MONITORING TERRESTRIAL ECOSYSTEMS BY ANALYSIS OF NUTRIENT EXPORT

R. V. O'NEILL, B. S. AUSMUS, D. R. JACKSON, R. I. VAN HOOK, P. VAN VORIS, C. WASHBURNE, and A. P. WATSON*

Environmental Sciences Division, Oak Ridge National Laboratory (operated by Union Carbide the Energy Research and Development Administration), Oak Ridge, Tenn. 37830, U.S.A.

(Received 22 October, 1976; in revised form 3 January, 1976)

Abstract. Current methodology for environmental impact assessment relies heavily on population parameters to detect ecological effects of perturbation. We believe that recent advances in ecosystem analysis permit the identification of monitoring points that reflect changes in the total system. Focusing on mechanisms of ecosystem homeostasis, we suggest soil nutrient loss as a sensitive, holistic measure of ecological effects. In three separate studies, attempts were made to detect the effects of toxic substances by monitoring relevant population parameters. In each case, disturbance could be detected in nutrient cycling, but no significant change was evident in the population/community parameters. These results indicate that indices of total ecosystem function may be feasible.

1. Introduction

Assessment of the environmental impact of human activities has become an increasingly important responsibility of society. Current methodology for impact assessment relies heavily on population parameters to detect significant ecological effects (Christensen *et al.*, 1977; Council on Environmental Quality, 1973). However, changes in population size or species composition may not disrupt ecosystem maintenance and persistence in the face of normal environmental fluctuations. While some more holistic parameter might be desirable (Barrett *et al.*, 1976), the state of the art of ecosystem analysis has precluded such an approach. Indeed, some authors have concluded that no practical measure of total ecosystem performance is likely to be found (May, 1975; Levin, 1975).

Recent advances in experimental (Borman and Likens, 1967; Harris *et al.*, 1973), analytical (Odum, 1969), and theoretical (Holling, 1973; Waide *et al.*, 1974; O'Neill *et al.*, 1975) studies of ecosystems permit a new perspective. These studies treat the ecosystem as an integrative system with homeostasis achieved through interactions among functional groups of organisms and abiotic components. For example, nutrient cycling results from the functional synchrony of autotrophs, heterotrophs, and soil organic matter (Harris *et al.*, 1973; Ausmus *et al.*, 1977). By focusing on such mechanisms it may now be possible to identify monitoring points that reflect changes in the total ecosystem.

A natural candidate for terrestrial monitoring would be the rate at which nutrients are leached from the soil. Because of the large number of interacting components, detrimental increases in nutrient loss might be detected irrespective of which specific

* Order of authorship does not connote relative contribution because this paper is the result of an integrated team effort.

Water, Air, and Soil Pollution **8** (1977) 271–277.

organisms or processes were being affected. In some cases, it may not be possible to predict the exact mode of action of a new pollutant. In other cases, it may be difficult or impossible to measure the direct effect on specific organisms or processes. Thus, physiological changes might affect the rates and timing of processes without measurable increase in population mortality. Control theory studies on forest element cycles (Shugart *et al.,* 1976) have also suggested nutrients in soil solution to be an optional monitoring point.

TABLE I

Experimental designs and parameters for three test systems of various sizes and complexity

Experimental unit				
Complexity	Size	Perturbation	Population parameters	System parameters
Soil core, no autotroph	20 cm^3	As	Soil microbe density, activity	Nutrients in leachate
Excised soil block *Acer rubrum*	0.06 m^3	Primary Pb smelter emissions	Aboveground autotrophic growth	Nutrients in leachate
Forested watershed	466 ha	Primary Pb smelter emissions [a]	Litter arthropod community diversity and biomass	Litter nutrient and mass pools

[a] Includes Cd, Cu, Pb, and Zn.

The present paper extracts data from three studies on the effects of toxic substances on different systems (Table I). The studies differed in primary objectives and were not specifically designed for the present analysis and, therefore, the results will be fully reported elsewhere. We report only sufficient data to illustrate one point: in all three studies, significant increases in nutrient loss could be detected even though there were no measurable changes in the population/community parameters chosen for the study.

2. Experimental Results

In the first experiment, soil cores (5 cm diameter and 5 cm depth) were excised from a mesic hardwood forest and a managed fescue pasture. The vegetation was removed and the cores were sealed in shrinkable polyvinyl chloride tubing, mounted in a funnel-test-tube assembly and maintained in an environmental chamber at field temperatures (13 to 16°C diurnally). Aqueous Na_2HAsO_4 was applied to the surface of treatment cores. The microcosms in this experiment had the smallest unit size, no autotrophs, and the most complete spectrum of population/community and ecosystem parameters measured.

