A REVIEW OF ECOLOGICAL FACTORS AFFECTING SEED GERMINATION OF SPECIES USED IN THE RECLAMATION OF WESTERN AUSTRALIAN BAUXITE MINING[1]

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Abstract: Full minesite reclamation requires an extensive knowledge of the germination requirements of a wide range of native species. This paper reviews research related to maximizing germination of broadcast seed in reclaimed minesites in the Darling Range of Western Australia. In this Mediterranean-type climate, some species require treatments comparable to that received during fires. Heat-shock treatments prior to broadcast seeding has resulted in establishment of many of these legume and soil seed-store species. Light is required in some native species to break dormancy, while in others, light prevents germination. Proper timing of reclamation site ripping is being trialed to maximize the burial of species which germinated best under dark conditions in the research laboratory. The effect of particular temperatures in breaking dormancy may also be important. In this climate, germination in nature is generally timed to coincide with cool temperatures when rainfall is most constant. In most species, the correct combination of a range of stimuli are required to maximise germination. Cooperative seed ecology research between The University of Western Australia and Alcoa of Australia Ltd. has lead to the better timing of top-soil return, maximization of germination by pre-treating particular species of the broadcast seed mixture, and the determination of species where interplanting of seedlings is essential.

Additional Key Words: Seed Dormancy, Heat Stimulus, Temperature Effects, Light Responses, Biodiversity

Introduction

The jarrah (*Eucalyptus marginata*) forest of southwestern Western Australia serves the public with renewable resources, such as saw timber, paper pulp, honey, and native cut-flowers; protects watersheds, which provide potable water for more than a million residents and irrigation for intensive agriculture; and provides a native environment for passive recreation, conservation and tourism. This forest occurs over mineral resources of bauxite, gold and coal worth millions of export dollars each year to the people of Western Australia. Alcoa of Australia Ltd. mines bauxite in three locations in the jarrah forest near metropolitan Perth under environmental conditions controlled by the Department of Conservation and Land Management of the Western Australian Government. Alcoa's stated reclamation objective is to establish a stable, self-generating jarrah forest ecosystem, planned to enhance or maintain water, timber, recreation, conservation and/or other nominated forest values (Koch and Ward 1994).

[1]Paper presented at the 1995 National Meeting of the American Society for Surface Mining and Reclamation, Gillette, Wyoming, June 5-8, 1995.

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Proceedings America Society of Mining and Reclamation, 1995 pp 125-135

DOI: 10.21000/JASMR95010125

https://doi.org/10.21000/JASMR95010125

The climate of the jarrah forest is typically Mediterranean with winter rainfall and a summer with little or no precipitation. Annual rainfall at the minesites ranges from 1200 to 1400 mm (48 to 55 inches). Average daily temperature maximum ranges from 30°C (86°F) in the hottest months of January and February to 15°C (59°F) in the coolest month of August. The average daily temperature minimum ranges from 15°C (59°F) in February to 6°C (43°F) in August. The soilsare pisolitic or massive laterite over a layer of kaolinitic clay.

The forest vegetation is generally dominated by *Eucalyptus marginata* with *E. calophylla*, the most common canopy associate (Bell and Heddle 1989). A middle-storey component of small trees occurs with *Banksia grandis*, *Allocasuarina fraseriana* and *Persoonia longifolia* being prominent. The understorey is dominated by a species-rich mixture of woody shrubs, suffrutescent subshrubs and herbs. Species richness can exceed 100 species per ha with the plant family distribution dominated by Leguminosae, Myrtaceae, Proteaceae, Orchidaceae, Cyperaceae and Restionaceae.

