RESEARCH ARTICLE

Effects of Prescribed Fire on Soil Invertebrates in Upland Forests on the Cumberland Plateau of Kentucky, USA

Paul J. Kalisz'

Janet E. Powell

Department of Forestry
University of Kentucky
Lexington, KY 40546-0073 USA

•

Corresponding author e-mail:
pkalisz@ca.uky.edu

Natural Areas Journal 20:336-341

ABSTRACT: This study reports on the changes in the soil invertebrate community on ridges on the Cumberland Plateau of Kentucky, USA, one year after a prescribed fire. There was a significant 36% reduction in the total dry mass of soil invertebrates as a result of the fire. Approximately 95% of the total loss of mass was due to significant reductions in mass of invertebrates in the forest floor, and approximately 60% was due to reductions in the mass of beetle (Coleoptera) larvae. In addition, burning resulted in declines in the number of invertebrate orders and in the frequency of occurrence of mesofaunal ants and of macrofaunal beetle larvae and adults. Beetles were ubiquitous in soils on these ridges and were the single most important order, accounting for 38% of the total dry mass of invertebrates. Given the importance of this group, managers need to consider the possibility that prescribed fire, especially if used repeatedly and at short intervals, may result in substantial and possibly long-lasting reductions in beetle populations. One possible approach to preventing this is to strive for spatial and temporal heterogeneity on multiple scales, leading to increased complexity after burning and increased probability that all biotic and abiotic components will survive within the postfire ecosystem.

Index terms: Coleoptera larvae, prescribed burning, soil invertebrates, soil macrofauna, soil mesofauna

INTRODUCTION

Prescribed fire is widely used as a tool in forestry to achieve goals such as removal of fuels that increase wildfire hazard and elimination of plants that compete with crop trees. In addition, fire is used under controlled conditions in wild forests and other ecosystems in an effort to reestablish the whole suite of processes and conditions that existed prior to human disturbance (Chandler et al. 1983a, b).

Many aspects of fire effects have been studied in an effort to learn to efficiently use this tool, and to prescribe fires with characteristics (e.g., intensity, season of burn, return-interval) that are appropriate to each ecosystem. Although there has been some interest in the effect of prescribed fire on soil invertebrate communities, studies dealing with this topic have concentrated on specific ecosystems and regions. Work has been done primarily in boreal forests (Huhta et al. 1967, 1969; Paquin and Coderre 1997; McCullough et al. 1998), in pine forests of the Coastal Plain and Piedmont of the eastern United States (Heyward 1936, Buffington 1967, Metz and Dindal 1975, Hermann et al. 1998), and in eucalypt forests of Australia (Abbott 1984, Majer 1984, Neumann and Tolhurst 1991, Collett et al. 1993).

In the hardwood forest region of the Cumberland Plateau of Kentucky (USA), fires probably played a part in shaping the ecosystems that occurred at the time of European settlement, especially on drier landscape positions. In the Red River Gorge region of the Daniel Boone National Forest there is some evidence (Wehner 1991) to support the theory that, prior to forest fragmentation and fire control by the U.S. Forest Service, ground fires were effective in limiting the occurrence of white pine *(Pinus strobus L.)* to moist landscape positions such as lower slopes and coves, and in preventing this species from invading dry forests on ridges (Figure 1). Consistent with this belief, present U.S. Forest Service policy is to periodically burn ridges to halt encroachment of white pine and thereby maintain or reestablish ecosystems dominated by dry-site hardwoods with variable numbers of pitch (P. *rigida* Mill.), shortleaf (P. *echinata* Mill.), and Virginia *(P. virginiana* Mill.) pines. This study re-ports on the effects of this policy on soil invertebrate communities on ridgetops one year after a prescribed fire.