Time-zero population parameters were determined with replicate cores. Analyses included: enzyme titer (urease, invertase, dehydrogenase, cellulase, amylase); bacterial density (dilution plate count); fungal biomass (Jones-Mollison slides); ATP concentration (chloroform extraction and analysis using the Calbiochem ATP stat Pak). Three replicates of each soil type were treated with 0, and 100 mg cm^{-2} As as $NaAsO_3$. Carbon dioxide efflux and nutrient leachate were monitored throughout a six-week experiment with water (added at seasonal rainfall averages) applied twice weekly. Mass balance of As was determined from leachate and soil subsamples at final harvest.

At the end of the six-week experiment, no significant differences were detected in the population parameters, as can be seen from the data in Table II. While the parameters given do not monitor a single population, they are indicators of the activity of a single functional group, the microbial decomposers. A significant ($P \leqslant 0.05$) increase was determined for the concentration of nutrients leached from the soil cores (e.g., Ca and NO_3–N as illustrated in Table II). Thus, an effect was detected in the system-level parameter, but not in the array of soil organism measurements.

TABLE II

Population and system level parameters measured in soil core microcosms treated with 100 ppm Na_2HAsO_4. (Values represent means ± S.E.)

Treatment	Population parameter		System parameter	
			Nutrient leached	
Level (mg cm^{-2})	ATP concentration[a] (μg g^{-1} soil)	Bacterial density (10^6 g^{-1} soil)	Ca (μg ml^{-1})	NO_3–N (μg ml^{-1})
0	1.58 ± 0.33	0.50 ± 0.11	20.3 ± 1.7	32.4 ± 4.8
100	1.52 ± 0.30	0.63 ± 0.18	29.4 ± 2.9	132.2 ± 26.0

[a] Chloroform extract stabilized in sodium bicarbonate buffer at pH = 7.2; analyzed using reaction of glucose with ATP in presence of hexokinase, measured spectrophotometrically at 340 nm.
[b] Standard dilution plating technique, 1 : 50 000 dilution.
[c] Measured in leachate from soil core following water addition; analyses for Ca by atomic absorption, for P by autotechnicon.

The second microcosm experiment had a larger unit size and included an autotrophic component. The design consisted of six boxes of intact Emory silt loam soil, each containing one red maple (*Acer rubrum*) sapling approximately 2 m high, with associated herbaceous ground cover. The soil blocks were excised with minimum disturbance from a stand of *Liriodendron tulipifera*. Each block was sealed in a wooden box and transported to a greenhouse where it remained for the duration of the experiment. Litter layers were removed and weighed. The original litter was replaced on three control microcosms. The three treated microcosms received equivalent weights of litter collected from a site 0.4 km downwind from a primary lead smelter (Watson *et al.*, 1976). The contaminated microcosms were also given weekly additions of particulate smelter emissions over a 12-week period. The total dose was 11 mg cm^{-2} of Pb with lesser amounts of Cu, Cd, and Zn. This is approximately one year's deposition (Jackson and Watson, 1977). Soil leachates were filtered through Whatman No. 40 paper and analyzed for heavy metals, Ca, Mg, and K.

After nine months of monitoring, no significant difference between controls and treatments could be detected in aboveground autotrophic growth measured as the sum of branch growth from the previous year's bud scale scars (Table III). However, mean values for Ca concentration in soil leachate were significantly higher ($P \leqslant 0.05$) for the treated systems. Nitrate concentration appears to be elevated (Table III) but it is not possible to demonstrate a statistical difference because of the small sample size and large variances. Because the experimental treatment was initiated following bud break, it is not anticipated that significant changes in tree growth will be detected until next year, since most of the nutrients required for new growth are taken up before bud burst. The experiment is being continued to determine the effect of nutrient loss on the subsequent year's growth, but the relevant point for this analysis is that a significant effect on nutrient leaching is already evident and measurable.

TABLE III

Population and system level parameters from microcosms of Emory silt loam soil containing *Acer rubrum* seedlings. (Values represent means ± S.E.)

Treatment	Population parameter	System parameter	
Smelter emissions (Pb mg cm^{-2})	Annual branch growth (cm)	Leachate concentration (mg ml^{-1}) Ca	NO_3–N
0	347 ± 42.8	6.6 ± 0.4	1.4 ± 1.39
11	346 ± 67.7	10.0 ± 0.8	11.0 ± 10.9

Because the experimental manipulation in both of these experiments involved the application of chemical toxicants, the results might be explainable by simple exchange processes in the soil. However, the data do not support this interpretation. Chemical exchange processes would be expected to begin immediately, yet there was a time delay of greater than a week before some elements began to be lost. Treated microcosms continue to lose nutrients long after exchange processes would be completed. It is also significant that N is leached in greater amounts than controls, even though it is largely immobilized in the organic components of the system and unavailable for chemical exchange. Finally, higher rates of CO_2 efflux were measured at the soil surface of treated microcosms, indicating that biological responses were indeed occurring.

