

CHANGES IN SOIL SOLUTION CHEMISTRY OF ANDISOLS FOLLOWING INVASION BY BRACKEN FERN

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Disturbed areas within the Grand Fir Mosaic (GFM) ecosystem of northern Idaho show little to no natural conifer regeneration. Clear-cut sites are invaded quickly by bracken fern successional communities and seem to be in an arrested state of secondary succession. This study compared the soil solution composition of Andisols supporting bracken fern successional communities with undisturbed forest to determine the effects of shifts in vegetation communities. Treatment areas included undisturbed forest, a 30-year-old bracken fern glade (clear-cut in 1965), and a natural bracken fern glade estimated to be centuries old. The natural bracken fern glade was divided into subplots, one of which has been weeded 2 to 3 times each growing season since 1988. Soil solution was collected in porous ceramic cup lysimeters at 12- and 25-cm depths. Samples were collected from May to July in 1994 and 1995. Solutions were analyzed for pH, Al, and dissolved organic carbon (DOC). The soil solution pH in the 30-year-old glade was consistently lower than in the other sites throughout the sampling period, and the 30-year-old glade was the only site to periodically register below pH 5. The natural bracken fern glade that had been weeded was more similar to the undisturbed forest, suggesting that bracken fern biomass does have an acidifying effect on soil solution. The highest Al concentration recorded was 1.6 mg/L in the 30-year-old glade, whereas in the undisturbed forest Al was often below the detection limit. Aluminum and DOC were found to be positively related, with *r* values of 0.533 and 0.824 for 1994 and 1995, respectively. These results indicate that bracken fern does have an acidifying effect on soil solution. Aluminum concentrations were lower than reported toxic levels for other conifer species and were correlated with DOC. These two findings suggest that Al toxicity may not be a major factor contributing to the lack of conifer regeneration within the GFM. (Soil Science 1998;163:814-821)

Key words: Soil solution chemistry, Andisols, bracken fern.

THE application of soil solution chemistry to the study of pedogenic processes is extremely useful because of its sensitivity to changes in vegetation (Nanzoyo et al. 1993). Pearson (1971, 1975) proposed that the composition of soil solution is the most appropriate expression of the soil environment governing plant response. This dynamic pedological approach (Singer et al. 1978) can

yield information not only about current pedological processes but also about conditions for plant growth, such as nutrient availability (possible deficiencies and toxicities).

The composition of soil solution reflects changes in vegetation and is, therefore, useful in monitoring the effects of management techniques and natural disturbances. Changes in soil solution chemistry have been documented following disturbances such as clear-cutting (Dahlgren and Driscoll 1994), invasion by new vegetation types (Dahlgren et al. 1991), and avalanches (Arthur and Fahey 1993). Although changes in soil solution chemistry are expected after clear-cutting, the effects are not usually

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long-lasting. Dahlgren and Driscoll (1994) observed that chemical responses to whole tree clear-cutting at Hubbard Brook, New Hampshire, maximized after 2 years and returned to background levels by the fourth and fifth years.

Some midelevation ecosystems in the Inland Pacific Northwest consist of stands of grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.) forest in a patchwork or mosaic pattern with various shrub and forb communities. These ecosystems are referred to collectively as the Grand Fir Mosaic (GFM) (Ferguson and Adams 1994). In the GFM of northern Idaho, successional communities dominated by bracken fern (*Pteridium aquilinum* (L.) Kuhn) are established quickly after timber harvest or natural disturbance such as fire or disease. These areas seem to remain in an arrested state of secondary succession, i.e., little or no natural conifer regeneration is observed where bracken fern-dominated successional communities have become established (Ferguson 1991; Sommer 1991). Many clear-cut sites within the GFM have continued to support bracken fern successional communities since timber harvest was initiated in the 1960s, a period of more than 30 years. Attempts to reestablish these sites by planting seedlings have met with very limited success (Ferguson and Adams 1994).

Recent investigations of the solid-phase chemistry and mineralogy of GFM soils have shown that a mineralogical shift, from allophanic to nonallophanic Andisols, is occurring in soils supporting bracken fern communities (Johnson-Maynard et al. 1997). Although nonallophanic Andisols are often associated with aluminum (Al) toxicity in plants (Shoji et al. 1985; Nanzyo et al. 1993), solid-phase studies do not necessarily give a complete picture of the soil environment experienced by plant roots. The objective of this study was to determine if there are significant changes in the soil solution chemistry of a site that is invaded by bracken fern, compared with adjacent undisturbed forest, as well as to provide a preliminary evaluation of the possibility of toxic levels of Al inhibiting natural conifer regeneration.