STUDY AREA

Biophysical Setting

This study was done during 1995 and 1996 in the Stanton Ranger District of the Daniel

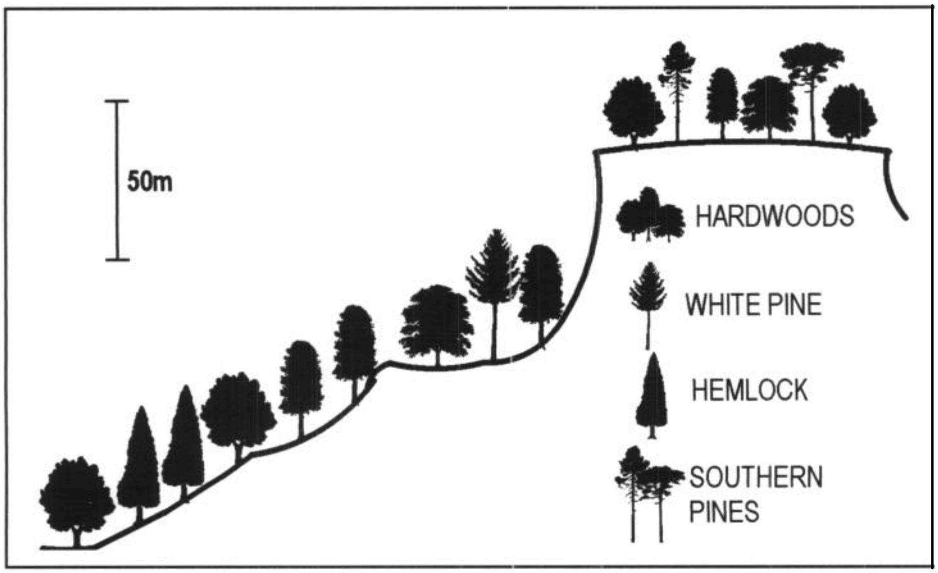

Figure 1. Block diagram illustrating the topography of he Red River Gorge region, Kentucky, and the distribution of selected types of trees on the study area.

Boone National Forest (37° 48'N, 83° 40'W). The climate is temperate, humid, and continental. Annual precipitation is 1130 mm and is evenly distributed through-out the year. Mean daily temperature maxima and minima are 6°C and -6°C in January, the coldest month of the year, and 30° C and 17° C in July, the warmest month of the year (Hill 1976). Weather was near average and similar in both years of this research. Averages during the February–March sampling periods of 1995 and 1996, respectively, were 5° C and 4° C for daily temperature, and 147 mm and 158 mm for monthly precipitation. Total precipitation amounts for 12-month periods preceding sampling were 1262 mm and 1222 mm, respectively, for 1995 and 1996. There were 36 days during the sampling periods of both years on which temperature mini-ma were below freezing (University of Kentucky Agricultural Weather Center, pers. corn.).

The study area lies along the western escarpment of the Cumberland Plateau (Fenneman 1938) of the Appalachian Mountains. Topography is rugged, with cliffs up to 150 m high separating lower landscape positions from dry uplands (Figure 1). Maximum elevation is about 395 m. Geologic substrate consists of horizontally bedded, Pennsylvanian-aged sandstones, siltstones, and shales with minor amounts o± coal, limestone, and dolomite (McDowell et al. 1981).

Soils on two of the three sites used in this study were formed in sandstone residuum. These sandy soils had sandy-loam textures and excessive drainage; they were classified as Typic and Lithic Dystrochrepts (Hayes 1993). Soils on the third site were formed in a mixture of siltstone and shale residuum. These loamy soils had silt-loam over silty-clay loam textures and impeded drainage at depths of 45–65 cm; they were classified as Aquic Hapludults (Avers et al. 1974). All soils were characterized by low nutrient concentrations and pH (pre-burn pH range = 3.0–3.8), and by thin 0 horizons (mean ash-free, oven-dry organic mass = 283 g m ^{2}) (Blankenship and Arthur 1999a).

The study area is in the Mixed Mesophytic Forest Region of Braun (1950). Basal area of forests on the sample plots was composed of 50–80% dry-site oaks *(Quercus coccinea* Muenchh., *Q. velutina* Lam., *Q. al ha* L., *Q. prinus* L.) and 10–30% pine *(Finus echinata, P. rigida, P. virginiana);* the understory was composed primarily of species of Ericaceae (Blankenship and Arthur 1999b).

