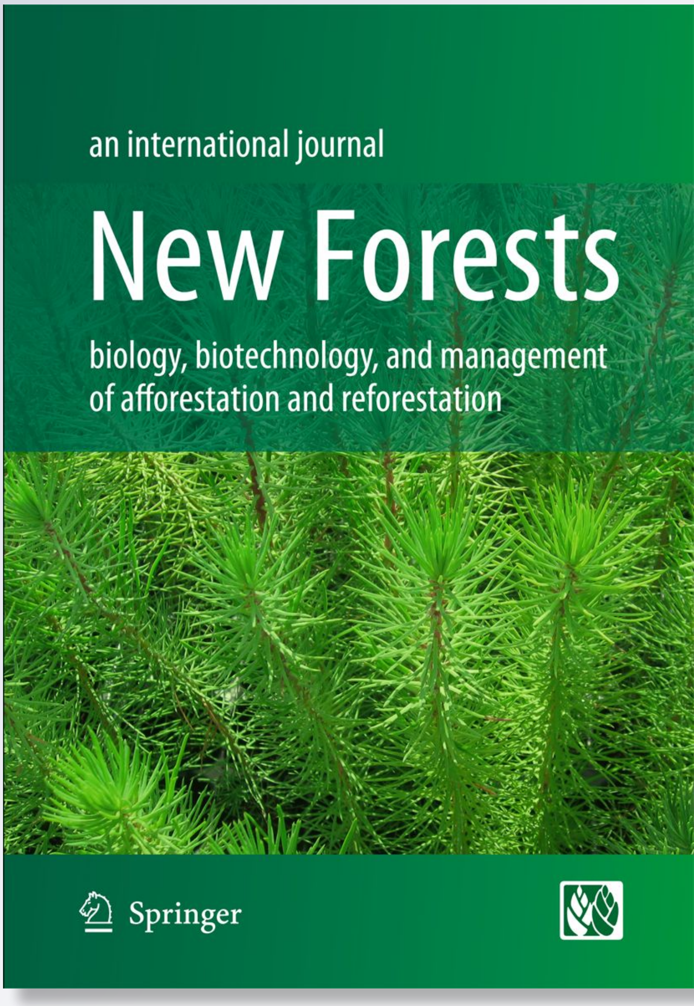

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Influence of herbaceous ground cover on forest restoration of eastern US coal surface mines

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Abstract Competitive effects of dense herbaceous vegetation (ground cover) can inhibit forest restoration on mine sites. Here we review the evidence of ground cover interactions with planted tree seedlings on coal surface mines of the eastern US, discuss recent research into these interactions, and draw conclusions concerning ground cover management when restoring forests on reclaimed coal mines. Reclaimed mine sites have a high potential to support productive forests, however forest establishment is inhibited by reclamation practices that included soil compaction, and the seeding of competitive ground covers. In the first few years after tree planting, a dense ground cover of grass and legume species commonly seeded on mine sites often affect growth and survival negatively. Herbaceous vegetation providing less extensive and competitive ground coverage may either facilitate or inhibit tree establishment, depending on site conditions. The use of quality planting stock promotes the competitive ability of seedlings by improving nutrient status and the ability to capture available resources. Herbaceous species have contrasting functional characteristics, and thus compete differently with trees for available resources. Negative

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interactions with trees are more frequently reported for non-native cool-season grasses than for native warm-season grasses, while the effects of legumes change over time. Further research is needed to fully understand the mechanisms of tree/ground cover interactions. The development of seeding mixes that can control erosion, facilitate survival and growth of planted trees, and allow establishment by unplanted native species would aid forest restoration on eastern US, coal mines.

Keywords Hardwoods · Competition · Grass · Legumes · Mine reclamation · Site preparation

Introduction

Dense herbaceous vegetation can result in the failure of forest regeneration in a number of circumstances, such as after timber harvest (George and Bazzaz 2003), in abandoned agricultural fields, and on mine sites (Davidson et al. 1984). Herbaceous vegetation can present a considerable challenge to forest management, particularly where herbaceous growth rates are high. Tree species differ in their degree of inhibition by herbaceous cover, with ground cover type also having differential effects (George and Bazzaz 2003). To ensure regeneration success, some form of competition control is required in the early years of stand development (Erdmann 1967; Seifert et al. 2007). For instance, regrowth of cherry (*Prunus serotina* Ehrh.) and maple (*Acer rubrum* L. and *A. saccharum* Marsh.) was much greater when herbaceous competition was controlled after timber harvest (Horsley and Marquis 1983). In areas where topsoil has been removed, such as reclaimed mine sites, an herbaceous ground cover is often seeded as part of the restoration plan.

Large areas of land have been affected by coal surface mining in the eastern US (Fig. 1), and forest restoration is a societal concern. Extensive areas were mined prior to the Surface Mining Control and Reclamation Act (SMCRA), a national law that mandates reclamation of coal mines. The SMCRA requires miners to "restore the land affected to a condition capable of supporting the uses that it was capable of supporting prior to any mining, or higher or better use …" [Sec. 515(b)(2)]. More than 7,000 km^2 have been mined within the region under SMCRA, and >100 km^2 are being mined each year (US OSM 2010).

