UPDATE OF ONGOING RESEARCH[1]

by

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Abstract. Reclamation with trees and shrubs with an emphasis on research studies is reviewed from early publications to the present. The value of and need for long-term studies of tree plantings is emphasized. New uses of trees in reclamation, and new research opportunities, are outlined. Assuming good planting practices, the chief problems in reclamation success with trees seem to be soil compaction and excessive and/or wrong kinds of ground cover coupled with animal damage to seedlings. Species trials and planting mixtures; tree planting with seedlings and with seed; fertilizers, soil amendments, and mulches; herbicides; animal damage; soil compaction; and the rooting medium are specifically discussed. How to predict tree performance from soil analyses remains the key research question.

Additional Key Words: animal damage, herbicides, planting mixtures, topsoil substitutes, tree planting, soil compaction

Introduction

I was asked to give an update of ongoing research on reclamation with trees and woody shrubs. I shall attempt to give a broad view, with specific attention to long-term tree performance as well as more immediate findings. Most kinds of trees used in reclamation are long lived, and plantings made 30 or more years ago may be of more value today than in the first years after planting. Follow-up studies are highly important. Soil properties change with time and the suitability of replaced topsoil versus alternative material, for example, may well later need to be re-evaluated. Research with trees needs to be long-term.

Acid and toxic spoils, still the image of mining for much of the public, have been sufficiently eliminated under the Surface Mining Control and Reclamation Act of 1977 (SMCRA) Title V, Control of the Environmental Impacts of Surface Coal Mining, that present research on that type of problem is almost totally carried out under Title IV Abandoned Mined Lands (AML). I understand that other speakers will present papers on the AML program, the landowner's perspective, and what can and cannot be done under present regulations, so I shall not deal with those topics.

Essentially all my dealings with the real world of landscapes, soils, and plants are in conjunction with the coal industry reclamation personnel. The people I have met are proud of their work, and are frequently called upon to defend it. This provides a communication channel to the academic world whose job it is to accumulate and evaluate knowledge. Industry reclamation personnel experience both success and failure with vastly more trees and with more varied site conditions than can any research program. For example, if a levee breaks and newly planted trees are under six feet of water for three weeks, a professor or forester lucky enough to hear about the problems on the mine can learn about flooding effects on tree seedlings. The findings from industry inevitably become part of the research picture, though many and probably most are not recorded. Industry personnel do the major part of academic research in terms of site preparation and often the planting itself.

Documented tree performance in industry plantings is rarely available. The degree of satisfaction or perceived success is highly variable,

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and seems to be related to amount of flexibility allowed by the regulatory authorities. Replacing topsoil (the soil on top) has no advocates that I have met, and is a prime candidate for intensive research.

Major coal companies in the central states commonly plant a hundred thousand, and up to a million, trees a year. The planting conditions--weather, soil, animal damage, and others--and the relative success of the plantings are not easily combined into a meaningful average or mean. In conversations with reclamation personnel from one company I am told they typically get 90% establishment rates. One year, however, their plantings were devastated by voles. They use small seedings and are currently testing different kinds of herbicides and rates of application.

A company in another state describes their typical establishment rates as 10%. Plantings are replaced one or more times. High vole populations are a recurrent problem in the lush herbaceous cover required under SMCRA. Although topsoil replacement and compaction are of major concern, they feel ripping gives the small animals better hiding places and easier access to roots for feeding. These sorts of problems are not part of the public record and likely would be disowned if reported. They are vitally important for understanding the overall reclamation picture, and guiding research programs.

My task in this paper is to review what is being done, to suggest what could be done, and to identify persons or organizations currently active in research on reclamation with trees and shrubs. I trust that the citing of papers will largely fulfill that responsibility. This paper will likely reflect that I am most familiar with work in Illinois, Indiana, and western Kentucky and most commonly interact with people in the central and eastern coal mining states. Willis Vogel, Nelson Rogers, and other USDA Forest Service personnel and those of other agencies and the universities together with former students have all shaped my thinking.

Reclamation research activities rarely are carried out by individuals working alone. A fundamental component of any reclamation research or demonstration project is a mining company willing to make its land available for these purposes. Government agencies, universities, technical societies, and coal associations typically carry out reclamation research and hold meetings and conferences that report and publish results.

The Reclamation Record

We are fortunate in having Forestation of Strip-Mined Land, Agriculture Handbook No. 166 by G.A. Limstrom, 1960, and other landmark publications that summarize results of research directed to the objectives of earlier years. The information in Limstrom's publication was obtained from research organized by A.G. Chapman of the USDA Forest Service Central States Forest Experiment Station, in cooperation with several state agricultural experiment stations and coal mining industry associations and companies. Many of these objectives, such as species selection and evaluation of the effects of soil compaction are still pertinent today. Herbaceous cover (weeds) was a relatively isolated problem in earlier years. Herbaceous cover, as required by SMCRA, created a problem of greater magnitude.

Other early publications that incorporated new findings and summarized the "state of the art" in reclamation included the 1969 Penn State symposium (Hutnik and Davis 1973), the 1976 Wooster, Ohio symposium (Schaller and Sutton 1978), and the 1980 Trees for Reclamation symposium in Lexington, Kentucky (USDA 1980). More recently a swelling volume of research activity and findings has led to numerous published proceedings of other conferences and proceedings. Several of these are listed in the References, as are books on reclamation with significant reforestation content.

