Restoring and Enhancing Productivity of Degraded Tephra-Derived Soils

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In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Abstract

Soil restoration (sometimes termed enhancement) is an important strategy for sustaining the productivity of managed forest landscapes. Tephra-derived soils have unique physical and chemical characteristics that affect their response to disturbance and restoration. A variety of factors reduce forest productivity on degraded soils. Site-specific information on soil physical conditions, organic matter, and nutrient status is required for efficient soil restoration, but only limited research is available to help interpret such information and guide efforts to restore tephra-derived soils. Based on site-specific conditions, reclamation treatments can be identified to control water, till compacted soils, restore organic matter, and revegetate disturbed areas. Successful reclamation investments will often involve simple treatments focusing on low cost options such as decompaction, topsoil replacement, fertilization, and tree planting. Avoiding difficult sites such those in high elevation environments, wet areas or fine textured soils is recommended where possible, as treatments to overcome such problems are likely to be expensive and have uncertain outcomes. Restoration efforts in volcanic terrain likely need to be accompanied by programs to monitor the beneficial effects of treatments on forest productivity, in relation to their costs.

Introduction

Soil restoration (sometimes termed enhancement) is an important strategy for sustaining the productivity of managed forested landscapes (Richardson and others 1999), and ecosystems (Cairns 1999). Restoration techniques play a role as (a) planned activities for improving the efficiency of accessing and harvesting timber while meeting soil conservation goals, or (b) a means to repair unanticipated damage to soils caused by harvesting, or where previous management approaches have been superseded by strategies that reduce the need for soil disturbance, and allow restoration of previously disturbed areas.

Tephra-derived soils have unique physical and chemical characteristics that affect their response to disturbance and restoration. Volcanic materials have undeveloped crystalline structure and weather rapidly in humid environments, producing soils that are characterized by high water holding capacity (Moldrup and others 2003) and cation exchange capacity, the ability to stabilize soil organic matter, and high reactivity towards phosphate. In the Pacific Northwest, mountainous topography leads to strong redistribution of ash fall materials that were likely deposited in fairly uniform layers throughout these landscapes. Strong environmental gradients also create diverse weathering and pedogenic environments in Pacific Northwest forest soils. For these reasons, the expression of andic soil characteristics shows great variation within landscapes, creating a wide range of conditions in tephra-affected soils, and a similar range of responses to soil disturbance and subsequent restoration or enhancement efforts.

In general, the goal of forest soil restoration is to recreate pre-disturbance growing conditions, so that tree growth rates on the reclaimed soil will approximate those of trees on undisturbed soils on similar sites. Effective soil restoration employs techniques that alleviate growth-limiting conditions on sites that have suffered degrading soil disturbance. Degraded soils are defined here as soils that have experienced disturbance leading to a loss in productivity. Forest productivity on degraded soils can be reduced by compaction that causes plant roots to experience limiting conditions of soil mechanical resistance, water availability, and aeration. Removal of surface soil layers may cause similar effects because organic matter may be depleted from the site, or because unproductive subsoil materials may be exposed. Degraded soils may also be more susceptible to erosion which can cause further loss of nutrients and organic matter that are essential for maintaining site productivity. Erosion can also cause serious off-site consequences for aquatic and terrestrial systems.

Site-specific information on soil physical conditions, organic matter, and nutrient status is required for efficient soil restoration, but only limited research is available to help interpret such information and guide efforts to restore degraded soils derived from tephra.

Restoration techniques aimed at controlling erosion include (a) those aimed at stabilizing soils such as slope recontouring, (b) those aimed at managing water such as ditching or outsloping and (c) those aimed at preventing soil detachment such as revegetation. For compacted soils, tillage is often required to restore conditions conducive for productive root growth. Restoration of organic matter, where appropriate, may be accomplished through replacing displaced topsoil materials, by mulching with organic materials such as logging debris, or through the soil building action of seeded cover crops.

This manuscript outlines the role of soil restoration in maintaining the productivity of managed forest landscapes, reviews the principles that govern how the unique characteristics of tephra-derived soils affect restoration planning in volcanic terrain, discusses how information available from elsewhere applies to reclamation techniques in volcanic terrain of the Pacific Northwest, and provides management recommendations to guide restoration and enhancement efforts.