The Fire

Portions of all three study sites were burned by U.S. Forest Service personnel in March, 1995, under conditions described in detail by Blankenship and Arthur (1999a). Burned areas were approximately 18 ha on the two sandy sites, and 36 ha on the loamy site. Fire temperatures at the ground surface ranged from 316°C to 398°C, and temperatures at a depth of 0.5 cm in the 0 horizon ranged from 204°C to 315°C (Blankenship and Arthur 1999a). Although loss of organic mass was not measured in 1995, similar prescribed fires in 1996 on nearby sites removed 32% of the mass of the O horizon (L-layer), or about 11% of the mass of the total 0 horizon (Blankenship and Arthur 1999a). Based on definitions presented by Chandler et al. (1983a: 172–173), the intensity of the prescribed fires used in the present study may be classified as "moderate" for the purpose of comparing our results to literature that describes fire intensity as light, moderate, or severe.

METHODS

Plot Layout

The three sites used in this study were 3000–4000 m apart and located on upland areas above cliffs (Figure 1). As described above, soil texture may be used to classify two of these sites as sandy and one as loamy. Total areas of the two sandy sites and the one loamy site were approximately 50 and 100 ha, respectively. Each site was divided into reference and burn treatments. Plot layout was as described by Blankenship and Arthur (1999a) except that only six randomly-located plots were used to sample the burn and reference treatments on each of the three sites.

Field Methods

We collected invertebrate samples from random points within six 0.04-ha plots on both reference and burn areas during February and March. Samples were collected less than one month before burning in 1995, and one year after burning, in 1996. Three types of samples were collected around each of two points in each plot on each sample date. (1) A square wooden frame was used to collect soil from an area of 0.1 m^2 and to a depth of 30 cm. This soil was immediately spread on a plastic mat and earthworms were hand-sorted and placed in containers of moist soil for trans-port to the laboratory. (2) Another square wooden frame was used to collect soil from an area of 0.05 m^2 and to a depth of 15 cm. This soil was separated into forest floor (0 horizon) and mineral soil and placed in plastic bags for transport to the laboratory for later hand-sorting of the macrofauna (specimens with width > 2 mm). (3) Two thin metal cylinders were pressed into the soil to collect cores 5.5 cm diameter by 5 cm deep. Both ends of the cylinders were covered with plastic caps to prevent soil loss and desiccation during transport to the laboratory for later funnel-collecting of the mesofauna (specimens with width < 2 mm).

Laboratory Methods

Earthworm color, behavior, and general morphology were recorded prior to anes-thetization with 10% EtOH. We recorded length and diameter for anesthetized worms, and identified earthworms based on external morphology. We hand sorted macrofauna from the forest floor and min-eral soil samples, using 10 X illuminated magnifiers as necessary. Specimens were stored in a refrigerator in 75% EtOH for later identification.

Mesofauna were extracted from the core samples using the Tullgren-type funnel apparatus described by Crossley and Blair (1991) and a three-day extraction period. The mesofauna were collected in vials of 75% EtOH. Specimens were stored in a refrigerator until they could be identified using keys and other information contained in Arnett (1993), Chu and Cutkomp (1992), Dindal (1990), and Stehr (1987, 1991). Length and width measurements were made as appropriate to allow calculation of dry mass. Nomenclature follows Dindal (1990) and Stehr (1987, 1991).

Sampling methods used in this study pro-vide reasonable estimates of numbers and mass of all macrofaunal and mesofaunal taxa except for the Enchytraeidae (Annelida; potworms) and Gastropoda (slugs and snails) (Edwards 1991). Data for Enchytraeidae and Gastropoda are there-fore not presented in this paper. Plant species nomenclature follows Preston (1989).

Statistical Analyses

Replicate samples were averaged by plot for each year to obtain annual means of each variable for each plot. Number per square meter and average size of inverte-brate specimens were used to calculate dry mass per square meter for the various taxa as follows: (1) direct measurement of mass—Oligochaeta (Annelida; earth-worms), Araneae (spiders), Formicidae (Hymenoptera; ants), Hemiptera (true bugs), Lepidoptera (moths and butterflies);
(2) using typical values or regression equa-tion from Persson and Lohm (1977)--Homoptera (leafhoppers, etc.), Hymenoptera (wasps), Protura (proturans);
(3) using regression equations from Ed-wards (1967)—Acarina (mites), Chilopoda (centipedes), Coleoptera (beetles), Collembola (springtails), Diplopoda (millipedes), Diplura (diplurans), Diptera (flies), Isopoda (pillbugs), Pauropoda (pauropods), Pseudoscorpionida (false scorpions), Symphyla (symphylans), Thysanoptera (thrips). We used dry mass per unit ground area as our primary test variable, adding mesofaunal and macrofaunal mass-es to get total mass. We summarized our data in terms of taxonomic categories rather than functional groups, since Gunn and Cherrett (1993) found a high degree of omnivory among soil invertebrates with no clear compartmentalization into func-tional or trophic groups.