Bauxite Mining Reclamation

The process of mining proceeds following a survey of resources by drilling holes on a 15 m grid to locate ore of acceptable quality without extensive concentration of silica which disrupts the processing of bauxite to alumina. Logging of the timber resources occurs ahead of the mining operations. The open-cut mining operation is relatively shallow with an average ore depth of 4 m and occurs in scattered pods of generally less than 10 ha in area. The present system of reclamation has evolved following extensive expenditure on research and consists of the following procedures. Topsoil and overburden are conserved during the mining process and used for reclamation. These materials are either freshly placed on mined-out pits or stockpiled and replaced when the mining of a particular area has been completed. The topsoil/overburden layer above the bauxite ore body varies in depth from only a few centimeters up to 1 m with the average approximately 40 cm. Where the layer is deep enough, it is stripped in two passes. The upper layer of approximately 5 cm is considered topsoil and contains a high concentration of organic matter, nutrients and seed (Tacey and Glossop 1980). Below 5 cm, the material (overburden) generally contains lower concentrations of these biologically important constituents. Following ore extraction with skip loaders and haul trucks, the vertical mine walls are blasted and re-contoured to blend with the existing landforms and to minimize overland drainage, and the overburden and topsoil layers are layered over the site. The areas are then "ripped", using large bulldozers equipped with a 1.9m bladed tine to break up the kaolinitic clay mine floor to increase drainage and root establishment. Broadcast application of a mixture of approximately 90 native forest species' seed is applied to the prepared minesite, and fertilizers are added to promote a rapid and diverse vegetation cover which prevents erosion, provides ecological habitat and diversity, accumulates high nutrient levels and accelerates nutrient cycling processes. A detailed account of the mining and reclamation processes is provided by Nichols et al. (1985). More recent amendments to the established reclamation practices appear in Koch and Ward (1994).

Seed Ecology Research

The broadcast seed mix is considered extremely important, as the topsoil seedbank generally does not contain a predominance of the species which constitute the climax vegetation understorey and almost no seed of the dominant tree species (Vlahos and Bell 1986). Recent data from the vegetation of reclaimed bauxite sites indicate that at least 39 species can be traced to the broadcast mix (Koch and Ward 1994). Also, conditions for establishment of newly germinated seedlings is problematical after the first few years, when shrub growth can out-compete establishing seedlings. Therefore, the species composition of the reclaimed minesites is determined predominantly by those species germinating in the first winter following the topsoil transfer and seed mix broadcasting (Koch and Ward 1994).

Seedling establishment under natural circumstances in the jarrah forest generally occurs only after fire, although a few individuals and species may invade established sites in interfire periods (Bell and Koch 1980). Established jarrah forest most closely conforms to the 'initial floristic composition' successional model of Egler (1954) due to a predominance of species capable of resprouting following fire. In addition to those species surviving the fire by resprouting from protected epicormic buds, a number of species, although the parent plants are killed by wildfire, set seedlings readily from dormant seeds dispersed to the soil during the interfire period. The flora of southwestern Western Australia also contains a large number of species which retain seeds in the canopy of the plant in woody, fire-protective fruits (Lamont et al. 1991). Fires initiate a slow release of seeds from fire-scarred fruits to relatively nutrient and moisture rich post-fire habitats where competition from already established plants is temporarily reduced (Bellairs and Bell 1993). The seeds of such serotinous fruitsare generally sensitive to high temperatures, but germinate readily when provided with moisture (Bell et al. 1987). Dormancy of seeds is common in the species of the jarrah forest and information related to the cues required to break dormancy is an important factor to maximize the germination of all seed broadcast onto mining reclamation sites (**Fig. 1**).

