

The Grand Fir Mosaic Ecosystem—History and Management Impacts

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Abstract

The Grand Fir Mosaic (GFM) ecosystem is found on ash-cap soils in some mid-elevation forests of northern Idaho and northeastern Oregon. Harvesting on GFM sites results in successional plant communities that are dominated by bracken fern (*Pteridium aquilinum*) and western coneflower (*Rudbeckia occidentalis*), and have large populations of pocket gophers (*Thomomys talpoides*). Succession to trees and shrubs is very slow on disturbed GFM sites. Four factors contribute to the protracted stages of bracken fern plant communities and the slow rate of succession to woody plants: (1) competition among plants for site resources, (2) allelopathy from bracken fern and western coneflower, (3) pocket gopher activity, and (4) a nonallophanic soil forming process. Nonallophanic soils occur under the bracken fern successional plant communities — they are dominated by Al-humus complexes, have strongly acid pH, have high KCl-extractable Al, and may cause Al toxicity to plants. Allophanic soils occur under forested conditions — they are dominated by allophane and imogolite, have weakly to moderately acid pH, and have low Al availability. Allophanic and nonallophanic soils exist side-by-side in the GFM, with mineralogy being dependent upon the dominant vegetation. Bracken fern and western coneflower, with below-ground carbon inputs from their well-developed root systems, provide a mechanism that promotes the shift from allophanic to nonallophanic soils. Recommendations for reforesting GFM sites are provided.

Introduction

Imagine a moist forest environment in the northern Rocky Mountains where supposedly seral plant communities dominated by bracken fern (*Pteridium aquilinum*) and western coneflower (*Rudbeckia occidentalis*) are really climax plant communities that persist within a matrix of overmature grand fir (*Abies grandis*) and western redcedar (*Thuja plicata*) forests. There are few wildfires here, so natural succession has reduced the occurrence of seral conifers such as lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), western white pine (*Pinus monticola*), and western larch (*Larix occidentalis*). Late successional, shade-tolerant species like grand fir, western redcedar, Pacific yew (*Taxus brevifolia*), and sometimes mountain

hemlock (*Tsuga mertensiana*) and subalpine fir (*Abies lasiocarpa*), are common along with mid-successional Engelmann spruce (*Picea engelmannii*). Regeneration of conifers in forest canopy openings is a slow and unreliable process in these low pH volcanic ash-cap soils that have abundant populations of pocket gophers (*Thomomys talpoides*). Disjunct and rare plant species occur in and near these forests, including evergreen synthyris (*Synthyris platycarpa*), Oregon bluebell (*Mertensia bella*), Dasynotus (*Dasynotus daubenmirei*), and Case's corydalis (*Corydalis caseana*). These moist forests are collectively called the Grand Fir Mosaic (GFM) ecosystem.

Grand Fir Mosaic forests occur on productive volcanic ash-cap soils in and near the Clearwater, Nez Perce, and southern St. Joe National Forests in northern Idaho, and the Umatilla National Forest in northeastern Oregon. The name for the GFM comes from the dominant conifer (grand fir) and the variety of sizes and shapes of natural openings in the forest canopy. The GFM encompasses approximately 500,000 acres at elevations primarily between 4,500 and 5,500 ft, but is found as low as 4,200 ft and as high as 6,000 ft (Ferguson and Johnson 1996). The most common habitat type is *Abies grandis*/*Asarum caudatum* (grand fir/wild ginger), a cool, moist habitat defined by Cooper and others (1991).

Successional plant communities in the GFM are dominated by bracken fern and western coneflower. Bracken fern is usually present in low densities under forest canopies, but rapidly expands following disturbance, and can reach heights of 6 ft and densities of 116,000 fronds per acre (Znerold 1979). Below-ground bracken biomass, primarily rhizomes and fine roots, may be as much as 27,280 lbs per acre (Jimenez 2005).