Soil materials are sometimes salvaged and used for soil construction on mines in this region, but fragmented geologic materials, known as mine spoils, are also used in some cases to construct surface media that become mine soils (Haering et al. 2004; Daniels and Amos 1985). Historically under SMCRA, mine soil materials are often graded smoothly with the intent of stabilizing the surface so as to prevent erosion, a procedure that compacts the soil. After grading, mine sites are generally seeded with a mixture of herbaceous species (typically, agricultural grasses and legumes), applied by hydroseeding along with fertilizer, and lime if needed. If shrubs or trees are prescribed, these are generally planted as bare-root seedlings within the hydroseeded area. Mine reclamation often initiates revegetation with a bare substrate, because the original vegetation has been removed by the mining process. Fast-growing and aggressive ground covers are often used on reclaimed minesites because the rapid establishment of herbaceous ground cover can aid in limiting erosion. These dense herbaceous covers often compete strongly with tree seedlings for light and moisture, and can even overtop the seedlings. Mine sites also have abiotic limitations to forest restoration, such as poor soil chemical and physical properties; however, on many mine sites, soil and spoil materials with properties favorable to

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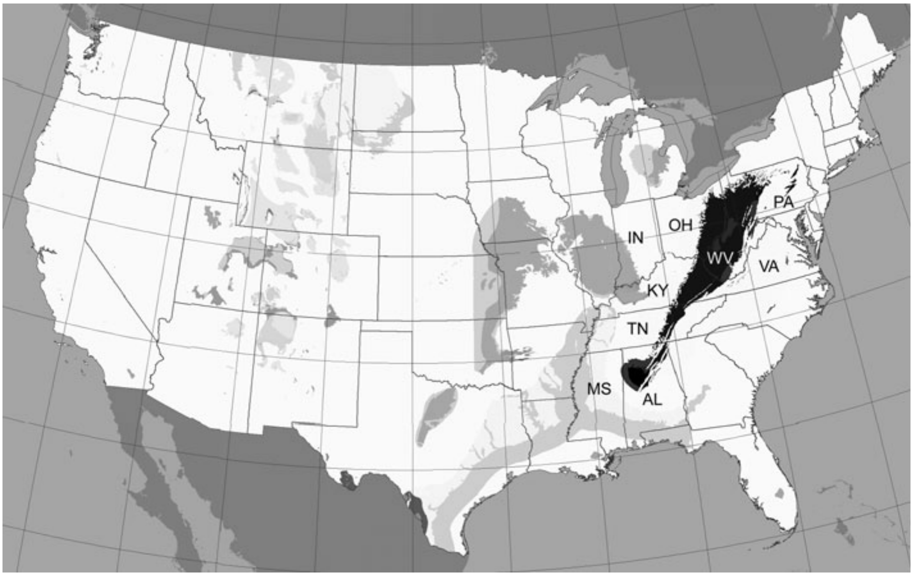

Fig. 1 Map showing coalfields of the US (*shaded areas*), and coal mining areas of the eastern US (*darkly shaded*)

establishment and growth of planted trees are available for mine soil-construction use (Skousen et al. 2011). While soil properties govern a reclaimed mine site's productivity over the long term, herbaceous vegetation initially exerts a strong influence over the potential for tree establishment and early growth.

Here we review the evidence of ground cover interactions with planted tree seedlings on coal surface mines of the eastern US, and draw conclusions concerning ground cover management when restoring forests on eastern US coal mines.

Evidence of tree-ground cover interactions on reclaimed mine sites

Early reclamation on coal mine sites

The first reported forest restoration research on mined lands began in the 1920s, and a number of short-term studies were undertaken in the 1940s and 1950s (Zeleznik and Skousen 1996); collectively, these early findings demonstrate the relative importance of competitive interactions to the success of mine reclamation. Reclamation in the eastern US in the 1960s through 1970s often involved tree planting, with or without seeding of herbaceous cover. A wide variety of tree species, native and non-native hardwoods and softwoods, were tested with varying success. Norway spruce (*Picea abi*es L. Karst) and three pine species (*Pinus* spp.) grown on Tennessee minesites with a cover crop of Korean clover (*Kummerowia stipulacea* (Maxim.) Makino) alone, had survival rates of 18–77 % after 9 years, but surviving trees had growth rates similar to those on un-mined land (Evans and Buckner 1978).

The rationale for establishing an herbaceous cover concurrently with tree planting, and the challenges inherent in this approach, were recognized more than 30 years ago

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(Vogel 1980). The seeding of non-native grasses and legume species with readily available seed, and the mining firms' capabilities to establish herbaceous vegetation rapidly increased through the 1960s and 1970s. The long-term persistence of such ground cover species, and consequent effects on forest establishment, have been documented in several studies. On five sites in Kentucky where mining had been completed in the 1960s, black locust (*Robinia pseudoacacia* L.) seeded during reclamation was no longer dominant in 1986, having been replaced by a diverse assemblage of tree species (Thompson and Wade 1991). Of the planted herbaceous species, tall fescue (*Schedonhorus phoenix* (Scop.) Holub var. Kentucky-31), and *Lespedeza* species were infrequent on the sites, but the warm-season grasses planted on two of the sites, switchgrass (*Panicum virgatum* L.) and big bluestem (*Andropogon gerardi* Vitman), remained. Two non-native planted legumes, perennial pea (*Lathyrus sylvestris* L.) and crown vetch (*Securigera varia* (L.) Lassen), were reported to have spread and inhibited invasion of woody plants. Crown vetch was also reported to be persistent and highly aggressive on a minesite in Illinois (Ashby et al. 1989), where Kentucky-31 fescue, Canada bluegrass (*Poa compressa* L.), and smooth brome (*Bromus inermis* Leyss.) were also found to occupy areas larger than their original plantings after 6 years. In contrast, tall fescue was the only ground cover species that remained of 15 species seeded on a site in Ohio and, although it dominated on most plots, the abundance of several tree species had increased in the 31 years since planting (Carter and Ungar 2002). However, seeded ground covers may have long-term effects on forest development by reducing diversity and biomass accumulation (Wade 2002).

Skousen et al. (1994) studied vegetation on 15 older mine sites in northern West Virginia. They found tree cover to be highly variable but responsive to soil conditions in a manner that suggested herbaceous vegetation interactions. Herbaceous communities were present on sites with soil pH > 5.0, while tree communities were dominant on those with pH < 5.0. On the pH > 5.0 sites, herbaceous plants rapidly invaded and formed an almost complete cover while few trees were present, likely due, in part, to the competitive effects of herbaceous species establishment. In contrast, native trees were dominant on the lower-pH areas where herbaceous competition was less evident. Working on three 20-year old mine sites, also in West Virginia, that had not been replanted with trees, Skousen et al. (2006) found that native Appalachian hardwood trees were able to establish on portions of those mines reclaimed prior to current regulations and therefore not seeded with herbaceous vegetation, while seeded areas supported only sparse tree cover several decades after reclamation.