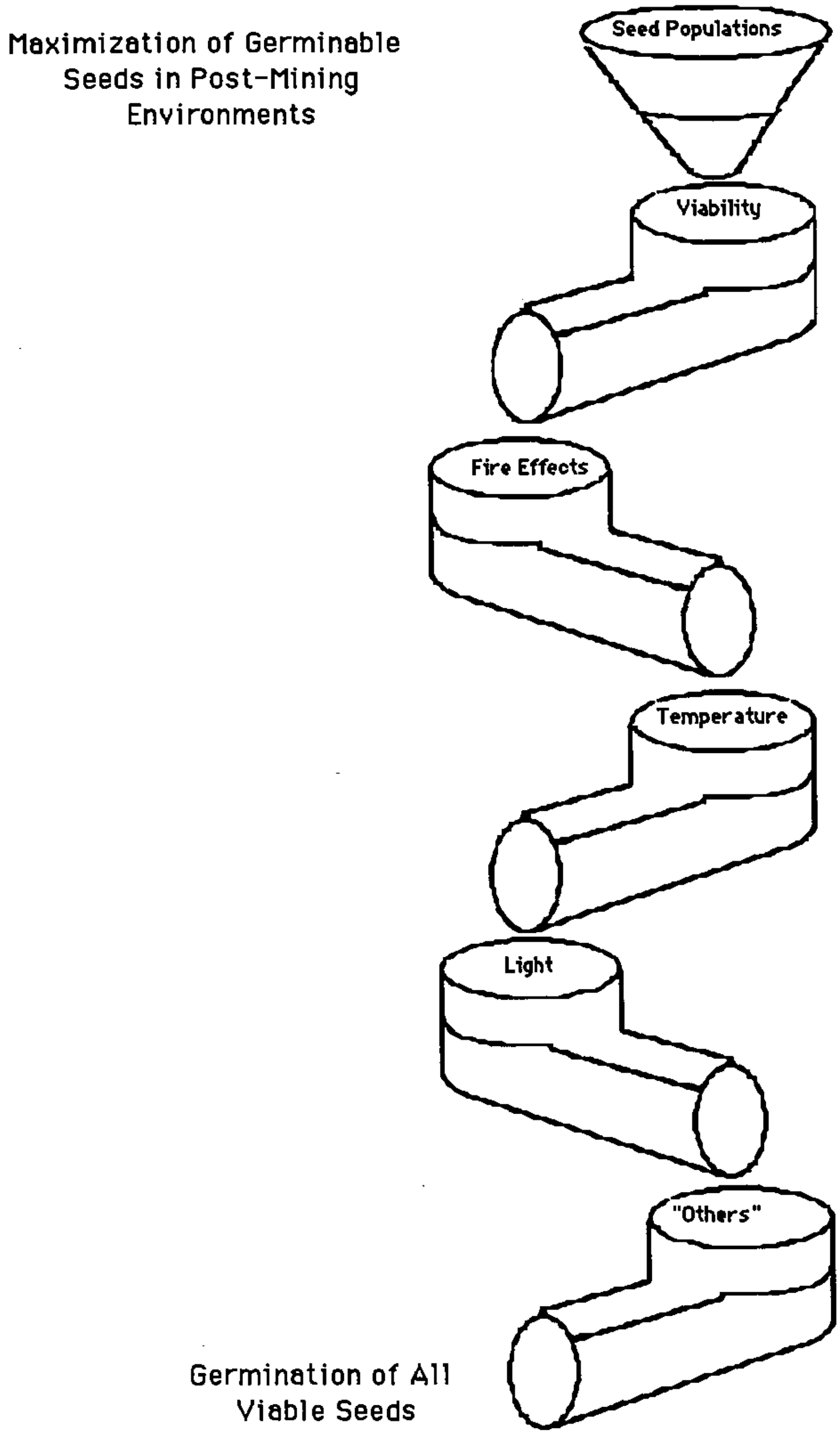
Viability Patterns

Environmental stresses of seasonal drought, poor soil nutrient availability, herbivory and competition can restrict plants from having sufficient carbohydrate reserves to complete the reproductive process each year. Problems related to inbreeding and outcrossing also contribute to the inviability of seeds produced by plants. In a review of Western Australia species, seed population viability ranged from 0-100% and the mean viability was only 32% overall (Bell et al. 1993) (**Table 1**).

Table 1. Viability of Western Australia seeds. The number of species included in the sample, mean±standard error of viability for the total species population, species separated by fire syndromes and species separated by seed storage syndromes are provided. (Adapted from Bell et al. 1993).

Characteristic	n	Range	Mean±se	Sig.diff.
Viability of All Species	443	0-100%	32.1 ± 1.7	
Viability of resprouters	292	0-100%	37.6 ±2.1	
Viability of reseeders	123	0-100%	36.2 ±3.0	N.S.
Viability of soil borne seeds	278	0-98%	20.5 ± 1.7	
Viability of canopy-borne seeds	164	0-100%	62.4 ± 2.5	p<0.001

Fig. 1. Schematic presentation of some steps which can be taken to maximize germination in post-mining environments.



Patterns of viability were observed, however, when aspects of the general ecology of groups of species were considered. Grouping species in relation to their shared response to recovery from fire (either resprouting from protected buds or establishing only through reseeding) showed no general pattern related to expected viability of the seed population (although seed production is generally much higher in seeder species) However, grouping species by seed-storage syndrome (whether seed banks occur in the soil or in the canopy) indicated that species that disperse seed from the plant upon ripening have lower seed population viability than species which retain their seed protected by serotinous fruits in the canopy. It is apparent that species which "invest" in a photosynthetically expensive, protective fruit structure will tend to insure that photosynthetic reserves are at least directed toward producing viable seeds. More than 350 species in Western Australia are canopy-borne seed species (Lamont *et al.* 1991). Although a detailed knowledge of viability of all such Western Australian species has not been carried out, the present research indicates that canopy-borne seeds are more likely to have the potential to germinate in restoration sites than species characterised as soil seed-store species.