The tradition of Limstrom's 1960 summary forestation publication has been continued with the publication of revegetation guides authored by Vogel successively for the USDI Fish and Wildlife Service (with Rafaill in 1978), the USDA Forest Service (1981), and the USDI Office of Surface Mining Reclamation and Enforcement (OSM) (1987). The latter two publications have species descriptions for grasses, forbs, trees, and shrubs, as well as extensive information on planting methods and environmental factors affecting vegetation.

One of the features of this outpouring of research results is its diffuse nature in terms of ready access in the literature. The conference proceedings may not be cited in abstract journals or in computer databases and are not regularly incorporated in library holdings. Relatively little of the reclamation literature is published in established journals, and efforts by publishers to develop new specialized journals such as Reclamation Review in 1978 have not been successful. The need for information transfer in reclamation has resulted in a number of published bibliographies by various agencies, covering reforestation as part of reclamation (see References). Similar bibliographies, not listed, with articles of interest have been published in Great Britain and other-coal producing countries by governmental agencies or with professional society sponsorship.

A continuing research publication outlet has been the technical papers, station notes, agricultural handbooks, and other publications of the USDA Forest Service. Early publications and reports were cited in the handbook by Limstrom (1960). An annotated bibliography of surface-mined land publications resulting from Forest Service research efforts in reclamation since 1962 was published in 1982. This publication was maintained by the eastern reclamation project office at Berea, KY, until the activities of that office were terminated by Congress in 1991. Forest Service employees in reclamation work helped found earlier state and regional associations from which the ASSMR evolved.

An important computer-produced publication in the late 1970s and early 1980s, first monthly then quarterly, with SEAMINFO computer searching, was SEAMALERT. SEAM (Surface Environment and Mining) also published a series of User Guides with greater orientation to mining and reclamation in the west. The Environmental Protection Agency (EPA) has had a substantial number of reclamation-related publications including an earlier Environmental Protection Technology Series with important publications on soils, and Interagency Energy/Environment R & D Program Reports with the USDA Cooperative Research. Reclamation-related EPA Project Summary publications are continuing. The Tennessee Valley Authority has carried out extensive reclamation studies in its area with numerous reports and publications. Universities known to me that have and/or are carrying on reclamation research programs after surface mining for coal are listed in Table 1.

OSM currently publishes RecTec, an annotated list of publications on reclamation, and has a mailing list of interested persons. Publication of RecTec had recently been discontinued by the USDA Forest Service, and earlier by Madisonville Community College (Kentucky). A Register of Research and Demonstration, Annotated List of Areas with brief descriptions of the research objectives and results has been compiled and is continuing cooperatively between the American Society for Surface Mining and Reclamation and Southern Illinois University at Carbondale (Kost and Ashby 1987, Smith and Ashby, 1989). Many of the areas listed in this register have been planted to trees. The data set has been computerized (IBM, Database IV) and should be edited and available on disks within the next 6 months.

Relatively recently the National Mine Land Reclamation Center, funded by the USDI Bureau of Mines, has sponsored reclamation research, including reclamation with trees. Acid mine drainage is the dominant reclamation issue in the Eastern Region, prime farmland restoration in the Midwest Region, and groundwater movement and uneven surface settling in the Western Region. A regional cooperative University program reflects fundamental differences in climate, geology, soil, and vegetation that dictate the types of reforestation programs suitable for each coal province. Research in Canada similarly is related to the physical and biological environment. An USDA-Cooperative State Research Service/Industry prime farmland cooperative reclamation project has supported research at the Universities of Illinois, Kentucky, and Missouri. These universities carry out an active program of research on compaction limits to plant growth on reclaimed soils. They have annual report and field meetings, a voluminous annual report, and numerous journal articles. Their impressive findings are applicable to work with trees on the same soil types and fields.

Reclamation Problems and Opportunities- The Driving Force for Research

There are several kinds of problems in reclamation with trees - those generally associated with tree planting in horticulture and forestry to be discussed later in the paper, those unique to reclamation, and those resulting from regulatory and associated operational constraints. New relatively intensive techniques are rapidly being developed in horticulture, especially urban forestry, to deal with soil compaction, moisture deficits, and other problems. The scale of tree planting in reclamation, and the relatively low levels of management, are so different from horticulture that any extrapolations of research findings need to be made with great caution. Another difference is greater flexibility in expected use for the results, and therefore justification for

Table 1. Universities having reclamation research programs with trees.

University of Alabama	[a]Virginia Polytechnic Institute and State University	[b]North Dakota State University
Auburn University	[a]West Viriginia University	[b]University of Wyoming
University of Tennessee	[a]Ohio State University	[b]Montana State University
University of Kentucky	[a]Purdue University	[b]Utah State University
Pennsylvania State University	[a]Southern Illinois University	
Ohio University		
University of Illinois		
University of Missouri		
Iowa State University		
University of Iowa		
Kansas State University		
South Dakota School of Mines		
University of North Dakota		
Texas A&M University		

[a]Relatively active reclamation programs in reforestation at present.
[b]Relatively active reclamation programs in rangeland at present.

research in horticulture. If reclamation is constrained by a regulator's concept of normal, accepted practices in a region, research tends to be constrained. Why not have irrigation in the mining regions of Illinois as well as along the Illinois and Wabash Rivers? Stripmine lakes, available for the asking, provide valuable wildlife and recreation as well as a water resource for plant needs during establishment and drought periods.