Dense ground cover on mines reclaimed under SMCRA

With the enactment of SMCRA, new reclamation standards encouraged "smooth grading" of soils, which compacted soil surfaces, and herbaceous covers that were easily and quickly established (Angel et al. 2005). Commonly used seeding prescriptions were mixtures of cool-season grasses, such as tall fescue and orchardgrass (*Dactylis glomerata* L.) and legumes such as clover species (*Trifolium* spp.) that are well suited for agricultural uses such as hay and pastures, but also form dense covers that compete with tree seedlings for light, water and nutrients (Carpenter and Albers 1981). Sericea lespedeza (*Lespedeza cuneata* (Dum. Cours.) G. Don), a non-native legume, was often included in reclamation seed mixes, and has since proved to be invasive. Black locust was often sown along with the herbaceous cover. One study of a coal mine reclaimed using a conventional seed mix in the 1990s found black locust and non-native woody plants present on the site >10 years after reclamation, but cool season grasses and legumes planted as groundcover during

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reclamation remained dominant and colonization by native forest trees was not observed (Klemow et al. 2010). A study of 25 post-SMCRA mine sites in four Appalachian states found that herbaceous communities often dominated these sites 6–25 years after planting, with the seeded and invasive tall fescue and sericea lespedeza being most common (Zipper et al. 2011). Tree planting fell out of favor, as attempts to establish trees on mine sites reclaimed under SMCRA often resulted in high mortality and poor growth (Burger and Fannon 2009) due to both soil conditions (Conrad et al. 2002) and herbaceous cover.

Several treatments have been tested on these sites to reduce ground cover competition with planted tree seedlings. An eastern Kentucky study compared early-season clipping, herbicide application, and "scalping" of tall-fescue dominated ground cover (including surface roots); no planted seedlings survived through a single growing season where no vegetation control was applied, and only scalping treatments limited herbaceous competition throughout the growing season (Carpenter and Albers 1981). Recent efforts to rehabilitate post-SMCRA mines for forest restoration show that mechanical treatments such as deep tillage can aid tree establishment through two mechanisms: alleviation of soil compaction and a temporary reduction in ground cover (McCarthy et al. 2008). On a West Virginia mine site, five planted hardwood species had first-year survival rates of 95–100 % in areas treated with ripping that were also mowed monthly throughout the first growing season to control an established ground cover of tall fescue, orchardgrass, and bird's-foot trefoil (*Lotus corniculatus* L.) (Skousen et al. 2009). However over 7 years, mowing had no effect on the survival of three tree species, and a negative effect on two, which the authors attributed to a greater ground cover density that resulted from mowing. The reduction of groundcover from mechanical treatments is temporary, so a follow-up herbicide treatment can aid seedlings survival (Burger et al. 2011). Andersen et al. (1989) found survival of black walnut (*Juglans nigra* L.) and northern red oak (*Quercus rubra* L.) on Indiana mine sites was <5 % when planted into existing herbaceous cover with no ground cover control but increased to >50 % when ground cover was controlled with herbicide. After 12 years, surviving trees had significantly greater height growth with ground cover control (Chaney et al. 1995). Competition control alone is not sufficient on these mine reclamation sites, and research shows its use in addition to the alleviation of soil compaction is often necessary to achieve optimal tree establishment (Ashby 1997; Fields-Johnson et al. 2008).

Research on newly-reclaimed sites has found an interaction between soil compaction and ground covers. On plots planted with a mixture of five grasses including annual and perennial ryegrass (*Lolium perenne* L. and *L. perenne* L. ssp. *multiflorum* (Lam.) Husnot) and five legumes, grading intensity was not found to affect total ground cover percentage, but more intensive grading did result in an increased dominance of grasses, greater erosion rates, and decreased height growth of planted trees (Torbert and Burger 1994). A study of 10 experimental sites in Virginia, West Virginia, and Kentucky found that soil bulk density and ground cover, together, explained 71 % of the variation in tree stocking; although bulk density differences were responsible for most of this variability, herbaceous ground cover exerted a statistically significant influence (Auch et al. 2005).

New mine forest restoration methods for active mines

New guidelines for forest restoration on newly reclaimed mines recognize the important role played by ground cover. These guidelines, called the Forestry Reclamation Approach (FRA), were established and are disseminated through the Appalachian Regional Reforestation Initiative (ARRI), a cooperative effort between regulatory agencies and

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reclamation scientists (Angel et al. 2005). These guidelines call for creation of a suitable medium for tree growth with a minimum depth of 1.2 m, placement of this material on the surface with minimal compaction, seeding of tree-compatible ground covers, and planting of tree species suitable for timber production and for attraction of wildlife using proper tree planting techniques (Burger et al. 2005). Tall fescue may be too competitive with trees for restoration of mine sites, and species currently recommended as tree-compatible ground covers for reclamation in the eastern US include timothy (*Phleum pretense* L.), winter rye (*Secale cereale* L.), foxtail millet (*Setaria italic* (L.) P.Beauv.), redtop (*Agrostis gigantea* Roth.), perennial ryegrass, Kobe lespedeza (*Kummerowia striata* (Thunb.) Schindl.), bird's-foot trefoil, and white clover (*Trifolium repens* L.) (Burger et al. 2009). These species are sown at lower cumulative rates than conventional reclamation ground covers, are generally short in stature, and have a low water and nutrient demand, suggesting that they will not compete aggressively with planted tree seedlings.