Soil borne seed species as an ecological group tend to produce fewer viable seeds in a population than canopy-borne seed species, but the range of 0% viable to 98% viable for the 278 species surveyed indicates that considerable variation exists. It is important in all restoration programs that the viability of seeds of all collections be considered. Although the tetrazolium chloride test (Lakon 1949) has difficulties, it is currently the best procedure to determine the proportion of viable seeds in any population. Mining companies who purchase seed should insist on a viability test being carried out on seed batches by the seed merchants. Viability tests will provide information to better plan the numbers required for broadcasting operations (Bell 1988; Bellairs and Bell 1993).

In nature, most populations of seeds have some individuals that remain dormant despite the provision of moisture and laboratory temperatures (Mayer and Poljakoff-Mayber 1989). Such a phenomenon insures that any particular environmental stress will not completely eliminate all members of a seed cohort, resulting in local extinction. Two subspecies of *Rhodanthe* and an undescribed species of *Craspedia*, all small ephemeral annuals of arid inland Western Australia, provide examples of cohorts of seed with dormant and readily germinable seeds (**Table 2**).

Table 2. Viability and germinability (mean±se) of three Australian Asteraceae following dry storage treatment (Bell and Plummer, unpublished data).

Species	Viability %	Initial Germination %	After 4 wks at 20°C Germination %
Craspedia sp.	99.0±1.0	16.0±1.5	50.7±4.8
Rhodanthe chlorocephala subsp. *splendida*	71.0±6.8	13.3±3.5	18.7±5.3
Rhodanthe chlorocephala subsp. *rosea*	76.0±6.9	73.3±2.7	84.0±8.3

The collection of *Craspedia* sp. was almost completely viable, yet only 16% were germinable in petri plates under conditions of adequate moisture, light and 20°C temperatures. The *Rhodanthe chlorocephela* subsp. *splendida* seed collection contained 71% viable seeds, yet only 13%

germinated in the laboratory. The ecological interpretation is that the proportion of the viable seed component of the cohort that remains dormant is a hedge against adverse conditions eliminating the first wave of germination. In contrast, most of the viable seeds were readily germinable in the collection of *Rhodanthe chlorocephala* subsp. *rosea* .

Seeds that do not readily germinate when provided with moisture and moderate temperatures may be dormant because the embryo is immature or requires dry storage. With time, the embryo reaches a stage where germination is possible. In cold, temperate climates some species seeds are immature when shed from the plant and germinate only after being exposed to a period of moist- and low-temperature conditions, termed "cold stratification". The embryo immaturity ensures that the seed will not germinate during the temperate winter conditions when freezing would kill any emerging seedlings. A period of embryo maturation or "after-ripening" is required to transform such dormant seeds into germinable seeds. In species that have evolved in temperate climates the appropriate storage temperatures for these seeds would be cold temperatures (mostly recommended at 4°C). In Australia, cold-storage-enhanced seed germination has been documented only for species of higher altitudes of the more temperate regions. In more sub-tropical climates, the after-ripening requirement carries seeds in a dormant condition across the summer and autumn period when germination presents problems for continued survival of seedlings. Under such conditions, it would appear more likely that storage under dry and warm conditions would be the 'more-ecologically-correct' conditions to maximize the after-ripening process. These seeds may actually be harmed by storage at 4°C. Storage of seeds for 1 month at 20°C in the *Craspedia* sp., resulted in greatly enhanced percentages of germination **(Table 2)**. Proper storage conditions for seeds for restoration programs should take into consideration aspects of the environment in which the species evolved.

Fire Simulation Pre-treatments

Considerable progress has been made in the breaking of dormancy in seeds with a hard testa, evolved to assist seeds in surviving fires (Bell 1988; Portlock *et al.* 1990; Bell et al. 1993). Boiling seeds for short durations or providing other forms of heat-shock to simulate the temperature effects of fires have been the most common laboratory techniques to break dormancy in these seeds. Some heat-shock response species are able to germinate due to the fracturing of the hard seed coat. Release from dormancy following heat shock has also been attributed to the effect of heat denaturing seed coat inhibitors. The species in Western Australia which respond to a heat shock are species stored naturally in the soil of fire-prone habitats. Typically, many legumes (e.g. *Acacia alata, Mirbelia dilatata* and *Oxylobium lanceolatum*) as well as non-legume, but soil-stored seed (e.g. *Conostylis setosa* and *Trymalium ledifolium*) have germination percentages which are considerably enhanced by heat-shock treatments or scarification to crack the hard testa **(Table 3)**. In contrast species which protect seed from the intense temperatures of fires in woody fruits (e.g. *Hakea lissocarpha*) or species which flower in response to fire and drop seeds to the soil in the next year (e.g. *Xanthorrhoea gracilis*) are killed by heat-shock treatments. Other post-fire environment cu
es, such as exposure to leachates of charred wood (Keeley *et al.* 1985; Bell *et al.* 1987) and/or smoke (Brown 1993) may also be effective pre-treatments to induce fire-responsive seeds to germinate in post-mining environments.