The reference plots were sampled in 1995 and 1996 to detect changes in the abun-dance of the various invertebrate taxa, in the absence of fire, that could aid in inter-pretation of differences between years on the plots that were burned. The burn plots were sampled before (1995) and after (1996) prescribed fire to test for changes that could be statistically ascribed to burn-ing. Only a few earthworms and milli-pedes were collected on the sandy sites. For this reason, abundances of these two taxa were compared between years only on the loamy site.

Logarithmic transformations were used as necessary to ensure that all variables satis-fied the assumptions of normality (based on Shapiro-Wilk statistic) and homogene-ity of variance (based on the Levene statis-tic) prior to comparing them between years and sites. Reference and burn plots were analyzed separately. We used simple fac-torial analysis of variance to test for differ-ences in dry mass and number of taxa, using years and sites as factors. We used chi-square analysis to test for differences between years in the frequency of occur-rence of the various taxa on burned plots. To do this, we set the chi-square expected number equal to the frequency of occur-rence found before burning and tested for differences after burning. Transformed variables were back-transformed prior to presentation of results. All statistical anal-yses were done with the SPSS computer program (SPSS 1997).

RESULTS

General

Twenty-seven invertebrate orders were collected on the research plots, including 18 orders of mesofauna and 20 orders of macrofauna. All specimens were indige-nous to the study area. The following sev-en taxa, in decreasing order of importance, together accounted for about 75% of total invertebrate dry mass on all reference and burn plots in 1995 before burning: beetle larvae, mites, fly larvae, centipedes, ants, springtails, and spiders. Beetle larvae and mites were predominant, accounting for 38% and 21% of the total invertebrate dry mass, respectively. The beetle family Ela-teridae (wireworms) accounted for 47% of the total beetle dry mass.

Reference Plots

There were no significant differences be-tween 1995 and 1996 in total invertebrate dry mass ($F=0.54$; $df=1,30$; $P=0.47$); in the number of invertebrate orders collect-ed ($F=3.91$; $df=1,30$; $P=0.06$); in the dry masses of earthworms ($F=0.35$; $df=1,10$; $P=0.57$) and millipedes ($F=0.10$; $df= 1,10$; $P=0.92$) on the loamy site; and in the dry masses of beetles ($F=0.01$; $df=1,10$; $P=0.93$) and mites ($F=0.63$; $df=1,10$;

P=0.45) on the loamy site; and in the dry masses of beetles (F=1.77; df=1,10; P=0.21) and mites (F=3.35; df=1,10; P=0.10) on one sandy site. On the other sandy site, beetle mass was significantly higher (F=9.73; df=1,10; P=0.01) and mite mass was significantly lower (F=14.51; df=1,10; P=0.003) in 1996 than in 1995. Overall, the results from the reference plots suggested that there were no interpretable trends in invertebrate populations on the ridges between 1995 and 1996.

Burned Plots

Total invertebrate dry mass was significantly lower (F=4.84; df=1,30; P=0.04) after the fire, with average values (mean ± SE) of 810 ± 105 mg m^{-2} in 1995 and 519 ± 72 mg m ^{2} in 1996. This reduction in dry mass was largely accounted for by a significant (F=8.37; df=1,30; P=0.007) de-crease in mass of invertebrates in the 0 horizon from 1995 to 1996 (490 ± 80 mg m^{-2} versus 211 ± 45 mg m^{-2}), whereas invertebrate mass in the mineral soil did not change (F=0.02; df=1,30; P=0.89; 314 ± 45 mg m^{-2}) (Figure 2). Among the dominant invertebrate taxa, there was no change in the dry mass of mites (F=1.86; df=1,30; P=0.18), fly larvae (F=0.18; df=1,30; P=0.68), springtails (F=0.01; df=1,30; P=0.93), or a grouping of surface-active taxa composed of centipedes, spiders, and ants (F=0.56; df=1,30; P=0.46). Conversely, there was a significant (F=8.05; df=1,30; P=0.008) 58% reduction in the dry mass of beetle larvae (299 ± 52 versus 125 ± 29 mg m^{-2}), and a significant (F=6.34; df=1,30; P=0.02) reduction in the number of orders (8 ± 0.4 versus 6.5 ± 0.4 orders/ plot) after the fire.