Soil Restoration to Conserve and Enhance Productivity in Forested Landscapes

Minimizing degrading soil disturbance (Page-Dumroese and others 2000) is an important first step to ensure that soils are maintained in a productive condition, and that forest management is sustainable. Throughout North America, regulatory systems are in place for preventing soil degradation during forest harvesting, access development, and other management activities (Powers and others 1998; USDA Forest Service Standards and Guidelines 2521.1 and 2521.2; CCFM 2002; BC Ministry of Forests 2001). These systems generally specify site specific limits for defined forms of degrading soil disturbance, and may also provide incentives for restoring soils that have been degraded by forest management activities.

In British Columbia, soil conservation policy allows more soil disturbance on sites with low sensitivity to soil-degrading processes (BC Ministry of Forests 2001). In the northwestern United States, higher intensity of soil compaction (i.e. 20% increase in bulk density) is considered acceptable on volcanic-ash derived soils (Powers and others 1998), compared to those developed on other parent materials (maximum 15% increase). These differences recognize that many undisturbed tephra-derived soils have low bulk density, but may also imply that they are less sensitive than other soils to modest changes in density. Tephra-derived soils may also respond differently than others to reclamation treatments.

Restoring degraded soils improves forest productivity. On access structures that are no longer needed, restoration and reforestation increases the land base available for growing trees, and can thereby increase future timber supplies. On areas that have suffered degrading soil disturbance, restoration can improve establishment success and productivity of planted trees compared to areas where soils are left in a degraded state. Achieving full benefit from soil restoration practices depends on the development of cost-effective reclamation techniques, and their application to sites where the cost of reclamation will be offset by improved productivity from the reclaimed lands (Richardson and others 1999).

Reclamation work should be subjected to cost benefit analysis the same as any other management activity. Such an approach avoids wrongly thinking of rehabilitation as an intrinsically good activity, where the true costs of reclamation work can be discounted or ignored. Costs of restoration work include dollar costs, diversion of scarce resources from other activities, consumption of fossil fuels, and risk to workers or property, along with potential negative consequences which may not be anticipated such as water diversion, erosion, slope failure, and weed infestation. At the same time, the potential benefits of reclamation work may also be understated if the analysis is restricted traditional economic measures (dollar costs only), or if inappropriate discount rates are applied to timber production. The social and environmental benefits of carrying out reclamation activities may have been neglected in the past, but recent evaluations have shown the important role that healthy ecosystems play in maintaining economies and societies (Hillel 1991). Such considerations are likely to become even more important as globalization and population growth exert increased pressure on natural environments all over the world.

In general, given the almost universal scarcity of resources, the uncertainty of cost benefit analyses, and the risks associated with undertaking any activity that imposes significant disturbance to a natural system, a prudent approach would focus reclamation efforts on sites where simple techniques have been shown to have success. Treatment of high risk sites and use of expensive or exotic treatments are likely best left to special situations where potential values are high, social factors warrant, or where such efforts are treated as an operational trial or where detailed monitoring will improve our overall understanding of rehabilitation and its role in forest management.

Characteristics of Tephra-Derived Soils as They Affect Growth-Limiting Conditions and Restoration Efforts

Variation in soil properties and growth-limiting factors in tephra-derived soils arise from (a) ecological characteristics of the site associated with climate, topography, parent materials, and vegetation, (b) chemical and physical characteristics of the tephra as it was deposited, and (c) redistribution and alteration of tephra in the landscape in response to topography, moisture etc.

Strategies for reclaiming soils without tephra influence have been developed in the Pacific Northwest and elsewhere, and specify different approaches for a range of soils in diverse geographic settings. The applicability of these to tephra-derived soils depends on the differences in soil properties brought about by the presence of tephra. Some questions to consider include:

- Have natural depositions of tephra led to improved soil fertility by providing a supply of readily available inorganic nutrients?
- What is the weathering state of the tephra? Tephra materials weather rapidly in humid surface environments, but in the Pacific Northwest there are many examples of relatively unweathered materials either because of dry climates or short duration of weathering since deposition.
- What is the particle size of the tephra materials? In the Pacific Northwest, variation in physical and chemical properties as they affect plant growth primarily results from particle size effects (including distance from the source) and post depositional alteration including organic matter retention and weathering.
- For a given particle size, tephra-derived soils tend to have physical characteristics (i.e. water holding capacity; specific surface; organic matter retention) that reflect those of other soil materials with finer texture (i.e. sandy tephra materials may behave more like loams derived from other parent materials).