MATERIALS AND METHODS

Study Area

The GFM occurs in the 1300- to 1800-m elevational range of the Clearwater River drainage of northern Idaho and in the Blue Mountains of northeastern Oregon and southeastern Washington (Fig. 1). The study area is located at an elevation of 1463 m, approximately 3 km south of Ea-

gle Point in the Clearwater National Forest, Sec. 35, T40N, R7E. Dominant soil parent materials in the study area include Mazama volcanic ash, which averages about 60 cm in thickness, and underlying colluvium and/or residuum derived from a fine-grained igneous rock that is chemically similar to granite. Sampling locations were chosen to allow comparison of soils under three different vegetation types or treatments. The treatments included undisturbed forest, a 30-year-old bracken fern glade (clear-cut and invaded by bracken fern in 1965), and a natural bracken fern site (present in the GFM before timber harvest) that is estimated to be centuries old. The natural bracken fern glade is divided into subplots, one of which has been weeded 2–3 times during each growing season since 1988. Sites are adjacent to one another and have similar slope, aspect, and parent material; vegetation type is the only factor that differs significantly. Although the effects of site and vegetation are confounded somewhat as a result of the lack of replication of sites, it is reasonable to conclude that vegetation type is causing differences in soil solution because of the careful selection of sites.

Differences in vegetation type are reflected within the classification of soils within the GFM. Soils in the undisturbed forest are classified as Typic Hapludands (Soil Survey Staff 1994; Johnson-Maynard et al. 1997). The 30-year-old bracken fern glade soils are classified as Alic Fulvudands; the Fulvi-great group indicates a higher C content in the upper 40 cm of the soil compared with the Hapludands of the undisturbed forest (Soil Survey Staff 1994). Soils of the natural bracken fern site are classified as Alic Hapludands, based on KCl-extractable Al > 2 cmol(+)/kg (Soil Survey Staff 1994; Johnson-Maynard et al. 1997).

To monitor soil solution chemistry, three sets of two porous cup suction lysimeters (5-cm-diam.) were placed at each site. Each set consisted of a 30.5-cm-long lysimeter and a 15-cm-long lysimeter buried to depths of 25 cm and 12 cm, respectively. To help minimize Al contamination of acid soil solution by the porcelain cups (Rasmussen 1989), lysimeters were leached with deionized water in the laboratory before installation and were then allowed to equilibrate in the field for an 8-month period before sample collection. The samplers used in this study were of a different type than the ones used in Rasmussen's study and have been reported as being appropriate for sampling acidic soil solutions when properly pretreated and equilibrated in the field