While tree survival on sites reclaimed using the FRA are much improved over that of sites done using traditional post-SMCRA reclamation methods, some inhibitory effects of ground covers on tree establishment are still noted. Seeded ground cover reduced the survival of planted hardwood species on a West Virginia mine site by 12–33 %, depending on the soil type, compared to unseeded control plots (DeLong and Skousen 2010). On a Pennsylvania coal mine, where the seeding rate of bird's-foot trefoil with tall fescue or orchardgrass was reduced by 40 % below standard rates, first year survival of northern red oak, red maple (*Acer rubrum* L.), black birch (*Betula nigra* L.), and aspen (*Populus grandidentata* Michx.) was increased compared to results of standard seeding practices (Hughes et al. 1992). Herbicidal control of dense ground cover comprised of conventional mine reclamation species in the immediate vicinity of planted tree seedlings has been shown to be effective in promoting hardwood establishment and early growth (Burger et al. 2008), increasing tree volume growth by factors of 2.5–5 times over 5 years. Designing seed mixtures to create an herbaceous cover that provides maximum ecological benefit, with a minimal negative effect on tree survival or growth is a current need for successful mine reclamation. Better understanding of mechanisms driving tree-ground cover interactions will be essential for designing seed mixtures for successful forest restoration on reclaimed eastern US coal mines, and for the broader scope of forest restoration.

Mechanisms of tree-ground cover interactions

Trees interact with their herbaceous neighbors in a variety of direct and indirect ways by competing for space, light, water, and nutrients. Some woody and herbaceous species exude phytotoxins that affect some, but not all competitors. The intensity of these competitive interactions differs greatly between species pairs; the coincidence or separation in timing of their growth, the above- and below-ground zones that they occupy, and their relative levels of adaptation to the specific growth environment.

Direct, negative interactions are due to competition for light, water, and nutrients among plants occupying adjacent or overlapping spaces. Allelopathic interactions can also occur when compounds released by the roots or decaying foliage of one plant inhibit its neighbors. Direct, positive interactions, or facilitation, can occur when one plant alters the physical environment in ways that are beneficial to its neighbors. Within a community of vegetation, for example, reduced wind speed and increased humidity can reduce evaporative losses from leaves relative to those of an exposed plant. Shading of the soil surface reduces temperatures in the boundary-layer at the soil-air interface, which can reach lethal

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temperatures in the direct sun. Below-ground, the ongoing process of root growth and decay affects soil density and infiltration rates, and contributions of organic material from dead roots and the incorporation of above-ground litter increase the soil water-holding capacity. Root systems may also alter the soil hydrology by re-distributing water through hydraulic lift, and root exudates alter soil pH, affecting nutrient availability (Eviner and Chapin 2003).

Indirect effects occur above and below ground through organisms at all trophic levels that are associated with plant roots and shoots. These interactions are complex, but can exert both positive and negative influences on neighboring plants. At the base of the food web, the vegetative community greatly influences the herbivore community, which drives nutrient cycling (Wardle 2002). For instance, grazing mammals reduce foliar area, but increase nutrient availability through dung and urine. The microbial community associated with vegetation may fix atmospheric N or provide nutrients through decomposition of litter, but may also bind N making it unavailable to plants. The balance of competitive and facilitative effects shifts over time, and is related to plant size, age, and density (Callaway and Walker 1997), and to levels of abiotic stress (Bertness and Callaway 1994). Competition intensity is also related to nutrient availability and community composition (Elmendorf and Moore 2007).

Competition for resources

Minesoils derived from rock spoils are typically low in plant-available N and P. A study of ground cover establishment on tailings' impoundments in the Mid-western US found that low surface moisture and a lack of available P were related to poor ground cover establishment (White and Nairn 2007). On reclaimed mines, a water-soluble fertilizer is often applied as a part of the ground cover seeding mix, and aids in the establishment of herbaceous vegetation by providing plant-available N and P. Working in the high-rainfall area of the southeastern US, Buckley and Franklin (2008) found that the highest fertilization rate tested (448 kg/ha 10-20-20) resulted in the greatest establishment of seeded legumes (Korean clover and bird's-foot trefoil) and greatest colonization by volunteer ground cover species. However, fertilization can also stimulate rapid and vigorous growth of herbaceous ground covers, resulting in increased competition with planted trees (Ramsey et al. 2001). Higher N availability, in particular, may increase growth and competitive effects of herbaceous covers (Davis et al. 1999).

Strong competitive effects of herbaceous ground covers on tree seedlings due to competition for water would be expected in dry climates (Davis et al. 1999), but may also occur in more mesic climates, especially during dry periods and on coarsely-textured substrates with poor water-holding capacity. However, groundcover can also have a positive influence on a mine site's hydrologic properties. Working on sloping Virginia mine sites, Fields-Johnson et al. (2012) reported that water infiltration showed a strong positive correlation with the presence of living groundcover vegetation. One likely reason for this effect is that live stems both obstruct water runoff and penetrate the soil surface, providing channels to allow water movement through the surface to the subsurface, in contrast to unvegetated areas on mine sites where fine-textured spoils are often subject to surface crusting and high runoff.

Competition for light may occur when tree seedlings are young. The degree to which shading inhibits tree seedlings depends on the relative heights of trees and herbaceous cover, and on the species of tree. Berkowitz et al. (1995) found that the presence of herbaceous vegetation facilitated survival of shade-tolerant sugar maple seedlings planted

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on old fields in New York state, but the competing vegetation slowed growth of all other planted tree species. Also working in old fields, DeSteven (1991) found the shade-intolerant yellow-poplar (*Liriodendron tulipifera* L.) to be the only species for which survival was reduced by increasing herbaceous ground coverage, but height growth of all hardwoods tested was greatly reduced by ground cover competition. Ground covers with short stature are recommended for mine reclamation to forest (Burger et al. 2009). The degree to which shading influences tree seedlings also depends on the spatial structure of the herbaceous vegetation and its seasonality. A high degree of spatial heterogeneity and annual variations in the herbaceous community may facilitate the establishment of woody species (Jurena and Archer 2003).