Morphological Characteristics of Tephra-Derived Soils

Tephra-derived soils include those where minor amounts of tephra were deposited to soil, but are no longer discernable as a distinct layer. In other soils, a distinct layer of tephra is present as an "ash-cap' of varying depth (fig. 1). Finally, some soils may be exclusively derived from volcanic materials to the depth of rooting, with little or no influence from other parent materials on the vegetation. Many soils will display intermediate characteristics to these idealized categories, especially where tephra layers become intermixed with subsoils during construction and use of access structures. Depending on the proportion of tephra, and characteristics such as particle size, special considerations may or may not be needed when developing reclamation strategies.

Physical Characteristics of Tephra-Derived Soils

The presence of weathering products with highly reactive surfaces lead to the common characteristics noted for weathered volcanic materials, including high water retention, organic matter stabilization, and well developed aggregate structure. The characteristics are inter-related as organic matter is partly stabilized because of the surface reactivity, while the presence of organic matter results in

Figure 1—Ash cap overlying ultramafic soil material in the Shulaps Range: interior British Columbia.

additional reactive surfaces. The expression of Andic characteristics depends on the degree of weathering of the material.

A key characteristic affecting reclamation is the low bulk density observed in many tephra-derived soils, owing in part to their low particle density but also to the tendency to develop well aggregated structures. Miller and others (1996) found that even after a substantial increase in bulk density of ash derived soils in central Washington, the bulk density was still less than 1000 kg m^{-3}. For this reason, threshold values for growth-limiting conditions need to be determined specifically for ash derived soils, rather than using values derived for other soils.

Relationships between soil texture and management impacts reflect the variable effects of ash characteristics and soil environments. For example, poorly crystalline weathering products act as a cement to create very stable aggregates in Andisols that occupy wet sites. Also, the weathering products of volcanic parent materials have high surface area compared to the clay minerals found in most other soils (Moldrup and others 2003). In addition, tephra particles often consist of porous and fragile materials, so coarse-grained tephra soils are often less resistant to fracture compared to non-tephra soils, and particle size distribution may shift towards finer size fractions following mechanical disturbance (Sahaphol and Miura 2005).

Tephra-derived soils retain large amounts of water compared to soils derived from other parent materials. Conversely, they are also subject to changes upon drying, which can include the development of water repellency (Poulenard and others 2004) and irreversible structural collapse (Poulenard and others 2003) which is most likely for soils formed in wet environments (Shoji and others 1996). In considering the impact of this characteristic on disturbance and reclamation, the high water retention may lead to a soil with low bearing strength, and high susceptibility to rutting when wet. It may also make tillage operations difficult when soils are moist. Despite this, the materials are expected to provide a good growing medium for plant roots, especially on mesic sites.

Unweathered tephra materials are often non-cohesive and prone to erosion by wind and water (Basher and Painter 1997; Arnalds and Kimble 2001), and this susceptibility may last for some time in unvegetated areas. For this reason, planning should consider measures for rapid revegetation of exposed tephra materials resulting from disturbance and reclamation. Tephra-derived materials with coarse particle sizes have also been used as a water conserving mulch (Tejedor and others 2002, 2003). This characteristic may also present challenges when considering the seedbed characteristics of coarse-textured tephra soils.

The unique physical conditions provide both challenges and opportunities, and both need to be considered when planning restoration treatments for tephra-derived soils.

Chemical Characteristics of Tephra-Derived Soils

The chemical characteristics of tephra vary depending on the geologic environment, and these characteristics are inherited by the soils derived from volcanic materials. In general, the composition of tephra materials in the Pacific Northwest are similar to those of rhyolite, which is expected to provide adequate supplies of mineral-bound plant available nutrients in unweathered or moderately weathered soils. The weathering products of volcanic ash have a high affinity for organic matter, and this characteristic accounts for many of the unique properties, including high cation exchange capacity, and high availability of organically bound plant nutrients. Anion exchange capacity derives from the creation of poorly crystalline oxides of Fe and Al, and also from short range order aluminosilicates like allophane. The anion exchange capacity accounts for the high reactivity of tephra-derived soils to phosphate. Despite these features, recent tephra deposits which characterize much of the Pacific Northwest may have similar fertility to other parent materials (McDaniel, this proceedings).

The presence of large amounts of organic matter in weathered ash deposits is expected to lead to soil materials that are resilient to disturbance, but unweathered materials in cold or dry environments, may have low levels of organic matter.