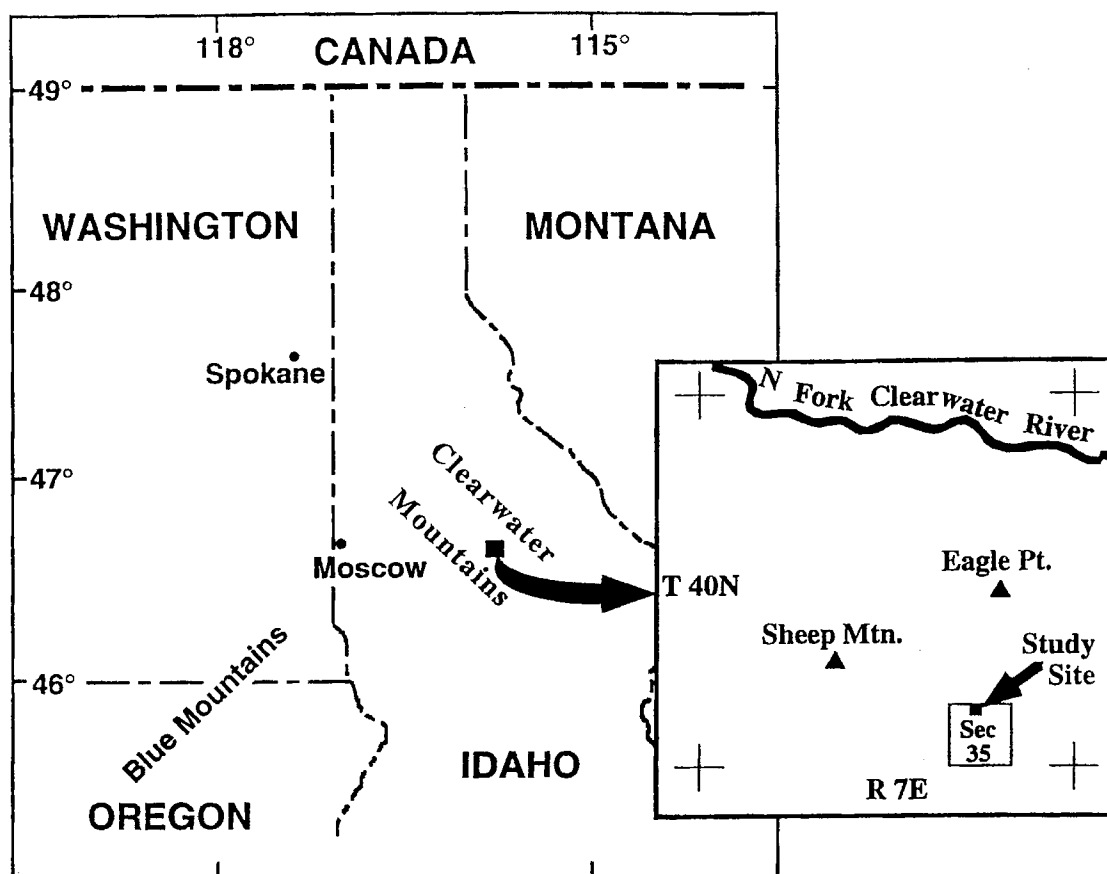


Fig. 1. Location of the study area in northern Idaho; inset shows location of the sampling site.

(Hughes and Reynolds 1990). Soil solution sampling in 1994 and 1995 was started in May, after snowmelt, and continued through July when the soils became too dry to obtain adequate sample. Solutions were extracted from the soil by placing a vacuum of approximately 0.7 MPa on the lysimeters for about 3 h. Solutions were then collected in a plastic flask, placed in a cooler, and transported back to the laboratory.

Laboratory Methods

After filtering through a 0.45- μ m filter, samples were immediately analyzed for pH. Aluminum and Fe concentrations of soil solution were measured by ICP spectroscopy. Dissolved organic carbon (DOC) was measured using a Dohrmann C analyzer. Only soil solutions from the deep (25 cm) lysimeters were analyzed for DOC because they yielded greater amounts of sample throughout the season. Data were analyzed by the general linear model procedure of SAS (SAS Corp. 1987). Analysis of variance was

used to test the null hypothesis that mean values for pH, DOC, and concentrations of Al and Fe in soil solution were not different between vegetation types. Significant differences were determined by protected least significant difference test at $P = 0.05$. For Al, Fe, and pH, no significant differences between the shallow (12 cm) and deep (25 cm) lysimeters were found within sites; therefore, data from these lysimeters were grouped to compute averages. As a result, Al, Fe, and pH values represent average conditions found in the 12 to 25-cm depth within the ash cap.

RESULTS AND DISCUSSION

pH

1994 pH data showed that soil solution from the 30-year-old bracken fern glade site had consistently lower pH values throughout the growing season (Fig. 2a) and was the only site in which pH dropped to 5 (July 1) during the sampling period. In acid soil solutions, pH 5 is a critical