The interaction between trees and ground covers changes over time: therefore it is important to note the seasonality and duration of competitive interactions, and to differentiate between effects on tree survival and on growth. On a newly planted site, herbaceous plants can modify the environment in a way that facilitates early survival of planted seedlings, but competition for resources can inhibit seedling growth. On a Kentucky mine site, ground cover up to 95 % had no effect on planted trees survival compared to control plots that lacked herbaceous cover, but tree growth was suppressed in the high groundcover plots over the first 3 years (Vogel 1973). During the growing season, ground covers compete with tree seedlings for available water and nutrients. Rizza et al. (2007a) found growing-season stress contributed significantly to mortality on a mine site in Tennessee, and attributed only 27–60 % of seedling death to planting stress, browsing injury, erosion, or overwintering. On newly reclaimed mine sites of the eastern US, levels of abiotic stress, and thus the balance between competition and facilitation between trees and herbaceous vegetation are likely to vary widely among sites due to differences in chemistry and water-holding capacity of the mine soil materials. While tree seedlings are often tolerant of short-term water or nutrient deficits, continuous competition or the cumulative effects of multiple stresses may make the *persistence* of ground cover competition an important influence on stand establishment over the long-term.

Importance of using quality planting stock

The ability of tree seedlings to compete with herbaceous covers soon after planting is related to planting stock quality, which is largely dictated by nursery practices. The term "quality" indicates growth and survival potential, which can be predicted by a number of morphological and physiological parameters (Mattsson 1996; Wilson and Jacobs 2006). In general, larger and more nutrient-rich seedlings tend to better resist transplanting stress and are more likely to out-compete associated vegetation (Cuesta et al. 2010). Morphological and physiological characteristics that increase the tolerance of tree seedlings to competition include large root-collar diameter and well-developed, physiologically vigorous root system (i.e., large root volume, number of first-order lateral roots) (Noland et al. 2001; Jacobs et al. 2005; Davis and Jacobs 2005); these characteristics may also predict performance on mine sites. Seedlings with longer roots may access deeper water reserves, reducing stress of low moisture in the upper part of the soil profile caused by herbaceous competition (Pinto et al. 2011). Roots of planted seedlings can grow quickly in uncompacted mine spoils, as Ashby et al. (1984) found white oak roots reaching a depth of 57 cm and providing seedlings with access to deep water supplies after the second growing season.

Beyond seedling morphology, specific nursery cultural practices may also increase the competitiveness and subsequent performance of tree seedlings on mine reclamation sites. Beyond seedling morphology, specific nursery cultural practices may also increase the

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competitiveness and subsequent performance of tree seedlings on mine reclamation sites. Higher nursery fertilization rates resulted in greater growth and survival of oak seedlings planted in Indiana (Salifu et al. 2008), likely due to a decrease in the sensitivity of planted seedlings to competition (Timmer 1997). Mycorrhizal inoculation may also increase the ability of trees to compete with ground cover in some situations. Both Barton et al. (2008) and Mullins et al. (1988) found mycorrhizal inoculation to increase the survival and growth of loblolly pine (*Pinus taeda* L.) planted into older reclaimed sites with a dense existing cover. However, a Virginia study found that natural mycorrhizal colonization occurred within 1 year in moderately acidic sandstone spoils, and that significant colonization also occurred for seedlings planted in siltstone spoils (Schoenholtz et al. 1987). These authors also found colonization improved the seedlings' capacity to access soil nutrients, as indicated by positive correlations of foliar phosphorous levels with colonization.

The relationship between ground cover and seedling establishment

Although greater herbaceous biomass may exert a greater degree of competition with planted trees for resources, there is not always a direct correlation between total ground coverage by herbaceous vegetation and tree growth. On mine sites with rapid and dense ground cover growth, competition for light may be a primary factor causing poor growth and survival of some planted tree seedlings. Ground cover of 20–50 % and approximately 0.5 m tall reduced photosynthetically active radiation (PAR) at 5 cm above ground by approximately 50 %, while cover greater than 75 % allowed for the transmission of only 20 % of PAR, shading small seedlings and lower foliage of larger seedlings (Rizza et al. 2007a). In this study a clear trend of decreasing diameter growth with increasing ground cover was observed for eastern redbud (*Cercis canadensis* L.) and Virginia pine (*Pinus virginiana* Mill.) after two growing seasons, but the growth of northern red oak was significantly reduced by the presence of ground cover >25 %. Neither the shade-intolerant yellow-poplar nor the shade-tolerant sugar maple showed a response of diameter growth to ground cover percentage and appeared to be more sensitive to ground cover species composition than percent cover, although both had the greatest survival at intermediate ground cover levels. The preference of these two species for an intermediate level of ground cover was also noted in a study of seedlings planted on old agricultural field (DeSteven 1991) suggesting that facilitation outweighs competition at low levels of ground cover. Herbaceous covers modify the environment around tree seedlings by providing shading and organic matter, and by providing channels from the surface to the subsurface. The establishment of surface-to-subsurface channels by the ground cover species' lower stems and roots may be especially influential on coal surface mines, where soils derived from mine spoils lacking in organic matter can form surface crusts that may limit movement of air and water. On a coarsely-textured mine soil in Tennessee where unshaded surface soil temperatures can reach 50 °C, Franklin and Buckley (2006) found an association of intermediate ground cover levels with the greatest growth of planted seedlings, which they attributed to an improvement in water relations. Seedling growth on a wide variety of non-mined early-successional sites in relation to ground cover competition was related to the duration of competition, and the tree species' suitability for individual site characteristics (Berkowitz et al. 1995), rather than to ground cover percentage.

