Adding Phosphorus to Forest Soils: Storage Capacity and Possible Risks

by ROBERT F. POWERS
Pacific Southwest Forest and Range Experiment Station,
U.S.D.A. Forest Service
Berkeley, Calif.
KÂNI IŞIK
Department of Biology
Hacettepe University
Ankara, Turkey
and
PAUL J. ZINKE
Department of Forestry
University of California
Berkeley, Calif.

Lake pollution through the indiscriminate loading of phosphorus in the soil of forest watersheds is becoming a matter of concern today. Phosphorus, scarce because of its low solubility and in constant demand by aquatic organisms, has the broadest potential of any nutrient to alter the biologic balance of lake waters (HUTCHINSON, 1957). When phosphorus is added to lake water low in nutrients, dominance by undesirable species, such as blue-green algae, may result (LOUCKS, 1972; SCHINDLER, 1974).

Economic and social pressures toward measures that may load forest soils with phosphorus are increasing, however. Although forest fertilization is in its infancy in the western United States, and nitrogen is presently used almost exclusively, our studies suggest that trees on certain forest soils respond strongly to higher levels of fertilizer P (POWERS, 1974). And since current projections show a widening gap between demand and supply of softwood products, forest fertilization may soon become a profitable practice (USDA FOREST SERV., 1972).

A second source of P input is tied to the heavy influx of recreationists to mountain areas where sewage disposal is becoming a major problem. Discharging sewage effluent high in P and N directly into waterways following secondary treatment carries heavy environmental risks. But tertiary treatment plants are costly, and rarely do they exist in rural communities. Alternatively, forests have been proposed as repositories of sewage wastes (PENNYPACKER et al., 1967; STATE OF CALIF., 1971).

Forests seem to be ideal sinks for high inputs of mineral matter, particularly P. The cycling power and perennial nature of forest vegetation tends to redistribute elements throughout the entire system, thus reducing their accumulation in any single system phase. In addition, acid forest soils effectively sorb large amounts of P into sparingly-soluble compounds of Al, Fe, and Mn, and possibly into the structural matrices of silicate clays. Tracer studies on Aiken-like soils (red acidic clay loams high in Al and Fe) have shown that 85 percent of surface-applied superphosphate with P at 1,136 kg/ha was held in the top 15 cm of soil (ULRICH et al., 1947). And more than 90 percent of PO_4 applied in solution at 35 ppm on granite alluvium to the point of water saturation was held in the top 30 cm of a soil near Lake Tahoe, California (FOSTER et al., 1965). But when is a soil overloaded with P? And what may be the consequences of loading it?

Bulletin of Environmental Contamination & Toxicology,
Vol. 14, No. 3 © 1975 by Springer-Verlag New York Inc.

We assumed that the P sorption capacity of a soil is not infinite, but varies with minerology, texture, pH, organic content, and cation composition. A simple means of integrating these complex variables is needed that quantifies the amount of P that can be sorbed by a given soil to the point of overloading. We reasoned that since the water-soluble fraction of soil P (a) expresses directly the integrated variables controlling P solubility, (b) is easily measured with equipment found in most analytic laboratories, and (c) is the P fraction transported from a terrestrial system in drainage, this would be the form of P that we should study.

This paper reports a method useful as a first approximation in determining the status of soil P and its overloading point, and raises certain points relevant to the enrichment of forest ecosystems with P.

METHODS

To illustrate our method we chose two upland soils typical of much of California's mixed-conifer zone (ROY AND MCDONALD, 1973), but contrasting in major characteristics from each other (Table 1). The first, a Cohasset soil series, was drawn from Placer County and derived from basic igneous rock. Cohasset soils are deep, fine-textured Alfisols (SOIL SURVEY STAFF, 1960) with high capacities for timber production, moisture retention, and P sorption. The second soil was a shallow-phase Sheetiron series formed from Colusa County Schist. Sheetiron soils are medium-textured Inceptisols of low productivity and moisture retention, and rank somewhere below Cohasset soils in P-sorbing capacity.

Bulk samples were drawn from the 0-40 cm depth at several points on each area, screened to 6.4 mm (1/4-inch), and composited by series in a twin-shell soil blender. (In practice, volume samples would be drawn and composited.) Subsamples were tested for pH by the saturation paste method and for moisture retention at 1/3 atmosphere by using a pressure membrane apparatus.

Series were divided into air-dry subsamples equivalent to a 100-gm ovendry weight and were placed in containers fitted with polyethylene liners. Commercial 20-percent single superphosphate ($CaH_4(PO_4)_2$) (containing about 12-percent S) was added in increasing amounts to successive samples (Table 2). Each sample received 10 mg N as NH_4NO_3 to stimulate microbial activity. Soils and fertilizers were mixed thoroughly, and distilled water was added to raise moisture near 1/3 atmospheres of tension (field capacity) by weight change. Containers were sealed and left to equilibrate at room temperature for one week.

At the end of one week soils were air-dried, mortered, and their 2-mm fractions separated. Subsamples were oven-dried for determining moisture content. Water-soluble P was extracted from each sample using the Bingham (1949) method. Extracts were analyzed by molybdate-blue colorimetry. Results were converted to ppm P on a dry-weight basis.