Table 3. Viability and germinability percentages prior to fire simulated heat-shock treatments of selected Western Australian native species. Data selected from Bell et al. (1987; 1993).

Species	Viability %	No Heat Treatment Germinability %	Heat Treatment Germinability %
Acacia alata	76	6	52
Mirbelia dilatata	32	0	39
Oxylobium lanceolatum	86	3	74
Conostylis setosa	--	2	47
Trymalium ledifolium	--	1	36
Hakea lissocarpha	80	92	0
Xanthorrhoea gracilis	80	53	0

Temperature Effects

Understanding temperature requirements is especially important in the timing of broadcast seeding for minesite restoration. Seeds tend to have germination optima in temperature which coincide with conditions which provide the greatest chance of survival of seedlings following germination (Bell et al. 1990, Bellairs and Bell 1990, Bell and Bellairs 1992). In the southwest of Western Australia, many forest species tend to germinate in highest percentages in low temperatures comparable to the late autumn and early winter period when the rainfall is also maximized (**Table 4**). For example, temperatures of 10-15°C produced the germination optima for a range of the legumes (Acacias and *Bossiaea*) and one of the two species of the Myrtaceae (*Kunzea recurva*). The second Myrtaceae, *Calothamnus rupestris*, and *Xanthorrhoea gracilis* showed germination optima at slightly higher temperatures. Understanding temperature requirements can assist reclamation scientists in the proper timing of broadcast seeding and possible requirements for s
upplementary watering.

Light Requirements

Knowledge of the ecology of species can also explain germination patterns concerning requirements for light or dark conditions before seed dormancy is broken (Bell 1993). Experiments in controlled temperatures with and without light indicated that most jarrah forest species germinate at higher percentages in the dark, especially at higher temperatures (**Table 5**). The ecological interpretation of this pattern is that surface germination early in the rainy season when temperatures are still relatively warm is likely to lead to seedling death due to rapid soil drying (Bell 1994). Buried in the soil and later in the rainy season when surface temperatures are lower are situations where survival of seedlings is more likely.

Light stimulated germination in *Banksia grandis* and *Hakea amplexicaulis* may also be adaptive for these particular species. *Banksia grandis* has become much more common since selection logging has provided sunlight gaps in the jarrah forest environment. *Hakea amplexicaulis*, also a serotinous species with large winged seeds, is most common where granite outcrops and shallow soils restrict the jarrah canopy cover. The ability to detect gaps in the canopy for seed germination could favor these two species.

Table 4. Germination percentages in a range of constant temperature incubation treatments of selected Australian native species after 3 wks under trial conditions in petri plates on moistened sponges. From Bell and Bellairs (1992).

	Germination (%)					
Species	5°C	10°C	15°C	20°C	25°C	30°C
Acacia browniana	0	77	30	10	0	0
Acacia drummondii	0	69	75	31	0	0
Acacia latericola	0	52	45	16	4	0
Acacia urophylla	0	92	94	65	8	6
Bossiaea ornata	0	20	35	9	0	0
Calothamnus rupestris	0	10	90	92	47	0
Kunzea recurva	2	3	75	48	0	0
Xanthorrhoea gracilis	0	45	88	83	0	0

Table 5. Percentage germination of jarrah forest species under controlled incubation temperatures of 13°C, 18°C, and 23°C in light or dark conditions (after Bell 1994).