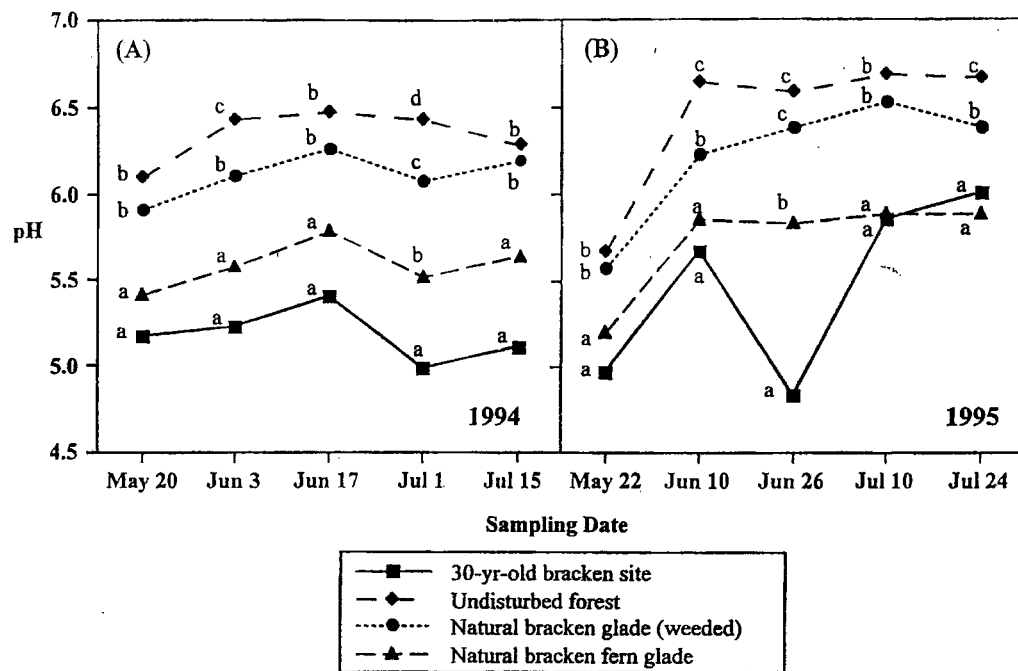


Fig. 2. Soil solution pH for sampling dates in (A) 1994 and (B) 1995. Data points labeled with the same letters within a sampling date are not significantly different ($\alpha = 0.05$).

point at which plants may start to experience Al toxicity (Wolt 1994). Statistical analysis shows that pH within the 30-year-old and natural bracken fern glades was significantly lower than in the undisturbed forest and the natural bracken fern glade (weeded) for every sampling date in 1994. The fact that the soil solution pH from the weeded natural bracken fern glade was not significantly different (in four of five sampling dates) from that of the undisturbed forest suggests that the removal of the above-ground bracken fern biomass does help raise pH relative to the unweeded bracken fern site.

Soil solution data collected in 1995 are similar to those of 1994 in that the pH of soil solution in the 30-year-old bracken fern glade was usually lower than the other sites throughout the sampling period (Fig. 2b). The lowest pH recorded was 4.8 in the 30-year-old glade on June 26, 1995. As was observed in the 1994 data, the 30-year-old bracken fern glade had the only solution dropping below 5.0 during the entire sampling period. The trend in pH with respect to time is similar to 1994 data in the undisturbed forest. The 30-year-old bracken fern glade was the only site to show a decrease in pH corresponding to the June 26, 1995, sampling. This site

also showed a seasonal decrease in pH for June 1994.

Combining the 2 years of data suggests that the soil solution from bracken fern-influenced soil does experience a seasonal drop in pH. Soil solution pH in the weeded subplot of the natural bracken fern glade was consistently, significantly higher than in the unweeded subplot, indicating that bracken fern biomass has an acidifying effect on soil solution.

Overall 1994–1995 pH data point to two important findings. First, soil solution pH of the 30-year-old bracken fern glade is consistently and significantly lower than that of the undisturbed forest and the natural bracken fern glade (weeded). The 30-year-old bracken fern site is also the only site that experienced soil solution pH values less than 5 during the 2-year sampling period. Secondly, the pH in the weeded subplot of the natural bracken fern glade was significantly higher than the unweeded subplot for every sampling date over the 2-year period. This indicates that above-ground bracken fern biomass has an acidifying effect on soil solution pH. Changes in soil pH were also noted in the solid phase of soils supporting bracken fern communities for as little as 30 years. The pH of 1:1

(soil:water) mixtures from soils of the 30-year-old and natural bracken fern sites were significantly lower than the undisturbed forest (Johnson-Maynard et al. 1997).

Aluminum

In 1994, soil solution Al concentrations, as expected, varied inversely with pH; i.e., the highest Al concentration corresponded to the lowest pH (Fig. 3a). The 30-year-old bracken fern glade was, therefore, highest in Al, whereas the undisturbed forest was often below the lower limit of the detection level (0.15 mg/L). Statistical differences were detected in three of the five sampling dates during 1994. The undisturbed forest was significantly lower in Al than the 30-year-old bracken fern glade on June 3 and 17 and July 1, 1994.

