Tolerance of Soil Organisms to Herbicide Applications in Ponderosa Pine Plantations: Initial Findings

Matt D. Busse, Nancy G. Rappaport, and Robert F. Powers[1]

Introduction

Control of competing vegetation is often a prerequisite for successful establishment of conifer plantations. By reducing competition for site resources (water, nutrients, light), vegetation control results in substantial increases in tree growth in California plantations (McDonald and Fiddler 1993, Powers and Reynolds 1999). Of the available methods to control vegetation, herbicides remain the preferred alternative by many due to their effectiveness and economic return (McDonald and Fiddler 1993). Current herbicide application exceeds 40,000 hectares annually in California forests (Calif. Dept. Pesticide Regulation 2000). Whether chemical control of forest vegetation is benign to the consortium of non-target organisms, however, has not been clearly demonstrated. In particular, the response of soil organisms to direct (toxic) or indirect (habitat modification) effects of herbicides requires investigation.

Soil organism communities are vital to conifer plantations and forests. Their collective role in cycling energy and nutrients is an underlying requirement for the survival, growth, and production of forest vegetation. Microorganisms, in particular fungi and bacteria, are directly responsible for decomposing organic matter and mineralizing nutrients (Tate 1995). Simply stated by Kennedy and Smith (1995), "ecosystem functioning is governed largely by soil microbial dynamics." Equally important is the diverse group of soil arthropods, which includes, in part, insects, mites, and spiders. Soil arthropods are responsible for bioturbation, shredding of litter, inoculation of litter with microbial spores, predation of other soil organisms, and selective microbivory that enhances decomposition and nutrient turnover (Wallwork 1983, Seastedt 1984). Their importance is well documented (Freckman 1994), as is their diversity and abundance in mineral soil and litter (Lattin 1990, Moldenke 1990).

Few field studies have documented the effects of herbicides on forest soil organisms (see Vitousek and Matson 1985, Moldenke 1992, Wardle and Parkinson 1992). Therefore, land managers must consider whether herbicides impair their role in forest function. This paper describes the response of soil organisms in ponderosa pine plantations to repetitive applications of the Roundup[2] formulation of glyphosate. Results are presented for the indirect effects of vegetation control on soil organisms. Specifically, we examine whether habitat modification resulting from continuous control of understory vegetation affects microbial and arthropod communities. Direct effects of Roundup on soil organisms will be reported in a subsequent publication.

Methods and Materials

Response of soil organisms to continuous vegetation control was tested at two sites: Whitmore, a moisture-limited plantation about 43 km east of Redding, California, and Feather Falls, a highly productive plantation about 35 km east of Oroville, California. Both plantations are part of the complex of "Garden of Eden" study sites in northern CA (Powers and Ferrell 1996). Site characteristics are listed in Table 1. The experimental design is completely randomized with eight treatment combinations of vegetation control, insect control, and fertilization. Each site has three replications of all treatments. A subset of treatments was selected to address our objective: (1) vegetation control using repeated Roundup applications, (2) control (no treatment). Roundup was applied annually at the recommended field rate using directed sprays. Understory vegetation on the control plots was dominated by whiteleaf manzanita, greenleaf manzanita, common manzanita, and deerbrush (see Powers and Reynolds for more detail). Herbicide-treated plots have been maintained free of understory vegetation for the length of the study. Differences between herbicide and control treatments were considered significant at $P < 0.05$.

Litter organisms. Microbial biomass and arthropod community size were measured using standard protocol. Briefly, microbial biomass was measured seasonally in 1995 and 1996 by the substrate-induced respiration method (Anderson and Domsch 1978). Composite samples (a pool of 10 subsamples per plot) were analyzed in duplicate within 24 h of collection. Arthropod sampling was conducted using polyethylene pitfall traps (Lemieux and Lindgren 1999) installed for 1-month intervals during the summer of 1999. Traps were filled to a 2 cm depth with

[1] USDA Forest Service, PSW Research Station, 2400 Washington Avenue, Redding, CA 96001.
[2] Mention of any trade product does not imply Forest Service endorsement.

propylene glycol as a killing agent to prevent cannibalism and predation within the traps. Five pitfall traps were installed per plot in mid-June. All traps were randomly located in the plot centers to avoid possible edge effect. One month later, arthropods were collected, extracted, sorted, and then stored in 70% ethanol. They were subsequently identified to the taxonomic level of Class for most groups, but to the level of Order for organisms in the Class Hexapoda (= Class Insecta). Only the most important groups (spiders, mites, millipedes, springtails, beetles) are analyzed here, although gross abundance of other groups is reported.

Table 1. Site characteristics for two Garden of Eden plantations (adapted from Powers and Reynolds [1999]). Soil characteristics are for the surface 0-15 cm.