Results from plot samples on a smelter-impacted watershed expand the analysis to a large spatial scale and natural field conditions. A one-year project was initiated in March 1974 to examine heavy metal impact on the litter component of Crooked Creek Watershed (CCW). A primary Pb smelter is located at the apex of the triangular watershed. Based on yearly averages of wind speed and direction, sampling stations with very similar overstory vegetation and soil types were established at 0.4 km intervals along a transect running northwest from the smelter stack (Watson *et al.*, 1976). Four, 0.1 m^2 replicates of litter were collected seasonally. Following Berlese-von Tullgren extraction of arthropods, litter was oven-dried to constant weight at 100°C. Replicate determinations were pooled to calculate litter standing crop as a function of distance from the stack.

Arthropod diversity (Table IV) does not indicate a significant ($P \leqslant 0.05$) effect at a site 2 km from the smelter when compared to a 21 km control site. However, system level effects are significant ($P \leqslant 0.05$), as illustrated by litter mass and nutrient pools in litter. While the measurement of the Mg pool immobilized in litter is not a measure of nutrient loss, it does indicate a disturbance to the recycling process which is detectable 2 km from the smelter. Differences in vegetation and soil (Watson *et al.*, 1976) between control and 2 km sites cannot account for the difference in litter mass, therefore, the increase pool size must be due to a reduction in decomposition rates. At sampling sites closer to the smelter, there is direct evidence of nutrient loss as well as evidence of the expected trend toward lower arthropod diversity as well as reduced biomass and density (Watson *et al.*, 1976).

TABLE IV

Population and system parameters measured in 02 litter on Crooked Creek Watershed at 2.0 and 21 (control) km from a Pb smelter in southeastern Missouri

		System parameters	
Distance from smelter (km)	Population parameter Litter invertebrate diversity[a]	Litter mass (g m^{-2})	Mg pool in litter (g m^{-2})
2.0	2.5 ± 0.23	1595 ± 171	1.9 ± 0.3
21.0 (Control)	2.3 ± 0.15	1008 ± 110	1.1 ± 0.2

[a] Shannon Index of general diversity

$$\left(H = -\sum_{i=1}^{s} \rho_i \ln \rho_i\right).$$

Error term is standard deviation.

Thus, in three independent studies, disturbances were detected in nutrient cycling, but not in the population/community parameters selected by the investigators. This, of course, does not prove that sensitive population parameters do not exist. However, it is not immediately apparent which parameters could have been chosen. Furthermore, changes in specific populations might imply very little about overall effects on the total ecosystem.

3. Discussion

Advances in the state of the art of ecosystem analysis led to a theoretical deduction about the existence and sensitivity of ecosystem homeostatic mechanisms. The experimental studies cited above lend credence to this deduction, since disturbances could be detected in nutrient cycling even though no effects were measured in the population/community parameters chosen for study.

The definitive test of the concept would be a long-term experiment that: (1) initially, showed only system-level effects; (2) subsequently (or at higher doses), showed both system and population effects; (3) eventually, showed disruption of the total ecosystem.

The experiments presented above relate primarily to the first criterion. Support for the second criterion can be obtained from the contaminated watershed in the third study. At 0.4 km from the smelter was a sampling site subjected to much higher doses than the 2 km site in Table IV. With higher doses, disruptions were measurable in nutrient cycling and also in population parameters (i.e., arthropod biomass, density and diversity, Watson *et al.*, 1976; Jackson and Watson, 1977). At present, only indirect evidence can be offered for the third criterion. Terrestrial ecosystems, such as forests, must recycle 50 to 95% of their annual requirement of critical nutrients such as nitrogen (Odum and Pigeon, 1970; Reichle *et al.*, 1973; Stark, 1973). Accelerated loss or immobilization of the soil nutrient pool must eventually have a direct effect on the productivity of the entire ecosystem, even though the effect might not be measurable for a number of years.

Although current evidence will require considerable confirmatory experimentation, the implications of these findings for environmental monitoring are already evident. The identification of a measurable ecosystem parameter would permit a new approach to impact assessment of terrestrial ecosystem. The possibility of an early-warning system indicates the importance of further study on the sensitivity of ecosystem parameters.