Reclamation planning should consider the need for organic matter and nutrient additions in consideration of soil conditions and forest productivity in undisturbed soils on similar site types in the area.

Planning Considerations for Restoring and Enhancing Productivity of Tephra-Derived Soils

The unique chemical and physical characteristics of soils derived from tephra play an important role in determining what treatments should be considered for rehabilitating or enhancing a degraded soil. To develop the most appropriate restoration approach, the following general questions need to be answered by collecting field information:

1. Is the soil degraded to the point that forest productivity or other values are likely to be significantly affected?
2. What growth-limiting conditions (e.g. compaction, organic matter loss) or other issues such as erosion, sediment delivery to streams, or visual concerns are present that require amelioration?
3. Are there site conditions or other factors (e.g. cultural resources) that preclude or favor the use of one rehabilitation technique or combination of treatments over another for addressing the growth limiting factor(s)?
4. Are proven treatments likely to increase site productivity to an extent where the associated costs will be returned?

Several research efforts in northwestern North America and elsewhere have recently focused on evaluating the effectiveness of commonly used soil rehabilitation techniques. Although research specifically addressing degraded tephra-derived soils in the Pacific Northwest is limited, the principles governing the success or failure of such work are expected to be similar to those from elsewhere, and on different soil types.

For tephra-influenced soils in coastal Washington, Miller and others (1996) observed that trees on compacted skid trails were growing at the same rate as trees in undisturbed soils and trails where soils were decompacted. They concluded that site specific factors determined the response to soil disturbance and rehabilitation. Where climatic factors were favorable, and soil properties of compacted soils remained within thresholds for growth limiting factors, productive forests could develop on disturbed soils. For the tephra-influenced soils studied by Miller and others (1996), despite a 50 percent increase in bulk density after harvest and values of bulk density that were 20 percent higher after 8 years, the disturbed soils still had bulk density below 1000 kg m^{-3}. Partly because of the results, the authors concluded that the relationship between pre-disturbance and post-disturbance bulk density, which has been used as an indicator of soil degradation in the United States, was not a good predictor of productivity effects.

The complex processes affecting seedling response to disturbance and rehabilitation were further illustrated by results from Priest River, Idaho, where soil compaction effects on tree root growth were studied on a soil derived from Mazama tephra. Douglas-fir and western white pine seedlings growing in compacted soils for one year had fewer nonmycorrhizal root tips compared to soils without compaction (Amaranthus and others 1996). Ectomycorrhizal root tip abundance and diversity was reduced by compaction for Douglas-fir, but not western white pine. Despite these results, seedling growth response was not significantly affected. Thus the initial response to compaction, and the need for rehabilitation treatments, not only varies for different soil and disturbance types, but also may depend on the tree species under management.

Recent results in British Columbia on a range of soil types and climatic conditions have shown that relatively simple rehabilitation treatments such as subsoiling followed by planting with lodgepole pine often produce well-stocked new forests (Plotnikoff and others 2002; Bulmer and Krzic 2003), but on wet sites, fine-textured soils, or where topsoil retrieval and replacement were not carried out, growth rates may lag those of undisturbed areas of adjacent plantations. Lodgepole pine is often planted on rehabilitated sites in British Columbia owing to high survival rates and rapid early growth. In contrast to the previous results, soil decompaction without tree planting led to unsatisfactory stocking on 100 sites in BC's southern interior (Bulmer and Staffeldt 2004), indicating that natural regeneration should only be relied on as a reforestation strategy after carefully evaluating the availability of a seed source.

These research studies show that it is difficult to generalize when predicting the response to disturbance and rehabilitation. Site-specific information is essential for determining which research efforts and conclusions apply to a particular site, and therefore which course of action is likely to be most successful and cost-effective. The following critical site factors can affect the response to soil disturbance and rehabilitation on a particular site:

- ***Climatic conditions*** such as temperature and annual water deficit affect the rooting characteristics of trees, and the extent to which they are limited by moisture availability, cold temperatures, short growing season, or other factors.
- ***Slope characteristics and surface drainage patterns*** affect the potential for erosion or slope failure that could affect resources on and off the site.
- ***Soil texture and tephra influence*** affect the response of the soil to the disturbance and subsequent rehabilitation treatments because fine textured materials have low strength when wet and are highly susceptible to compaction, while the pore system in coarse-textured materials is generally resistant to compaction, and less likely to suffer soil degradation associated with machine traffic.
- ***Moisture regime*** strongly affects the tree growth limiting factors, and the likelihood of realizing suitable conditions for tillage equipment. Wet sites in particular often suffer increased soil disturbance because of low soil strength, and restoration efforts face challenges because of poor soil structure resulting from tillage of wet soils.
- ***Presence of unfavorable subsoils*** and the extent to which surface soil displacement has exposed them or may force plant roots to grow in them.
- ***Rooting depth*** in undisturbed soils, potential rooting depth on the disturbed site, and the depth of soil disturbance affect the response of trees.