Although Al concentrations in soil solutions collected in 1995 were more variable, they showed the same general trend of the 30-year-old bracken fern glade, i.e., they were highest whereas the undisturbed forest was lowest (Fig. 3b). Soil solution from the 30-year-old glade was significantly higher in Al for every sampling date in 1995. Aluminum concentrations were also much higher in 1995 relative to 1994. The reason for this difference is not entirely clear, but it

may be related to climatic differences. Approximately 3.3 cm more rain fell during the months of May and June in 1994 than fell in May and June 1995, resulting in a dilution of the Al in soil solution. The effectiveness of weeding the natural glade is somewhat less clear when looking at 1995 data. This problem reflects the need for further monitoring to avoid skewed data caused by climatic conditions.

Solution culture studies have been conducted to determine the effects of Al on tree growth. Unfortunately, none of these studies has considered grand fir. Hutchinson et al. (1986) found reduced biomass of spruces grown in nutrient solution containing from 0.19 to 0.37 mmol Al/L (5.1 to 10 mg/L) and in various pines with 1.48 to 2.96 mmol Al/L (40 to 80 mg/L). It is important to consider that these numbers represent total Al in solution and that the toxic portion would be much smaller. Thornton et al. (1987), for example, reported the toxic threshold for root elongation of red spruce (*Picea rubens* Sarg.) seedlings as 0.25 mmol Al/L (6.75 mg/L), with an estimated Al^{+3} activity of 0.05 mmol Al/L (1.35 mg/L). Aluminum concentrations measured in this study are generally below the toxic levels reported for other species. This indicates

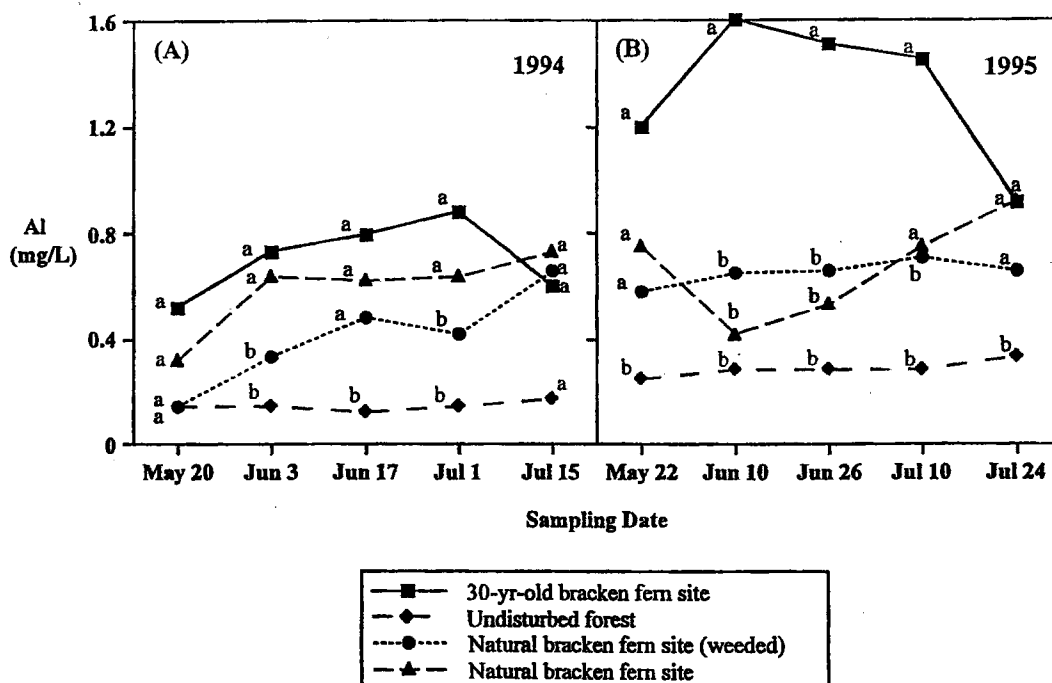


Fig. 3. Soil solution Al concentrations for (A) 1994 and (B) 1995. Data points labeled with the same letters within a sampling date are not significantly different ($\alpha = 0.05$).

that Al toxicity may not be a major contributor to the regeneration problem within the GFM.