Of particular interest is the success in using microcosm systems to detect system-level effects. In the experiments described above, the microcosms displayed the same qualitative behavior as the watershed system. Excised portions of ecosystems have intrinsic problems due to small size and limited persistence. But if the limitations are considered carefully in experimental design, microcosms may prove to be feasible test systems for exploring hypotheses concerning ecosystem function and homeostasis.

Perhaps the most tantalizing aspect of these studies concerns the mechanisms resulting in nutrient leakage. In some cases, the effect may be due largely to the disruption of physical-chemical mechanisms in the soil. In other cases, the effects may be on the metabolism of biotic components of the system, resulting in physiological changes which have not yet been manifested in significant mortality. However, it is important to emphasize that elucidation of the mechanisms is independent of the implications of the phenomenon. The existence of measurable system-level parameters seems to be confirmed, whatever the responsible mechanisms.

Acknowledgments

Research supported in part by the U.S. Environmental Protection Agency (IAG-DS-0713) and in part by the National Science Foundation's Ecosystem Analysis (AG-199) and RANN (AEN-72-01243A03) Programs through interagency agreements with the Energy Research and Development Administration under contract with Union Carbide Corporation. Contribution No. 276, Eastern Deciduous Forest Biome; Publication No. 981, Environmental Sciences Division, ORNL.

References

Ausmus, B. S., Edwards, N. T. and Witkamp, M.: 1977, in A. MacFadyen and J. M. Anderson (eds.), *Proceedings of the British Ecological Society Symposium on Decomposition*. Blackwell Scientific Press, Oxford, in press.

Barrett, G. W., Van Dyne, G. M., and Odum, E. P.: 1976, *Bioscience* **26**, 192.

Bormann, F. H. and Likens, G. E.: 1967, *Science* **155**, 424.

Christensen, S. W., Van Winkle, W., and Mattice, J. S.: 1977, in R. K. Sharma, J. D. Buffington, and J. T. McFadden (eds.), *The biological significance of environmental impacts*. Energy Research and Development Administration, Washington, D.C., in press.

Council on Environmental Quality: 1973, Preparation of environmental impact statement: Guidelines 38, *Federal Register*, pp. 20550–20562.

Harris, W. F., Goldstein, R. A., and Henderson, G. S.: 1973, in *Proceedings of working party on forest biomass of IUFRO*, H. Young (ed), Analysis of forest biomass pools, annual primary production and turnover of biomass for a mixed deciduous forest watershed. pp. 41–64. Univ. Main Press, Orono, Maine.

Holling, C. S.: 1973, *Ann. Rev. Ecol. Syst.* **4**, 1.

Jackson, D. R. and Watson, A. P.: 1977, *J. Environmental Quality*, in press.

Levin, S. A. (ed.): 1975, *Ecosystem analysis and prediction*, SIAM Press, Philadelphia, Pa., p. 129.

May, R. M.: 1975, in *Unifying concepts in ecology*, W. H. Van Dobben and R. H. Lowe-McConnell (eds.), Stability in Ecosystems: Some comments, pp. 161–168. Dr. W. Junk b.v. Publishers, The Hague.

Odum, E. P.: 1969, *Science* **164**, 262.

Odum, H. T. and Pigeon, R. F.: 1970, *A Tropical Rain Forest*, USAEC, Division of Technical Information, Washington, D.C. 1650 pp.

O'Neill, R. V., Harris, W. F., Ausmus, B. S., and Reichle, D. E.: 1975, in *Mineral Cycling in Southeastern Ecosystems*, F. G Howell, J. B. Gentry, and M. H. Smith (eds.), ERDA Symposium Series, CONF-740513, Washington, D.C., p. 28.

Reichle, D. E., O'Neill, R. V., and Olson, J. S. (eds.): 1973, *Modeling Forest Ecosystems*, EDFB-IBP 73–7, Oak Ridge National Laboratory, Oak Ridge, TN. 339 pp.

Shugart, H. H., Reichle, D. E., Edwards, N. T., and Kercher, J. R.: 1976, *Ecology* **57**, 99.

Stark, N.: 1973, *Nutrient Cycling in a Jeffrey Pine Ecosystem*, Institute for Microbiology, University of Montana, Missoula, Montana. 389 pp.

Waide, J. B., Krebs, J. E., Clarkson, S. P., and Setzler, E. M.: 1974, *Progress in Theoretical Biology*, Vol. 3, Academic Press, N.Y. p. 261.

Watson, A. P., Van Hook, R. I., Jackson, D. R., and Reichle, D. E.: 1976, Impact of a lead mining–smelting complex on the forest-floor litter arthropod fauna in the New Lead Belt region of Southeast Missouri. ORNL/NSF/EATC-30, Oak Ridge National Laboratory, Oak Ridge, TN. 163 pp.