Bracken fern glades are plant communities dominated by bracken fern and western coneflower that appear to persist for millennia. Charcoal samples found at or near the lower boundary of GFM ash-caps were found to be $1,335 \pm 75$ and $7,755 \pm 75$ cal. yrs BP using radiocarbon dating (Jimenez 2005). These charcoal samples suggest that woody vegetation has been absent for thousands of years, perhaps dating back to the time of ash deposition during the eruption of Mt. Mazama (Crater Lake, OR) ~7,600 yrs BP (Zdanowicz and others 1999).

Pocket gophers also alter the course of secondary succession in the GFM, particularly for planted conifers. Entire plantations of seedlings can be killed by pocket gophers. Small seedlings are usually pulled from below ground into tunnels where the whole tree is eaten. Gophers may eat all or most of the root system of larger seedlings and saplings.

Our investigations on the GFM were initiated because of difficulty in regenerating harvested areas in the GFM. The first task was to define key ecological processes that might account for the lack of regeneration and the absence of other woody species. Research was planned and implemented to study competition and allelopathy from bracken fern and western coneflower, effects of pocket gophers, environmental characteristics of the GFM relative to adjacent forests, and soil development.

Bracken Fern, Western Coneflower, Pocket Gopher, and Environmental Research

There is abundant research on bracken fern from around the world dealing with allelopathy, competition, encroachment rates, and harm to crops, livestock,

and humans. The allelopathic potential of bracken fern has been demonstrated by several researchers, including Stewart (1975) and Gliessman (1976). The allelopathic potential of bracken fern in the GFM was demonstrated by Ferguson and Boyd (1988), who found that most of the seeds that germinated on soil dominated by bracken fern died before the seedcoat was shed. Ferguson (1991) demonstrated allelopathic potential for western coneflower in laboratory tests. Volatile compounds (vapors) from western coneflower reduced or delayed seed germination, and water extracts reduced growth of the seedling radicle.

Growth and mortality of planted conifers at GFM sites was reported by Ferguson and Adams (1994) and Ferguson (1999). Hand weeding of bracken fern and western coneflower from planting sites increased height growth of planted conifer seedlings. Pocket gophers killed from 24 to 59 percent of the seedlings, depending on species. Of the seedlings killed by pocket gophers, 77 percent were killed the first summer (following spring planting) and the first or second winter, but few seedlings were killed the second or third summers.

Environmental conditions were studied by Ferguson and Byrne (2000) to see if they differed between GFM and non-GFM sites in the same vicinity. Remote monitoring stations were used to sample harvested areas at a GFM site and three adjacent habitat types (non-GFM grand fir, subalpine fir, and western redcedar). Variables sampled were wind speed and wind direction at 9 ft above the soil surface; precipitation; solar radiation; relative humidity at 4.5 ft; air temperature at 4.5 ft; soil temperature on the soil surface, 1 inch, and 8 inches depth; soil water potential at 1 inch and 8 inches; and soil pH at 1 inch.

Comparison of the GFM site to non-GFM sites in the same vicinity showed that the GFM site had a shorter growing season, even though one of the sites was a subalpine fir habitat type 140 ft higher in elevation than the GFM site. Snow melted at the GFM site an average of 9 days later than at the subalpine fir habitat type, 24 days later than at the non-GFM grand fir habitat type, and 52 days later than at the western redcedar habitat type.

Average GFM soil temperatures at 1 and 8 inches were cooler than the non-GFM sites in April and May because of late snowpacks at the GFM site. During the rest of the growing season, the GFM site was warmer than the subalpine fir habitat type, but cooler than the grand fir and western redcedar habitat types.

Summer soil moisture at the GFM site did not dry to the permanent wilting point as often as the non-GFM sites. Soils at 8 inches dried to a water potential of -15 bars in only 2 of 6 years of monitoring at the GFM site, while -15 bars was reached during 4 of the 6 monitoring years at the non-GFM grand fir habitat type, 4 of 5 years at the western redcedar habitat type, and 5 of 5 years at the subalpine fir habitat type.