Regulatory constraints in Illinois that I believe to affect tree performance adversely are restrictions on amount of coarse fragments that benefit tree growth in minesoils (Ashby et al. 1984); reclassification of important acreages as prime farmland fragipan soils - an apparent contradiction of SMCRA - so that problem soils are replaced; requirements for topsoil replacement when an alternative rooting medium clearly seems (but cannot be literally proven at the time) superior for trees and in the long term for other land use; requirements for use of native tree species without reasons why or a clear understanding of which species are truly native, resident, or exotic; excessive grading; and unwarranted on-the-ground requirements for excessive ground cover. Except for unusually high intensity storms less dense cover controls erosion adequately, and sediment ponds are a back-up safety feature. Other states seem to have requirements that adversely affect tree performance. The coal industry in the midwest was a significant source of financial support for research on trees following passage of SMCRA until they saw little or no effect of research findings on permitted operations. We are not likely ever to know the best ways to reclaim land after mining if some ways cannot be tried.

The majority of recognized problems known to me under Title V relate to massive post-grading soil compaction (Limstrom 1960, Philo et al. 1982, Josiah 1986), excessive and/or wrong kinds of herbaceous ground cover (Parr 1982, Philo et al. 1983, Ashby et al. 1988, von Althen 1990a, Van Sambeek and McBride 1991), and animal damage associated with the required ground cover (Swihart and Conover 1988, von Althen 1990a). Other problems include undesirable replaced surface soils and lack of suitable soil organisms. These problems are not unique to reclamation with trees and, especially for soil compaction, important work is being carried out in reclamation with non-woody plants.

Research Direction

A question important for research direction is, what needs will trees planted on mined lands serve? A present need, and increasingly so in the future, is high quality timber, now found on pre-law mined lands. Research focused on quality timber has tended to predominate in the past. The midwest and eastern U.S. are prime areas for producing fine hardwoods and mined land could serve as an important national resource. Superior growth, however, is only possible for these trees on sites with deep, well-drained soils having good reserves of essential plant nutrients. Soil compaction and replaced topsoils pose problems in meeting these needs.

Trees can serve many other needs. In the midwest a widely recognized value is wildlife habitat. Differing kinds of trees and less concern for superior growth form are possible. Non-commercial species may even be desired. Research studies often do include shrubs and trees not considered to be of commercial value. I understand that in Illinois only 15% of species traditionally considered to be non-commercial are permitted.

New species are becoming of commercial importance as described in Forest Research West for December 1990. Large paper companies have planted thousands of acres for short-term woody crop, or biomass, production. The chief species in the Pacific Northwest and Lake States is hybrid cottonwood, and in the South is sycamore with the output largely used for pulp, a forestry product. Genetically-improved trees are grown in large blocks and harvested by special machines with little manual labor at intervals of 6 to 8 years. The cut stumps sprout readily for later harvests, saving replanting costs. Whether using non-native hybrids and non-commercial species would be approved for use in reclamation is not known. Biomass production seems to be an ideal use for mined land.

Trees grown for biomass energy, chemical feedstock, pulp, and other needs have quite different environmental and managerial requirements than those grown for long-term timber production. This type of use for mined lands with a short-term economic return would promote new research directions that could include ripping, water harvesting or irrigation, more intensive ground cover and animal control, and other managerial inputs. Cooperative research and demonstration projects to develop a local user industry would greatly benefit many coal-mining areas. Another forestry practice new in this country that could well be adapted to reclamation is agroforestry, developed by Gene Garret and others at the University of Missouri, often in the form of alley cropping. Soybeans or other crops are grown between rows of black walnut or other high-value hardwoods. As the trees grow larger the width of the crop rows is reduced until the trees take over. This gives an early economic return, with incentives for research on intensive management such as control of herbaceous competition and small mammal populations harmful to trees. With black walnuts a valuable nut crop can be gathered in intermediate and later years. Ripping would be needed to grow walnuts on graded lands, with the walnuts planted in the rips. If root development and other conditions are favorable, mature walnut trees properly tended attain values of $10,000 apiece or more in 60 to 80 or more years.

The 2nd Conference on Agroforestry in North America sponsored by the University of Missouri, the USDA North Central Forest Experiment Station, Hammond Products Co., and others, was held last August in Missouri. To quote the meeting brochure, "Agroforestry (growing crops and trees together) has the potential to (1) minimize costs of conservation measures (e.g. terrace construction) (2) reduce soil erosion, (3) improve wildlife habitat, (4) improve water quality, (5) help build a resource base for value-added businesses and (6) provide an above average internal rate of return for landowners who practice it." A perspective on agroforestry was given in Forest Research West for April 1991. Roles of trees listed were "to conserve valuable topsoil, maintain water quality, increase landscape and biological diversity, provide harborage for natural enemies of crop pests, increase preparedness for climate change, improve environmental quality and quality of human environments, increase energy efficiency, and protect wildlife."