Despite the significantly higher levels of Al in the soil solution from bracken fern-influenced soils, the occurrence of Al toxicity cannot be proven for two reasons. First, Al threshold values have not been reported for grand fir. Second, most of the studies report toxic levels of total Al in solution instead of Al activities.

Dissolved Organic Carbon

Dissolved organic carbon is an important component of soil solution. These soluble substances can exert a substantial influence on ion leaching processes, nutrient cycling, microbial community dynamics, and mineral weathering (Evans et al. 1988). In this study, interactions between Al and DOC are extremely important because of differences in bioavailability of organically complexed Al and free Al^{+3} (Hue et al. 1986). In 1994, dissolved organic carbon at 25 cm was highest in the 30-year-old bracken fern glade soil solution for every sampling date except June 17 (Fig. 4a). Dissolved organic carbon in the 30-year-old bracken fern glade was also significantly higher than in the undisturbed forest on May 20 and July 15. A general trend existed where DOC was highest in early spring (May 20), decreased throughout June, and then in-

creased to the maximum level in July. July was also when the soil became too dry to yield sufficient soil solution sample for analysis. It was expected that DOC would be higher in spring because of the flush of organic acids released from decomposition of the plant biomass.

In 1995, DOC levels were significantly higher in the 30-year-old bracken fern glade relative to the undisturbed forest for every sampling period (Fig. 4b). DOC in the natural bracken fern glade was significantly higher than in the undisturbed forest for every sampling period and significantly lower than in the 30-year-old bracken fern glade for all but one sampling date. There is no apparent trend of DOC concentration with time among sites in 1995 data. Soil organic carbon contents indicate that DOC is being immobilized rapidly within the ashcap of the bracken fern influenced soils. Organic carbon ranged from 5.4% in the 30-year-old soil to 3.7 in the undisturbed forest (Johnson-Maynard et al. 1997).

Temporal variation in DOC is a factor that influences the Al chemistry of soil solutions greatly (Nilsson and Bergkvist 1983). Dissolved organic carbon and Al/Fe in soil solution samples collected at sites within the GFM during the 1994 (data not shown) and 1995 growing seasons are significantly and positively correlated, with r values of 0.533 and 0.824, respectively (Figs. 5a

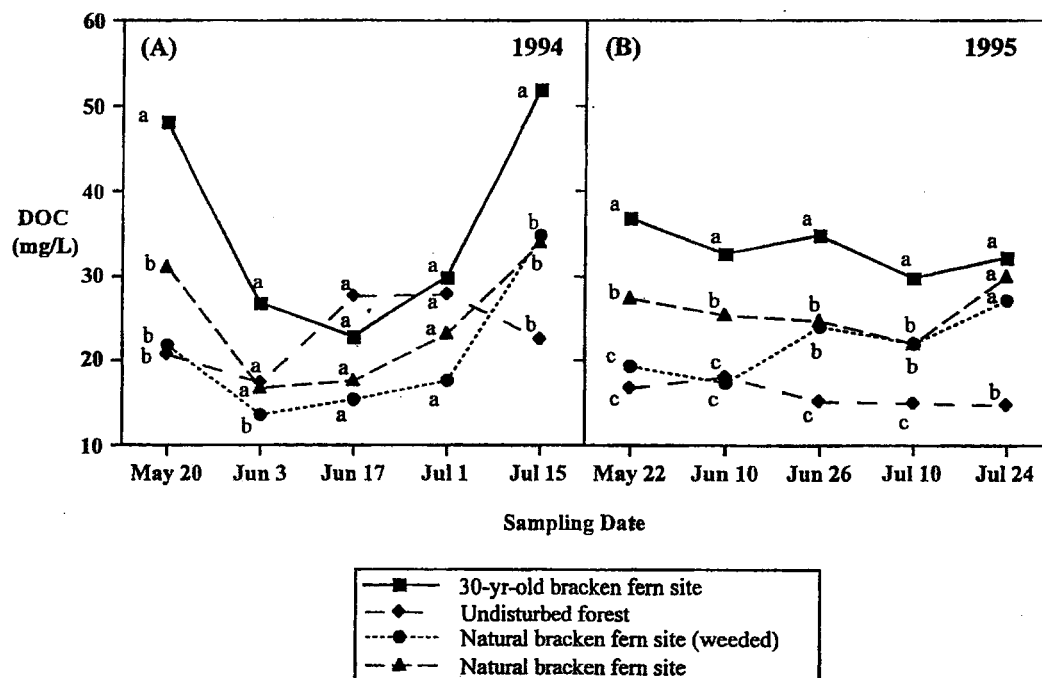


Fig. 4. Dissolved organic carbon (DOC) concentrations in soil solutions collected in (A) 1994 and (B) 1995. Data points labeled with the same letters within a sampling date are not significantly different ($\alpha = 0.05$).