The most insightful variable measured was soil pH at 1-inch depth. The GFM site was different from the other three sites because soil pH cycled from about 6.0 in the spring to 4.0 in the summer and back to 6.0 in the fall (fig. 1). Each year for 7 years, soil pH was lower than 5.0 for several weeks to a few months. A soil pH below 5.0 is a commonly cited threshold where Al toxicity is common to many crops (Shoji and others 1993). A laboratory study has shown that exchangeable Al increases exponentially in GFM soils as pH decreases below 5.0 (Page-Dumroese and others, this proceedings).

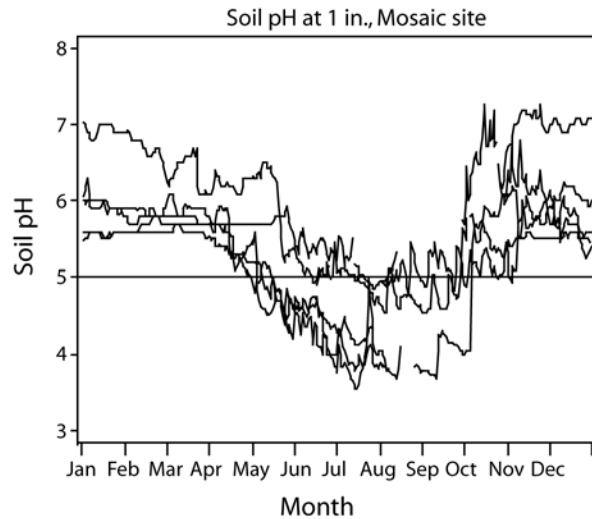


Figure 1—Average daily soil pH at 1 inch for a GFM site, 1989 through 1995 (Ferguson and Byrne 2000). Each line is a different year of data, and discontinuous lines are periods of time when soils were too dry to collect pH measurements. The horizontal line at pH 5 shows a commonly cited threshold where plants start to experience Al toxicity.

Ash-cap Soil Relationships

Allophanic and Nonallophanic Andisols

The Andisol soil order includes soils that are characterized by andic soil properties that arise from the presence of significant amounts of noncrystalline aluminosilicates such as allophane and imogolite, Al-humus complexes, and/or poorly crystalline Fe oxides (Soil Survey Staff 2003). A lack of illuvial B horizons indicates that the process of translocation is not significant within the Andisol order (Ugolini and others 1988; Dahlgren and others 1991) and clearly separates Andisols from other soil orders with similar mineralogical components.

Andisols are commonly described as being allophanic or nonallophanic, depending on the nature of the minerals present. Allophanic Andisols are dominated by allophane, imogolite, and clay minerals; are weakly to moderately acid; and have low KCl-extractable Al and low Al saturation (table 1) (Shoji and others 1985; Nanzyo and others 1993). Nonallophanic Andisols have Al-humus complexes and crystalline clay minerals as their dominant mineralogical components, and contain

Table 1—Comparative characteristics of allophanic and nonallophanic Andisols.

Characteristic	Allophanic	Nonallophanic
Mineralogy	More allophane and imogolite; less Al-humus complexes	Less allophane and imogolite; more Al-humus complexes
Soil acidity	Weakly to moderately acid	Strongly acid
Exchangeable Al	Low	High
Al toxicity	Rare	Common

a substantially smaller proportion of allophane and imogolite as compared to allophanic Andisols. In addition, nonallophanic soils are strongly to very strongly acid, have high KCl-extractable Al, and commonly exhibit Al toxicity (table 1) (Shoji and others 1985; Nanzyo and others 1993). Al-humus complexes and high concentrations of exchangeable Al in nonallophanic Andisols result in rapid dissolution and equilibrium between Al in solid and solution phases. Allophanic Andisols are dominated by allophane and imogolite, which have slower dissolution rates and, therefore, result in slower release of Al into soil solution (Dahlgren and Saigusa 1994; Dahlgren and others 2004). The rapid release rates of Al in nonallophanic Andisols provide a source of Al for plant uptake. Due to the possibility of Al toxicity, the distinction of allophanic and nonallophanic Andisols is important for management purposes.