Growing crops and trees together could be an ideal use of lands surface mined for coal and would stimulate interest in and support for new kinds of research. A promising linkage would be the recently reported ability of some trees, such as hybrid cottonwood, to root to depths of approximately 1.5 meters or more within 8 years or less in highly compacted soils (Ashby and McCarthy 1990). Possible tolerance to low soil oxygen levels by hybrid cottonwood may be a feature in common with baldcypress, lowland bur oak, and sycamore that also root relatively deeply in compacted soils. Trees can thus be used for biological ripping to prepare better soils for later timber or crop production. The full benefits of successful reclamation with trees cannot be judged in the first years after establishment. Research development of agroforesty in reclamation is needed.

Values of trees for aesthetic and environmental quality have received greatly increased public and agency awareness in recent years. Timber values have been accorded much less importance than even a few years ago. Trees can be important in landscape design even if not of timber quality. The role of trees in reducing atmospheric CO_2 levels, and in improved water quality has increasingly been recognized. All of these relationships illustrate how research direction is a function of projected uses for trees.

Species Trials and Planting Mixtures

Species trials, not mentioned above, are probably the most common direct or indirect type of research to try to cope with soil compaction, ground cover competition, and animal damage. Species trials also give information on climatic and edaphic (soil) adaptation of new species for use in reclamation, assuming their use is permitted by the regulatory authorities. This type of research or trial is so pervasive that I shall not cite references. The interpretation of results should be related to understanding whether a tree species is a "generalist" such as black locust, or has more specific site requirements, such as black walnut.

Species trials have been many and varied. Mine reclamation personnel often add to their plantings a few trees or shrubs of new species that seem promising for better survival, growth, or reclamation benefits. The USDA Soil Conservation Service Plant Materials Centers throughout the country have a continuing program of plant trials using new species and new varieties and hybrids of established species, and some of these trials have been on reclaimed lands (USDA SCS 1978). Reclamation research on compaction or other factors affecting woody plant performance often include these and other new plants if promising candidate species are available. Annual reports on the results of species and hybrid trials are available.

I am not aware of research on genetic improvement of woody plant materials for reclamation, a technique of great importance in agriculture for herbaceous crops. Tree breeding and/or selection requires a time scale of decades, and economic returns from such research tend to be viewed as remote at best for timber production. Genetic improvement programs are in place for woody biomass production.

Much research pre-law included interplanting or underplanting economically valuable trees with nitrogen-fixing species, short-lived species such as pines, and other mixtures. Continuing non-reclamation research with interplanting has given promising results (Campbell and Dawson 1989, von Althen 1990b). This type of research and practice in reclamation is limited by the restrictions on percent non-commercial species. Interplantings have promise for lessening damage from wildlife. They may bring new problems of herbicide usage. Interest has successively waxed and waned for use of black locust, European alder, and autumn olive as companion species to fix nitrogen and/or be out-grown or outlived to achieve desired densities and tree form for mature stands.

Choice of ground cover species and planting arrangements can markedly affect tree performance (Vogel 1987). The modest amount of research on the best ground cover species to plant in areas for tree planting could well be expanded greatly. Techniques for assessing effectiveness in controlling erosion also need to be developed so that realistic ground cover standards that will enhance tree performance can be developed. Finding types of ground cover with the lowest populations of animals destructive to trees is greatly needed and scarcely studied (von Althen 1990a). More work is needed on the timing of tree planting relative to ground cover (Ashby et al. 1988). Planting trees before or at the same time as the ground cover has given promising results (Anderson et al. 1989, Vogel 1980).

Trees have a springtime growth flush concurrent with cool-season grasses and legumes. Warm-season (prairie) grasses are quiescent in the spring and grow vigorously in mid-summer when many kinds of trees have lessened environmental demands. White oak, for example, may complete its height growth for the year by June. Prairie grasses typically root deeply (Weaver 1920) and have grown well in reclamation studies (Ashby et al. 1989). Grass roots are not long lived so that channels would be available for penetration by tree roots under living stands. The mulch of dead grass is highly effective for erosion control and may also benefit tree seedlings. Black walnuts or large seeded oak acorns that give high germination rates could be fall planted in established stands of these grasses. The tree seedlings would start growth early in the spring and get established before grass growth is active. Research on this technique seems promising.

Tree Planting with Seedlings

Probably the single most important part of reforestation is the planting operation itself, together with the quality of the tree seedlings. Personal and other industry experience, more than published research, seem to have the greatest effect on planting practices. There are a number of seemingly little things than can (and do) go wrong in tree planting. Their effect is multiplicative. For example, if only 80% of the seedlings are viable after storage and only 80% of the 80% are viable after roots dry out during planting operations, only two-thirds (64%) of the seedlings are alive when planted. Further losses may result from improper planting, herbaceous competition, and animal damage, all of which are highly likely. A modest 20% decrease in survival for 5 seemingly routine planting operations gives only a 33% overall first-season establishment under good growing conditions. Drought and other stress on weakened seedlings can bring about much greater losses.

I am not aware of ongoing reclamation research on quality of tree seedlings. Paul Kormanik at the University of Georgia has recently emphasized the importance of a high number of lateral roots. Reclamation personnel strive to buy the best seedlings available and have strong opinions as to what constitutes desirable planting stock. Keeping roots moist in storage and shipment is high priority among planters but apparently less so among nurserymen. How important it may be in reclamation does not seem to have been documented. Some reclamation supervisors like to plant larger, and some smaller (perhaps 30 cm tall) seedlings. Relative shoot/root ratios or balance, including the wisdom of pruning shoots and/or roots has an extensive literature and is frequently discussed with few answers. Reports by Kormanik (1988) in the forestry literature that seedling vigor is related to the number of lateral roots will no doubt focus attention on that criterion for seedling selection. Evaluation of root growth potential is a currently active field (Rietveld and Tinus 1990) that has important implications for reclamation. Techniques such as dipping roots in growth regulator or nutrient solutions have been tried without clear results.