	Whitmore	Feather Falls
Site index (m)	23	30
Elevation (m)	730	1220
Annual precipitation (cm)	114	178
Mean August air temp (°C)	25.4	19.2
Year planted	1986	1988
Shrub cover at 10 years (%)	79	72
Soil pH	5.6	5.4
Soil organic C ($g\ g^{-1}$)	39.1	66.9
Clay content ($g\ g^{-1}$)	34	36

Mineral soil organisms. Indices of microbial community size and function were made seasonally in 1998. Microbial biomass (Anderson and Domsch 1978), carbon mineralization (Zibilske 1994), and mineralizable nitrogen (Powers 1980) were measured using composite samples collected from the upper 15 cm of mineral soil. Arthropod population size and diversity were not determined.

Results and Discussion

Litter organisms. Minor or no changes in microbial biomass and arthropod community size were found after 8-14 years of vegetation control. Microbial biomass of litter was similar between control and herbicide plots at Whitmore despite a strong seasonal fluctuation (Table 2). A slight reduction in microbial biomass due to herbicide treatment was found at Feather Falls, although the difference was significant in spring only. Analysis of litter chemistry is in progress and may explain the observed treatment responses and site differences. For arthropods, the only significant difference between control and herbicide plots was for springtails at Feather Falls (Table 3). A three-fold decline in springtails was also seen at Whitmore, although the treatment effect was not significant due to plot-to-plot variation. Eaton et al. (in press) reported a similar pattern of springtail response to herbicides in a long-term forest soil productivity study. For all other faunal groups, the differences in trap catches between treatments were insignificant, and, in fact, the absolute numbers were remarkably similar between treatments, with the exception of beetles at Whitmore.

There are several possible explanations for the decreased abundance of springtails in the herbicide plots. First, springtails are noted for their sensitivity to desiccation and high temperatures (Christianson 1990, Villani et al. 1999), so the absence of angiosperm leaf litter caused by herbicide treatment may have altered the habitat to the detriment of springtails. That is, the elimination of understory vegetation may have resulted in greater exposure of springtails to heat and desiccation, both directly (because of increased insolation) and indirectly (because of reduced mulching from angiosperm litter). Second, the herbicide could have toxic effects on springtails. No evidence of direct toxicity to springtails has been reported for formulations of glyphosate, however. Third, the higher numbers of springtails in control plots could result from the increase in favored substrate, angiosperm litter. There is evidence that springtails are more abundant in angiosperm litter than in conifer litter, whereas orabatid mites dominate conifer litter (Wallwork 1976, Wallwork 1983). As expected, the herbicide plots were deficient in angiosperm litter compared with control plots. The most plausible explanation for the difference in springtail numbers between treated and control plots, then, is that the application of herbicides, in reducing angiosperm litterfall, also reduced the favored food source for springtails. Further studies comparing springtail populations in mechanically-grubbed vs. herbicide-treated plots will be necessary to resolve this question.

Table 2. Seasonal microbial biomass (g C/ kg) of litter from two Garden of Eden plantations. Data are means (standard deviations) of three replicates.

	Whitmore		Feather Falls	
	Herbicide	Control	Herbicide	Control
Spring	5.9	5.6	5.7	7.1*
Summer	11.4	12.5	9.7	11.5
Fall	7.2	7.1	14.0	16.4

* significant difference between herbicide and control treatments at $\alpha = 0.05$, Tukey's hsd.

Table 3. Arthropod community size (mean number per trap) in litter at two Garden of Eden plantations.

	Whitmore		Feather Falls	
Community	Herbicide	Control	Herbicide	Control
Mites	9.27	7.53	4.86	4.31
Spiders	9.02	5.40	8.17	8.53
Beetles	2.93	10.62	7.10	7.83
Springtails	1.87	6.45	24.40	56.60*
Other arachnids	0.00	0.00	2.40	4.00
Other insects	168.00	179.93	99.80	82.50
Myriapods	0.47	0.23	0.20	0.80

* significant difference between herbicide and control treatments at $\alpha = 0.05$, Tukey's hsd.