There was no change in dry mass of earth-worms (F=0.22; df=1,10; P=0.65) and millipedes (F=1.04; df=1,10; P=0.33) on the loamy site. Average dry masses of earth-worms (mean ± SE=724 ± 421 mg m^{-2}) and millipedes (mean ± SE=63 ± 47 mg rri^{-2}) on the loamy site were similar to mean values that we recorded for high-quality habitats on lower and protected slopes in a region-wide survey of the Appalachian Mountains of Kentucky (P.J. Kalisz, unpubl. data).

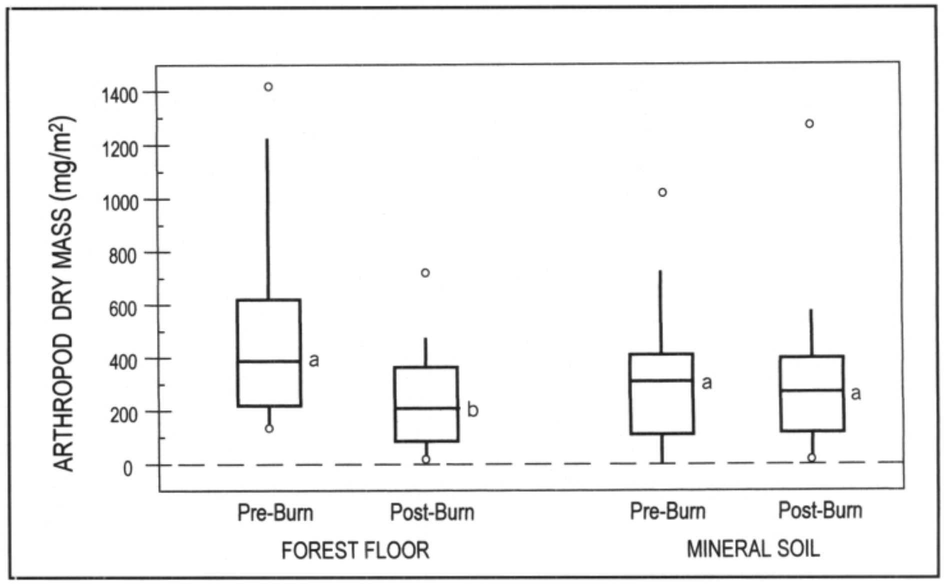

Figure 2. Box charts showing the distributions of arthropod dry mass in the forest floor and in the mineral soil less than one month before burning in 1995, and one year after burning, in 1996. The top, middle, and bottom horizontal lines of the box mark, respectively, the 75th, 50th, and 25th percentiles; the vertical lines point to the 90th and 10th percentiles; data points beyond the 90th and 10th percentiles a re shown with open circles. Different letters indicate a significant difference between pre-burn and post-burn dry masses.

Ten invertebrate orders (Pseudoscorpionida, Protura, Araneae, Lepidoptera, Diptera, Scolopendromorpha [centipedes], Lithobiomorpha [centipedes], Geophilomorpha [centipedes], Diplura, Diplopoda) that were common enough to statistically test did rot change in frequency of occurrence between 1995 and 1996. Mesofaunal ants (X^2= 8.43; P=0.004), macrofaunal beetle larvae (X^2=9.53; P=0.002), and beetle adults (X^2=5.84; P=0.02) were significantly less frequent after the fire. Symphyplecna, a suborder of springtails, on the other hand, was significantly (X^2=6.92; P=0.009) more frequent after the burn.