Dipping roots into and coating them with a slurry of water and super-absorbent materials (such as Terra-Sorb™, Supersorb™) during planting is now practiced to some extent, perhaps more as a result of salesmanship than research findings. To the extent there has been research, claims of increased drought resistance are commonly discounted. Using these materials to keep roots from drying out as a relatively inexpensive safeguard against carelessness during planting has been accepted by many planters. Our studies have not documented benefits if careful planting practices are otherwise followed.

New ways of getting seedlings into the ground using planting machines continue to be developed. Improvements include deeper planting slits and therefore seedlings with longer roots can be planted, better closure of slits, better handling of slash or rocks on the soil surface, greater maneuverability for planting on irregular topography, multiple planters, and tractor-mounted tanks and rigs for automatic herbicide application. Equipment acceptance again seems to be based more on salesmanship and word-of-mouth planting experience than on research comparisons. Design and time-on-the-ground by machinery need to be monitored closely to minimize compaction.

Mycorrhizal inoculation has been enthusiastically promoted by various people at various times. Work with pines in the east seems most promising. Our research, and that of others, has shown little effect of the root fungi with hardwoods in the midwest. Natural inoculation of both ecto- and endophytes seems to take place readily, and fungal populations on or in roots of inoculated seedlings may change rapidly after planting. Greater phosphorous uptake can be attributed to mycorrhizae. The common assumption of greater water uptake is highly questionable. Research on mycorrhizae commonly is an adjunct to other research programs. I am not aware of coal company personnel including the use of mycorrhizae in their plantings.

Canadian foresters now plant more containerized than other types of seedlings. This method seems to be most successful with conifers, especially those with naturally weak seedlings such as spruce. Based on our experience and other studies the use of containerized seedlings has not found much acceptance in hardwood plantings. Perhaps further research someday will change that viewpoint.

Tree spades and front-end loaders are used to plant large trees up to several inches in diameter breast height. The cost per tree is high, survival may be low, and the demand in reclamation is unlikely to be great enough to justify research expenditures. Transplant shock as a rule is greater with larger compared to smaller seedling. Black walnut from seed often equals or exceeds planted seedlings in height after 3 to 5 years. We can profit from research in urban forestry and highway plantings.

<u>Tree Planting with Seed</u>

Planting seed is a way to avoid poor handling and planting of seedlings. There have been numerous seed planting studies. Large-seeded species typically are more successful than small-seeded trees (Graves et al. 1980). The results for seedlings established from seed are usually quite similar to those with planted seedlings.

Our earlier studies showed that seedlings are best planted in the spring, and seed of several species in the fall, assuming that destruction of the seed by local animal life is not a problem. There are exceptions, such as silver maple and cottonwood. In the spring both usually produce copious short-lived seed that has to be kept moist and planted quickly before it loses viability.

White, chestnut, and other oaks in that group germinate in the autumn and need to be planted then. If stored, the radicles elongate and make handling difficult. Black, red and other oaks in that group, black walnut, and numerous other temperate-zone trees have seed dormancy. The acorns or nuts must be stratified by moist cold storage for three months to get good germination (USDA 1948). Attention must be paid to proper seed handling, especially when using species new to a project.

Direct seeding of small-seeded trees was early shown to be successful and has been widely used with black locust as part of a hydroseeder mix in Appalachia. More recently other species such as ash have been added to hydroseeder mixes, and given acceptable results. The number of trees desired can be relatively inexpensively achieved by adjusting the planting rate. We and others have found small-seeded trees such as black cherry and hackberry and to a lesser extent persimmon to fail conspicuously when planted using mattocks. These species commonly invade developing stands of planted trees, presumably from seed carried in by animals, and seed germination is often promoted by passage through a digestive system.

Large seeded species, black walnut, bur and other oaks, and hickories, have successfully been planted with a mattock or other tool. Modified corn planters have been developed for use on mined and other lands. Direct seeding of these species seems to be uncommon in industry, and I do not know of current research focused on the use of seed versus seedlings. Some direct seeding may be done as part of other research studies.

A relatively recent development has been direct haul placement of surface soil from under a forest canopy on reclaimed areas planted to trees. Success with trees has been increased using these natural seed banks (Wade 1989). Brenner (et al. 1984) in Pennsylvania has been promoting ecological restoration for many years, and the newly organized Society for Ecological Restoration has had a strong interest in mine reclamation as an important part of restoration ecology (Jordan et al. 1987). If acceptable to the regulatory authorities and mining industry (Wade 1988), reclamation of self-sustaining ecosystems with emphasis on ecological restoration would greatly stimulate research by bringing a host of highly trained and dedicated persons into reclamation.

Fertilizers, Soil Amendments, and Mulches

Research on fertilizers has commonly been an adjunct to other studies. Site preparation under SMCRA includes liming and fertilizing to levels approved by the regulatory authority. These soil fertility recommendations have been developed for the growth of the requisite herbaceous ground cover. Fertilizing small trees within the herbaceous cover increases the growth of and competition from the ground cover and has often had negative effects on tree survival and/or growth (Ashby 1990). Although trees seem not to need high fertility levels, results in the nursery trade suggest that with adequate control of ground cover, fertilization may be beneficial.