The expected loss of forest productivity if the site was left alone needs to be balanced against the benefits of intervention to improve conditions on the site. In cases where the expected benefits are small, no treatment would be indicated, and planted trees could simply be monitored to evaluate the need for fertilizer inputs or other activities to maintain growth rates at desirable levels. In such cases, site productivity may be slightly lower than if soil disturbance had not occurred, but the loss in productivity may be small compared to cost of restoration treatments.

In summary, reclamation treatments will likely deliver the most benefit when:

- Climatic and other site conditions favour productive tree growth
- Severe soil disturbance will likely prevent seedling establishment and significantly reduce growth without intervention
- Proven and relatively inexpensive treatments such as decompaction, topsoil replacement, and revegetation are applied to mesic sites with medium and coarse textured soils
- Difficult sites, wet areas and fine-textured soils are avoided, as treatments to overcome these challenges are expensive and benefits unproven.

Restoration Treatments and Unique Aspects of Their Application to Tephra-Derived Soil

Where soil disturbance is likely to reduce tree growth to an unsatisfactory degree, and treatments are indicated, a basic approach to rehabilitation would involve attempting to create site conditions approximating those of undisturbed soils on similar sites in the area, even though this may not always be possible (e.g. where surface soils have been displaced and their retrieval is not feasible). The conditions on undisturbed sites likely reflect what is conducive to productive forest growth in the area. To develop a cost effective plan for implementing reclamation treatments, there is a need to consider:

- The extent to which conditions on the site are expected to exceed thresholds of growth limiting factors such as aeration porosity, soil mechanical resistance, water availability, and nutrient content.
- Availability of displaced surface soil that could be retrieved and nature of surface soils in nearby undisturbed soils on similar sites
- Stones, stumps or other factors that may affect the operation of equipment
- Presence of existing vegetation, and likely seed sources for preferred crop trees and other species to be re-established on the site
- Expected wildlife or cattle use that may affect the success of reforestation or revegetation efforts

Based on site-specific conditions, reclamation treatments can be identified to address each of four objectives.

Managing Water and Preventing Erosion

Water management and erosion control is the first step in reclamation planning. Without a stable substrate that is free of erosion, the beneficial effects of restoration treatments could be destroyed by removal of organic rich surface soil layers, or by exposure of less fertile subsoils. In addition, the high costs of potential off-site effects on water quality, fish, and property require that water and erosion control is given highest priority. Site water management is also essential for correcting detrimental effects of soil disturbance on the soil drainage class and moisture regime.

Water management may be as simple as building a ditch to divert surface water away from a road or landing, or could involve more expensive options such as slope recontouring designed with internal drainage to restore the flow of subsurface water.

Erodibility may be related to poor cohesion of recently deposited tephra materials, high water retention, and low internal strength of deposits. These factors may be offset by high porosity. The characteristics of the subsoils and other site attributes need to be considered before selecting treatments.

Localized erosion was observed in Diamond Lake District, Umpqua National Forest, when surface water flow patterns were disturbed by compaction of deep pumice soils, routing water to the edge of the unit. Routed water affected residual topsoil left post-harvest, and, where compaction endures for long periods, water routing and erosion would continue into the future without tillage.

Treatments to control erosion include:

- outsloping decompaction
- slope recontouring
- diverting / managing surface water
- revegetation

Where water management, erosion, slope stability issues do not pose severe restrictions, the next step is to proceed with efforts to restore site productivity.

Tillage to Restore Soil Physical Conditions

For compacted soils with high soil strength or those that have suffered deterioration of the pore system, restoring soil physical conditions is an essential part of reclamation. Compaction affects the pore system mostly by reducing the number of large pores. This leads to increased water retention and reduced infiltration, and may lead to soils with insufficient air for plant roots.