Because of the impact of Andisol mineralogy on plant productivity (Dahlgren and others 2004), it is important to understand the factors that control mineral formation and weathering within the order. Differences in parent material such as tephra age, geochemistry, hydraulic properties, and additions of exogenous materials such as loess (Inoue and Naruse 1987; Vacca and others 2003) have been reported to influence the development of certain mineralogical components within ash-influenced soils. Other factors that are more influenced by management include organic matter and pH (Shoji and Fujiwara 1984; Johnson-Maynard and others 1997). The formation of allophanic Andisols tends to be favored in environments where pH is greater than 5. In contrast, nonallophanic Andisols are predominately found in more acidic (pH < 5) environments with higher concentrations of organic matter (Shoji and Fujiwara 1984; Shoji and others 1993).

The relationship between organic matter, pH, and Al availability indicates that plant communities may play a role in influencing Andisol properties. Specific examples of the impact of vegetation and vegetation conversion on Andisol morphology and chemistry have been reported. Japanese pampas grass (*Miscanthus sinensis*), for example, is associated with the formation of dark, humus-rich, surface horizons known as melanic epipedons (Shoji and others 1990). Biomass production by Japanese pampas grass was estimated to be 4,840 lbs per acre above ground and 15,500 lbs per acre below ground. With all of the above-ground and one-quarter of the below-ground parts added to the soil each year, Japanese pampas grass creates conditions that promote accumulation and humification of soil organic matter resulting in the formation of melanic epipedons (Shoji and others 1993). Dahlgren and others (1991) reported lowering of soil solution pH with a corresponding increase in Al concentrations in A horizons of Alic Melanudands where Japanese oak (*Quercus serrata*) replaced Japanese pampas grass. The accumulation of organic matter was a distinguishing feature between soils under the two vegetation types. Another example of the effect of plants on Andisols can be found on the North Island of New Zealand where Andisols rarely display thick dark humus horizons except where native podocarp forest has been converted to bracken fern (*Pteridium aquilinum* var. *esculentum*) (Leamy and others 1980).

Andisols in the Grand Fir Mosaic

Sommer (1991) sampled soils and foliage in three GFM plant communities: mature forest, natural bracken fern glade, and bracken-invaded clearcut. Soil pH was lower and exchangeable Al was higher in bracken-dominated plant communities than in the mature forest. Soil and foliar nutrients were adequate for conifer

growth, although Al was approaching levels known to be toxic to some plant species. Small sample size and high variability prevented conclusive results, but evidence suggested that disturbed forest sites in the GFM are invaded by bracken fern plant communities and become more like bracken fern glades.

The important documentation of both allophanic and nonallophanic Andisols in the GFM was reported by Johnson-Maynard and others (1997). Soil chemical and mineralogical properties were studied in adjacent mature forest, natural bracken fern glade, and bracken-invaded clearcut. Retrospective comparison of the 30-year-old clearcut to the mature forest and bracken fern glade showed a conversion from allophanic to nonallophanic soils (fig. 2). Soils in the forest were dominated by short-range-order Al-Fe minerals, had low exchangeable Al, and had pH >5, all of which are consistent with characteristics of allophanic soils (table 1). Soils in the bracken-invaded clearcut and bracken fern glade were dominated by Al-humus complexes, had high exchangeable Al, and pH <5, which is consistent with nonallophanic soils. Johnson-Maynard and others (1997) were the first to report nonallophanic Andisols in northern Idaho. Also, they were the first, to our knowledge, to report a conversion from allophanic to nonallophanic mineralogy. Allophanic and nonallophanic soils exist side-by-side in the GFM, their expression being dependent upon the dominant plant community.