Several types of soil amendments and mulches have been used in reclamation. Use of sewage sludge has been demonstrated to be beneficial (Sopper et al. 1982, Van Sambeek et al. 1992). Sewage sludge can, however, markedly increase herbaceous growth, and public concerns about odors, heavy metals, or other possible effects may limit its use on Title V lands, even for growing trees in remote areas. On some Title IV AML lands, however, the severe limitations for tree planting are generally understood so that acceptance of sludge use is much greater, and problems such as heavy metals may already be present.

Organic mulches, such as sawdust, wood chips, or shredded bark, are currently little used or studied because of logistic problems of dependable sources, transport, and stabilization in the field together with reported limitations as well as benefits in tree performance (Slick and Curtis 1985). Thin, easily handled plastic sheets or strips are used for area plantings in horticulture and have been tried on a limited scale in reclamation (Horn and Ward 1969, unpublished work by Ashby). Thin plastic squares or disks or excelsior pads (Davidson 1989) to put around individual trees give more flexibility in use and are less cumbersome for disposal later if needed. Research with plastic materials to control ground cover plus added benefits of moisture conservation seems likely to continue and expand, even though their use adds another layer of cost. At present, biodegradable plastic costs about twice as much initially, and may save costs if plastic sheets later have to be removed. The cost of coming back and replanting trees, especially where mortality has been spotty, is appreciable. Delays in release of bond monies are costly and help justify added expenses of tree establishment.

A relatively new, highly-touted tree shelter costing $2.00 or more depending on height placed around a tree seedling and wired to a stake has been reported to increase survival and greatly increase growth (Tubex Tree Grower's Guide 1992). These plastic tubes have been more used in forestry and horticulture than in reclamation. They come in various diameters and lengths and give protection from animal damage. Improved water relations and other benefits have been listed. Some trees may, however, be deformed and have died from birds perching on the tops of tubes and creating excessive nitrate levels from their droppings and weeds within the tubes smothering the tree seedlings. The plastic of the tubes is supposed to disintegrate about the time the trees have grown well beyond them. The tubes could be very useful in critical areas, and research is needed on best tree species to use with them, proper use of herbicides, and possible benefits of fertilizer tablets in conjunction with them. The total estimated cost could be several dollars per tree.

Herbicides

Herbicides have been and continue to be the main means of controlling ground cover (Parr 1982, von Althen 1990a). A complication with herbicide use, and research, is uncertainty about continuing availability of various chemicals, as well as the development of new ones, not necessarily for reasons of human health and safety but primarily because of economics. The costs to a company of registration and re-registration of agricultural chemicals under regulations, with continuing changes, of the Environmental Protection Agency have to be balanced with the expected sales in a limited market. Most of the forestry market for herbicides is for chemicals to get rid of broadleaved woody species in the clearing of power lines and roadsides or release of pines. Some specialized herbicides for control of grasses can be used with tree seedlings in leaf. Herbicides to control broadleaf weeds generally cannot be used with deciduous species. Although use of dormant-season and pre-emergent herbicides merits research, they may cause damage to tree seedlings. The best present approach seems to be a thorough pre-planting spray program, coupled with spraying at the time dormant tree seedlings are planted. Alternatives to use of herbicides, such as mulches, short-lived nurse crops, etc. are needed.

Animal Damage

Damage from animals and what to do about it has been well studied for orchards (Swihart and Conover 1988) and to some extent for hardwood forestry plantings (von Althen 1990a). It has caused severe problems. So far it does not seem to have been a field of research in reclamation. The present open meadow areas with dispersed trees on mined lands are ideal habitat for many girdling and browsing animals. The amount of animal damage varies from locality to locality and year to year, perhaps justifying the hope that the trees can outgrow the damage before they are destroyed. Just as you take satisfaction that saplings are safe from browsing, they can be battered to pieces by buck rub in the winter.

Practical measures to offset damage include costly deer fences of varying types and effectiveness; hawk and owl perches for controlling rabbits, mice and voles if herbaceous cover around tree seedlings does not unduly limit on-the-ground visibility; tree shelters; repellents of questionable value; and poisons, the use of which is actively opposed by other interest groups. Some types of animal damage can be offset by choice of unpalatable species. Possible alternatives would be to interplant species desirable both to man and wildlife with less desirable species or to plant so thickly that deer use will physically be reduced. The grassy areas tend to have much higher mouse and meadow vole populations than wooded areas. Research on how to lessen animal damage in reclamation is greatly needed.

Soil Compaction

Papers on the adverse effects of compaction on tree growth were published over 30 years ago, long before SMCRA (Limstrom 1960). This once relatively uncommon problem became pervasive with universal grading under SMCRA and especially as a result of topsoil, often not beneficial, replacement. Research to demonstrate that mixed overburden is a more suitable rooting medium as allowed by regulations should be highest priority.

Most research on compaction effects in reclamation and most equipment development for compaction mitigation has been for corn, with less attention to trees. Early ripping studies documented marked improvement in survival and growth of species such as black walnut, known to require well-drained soils (Philo et al. 1982, Josiah 1986). My present studies, and associated studies at Southern Illinois University, were made possible by a ripper being available on a mine, with tree plots planted in conjunction with research on row-crop production. Our quarterly and annual reports to the National Mined Land Reclamation Center include data on improved tree growth from ripping and from intensive control of ground cover. Manuscripts are in preparation.