DISCUSSION

Effects of Prescribed Fire on Soil Invertebrates

Given the lack of trends on the reference plots, the 36% reduction in total dry mass of soil invertebrates recorded on the burn plots may be considered a result of the fire. Approximately 96% of the total loss of mass was due to significant reductions in mass of invertebrates in the forest floor, and approximately 60% was due to reductions in the mass of beetle larvae. Beetle dry mass, and the frequency of occurrence of beetle larvae and adults, were significantly lower after the fire. Substantial reductions in the abundance of beetles following moderate-intensity prescribed fires have also been recorded in boreal forests in Finland (Huhta et al. 1967), in pine forests on the Coastal Plain of the United States. (Buffington 1967), and in eucalypt forests in Australia (Majer 1984). The Elateridae comprises 73 genera and 885 species in the United States and Canada (Arnett 1993), and is the most widely distributed and abundant beetle family in forest soils (Bornebusch 1930). In our study, this family was found in 90% of all samples collected, and accounted for about 50% of the total beetle dry weight. In terms of the energetics of soil systems, the elaterids are notably important because of their exceptionally high energy turnover and diverse feeding habits (Eisenbeis and Wichard 1987: 340). Since elaterids occur primarily in the litter layer (Bornebusch 1930, Eisenbeis and Wichard 1987), they may be affected by even moderate and light prescribed fires, such as the fires used on our study area.

The importance of beetle larvae in soils on these ridgetops is increased by the fact that earthworms and millipedes, which are of-ten considered dominant soil animals of high-quality sites (e.g., Bornebusch 1930), are not common on dry, infertile, and coarse-textured forest soils. In our study area, these organisms were rare on the sandy sites but were relatively abundant on the loamy site where finer soil textures and impeded drainage improved the over-all soil quality.

We found no effect of fire on the dry mass of mites, the second-most important invertebrate taxon on our study sites. Fires adversely affect mites chiefly by eliminating fungal mycelia and by raising soil pH (Huhta et al. 1969). Blankenship and Arthur (1999a), working on the same plots used in our study, found no significant fire effect on active fungal biomass, and recorded a statistically significant but biologically insignificant pH increase of only 0.2 units in the O horizon 6 months after the fire.

We found no significant effect of prescribed fire on the dry mass of springtails, but did record an increase in the frequency of occurrence of the springtail suborder Symphypleona. The former result is in accordance with other studies that have recorded slight increases (Huhta et al. 1967, Majer 1984) or only brief decreases (Collett et al. 1993) in the abundance of springtails following prescribed fire. In part, the lack of effect may be due to the fact that < 10% of springtails inhabit the O horizon (Metz and Dindal 1975), the soil layer that is primarily affected by moderate-intensity burning. Furthermore, our own observations and unpublished data indicate that Neelidae and Sminthuridae, the two spring-tail families in the suborder Symphypleona, are more common and numerous in richer soils, such as those that occur on lower slopes and in coves. If these families are positively related to fertility, fire-induced improvements in soil fertility, such as the transient increase in available soil nitrogen recorded by Blankenship and Arthur (1999a) in our study areas, could explain why the Symphypleona were significantly more common after the pre-scribed fire.

Recommendations on the Use of Prescribed Fire

White pine invasion of ridgetops in the Red River Gorge seems to be a recent phenomenon stimulated by forest fragmentation and interference with the normal fire regime (Wehner 1991). As used on the study area, prescribed fire seems effective at controlling pine invasion and protecting, and potentially restoring, natural plant communities (Blankenship and Arthur 1999b). However, fire is a powerful tool that may have unexpected effects on non-target ecosystem components. Huhta et al. (1967) found that beetle populations were still depressed four years after burning, and they classified beetles into a grouping of soil invertebrates that "remain permanently at very low levels of density, few if any signs of recovery being observed" (Huhta et al. 1967: 123). Our study documented conditions one year after burning, and invertebrate community structure and composition will likely continue to change with time. Nevertheless, given the numerical and functional importance of beetle larvae in the soils of these ridgetop sites, managers need to consider the possibility that prescribed fire, especially if repeated at short intervals, may result in significant and possibly long-lasting reductions in beetle populations, and may therefore interfere with normal ecosystem processes such as decomposition arid nutrient-cycling.