The chemistry of soil water moving through soils of the GFM has also been studied in the GFM (Johnson-Maynard and others 1998), using the same study sites as Johnson-Maynard and others (1997). Soil water chemistry was consistent with the preferential formation of Al-humus complexes in bracken-dominated sites that had once been forested. Soil solution was also collected from a weeded area in a bracken fern glade where bracken fern and western coneflower were hand weeded for 6 years prior to sampling (Ferguson 1999). Soil water pH, Al, and dissolved organic carbon in the weeded area were more similar to the forest than to soil water collected from under the bracken fern glade. Weeding appeared to result in soil water with chemical composition more similar to that measured in

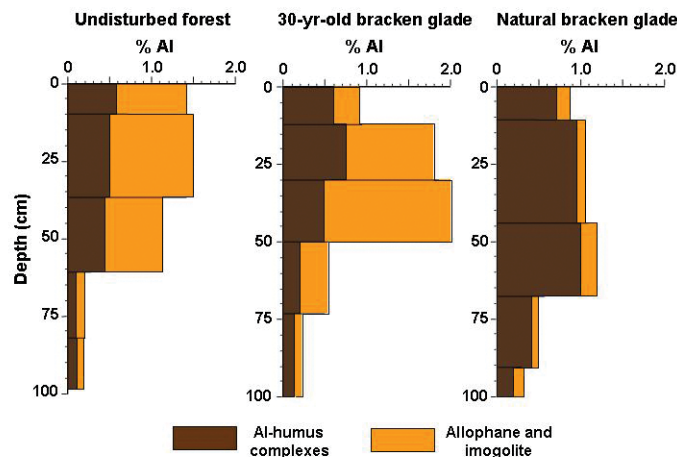


Figure 2—Depth distribution of Al in soil fractions as determined by selective dissolution techniques (adapted from Johnson-Maynard 1995).

the undisturbed forest, suggesting that the growth of bracken fern and western coneflower play an important role in the conversion from allophanic to nonallophanic soils.

Although soil water Al concentrations were highest in bracken-dominated plant communities, they were lower than published toxicity levels for other conifer species. More work is indicated to determine toxic levels for plant species in the GFM and to determine the different forms and toxicity of Al in soil solution.

Discussion

Research on the GFM ecosystem has identified four factors that, individually and collectively, may account for the slow rate of secondary succession to woody vegetation following disturbances that create openings in the forest canopy. The first factor is competition among plants for site resources such as light, water, nutrients, and growing space. Competition can be intense because forb communities dominated by bracken fern and western coneflower expand rapidly into previously forested openings.

The second factor is allelopathy. Direct and indirect effects of phytotoxins released by plants can reduce the successful establishment and growth of other species. The allelopathic potential of bracken fern and western coneflower has been demonstrated (Stewart 1975; Gliessman 1976; Ferguson 1991). The quantification of the individual effects attributable to allelopathy and competition is difficult because removal of a plant from its natural environment simultaneously removes the source of allelopathy and competition. Ecologists use the term “interference” to refer to the combined effects of allelopathy and competition (Muller 1969).

The third factor is large populations of pocket gophers. Gophers can cause a substantial amount of mortality to planted and natural seedlings in the GFM. Most gopher-caused mortality to planted seedlings takes place the first summer after planting and during the first and second winters (Ferguson 1999; Ferguson and others 2005). Partial removal of the overstory canopy allows enough light to reach planted seedlings so they can survive and grow — albeit slower than in full sunlight — and also reduces abundance of pocket gophers, bracken fern, and western coneflower (Ferguson and others 2005).

The fourth factor is a nonallophanic soil forming process. The data collected by Johnson-Maynard and others (1997, 1998) demonstrate the conversion of allophanic to nonallophanic mineralogy based on the criteria summarized in table 1. In the undisturbed forest, the dominant secondary mineralogical component of soils is inorganic, short-range order minerals, which is consistent with allophanic type Andisols. In bracken/coneflower dominated areas, Al-humus complexes are the dominant component of soils, consistent with what has been described in nonallophanic soils.

Allophanic and nonallophanic soils exist side-by-side in the GFM, with mineralogy dependent upon the dominant vegetation (fig. 2). Allophanic conditions occur when vegetation is dominated by coniferous trees, but nonallophanic conditions occur when sites are dominated by bracken fern and western coneflower (Johnson-Maynard and others 1997). When bracken fern and western coneflower are removed, soil water chemistry is similar to that under allophanic GFM soils (Johnson-Maynard and others 1998), indicating that bracken fern and western coneflower are a mechanism in promoting nonallophanic soils. It is likely that bracken fern and western coneflower are not only sources of large annual additions of carbon

to the soil, thus favoring the formation of Al-humus complexes, but also sources of organic acids that lower soil pH (Johnson-Maynard and others 1998).