Ripping, in addition to making an opening in the soil for root penetration, also disrupts the herbaceous cover along a rip and helps channel storage water down into the soil and increases gas exchange in the rips. How much each of these changes affects tree growth is not known. Research that identified each of these effects could improve the efficiency of ripping. Research to test differences in tree species responses to ripping could also enhance reclamation planning and success.

Plants whose roots can penetrate compacted soils are known and their use may in the long-term be more valuable than mechanical ripping (Ashby and McCarthy 1990). The root channels provide continuous pathways for movement of water and air, and they are lined with organic matter that provides a discontinuity in the soil matrix. Mechanically-ripped soils have been reported to flow together as a unit mass.

In the midwest the trees with deepest rooting on compacted minesoils found so far have been baldcypress, hybrid cottonwood, bur oak, and sycamore (Ashby and McCarthy 1990). Bahiagrass, a southern species, has been reported to be very effective in penetrating soils with high soil strength and could benefit reclamation in areas to which it is climatically adapted. Further research to identify species able to break the compaction barrier is needed. A practical use of deeply-rooting plants could be to interplant them with high-value hardwoods. For example, rapidly-growing hybrid cottonwood cuttings could be planted thickly between rows of red oak. The cottonwood could be harvested in perhaps two rotations for biomass, and then killed with herbicides after 10-12 years. The red oak could later take over the dead cottonwood root channels and grow vigorously to produce valuable timber. Biological ripping will be relatively more effective to the extent that the trees and other plants able to root deeply in compacted soils can grow vigorously. This means that all other factors should be as favorable as possible.

Drought stress as a result of poor root-system development is greatly increased on compacted soils. An obvious remedy is irrigation, ideally suited to mined lands in that end-cut and incline lakes offer a dependable supply of mineral-rich water. Final cut water is, however, not always suitable in the west for irrigation. Use of irrigation has not been permitted for bond release in row-crop production in Illinois under a "normal practice" provision. I do not know that a ruling on the use of irrigation in reforestation has been made. Such rulings need to look forward to innovative tree-planting possibilities and longer-term soil development.

Drip irrigation that uses relatively little water has been developed for climatically-dry areas such as Israel and used in southern Illinois to establish trees. Water harvesting (pitting, gouging, microterraces, etc.) has been used to establish shrubs and some trees in the southwest and western coal regions. I do not know whether this amount of surface roughness would be permitted in corn country. Greater water availability would make possible better establishment of commercial forest trees and of agroforestry plantings and speed soil loosening by deep-rooted plants. Research on better use of our overall water resources is needed for maximum effectiveness in reclamation with trees.

Rooting Medium

The most obvious, and likely most important, difference between pre- and post-mined lands is the rooting medium. SMCRA has numerous specific provisions on soil replacement grading, and other issues of critical importance in reclamation. A persistent question is whether replacing topsoil is needed, or beneficial, for trees (Vogel and Gray 1987). The answer to this question greatly affects reclamation costs and has been a major bone of contention between the coal industry and the regulatory authorities, including continuing lawsuits.

Probably the most valuable research finding for reforestation would be what constitutes a good topsoil substitute. There will be no one answer, because natural soils vary greatly from one area to another, as do other geologic materials in the overburden. Topsoil substitutions in eastern Kentucky and in central Illinois are quite different. I shall review some of the earlier work on soil analysis and classification.

Richard M. Smith and his co-workers and students at West Virginia University, especially John Ammons, John Sencindiver, and Andy Sobek, have carried out numerous soil studies in the Appalachian and also in the Interior Coal Province (Smith et al. 1974, Smith et al. 1976, Ammons 1979). They established much of the methodology subsequently used, and found that alternative materials could be advantageous compared to pre-mining topsoils. Coarse fragments in soils were found to be beneficial for tree growth (Ashby et al. 1984). Significant work on analyzing eastern and midwestern reclamation soils has been carried out at Ohio State University (OARDC at Wooster by Kost, Larson, Sutton and Vimmerstedt), Purdue University in Indiana by Byrnes, Pope and others, and the USDA Forest Service reclamation center at Berea, KY with Berg, Plass, Vogel and others. Western soils have been studied under the auspices of the Western Soils and Overburden Task Group (Williams and Schuman 1987).

Minesoil classification is being developed by the USDA Soil Conservation Service as part of the national soil survey. More local classification has been carried out by Sencindiver in West Virginia and by Lyle (Lyle et al. 1979) in Alabama. As with classification of natural soils, tree performance cannot reliably be predicted from a named soil type. How to predict plant growth, tree performance, from soil analyses remains a major research question.

Summary

Research in the past 70 years of surface coal mining and reclamation in the central United States has dealt predominantly with meeting immediate needs for greater reclamation success. The goals of reclamation have, however, differed both from one coal-mining area to another, and from earlier to later times. Since 1977 reclamation operations and research have been dominated by SMCRA and the corresponding state laws, regulations, and enforcement.

Before the passage of SMCRA roughly 80% of reclamation operations and research for the time period to date had been carried out. Many of the trees planted then are now 60 years old, and in various places the cast overburden has weathered to form rich soils. Few post-SMCRA plantings are 10 years old, and the possibilities for soil development are consequently unknown. Reclamation research and publication volume have been relatively much greater post-SMCRA.