There are reasons to believe that trees growing in some soils rich in volcanic ash may respond differently to compaction than for other parent materials. The highly developed aggregate structure of weathered and developed soils derived from volcanic materials in other areas has been well documented, suggesting that stable aggregates in such soils may survive the compaction process, and provide stability for large pores. For the Pacific Northwest, recent tephra deposits likely have relatively stable macrostructure where particle strength is high enough to resist particle breakage. On mesic and dry sites, these characteristics may lead to a soil that is able to withstand compaction and still provide a productive environment for plant roots, and/or one that is able to naturally regenerate soil conditions suitable for productive forest growth following disturbance. Despite this, some specific challenges could include:

- **Water retention**: On wetter sites, the high water retentivity of tephra soils may lead to similar problems as identified for fine-textured soils, and could be especially problematic in low-lying landscape positions. The major problems would include excessive soil water, and lack of aeration.
- **Particle breakage**: Some volcanic materials are susceptible to particle breakage when disturbed, which increases the proportion of fines in the particle size distribution. Particle breakage may be a factor in poor performance of regeneration on some sites in Oregon.
- **Irreversible drying**: Cementation may lead to massive structure with high soil strengths that plant roots are incapable of penetrating. Although this phenomenon is not expected to be widespread in the Pacific Northwest, it

could affect results in low lying landscape positions with weathered soils and where soil structure has been destroyed (puddling) by repeated machine traffic, and where sites are subject to occasional drying in summer.

Where tillage is required, a variety of implements are available, including winged subsoilers, rock ripper, excavators with brush rakes, mulching heads, or custom attachments such as the subsoiling grapple rake and subsoiling excavating bucket. The best implement for the job likely depends on factors such as required depth, soil strength, water status, and logistics (e.g. availability of prime movers).

An example of an implement that was purpose-built for decompacting soils in volcanic terrain is the subsoiling grapple rake, which was developed and used in the Diamond Lake Ranger District, Umpqua National Forest (Archuleta and Karr 2004). This implement is a grapple rake fitted with subsoiling shanks and wings. It was designed to mitigate either legacy compaction or newly created harvest impacts, and is best employed when used in concert with an ongoing activity, such as post-harvest slash reduction. At Diamond Lake, the combination of these activities reduced the overall cost of individual projects with a minor increase to either slash piling or subsoiling costs. The subsoiling excavator bucket is another implement that is also equipped with shanks, and allows cost-effective decommissioning of roads. This implement also reduces the subsoiling rate on small tillage projects and makes additional equipment (i.e. dozer and tillage implement) redundant.

Tillage is aimed at alleviating the effects of detrimental compaction, which include increases in soil strength, reduced aeration, and excessive water retention. Although the effectiveness of tillage has been questioned on fine-textured soils in central Alberta where subsoils stayed wet and soft for long periods during the year (McNabb 1994), such issues may be less of a concern in fine-textured tephra-derived soils in the Pacific Northwest because of (a) the strong aggregation expected in fine-textured soils derived from volcanic materials, and (b) dryer climates. For relatively fresh volcanic parent materials, particle sizes may be coarse and water infiltration and aeration may not be limiting.

In summary, for successful tillage, consider:

- tillage is used to reduce soil strength and restore the pore system,
- a variety of implements are available,
- use the rooting depth in natural forests on similar sites as a guide to tillage depth
- for dispersed disturbance, and to reduce costs, consider spot tillage
- the effects of tilling wet volcanic soils, which may be subject to irreversible drying or consolidation, need to be evaluated through monitoring

Restoring Organic Matter and Nutrients

In general, the most effective means of restoring surface soil organic matter is to retrieve and replace displaced topsoil. In situations where recovery of displaced surface soil is not practical, other potential strategies include distributing green logging slash from harvesting operations over the reclaimed area. In central BC, chipped waste logs enhanced soil properties and contributed to successful establishment and early growth of white spruce seedlings (Sanborn and others 2004). Despite their benefits, organic amendments are generally only suitable if they are locally available, as they are expensive to transport.

Since tephra derived materials are known to have a high affinity for soil organic matter, a cost-effective alternative could involve revegetation with grasses and legumes that can build soil organic matter through decomposition of their root systems. In one study (not an ash soil), Bendfeldt and others (2001) showed that vegetation inputs of C were an important source of surface soil organic matter levels after sixteen years on reclaimed mine soil that also received an initial amendment with wood waste.