Mineral soil organisms. Response of microbial biomass, C mineralization, and mineralizable N to vegetation control is presented in Figure 1. Again, the lack of treatment response is remarkable. Thirteen years of vegetation control at Whitmore and 11 years at Feather Falls produced no measurable differences in microbial characteristics in the surface mineral soil when compared to the control treatment. Certainly, these indices of microbial population size and activity by no means represent a thorough analysis of microbial dynamics. Instead they are indicative of gross-level changes in total community size, organic matter utilization, and N availability. Whether individual species or groups of functionally-related species respond differentially to vegetation control was not tested. Nevertheless, microbial biomass, C mineralization , and mineralizeable N are considered sensitive measures of microbial changes following disturbance and habitat modification (Tate 1995), and provide strong evidence that vegetation control had an inconsequential affect on soil microorganisms and the important soil processes they mediate. In direct contrast to our results, Busse et al. (1996) found that 35 years of vegetation control in naturally regenerated ponderosa pine stands in central Oregon led to a sharp decline in microbial biomass in surface mineral soil. Total soil C also was lower in their study where vegetation had been controlled, suggesting that the reduction in microbial community size was related to a decline in available C substrates. In comparison, we found soil C content was unaffected by vegetation control at either Whitmore or Feather Falls. This raises an interesting question. Why would soil C be affected by vegetation control in central Oregon, yet show no response at Whitmore and Feather Falls plantations? Unfortunately, no single answer is satisfactory. Accumulation of soil C is a dynamic process in which input from litterfall, root turnover, and root exudates is balanced by decomposition and release of soil C as CO_2. Ultimately, the balance between C input and output is a function of countless, interactive factors, such as soil type, temperature and moisture regime, initial soil C and nutrient content, plant diversity and cover, length of growing season, and length of treatment. Discrepancies in soil C accumulation and treatment response between the two studies confirm that these vegetation-control experiments are site specific, and, as a result, should not be extrapolated to other forest types.

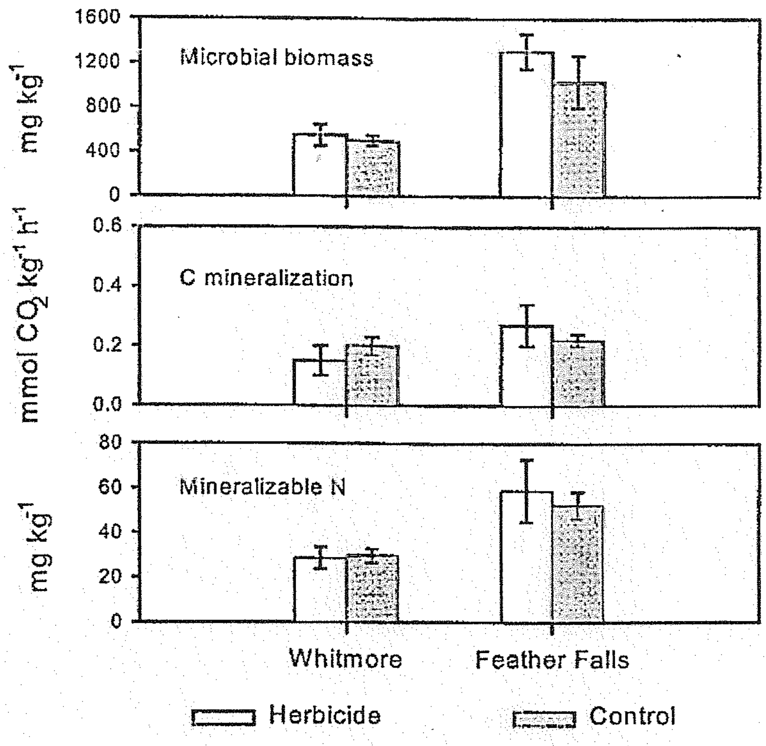

Figure 1. Microbial characteristics in mineral soil after prolonged understory vegetation control at two Garden of Eden plantations (13 years at Whitmore, 11 years at Feather Falls). Vertical bars are standard deviations.

The tolerance of litter and soil organisms to herbicide treatment at Whitmore and Feather Falls can be viewed from a larger perspective by considering the benefits of vegetation control to tree growth. Initial, 10-year volume growth of ponderosa pine was 306% greater at Whitmore and 65% greater at Feather Falls with herbicide use (Table 4). Changes in soil organism community sizes, in comparison, were nominal. Although this is a classic example of comparing "apples and oranges," it underscores the relative resilience of different organism types to disturbance. Soil organism communities, and microbial communities in particular, are recognized for their ability to adapt to disturbance as a consequence of their abundance, physiological diversity, and genetic malleability (Atlas 1984, Madsen 1996). Habitat modifications and changes in available substrates, moisture, and temperature created by continuous vegetation control were inconsequential to the soil organism community, yet produced substantial improvements in tree growth.

Conclusions

Our results are a coarse-grained evaluation of herbicide effects on soil organism communities. A finer level of taxonomic resolution may reveal community shifts that are functionally important in terms of soil processes. At this point in our investigation, however, there is no evidence that vegetation control using Roundup has any detrimental effects on soil organisms or their functional role in forests.

Table 4. Comparative changes in soil organisms and ponderosa pine following a minimum of 8 years of continuous vegetation control. Tree volume at year 10 is from Powers and Reynolds (1999).

	Whitmore			Feather Falls		
	Herbicide	Control	% change	Herbicide	Control	% change
Microbial biomass (mg/kg)						
Litter	8,151	8,586	-4	9795	11664	-16
Mineral soil	451	483	-7	811	764	6
Arthropod (no./trap)	187	215	-13	147	165	-11
Tree volume (m^3/ha)	18.4	4.5	306	56	34	65

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