Reforesting GFM Sites

In this section, we discuss management strategies for reforesting GFM sites as they relate to the nonallophanic soil forming process. The most important point to remember is that natural regeneration of woody plant species will be a slow and unreliable process within the GFM. We know of many examples of cutover GFM forests that have little woody vegetation after 20 to 30 years. Seeds that germinate in openings in the GFM forest canopy are subject to competition, allelopathy, pocket gophers, and Al toxicity. These four factors can combine to virtually eliminate the natural establishment of trees and other woody plant species.

Prompt planting following a disturbance will help seedlings become established before the site has abundant bracken fern, western coneflower, and pocket gophers. Planting larger vs. smaller seedlings helps increase survival and growth rates. Planted seedlings in clearcuts need to be protected from pocket gophers until the third spring after they are planted.

Partial cuttings, where only a portion of the overstory trees are removed, retain the shrub component better than clearcuts, and result in less bracken fern, western coneflower, and gopher-caused damage to seedlings (Ferguson and others 2005). Planted trees do not need protection from pocket gophers in partial cuttings; however, they will not grow as fast as in clearcuts. After seedlings are established (5 to 10 years), all or part of the remaining overstory trees can be removed to improve growth of seedlings.

The overall performance of some planted conifer species was better in trial plantings on GFM sites (Ferguson 1999; Ferguson and others 2005). Engelmann spruce and western white pine grew well, had little mortality from non-gopher causes, and had little top damage from snow or senescing bracken fern fronds. Douglas-fir also did quite well, especially if larger seedlings were planted. Lodgepole pine grew rapidly, but this species often suffered severe snow damage to tops, limbs, and stems. Western larch had very high overall mortality, both from gopher and non-gopher causes, but surviving trees grew rapidly. Another concern with western larch is top damage and severe lean caused by snowloads in the GFM.

Research Questions

Much has been learned about ash-cap soils and management options for the GFM, and additional research would help fill the gaps in our knowledge. Research studies show that allophanic and nonallophanic soil forming processes exist side-by-side in the GFM. Allophanic processes occur where conifers dominate the site, and nonallophanic processes occur where bracken fern and western coneflower dominate. It would be helpful to study allophanic vs. nonallophanic mineralogy across a range of overstory densities, and determine how quickly allophanic processes turn into nonallophanic processes following harvest or other activities that reduce the density of the forest canopy.

Another key research topic is to understand why pH is cyclic in GFM sites dominated by bracken/coneflower successional plant communities (fig. 1). Comparisons of seasonal patterns in pH under bracken fern glades to undisturbed grand fir forests may shed light on the mechanisms behind this observation.

Soil pH values cycle below 5.0 during part of the growing season, which could result in Al toxicity (Page-Dumroese and others, this proceedings). However, little is known about Al toxicity thresholds for plant species and their mycorrhizal associations in the GFM. We would expect that Al toxicity varies with Al concentration, the various Al compounds that exist in ash-cap soils, and size/age of plant species. The cyclic nature of soil pH in the GFM may also interfere with nutrient availability (see Page-Dumroese and others, these proceedings). More information is needed on availability of nutrients other than Al, especially nitrogen. Recent work has suggested that additions of lime are effective in raising pH and reducing levels of bioavailable Al in nonallophanic Andisols (Takahashi and others 2006). Liming experiments could therefore be used to provide valuable information about the role of pH and active forms of Al in tree regeneration problems observed in the GFM.

The allelopathic potential of bracken fern has been demonstrated by several researchers around the world, but we only have rudimentary knowledge of allelopathy in western coneflower. Ferguson (1991) demonstrated the allelopathic potential of western coneflower in laboratory tests, but additional research is needed under field conditions.

The answers to these research questions would improve our knowledge of the mechanisms that delay secondary succession to woody plant species in the GFM, thereby helping refine management recommendations for GFM ash-cap soils.

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