Site quality at both the macro- and micro-scale interacts with herbaceous ground cover to determine the intensity of competition. Soil characteristics differ greatly among mine sites, with some being more similar to the region's native soils, and thus more favorable to native tree species than others. Mine soils derived from the weathered materials of

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near-surface overburdens often occur with moderately acidic pH and low levels of soluble salts, properties that are similar to the region's surface soils (Skousen et al. 2011). In contrast, non-pyritic unweathered overburden often gives rise to surface soils that are more alkaline than the region's native soils. The circumneutral-to- alkaline properties of unweathered spoils often make them more favorable to the agricultural grasses and legumes commonly grown on Appalachian mines, contributing to the competitive vigor of those seeded species (Roberts et al. 1988) while also depressing growth rates for planted trees that prefer more acidic conditions (Torbert et al. 1990). When herbaceous cover is not seeded, mine soils constructed from favorable weathered overburdens often develop higher levels of naturally colonizing herbaceous ground cover than soils produced from unweathered spoils while also supporting more rapid tree growth (Angel et al. 2008; Emerson et al. 2009; Skousen et al. 2011). Thus tree seedlings are more likely to both experience and tolerate competition on mine sites with substrates that have properties similar to the region's natural soils.

In field experiments designed to manipulate the intensity of ground cover competition, natural recruitment of herbaceous species often occurs in areas with a low density of seeded cover, making it difficult to partition the effects of ground cover percentage and species. A recent study on a reclaimed Virginia minesite (Fields-Johnson et al. 2012) tested the effects of three ground cover treatments on the growth and survival of planted tree seedlings, predominantly hardwoods. Plots seeded with 22 kg/ha of annual ryegrass alone had the lowest percentage of ground cover in both the first (46 %) and second year (55 %) of the study. Nominal differences in survival of tree seedlings were noted by the end of the second growing season, with survival being greatest (75 %) in the annual ryegrass treatment, which also hosted a significantly greater number of volunteer herbaceous species. Plots seeded with a 90 kg/ha of a conventional reclamation seed mixture of primarily winter rye, orchardgrass, perennial ryegrass, and agricultural legumes, were found to have the highest percentage of ground cover (83 %), and nominally lowest tree survival rate (65 %). The study also found that 2 years after seeding, annual ryegrass itself was providing only <2 % of total ground cover in the ryegrass-seeded plots, with the bulk of living ground cover provided by non-seeded volunteers—primarily invasive grasses and legumes seeded on adjacent experimental plots. However the annual ryegrass-seeded plots also had greater native herbaceous species richness than the conventionally seeded plots.

Results from many studies across this area (Table 1) were compiled, and plot or treatment means plotted to test the relationship between ground cover percentage and tree survival (Fig. 2). Treatment means across all tree species within a study were used as reported, or were estimated based on planting and mean survival rates of individual species. Sites or treatments with compacted soil were not included in the analysis. Where multiple year data were given, the latest date for which both ground cover percentage and tree survival was used. A curve-fitting procedure was used to test the entire data set, then data were eliminated in intervals of 10 % to determine the interval over which the correlation was most significant. Results clarify that a very dense ground cover is detrimental to tree establishment. At ground coverage of less than approximately 60 % however, tree survival varies widely. At low levels of ground cover, the balance of facilitative versus competitive effects is likely determined by numerous factors including soil properties, resource availability, planting stock, and selection of tree and ground cover species.

Influence of ground cover species composition

Herbaceous species differ in their morphology, rates of resource use, preferred forms and ratios of nutrients used, timing and spatial distributions of resource use, and herbivore and

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Table 1 Summary of research findings for studies of ground cover effects on trees planted on uncompacted spoils in the eastern United States

Year planted/ State	Age at report	# GC spp.	Type of GC	GC density (%)	# tree spp.	Tree survival (%)	Summary of significant findings	Reference
1981 IN	7	2	I GL	7–98	2	18–91	+ve Effect of herbicidal control on growth and survival	Andersen et al. (1989)[a]
1981 VA	3	5	I GL	70–100	14	6–92	Effect of herbicidal control on growth differed with tree species +ve effect of herbicidal control on survival	Torbert et al. (1985)
1987 VA	2	7	I GL	90–100	1	60–90	Wood chip amendment reduced ground cover with a +ve effect on growth and survival	Schoenholtz et al. (1992)
2002 VA	3	5	I GL	10–90	10	58–67	Greatest tree growth and survival at medium level of herbicidal control	Burger et al. (2005)[a]
2002 VA	5	4	I GL	70–95	9	58–69	+ve effect of herbicidal control on growth and survival	Burger et al. (2008)[a]
2005 TN	2	2–23	N vs I GL	35–54	5	51–59	Greatest survival at moderate GC density Greater tree growth in native covers	Rizza et al. (2007a)[a]
2006 TN	2	7	N GL	15–57	4	21–97	No effect of GC density on survival	Buckley and Franklin (2008)[a]
2007 VA	1	1	I G vs GL	55–83	13	65–75	−ve effect of GC density on survival	Fields-Johnson et al. (2009)[a]
2007 TN	1	7	N GL	10–44	4	72–83	No effect of GC density on survival	Franklin and Buckley (2009)[a]
2007 MS	1	2	N G	18–99	1	29–44	No effect of GC density on survival	Lang (2009)[a]

Shown for each study are the year trees were planted, state in which the study was conducted, age at which tree growth and survival was reported, number of ground cover species included in the planting mix (#GC spp.), type of ground cover species planted (*I* introduced, *N* native, *G* grasses, *L* legumes), the range of mean ground cover densities reported as a result of treatments, the number of tree species planted, and the range of mean survival rates of planted trees across species and treatments