In the absence of an established discipline and journals, reclamation publication outlets have been diverse and scattered. Conference proceedings, not routinely accessioned by libraries, have been a major publication outlet. Being part of the reclamation community gives access to much published and unpublished material likely to be missed otherwise. There are numerous bibliographies, some not very useful.

I consider any planting from which we can learn more about plant performance in reclamation to have research value, even if not set up for statistical data handling. The mining companies plant hundreds of thousands of trees a year compared to only hundreds, if that many, in most research studies. There is a wealth of information to be gained from these plantings.

Industry reclamation personnel do not commonly take very detailed data of tree performance in their plantings or publish the results. Academic/industry contacts to gain this sort ,of information can be furthered by field trips, visits, and attendance at conferences attended by industry personnel. Some of the information may be semi-confidential, and mutual respect is important.

Research is highly conditioned by available funding. The coal industry tends to support research for new types of reclamation. If research findings have little or no effect on regulatory requirements, funding for and that type of research will be limited. The agendas of government agencies seem to be geared to showing that reclamation is workable within a regulatory framework. Research on ungraded areas, for example, can only be done on pre-law lands and none of these areas have fresh minesoils.

Effects of grading--soil compaction, associated erosion hazards from high runoff rates and consequent requirements for dense vegetative cover, and extensive damage to young trees from abundant animal populations in the herbaceous cover--have limited the success of many plantings. Soil compaction problems in crop production have generated substantial funding and extensive research and publication. Compaction problems have recently also come to the forefront in other fields--horticulture, urban forestry, forest harvesting, and row-crop agriculture--with findings of importance in reclamation.

Topsoil replacement is considered by many industry and academic persons to be detrimental to tree performance and to contribute substantially to soil compaction problems. The value of coarse fragments apparently still needs to be further documented and demonstrated. Research (demonstration?) to show that leaving rough surfaces with varied microsites for improved water relations and success in tree seedling establishment in the central states is needed.

Mechanical ripping is widely accepted as a feasible, if costly, remedy for limitations to plant growth from soil compaction. Research on the long-term effectiveness of ripping is needed in view of findings that under cropping conditions compaction may reappear. A biologically desirable, long-term solution may be to develop soil porosity with trees and other plants able to root deeply in compacted soils. Baldcypress, hybrid cottonwood, bur oak, and to a lesser extent sycamore, all bottomland species, have rooted deeply in post-SMCRA reclamation plantings.

Another major activity in reclamation has been testing of plant materials, and introduction of new plants. Both trees that may be less limited hy ground cover or compaction, and types of ground cover less limiting to trees are routinely tested as part of various types of plantings. Planting mixtures, use of seed versus seedlings or cuttings, and seed bank replacement using soil from natural forest stands are included. Studies of planting season, dormancy or other physiological conditions, pruning, size of plant materials, evaluation of root-growth potential, and use of root coatings with hydrophilic materials are also carried out. Research on use of mycorrhizae and of nitrogen-fixing symbionts continues to be more active outside rather than within the reclamation community.

Fertilizers, soil amendments, plastic sheets and other mulches, and tree shelters have been tried with both positive and negative results. Continuing work has been carried out to find the right herbicide or herbicides for ground-cover control, and the science of herbicide use sometimes seems to at the level of placing bets at a horse race. There are many variables that affect results with herbicides. Research and more favorable regulatory opportunities for chemical companies to develop and market herbicides profitably are needed.

Most studies on animal damage to trees seem to be carried out in horticulture, and somewhat in forestry. Small mammal populations cycle from year to year and with luck a planting may escape damage. Bond likely has been released before deer damage becomes serious. I believe that careful research on the amount of damage by voles, mice, rabbits, deer, cutworms, and other animals would show such damage to be a major factor affecting reclamation success.

Reclamation needs to benefit from incorporating new concepts from active research in other related fields. Large expanses of mined land under single ownership freshly created for plant growth under single ownership seem to be ideal sites for woody biomass and agroforestry plantings. These are non-traditional types of tree plantings. Ecosystem restoration is currently a very active interest. Cooperative studies, including funding, with workers in these fields offer much promise. Regulatory constraints, and marketing possibilities, need to be considered.

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Appendix. A list of scientific and common names of plants mentioned in the text.

Acer saccharinum	Silver maple
Alnus glutinosa	European alder
Andropogon gerardii	Big bluestem
Carya spp.	Hickory
Celtis occidentalis	Hackberry
Diospyros virginiana	Persimmon
Eleagnus umbellata	Autumn olive
Festuca arundinacea	Tall fescue
Fraxinus spp.	Ash
Glycine max	Soybean
Juglans nigra	Black walnut
Medicago sativa	Alfalfa
Panicum virgatum	Switchgrass
Paspalum notatum	Bahiagrass
Platanus occidentalis	Sycamore
Populus deltoides	Cottonwood
Populus X	Hybrid cottonwood
Prunus serotina	Black cherry
Quercus alba	White oak
Q. macrocarpa	Bur oak
Q. prinus	Chestnut oak
Q. rubra	Red oak
Q. velutina	Black oak
Robinia pseudoacacia	Black locust
Sorghastrum nutans	Indiangrass
Taxodium distichum	Baldcypress