Many researchers have recommended caution in the use of fire in order to prevent unwanted side-effects (e.g.., Neumann and Tolhurst 1991, Collett et al. 1993, Greenslade 1993). In the case of prescribed burning, application of the "precautionary principle" (Bodansky 1991) may be necessary since ecosystems are complex and interrelated, and many fire-effects may be unknown or have low predictability. The pre-cautionary principle states that, rather than waiting for certainty or high levels of statistical probability, managers should operate in anticipation of potential unwanted effects in order to minimize their severity. In the case of fire, one possible approach is to strive for spatial and temporal heterogeneity on multiple scales, leading to increased complexity after burning and increased probability that all biotic and abiotic components will survive within the postfire ecosystem. From the perspective of conservation of soil biota this is important since natural soils are characterized by a patchy distribution of resources that permits less-efficient and more-efficient species to coexist, leading to high diversity within soil communities (Lee 1994). To protect against management-induced habitat uniformity, Heyward (1936) recommended conservation of unburned patches of vegetation and litter as refugia on burned pine sites in the southeastern United States, and Niemela (1997) suggested that overall management plans for boreal forests be structured to promote maintenance of sufficient amounts of microhabitat or "micro-ecosystems" within the managed forest.

ACKNOWLEDGMENTS

We thank Pam Broadston, Amy Carrico, and Ann Jewell for help in the field and laboratory; Donnie Richardson and staff of the Stanton Ranger District, Daniel Boone National Forest, for general organizational support; Lee Townsend, Department of Entomology, University of Kentucky, for taxonomic assistance; and an anonymous reviewer for comments on the manuscript. This is a publication of the Kentucky Agricultural Experiment Station.

Paul Kalisz is a faculty member in the College of Agriculture with a research and teaching appointment in Forest Soils and Silviculture.

Janet Powell is a graduate student in the College of Social Work and an independent consultant in computer applications.

LITERATURE CITED

Abbott, I. 1984 . Changes in the abundance and activity of certain soil and litter fauna in the jarrah forest of Western Australia. Australian Journal of Soil Research 22:463-469.

Arnett, R.H., Jr. 1993. American Insects. The Sandhill Crane Press, Gainesville, Fla. 850 pp.

Avers, P.E., J.S. Austin, J.K. Long, P.M. Love, and C.W. Hail. 1974. Soil Survey of Menifee and Rowan Counties and Northwestern Morgan County, Kentucky. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C. 88 pp.

Blankenship, B.A. and M.A. Arthur. 1999a. Soil nutrient and microbial response to pre-scribed fire in an oak-pine ecosystem in eastern Kentucky. Pp. 39-47 *in* J.W. Stringer and D.L. Loftis, eds., Proceedings of the 12th Central Hardwoods Conference. General Technical Report SRS-24, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, N.C.

Blankenship, B.A. 1999b. Prescribed fire affects eastern white pine recruitment and survival on eastern Kentucky ridgetops. Southern Journal of Applied Forestry 23:144-150.

Bodansky, D. 1991. Scientific uncertainty and the precautionary principle. Environment 3:4-44.

Bornebusch, C.H. 1930. The fauna of forest soil. Det forstlige forsogsvaesen i Danmark XI:1-224.

Braun, E.L. 1950. Deciduous Forests of East-ern North America. Hafner, New York. 596 pp.

Buffington, J.D. 1967. Soil arthropod populations of the New Jersey Pine Barrens as affected by fire. Annals of the Entomological Society of America 60:530-535.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983a. Fire in Forestry. Volume I: Forest Fire Behavior and Effects. John Wiley and Sons, New York. 450 pp.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983b. Fire in Forestry. Volume II: Forest Fire Management and Organization. John Wiley and Sons, New York. 336 pp.

Chu, H.F. and L.K. Cutkomp. 1992. How to Know the Immature Insects. Second Ed. Wm. C. Brown Communications, Dubuque, Iowa. 346 pp.

Collett, N.G., F.G. Neumann, and K.G. Tolhurst. 1993. Effects of two short rotation prescribed fires in spring on surface-active arthropods and earthworms in dry sclerophyll eucalypt forests of west-central Victoria. Australian Forestry 56:49-60.

Crossley, D.A. and J.M. Blair. 1991. A high-efficiency, "low-technology" Tullgren-type extractor for soil microarthropods. Agriculture, Ecosystems and Environment 34:187-192.

Dindal, D.D. (ed.). 1990. Soil Biology Guide. John Wiley and Sons, New York. 1349 pp.

Edwards, C.A. 1967. Relationships between weights, volumes and numbers of soil animals. Pp. 585-594 *in* O. Graff and J.E. Satchell, eds., Progress in Soil Biology. North-Holland Publishing Company, Amsterdam, Netherlands.