[a] Treatment or plot-level means used for analysis reported in Fig. 1

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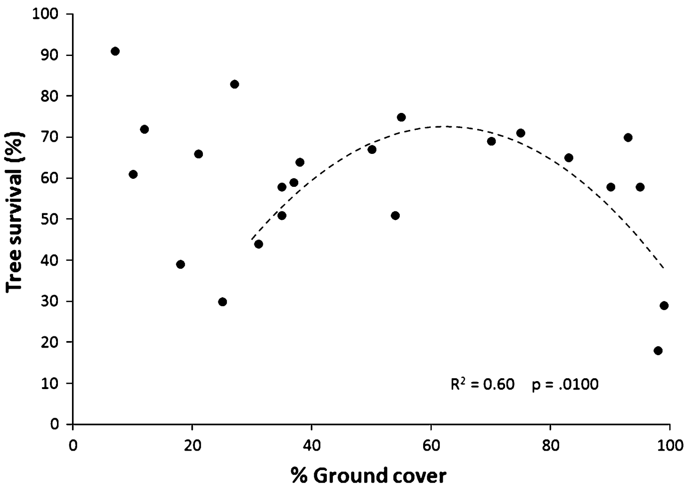

Fig. 2 Relationship between ground cover density, and survival of tree seedlings planted on reclaimed surface mines in the eastern US. See Table 1 for study details. The relationship is significant at ground cover percentages between 30 and 100, $y = -0.026x^2 + 3.249x - 28.91$, with a maximum survival rate at 62 % ground cover

microbial associations (Eviner and Hawkes 2008). Allelopathy may also occur, and has been implicated in the inhibition of black cherry height growth by grasses and ferns (Horsley 1977). It is thus reasonable to expect groundcover species to differ in degree of competitiveness with young trees. Anecdotal and research evidence suggests that ground cover species composition can have a significant influence on tree growth. Newly reclaimed mine sites differ from timber harvest sites and agricultural fields in their relative absence of established herbaceous plants and propagules. Mine operators choose which species to plant, although wind-blown volunteer species colonize where coverage of planted ground cover is low enough to allow their establishment. Due to our limited knowledge of tree-herbaceous interactions, and the need to minimize the potential of seeding failure, relatively few species have been tested as potential tree-compatible ground covers. Environmental conditions affect plant traits and plant-soil interactions (Eviner and Hawkes 2008), making competitive interactions difficult to predict. However, three groups with very different functional traits (i.e., cool-season grasses, warm-season grasses, and legumes) have been tested on reclaimed mine sites, and may have differential effects on tree seedlings.

Cool-season grasses are those with spring and fall growth periods separated by summer dormancy. In the eastern US, non-native, cool-season grasses are primarily seeded on surface mines for erosion control and forage. They generally have fibrous roots that develop quickly, and occupy a large proportion of the upper 45 cm of soil (Weaver 1926). Annual and perennial ryegrasses (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot and *L. perenne* L.) are both cool-season grasses that are used commonly in reclamation seeding mixtures due to their reliability and speed of establishment. An inhibitory effect of ryegrass on the growth of hardwoods has been noted in several studies and it appears to be related to below-ground processes rather than competition for light. In a comparison of four ground cover mixtures, the two containing perennial rye grass resulted in a higher mortality of planted tree seedlings than those containing warm-season grasses (Rizza et al. 2007b),

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although light reduction appears to be a factor only for the smallest seedlings (Rizza et al. 2007a). In both a pot experiment using northern red oak grown with annual ryegrass in mine soil, (Aubuchon 2010) and a field experiment (Picon-Cochard et al. 2001) examining the competitive effects of winter rye on black walnut, transpiration rates of the seedlings were reduced under drought conditions when grown with the grass. Aubuchon (2010) found that pots with annual ryegrass had the greatest mass of herbaceous roots and the lowest soil moisture, which likely compounded the stress induced by significant reductions in fine root growth of oak seedlings, in contrast to those grown with alfalfa (*Medicago sativa* L., a legume), switchgrass (a warm-season grass), or without ground cover competition. Harmer and Robertson (2003) also found an inhibitory effect of cool-season grasses on root growth of hardwoods. In a review of grass effects on trees (Messenger 1976), the inhibitory effect of cool-season grasses, perennial ryegrass in particular, on tree growth was noted, with evidence that inhibition was due to the depression of tree root growth, and competition for water, potassium, and N. It is quite possible that there are differences in the response of Appalachian hardwood tree species to the competitive effects of cool-season grasses due to differences in rooting characteristics, however this has not been studied on minesites.

Warm-season grasses are characterized by an active growth period during summer, with deep, coarse, poorly branched root systems (Weaver 1926), and those found in the eastern US are primarily native species. Native warm-season grasses have been tested as an alternative tree-compatible ground cover for mine reclamation. Although species tall in stature may overtop tree seedlings, their primary growing season differs from that of trees, therefore some native warm season grasses may prove to be less competitive than ground covers with a primary flush of growth in the spring. An extensive study of competitive interactions of oak seedlings planted into warm- and cool-season grasses on an old-field site in the Midwestern US showed that oak seedling survival was greater in warm-season than in cool-season grasses, particularly under dry conditions (Davis et al. 2005). However in contrast to Aubuchon (2010), these differences could not be explained by differences in root biomass of the different grasses, or their effect on soil water or N availability. The authors concluded that secondary below-ground factors, such as allelopathy or soil biota, were likely driving the differences in observed competition between oaks and grasses. On a southern Illinois research site, warm-season grasses indiangrass (*Sorghastrum nutans* (L.) Nash., switchgrass, and big bluestem began growth late in the year, and formed a dense cover that persisted for the 6 years of the study (Ashby et al. 1989); yet few negative impacts on trees were reported. Hardwood seedlings planted into a 2-year-old established cover of native warm-season grasses had a first-year survival rate >85 %, and no relationship between ground cover percentage and tree survival or growth was found despite an extreme drought during the year following tree planting (Franklin and Buckley 2009). On a reclaimed lignite mine in Mississippi, Lang (2006) reported 3-year survival rates of 70–90 % of loblolly pine planted into a dense cover of browntop millet (*Urochloa ramosa* (L.) Nguyen) and bermudagrass (*Cynodon dactylon* (L.) Pers.) established in the previous growing season. Over 3 years, bermudagrass was partially replaced by native herbaceous species while growth rates of pine increased.