	13°C		18°C		23°C	
Species	Light	Dark	Light	Dark	Light	Dark
Heat Pre-treatment Requiring Species						
Acacia drummondii	82	85	10	14	0	0
Acacia pulchella	60	88	28	82	0	33
Daviesia cordata	55	73	50	79	11	65
Gompholobium knightianum	10	49	5	42	9	3
Kennedia coccinea	14	32	10	37	0	11
Trymalium ledifolium	28	42	0	23	0	0
Species Not Requiring Heat Pre-treatment						
Eucalyptus marginata	77	80	28	70	4	68
Eucalyptus calophylla	73	90	80	98	28	90
Xanthorrhoea gracilis	97	98	88	81	2	55
Xanthorrhoea preissii	80	86	84	85	38	82
Banksia grandis	89	69	24	5	0	0
Hakea amplexicaulis	80	38	70	52	0	6

Application to Reclamation

Understanding the combined effects of a number of cues occurring simultaneously can improve the efficiency of seedling establishment in managing the top-soil return or broadcast seeding operations on post-mining landscapes. For example, it would be beneficial to rip and disk habitats just after broadcast seeding if the seeds sown germinated best in the dark. On the other hand, broadcasting species that require a light-stimulus to break dormancy would appear to be best at some later time when the disturbance of the site preparation activities has settled down and just before the beginning of the winter rainy period.

Knowledge of the ecology of plant species can be used to maximize the species return to minesites following disturbance. Although there is no substitution for research directly aimed at target species, information gained on species which share generic, fire response or seed store syndromes with the target species could be a first approximation in a reclamation program. In most Australian cases, it is important to provide post-mining habitats with as many of the pre-mining vegetation species as possible as establishment tends to occur only in the first few years following disturbance. Maximizing the richness of the post-mining habitats will have numerous ecological advantages over near-monocultures. Bennett (1993/94) notes that conserving biological diversity is the key to ecologically-sustained development. Maximizing biodiversity in bauxite-mine reclamation will ensure these areas will continue to provide the people of Western Australia with all the expected amenities provided by the original forest environment.

Acknowledgments

Funds for this research were provided in part by an Australian Research Committee Small Grant. Seeds were provided gratis by Alcoa of Australia Ltd. Travel support by The University of Western Australia is acknowledged with appreciation.

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INTERPLANTING LOBLOLLY PINE WITH NITROGEN-FIXING NURSE TREES ON A RECLAIMED SURFACE MINE IN VIRGINIA [1]

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Abstract: In 1980, an experiment was established to study the effect of interplanting loblolly pine (*Pinus taeda*) with nitrogen-fixing nurse-trees. The study area was surface mined and reclaimed in 1979. In accordance with current reclamation regulations, the site was revegetated with an herbaceous ground cover which included perennial legumes. Loblolly pine was planted on a 3 m by 1.5 m spacing and interplanted with either 1) black locust (*Robinia psuedoacacia*), 2) black alder (*Alnus glutinosa*), or 3) no nurse-tree (control treatment). After nine years, the growth of the pines was not improved by the nurse-trees. Soil nitrogen and forest floor litter nitrogen contents were about 10% higher in the nurse-tree treatments, but the additional nitrogen did not result in improved nitrogen nutrition for the pines as evidenced by foliar nutrient analysis. Apparently the herbaceous legumes provided enough nitrogen to serve the needs of the loblolly pine during this nine year study.

Additional Key Words: reclamation, productivity.

Introduction

Nitrogen is the nutrient element required in greatest quantity by most trees and other plants. Unlike all other plant nutrient elements, plant available nitrogen is not derived from the weathering of soil parent material. Nitrogen must enter the soil indirectly from the atmosphere, through fixation by micro-organisms and by incorporation of plant biomass. An important consideration for forest land reclamation is the need to establish a plant community which includes some species capable of fixing nitrogen such that soil organic matter and nitrogen levels will increase through time and be able to support long-term forest productivity.

Conceptually it seems logical that revegetation of reclaimed forest land should include herbaceous and woody nitrogen fixing species. Perennial herbaceous legumes such as birdsfoot trefoil (*Lotus corniculatus*), Serecia lespedeza (*Lespedeza cuneata*), and crown vetch (*Coronilla varia*) are able to survive on minesoils and are capable of fixing substantial amounts of nitrogen in the first few years after reclamation. Nitrogen fixing shrubs and trees could provide additional nitrogen, especially in later years when the ground cover declines because of shading by the trees and from the accumulation of a leaf litter layer.

The benefits of nitrogen fixing nurse-trees such as black locust and black alder are well known. Both species have the ability to substantially increase minesoil nitrogen levels. In a study of soil nitrogen on reclaimed sites that had been seeded with black locust in West Virginia, Jencks

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[1] Paper presented at the 1995 National Meeting of the American Society for Surface Mining and Reclamation, Gillette, Wyoming, June 5-8, 1995.

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