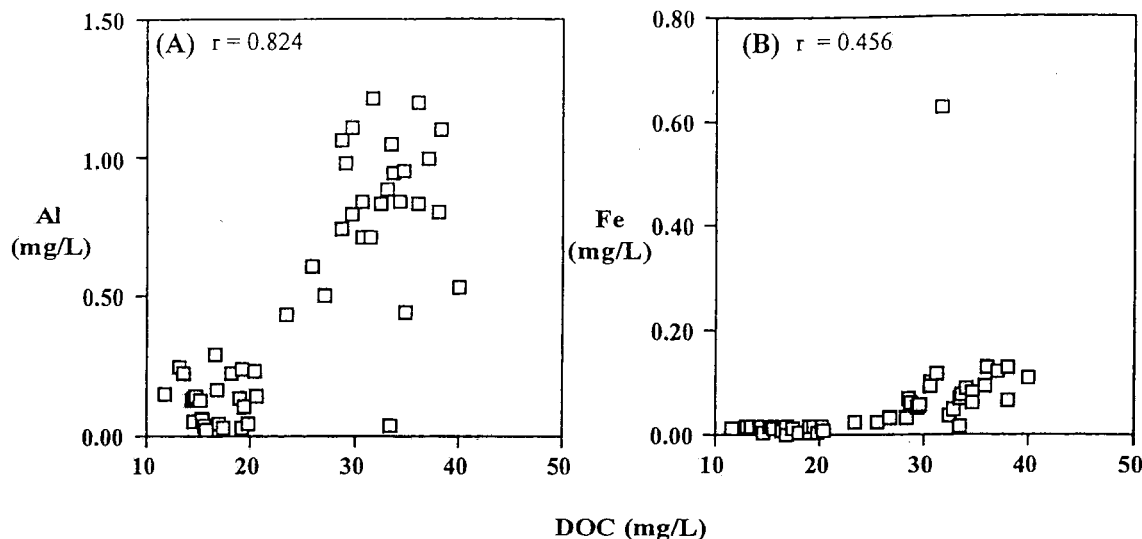


Fig. 5. Relationship between (A) Al and (B) Fe with DOC (at 25-cm depth) in soil solution samples from 1995.

and b). Solid phase data showing accumulations of Al/Fe-humus complexes in the Bw1 and Bw2 horizons of the 30-year-old and natural bracken fern glades (Johnson-Maynard et al. 1997) suggest that the intimate relationship between Al/Fe and DOC may be altering the balance of soil-forming processes.

The relationship between DOC and Al shown in Fig. 5 cannot, by itself, be used to determine the possibility of Al toxicity. Nonallophanic Andisols have a large organic pool that controls Al availability, a situation in which one would expect to see decreased Al toxicity, yet Al toxicity is commonly reported in nonallophanic Andisols. Further data about Al speciation in soil solution are needed to evaluate the possibility that Al toxicity prevents natural conifer regeneration in soils of the GFM.

CONCLUSIONS

Soil solution pH was significantly lower in the 30-year-old bracken fern glade. This was caused by the presence of bracken fern and the resulting lack of secondary succession. The pH of soil solution samples from bracken fern-influenced soils showed a seasonal decrease, and occasionally it reached a value of 5. Soil pH data indicate that the presence of bracken fern biomass can decrease pH significantly within a relatively short time span. Aluminum in soil solution was also significantly higher within the volcanic ash cap of the 30-year-old and natural bracken fern glades for most of the sampling dates. Although a toxic level of Al has not been reported for grand

fir, the concentrations measured in the GFM are generally lower than values reported for other species. This indicates that Al toxicity is not responsible for the lack of natural conifer regeneration. Dissolved organic carbon also tends to be highest in the bracken fern-influenced soils and is correlated positively with total Al and Fe in soil solution. The relationship between DOC and Al/Fe is consistent with mineralogical data and indicates that formation of soluble metal-humus complexes is an important process in Andisols supporting bracken fern communities.

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