Legumes vary widely in stature, rooting habit, and season of growth. Although they may improve soil fertility through fixation of atmospheric N, some deleterious effects on trees have also been reported. Lang et al. (2009) found that when volunteer partridge pea (*Chamaecrista fasciculata* (Michx.)), white clover, or sericea lespedeza made up >30 % of the ground cover, there was a strong negative impact on planted pine survival. Ashby et al. (1989) concluded that alfalfa would be too competitive for planting with trees in southern

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Fig. 3 Left: a butternut (*Juglans cinerea* L.) seedling planted into a conventional ground cover mixture of cool-season grasses and legumes, showing chlorosis and dieback. *Right* vigorous seedlings of dogwood (*Cornus florida* L.) with autumn coloration, and Virginia pine (*Pinus virginiana* Mill.) planted with a diverse, native ground cover mixture

Illinois, and recommended bird's-foot trefoil as an alternative. Further south, in Tennessee, the opposite appears to be the case: bird's-foot trefoil is dense and persistent while alfalfa generally declines after several years due to a proliferation of insect pests. Alfalfa was found to have a small inhibitory effect on the growth of northern red oak seedlings in a pot study but not on Tennessee field sites, where it created coverage of <50 % in the first 2 years (Klobucar 2010). It is possible that this study may have been too short to detect a positive effect of legumes on tree growth. In Kentucky, tree growth on legume-dominated plots exceeded that of grass-dominated or bare ground control plots in Kentucky, but not until the end of the fourth growing season (Vogel 1973). The finding that legumes' effect on tree growth required several years for detection is not surprising, given that reclaimed mines are commonly fertilized with N during revegetation.

The interaction between ground covers and the soil microbial community may be the key to restoration success (Eviner and Hawkes 2008). While some of these interactions have been reported for reclaimed mine sites, there is insufficient knowledge to judge their relative importance to forest establishment. Ground cover species present in the early years after reclamation can influence the below-ground microbial community and the formation of soil aggregates (Wick et al. 2007). On reclaimed sites in the western US, recovery of the microbial community occurred more slowly in areas dominated by grasses than on areas dominated by sagebrush (Rana et al. 2007). Planted ground cover species are known to influence microbial ecology, and this effect could significantly influence tree growth. The size of the microbial population was found to be associated with the growth of white oak on a reclaimed minesite in Virginia (Showalter et al. 2007). A better understanding of these relationships will help to refine reclamation recommendations to optimize tree growth.

Each ground cover species has a suite of functional traits that influence site development and forest establishment. Scholes and Archer (1997) suggested that soil heterogeneity in the rooting zone, and horizontal spatial distribution of roots are important components of

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tree-grass interactions, in addition to differential use of soil resources by both season and depth. Ideally, ground covers for forest restoration can be selected for characteristics that minimize competition with trees. It has been suggested that use of a greater number of species in a ground cover mixture might be beneficial (Eviner and Hawkes 2008). Research has found that certain ground cover seeding prescriptions are conducive to recruitment of non-planted species (Fields-Johnson et al. 2012; Klobucar 2010). An increased diversity of growth forms of terrestrial plants has been found to have a positive influence on nutrient cycling, water infiltration, carbon sequestration, invasion resistance, and biomass production (de Bello et al. 2010). Because tree roots can expand rapidly into areas of high water and nutrient content, the heterogeneous soil environment below a diverse herbaceous layer (Fig. 3) may allow a tree seedling to exploit patches of soil that are seasonally high in resources, low in competition, and contain a favorable microbial environment.

Conclusion

Trees interact with neighboring plants in both direct and indirect ways, and competitive interactions can be problematic to successful forest restoration on mine sites where trees and ground cover must be established concurrently. While natural regeneration of mined land resulted in productive forests in the past, present practices for reclamation to forest must, by law, include the establishment of trees and herbaceous ground covers. Excessive herbaceous ground coverage competes with planted seedlings and negatively affects establishment success of planted seedlings. At lower ground cover levels, herbaceous vegetation can facilitate tree survival in the early years after planting, but at the same time may reduce growth, with the balance of beneficial and detrimental effects being dependent on species and site factors. High seedling quality can improve the ability of planted seedlings to compete with herbaceous vegetation through decreased transplanting stress and re-translocation of nutrient reserves, which is particularly important on minesites where the substrate is often coarse and nutrient-poor. Herbicidal control has improved tree growth rates in competitive herbaceous cover, but soil properties will affect the seedlings capacity to tolerate herbaceous competition. Planted ground covers with a low to moderate density, and of species unlikely to persist longer than a few years should promote forest development on soils favorable to the development of planted trees.

Design of seed mixtures requires an understanding of the mechanisms driving tree-ground cover interactions. The success of forest restoration efforts on mine sites will be enhanced by development of ground cover seeding mixtures that can provide maximum ecological benefit, with a minimal negative effect on tree growth and survival. Herbaceous species differ in functional traits that influence site development and forest establishment, and there is evidence that the species composition of planted ground cover influences planted trees. Cool-season grasses have a negative influence on tree establishment, whereas reports of negative impacts of warm-season grasses are rare. The influence of legumes appears to be species and time-dependent. Studies outside of mine reclamation suggest that the species of herbaceous cover may be an important factor in forest establishment through both direct and indirect effects, and that high ground cover diversity may be beneficial. Further research is needed to elucidate these interactions, to identify characteristics of ground covers and ground cover seeding methods that create optimal conditions for the early growth of trees, and to define how groundcover species and seeding rates can be adapted to mine soil properties. A better understanding of these relationships will help to refine practices to enhance forest restoration and to optimize tree growth.

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