Edwards, C.A. 1991. The assessment of populations of soil-inhabiting invertebrates. Agriculture, Ecosystems and Environment 34:145-176.

:Eisenbeis, G. and W. Wichard. 1987. Atlas on the Biology of Soil Arthropods. Springer-Verlag, Berlin. 428 pp.

Fenneman, N.M. 1938. Physiography of the Eastern United States. McGraw-Hill, New York. 714 pp.

Greenslade, P. 1993. Australian native steppe-type landscapes: neglected areas for invertebrate conservation in Australia. Pp. 51-73 *in:* K.J. Gaston, T.R. New, and M.J. Sam-ways, eds., Perspectives on Insect Conservation. Intercept, Ltd., Andover, UK.

Gunn, A. and J.M. Cherrett. 1993. The exploitation of food resources by soil meso- and macro invertebrates. Pedobiologia 37:303-320.

Hayes, R.A. 1993. Soil Survey of Powell and Wolfe Counties, Kentucky. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C. 173 pp.

Hermann, S.M., T. Van Hook, R.W. Flowers, L.A. Brennan, J.S. Glitzenstein, J.L. Walker, and R.L. Meyers. 1998. Fire and biodiversity: studies of vegetation and arthropods. Transactions North American Annual Wildlife and Natural Resources Conference 63:384-401.

Heyward, F. 1936. Some changes in the soil fauna associated with forest fires in the longleaf pine region. Ecology 17:659-666.

Hill, J.D. 1976. Climate of Kentucky. Progress Report 221, University of Kentucky Agri-cultural Experiment Station, Lexington. 88 pp.

Huhta, V., E. Karppinen, M. Nurminen, and A. Valpas. 1967. Effect of silvicultural practices upon arthropod, annelid and nematode populations in coniferous forest soil. Annales Zoologici Fennici 4:87-145.

Huhta, V., M. Nurminen, and A. Valpas. 1969. Further notes on the effect of silvicultural practices upon the fauna of coniferous forest soil. Annales Zoologici Fennici 6:327-334.

Lee, K.E. 1994. The biodiversity of soil organisms. Applied Soil Ecology 1:251-254.

Majer, J.D. 1984. Short-term responses of soil and litter invertebrates to a cool autumn burn in jarrah *(Eucalyptus marginata)* in Western Australia. Pedobiologia 26:229-247.

McCullough, D.G., R.A. Werner, and D. Neumann. 1998. Fire and insects in northern and boreal forest ecosystems of North America. Annual Review of Entomology 43:107-127.

McDowell, R.C., G.J. Grabowski Jr., and S.L. Moore. 1981. Geologic map of Kentucky. U.S. Geological Survey, Washington, D.C.

Metz, L.J. and D.L. Dindal. 1975. Collembola populations and prescribed burning. Environmental Entomology 4:583-587.

Neumann, F.G. and K. Tolhurst. 1991. Effects of fuel reduction burning on epigeal arthropods and earthworms in dry sclerophyll eucalypt forests of west-central Victoria. Australian Journal of Ecology 16:315-330.

Niemela, J. 1997. Invertebrates and boreal forest management. Conservation Biology 11:601-610.

Paquin, P. and D. Coderre. 1997. Deforestation and fire impact on edaphic insect larvae and other macroarthropods. Environmental Entomology 26:21-30.

Persson, T. and U. Lohm. 1977. Energetical significance of the annelids and arthropods in Swedish grassland soil. Ecological Bulletin No. 23, Natural Science Research Council, Stockholm, Sweden. 211 pp.

Preston, R.J., Jr. 1989. North American Trees. Fourth Ed. Iowa State University Press, Ames. 407 pp.

SPSS. 1997. SPSS Base 7.5 for Windows: User's Guide. SPSS, Inc., Chicago. 628 pp.

Stehr, F.W. (ed.). 1987. Immature Insects. Volume 1. Kendall/Hunt Publishing Company, Dubuque, Iowa. 754 pp.

Stehr, F.W. (ed.). 1991. Immature Insects. Volume 2. Kendall/Hunt Publishing Company, Dubuque, Iowa. 975 pp.

Wehner, R.R. 1991. The status of white pine *(Pinus strobus)* in the Clifty Wilderness, Kentucky. MS thesis, University of Kentucky, Department of Forestry, Lexington. 67 pp.