In summary, to restore organic matter and nutrients, consider:

- Organic matter is an essential component of productive soil, but forest ecosystems vary in the amount present in surface soils.
- Retrieval of displaced topsoil is a cost effective approach for restoring suitable growing conditions.
- Use the characteristics of surface soils on similar sites as a guide to what surface soil organic matter levels are appropriate, and its distribution as a surface layer or incorporated into surface soils.
- Revegetation with agronomic grasses and legumes can contribute significant quantities of organic matter over time.
- Organic amendments can effectively restore soil conditions, but are expensive to transport.

Revegetation

Successful revegetation and reforestation of disturbed areas is an important final step in reclamation efforts. In many cases, the objective for the reclamation is defined by the type of vegetation cover desired. For example, grass and legume cover may be prescribed to prevent erosion, forest restoration provides for timber, or other values may have priority such as wildlife, watershed values, and aesthetics. Tree planting is the most common and effective means to establish a new forest, but natural regeneration could be effective if a seed source and suitable seedbed conditions were present.

For successful and cost-effective revegetation, consider

- **Revegetation** is essential for erosion control in sloping terrain.
- **Seeding agronomic grasses** and legumes are proven means to prevent erosion.
- **Seedbed characteristics** are often best immediately after tillage operations are complete.
- **Droughtiness**; may hamper revegetation efforts in coarse-textured tephras where low water retention results in a lack of seedbed moisture. Seeding treatments in such soils would have to be considered carefully, and consider the timing in relation to expected precipitation, along with the possible need for mulches to conserve moisture.
- **Ingress of native vegetation** may occur without intervention where disturbances are small (e.g. roads and trails).
- **Natural regeneration** of tree seedlings may be a low cost alternative to planting where a seed source is available and slightly longer regen delay is acceptable.

Information and Research Needs

The published information base is limited and provides few specific examples of the effects of soil disturbance, enhancement and restoration on forest site productivity in volcanic terrain in western North America. The lack of information partly reflects the difficulty and expense in designing and implementing studies that are relevant to the wide range of site types, soil conditions, and tree species that occur in the region. Despite this, there is considerable information on soil disturbance and restoration effects for other soil types in similar climates and much of this information can likely be extrapolated to volcanic soils in the Northwest. In addition, soil scientists and forest managers in the region have considerable experience with how the soils respond to management.

To address the lack of specific published information, a useful approach would be to combine existing research from elsewhere with local knowledge of the soils response to management through retrospective study, monitoring, and operational trials. Although these approaches have their limitations for resolving detailed questions, they are extremely useful for answering the broad questions that arise during the initial stages of a detailed research program. Specific questions to be addressed (and suggested approach to study) include:

- Identifying sites most susceptible to degradation, and those where restoration or enhancement provide the greatest benefit (*monitoring and retrospective study*)
- Evaluating a range of treatment options for restoring and enhancing productivity (*monitoring results and operational trials*)
- Characterizing the effect of typical operations on soil properties such as bulk density, penetration resistance, and organic matter (*research*)
- Determining thresholds for unacceptable productivity decline on the most common site types (*research*)

Management Recommendations

1. Evaluate costs and benefits: Soil restoration and enhancement should be considered investments where the expected benefits, costs and risks are carefully evaluated. In general, it is best to focus efforts on sites with the best expected return on restoration dollars, and use low cost, reliable methods for restoration. The benefits of restoration and enhancement efforts typically include:

- increased timber supply,
- reduced environmental liability associated with roads,
- improved watershed, wildlife, and aesthetic values.

2. Have a site-specific plan: Evaluate limitations to productivity, risk of erosion, and other site specific factors, and then set realistic objectives for the work. Where legacy impacts are present, combination machines such as the subsoiling grapple rake and subsoiling excavator bucket may allow restoration to be blended into other work such as brush piling or road decommissioning.

3. Start simple (and cheap): Try the simple solution first. Consider treatments in the following order:

- do nothing (i.e. rely on natural regeneration to recolonize lightly disturbed areas)

- tree planting
- fertilization
- decompaction / tillage plus topsoil recovery
- organic amendments
- re-establishing native species by planting

4. *Keep learning*: Monitor the results of your efforts and those of others.

Acknowledgments

Research described here was supported by British Columbia's Forest Science Program and other funding sources. Umpqua National Forest supported work of J. Archuleta. Mike Karr provided work on the subsoiling equipment on the Umpqua National Forest.

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