TABLE 1

Properties of Cohasset and Sheetiron soil series in California

Soil attribute	Properties of the series*		Properties of the samples	
	Cohasset	Sheetiron	Cohasset	Sheetiron
Parent material	Basic igneous	Schist	Basic igneous	Schist
Texture	Loam	Gravelly loam	Loam	Gravelly loam
Timber productivity	High	Low	35.0†	20.7
Characteristics of surface horizons:				
CEC (meq/100 gms)	16-33	7-24	20.6	12.0
Base saturation (%)	30-73	30-60	34.0	52.3
pH	5.0-6.7	5.1-6.1	5.9	5.7
H_2O-soluble P (ppm)	0.02-0.08	0.06-1.40	0.04	0.28
H_2O at 1/3 atmos. (%)	22-43	24-38	42	22

* Personal communication with Wilmer L. Colwell, Jr., Project Leader, California Cooperative Soil-Vegetation Survey, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

† Heights of dominant trees (m) at 50 years, breast-height age.

TABLE 2

Phosphorus treatment levels and P solubility changes for Cohasset and Sheetiron soil samples

P added per kg of soil ...*			Water soluble P at equilibrium	
as 20-percent superphosphate	as P_2O_5	as P	Cohasset	Sheetiron
gms			ppm	
0.0	0.0	0.00	0.04	0.28
0.5	0.1	0.04	0.04	0.28
1.0	0.2	0.09	0.08	0.31
2.0	0.4	0.17	0.12	0.94
4.0	0.8	0.35	0.12	1.66
8.0	1.6	0.70	0.19	7.44
12.5	2.5	1.09	2.40	--†
16.0	3.2	1.40	0.80	21.12
20.0	4.0	1.75	7.36	--
40.0	8.0	3.50	32.15	--
60.0	12.0	5.24	35.42	--
90.0	18.0	7.87	43.51	--

* For our demonstration purposes we assume a fertilizer P_2O_5 content of 20 percent. If greater precision is required, the actual P_2O_5 content must be determined quantitatively.

† Not determined in the experiment.

RESULTS

Initial levels of water-soluble P were 0.04 ppm for the Cohasset samples, and 0.28 ppm for the Sheetiron samples. They fell within the ranges found for each soil throughout California (Table 1). A plot in which P solubility was compared to treatment load showed that the Cohasset series fine fraction had both a greater sorption capacity and a greater storage potential--the point where the calibration curve breaks sharply--than did the Sheetiron series (Fig. 1). Solubility of P did not increase appreciably until about 0.15 gms of P per kg had been added to the Sheetiron soil and 0.80 gms/kg to the Cohasset. Incubating the same samples for an additional four weeks did not increase P retention.

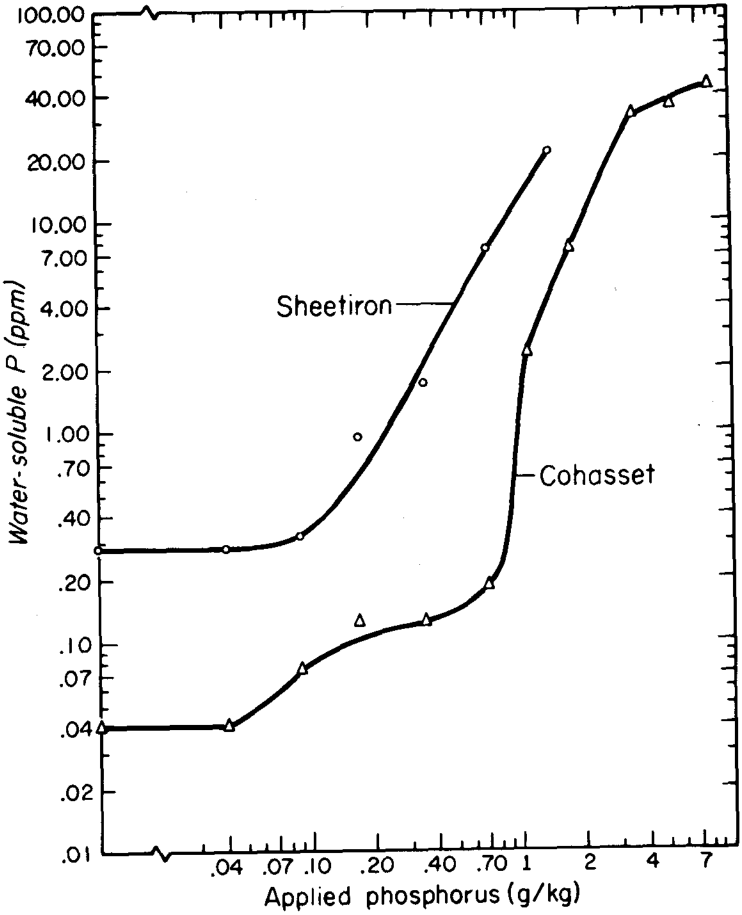

Figure 1.--Phosphate solubility as a function of phosphorus added to two forest soils. The axes are scaled logarithmically.

DISCUSSION

Estimating the Storage Capacity

The five-fold difference in P storage capacity between the two soil series fine fractions understates the real storage difference. Since the Sheetiron series is shallower and has about half the water holding capacity of the Cohasset soil, a given volume of phosphate solution saturating the Sheetiron soil and causing leaching of excess P would wet the Cohasset soil only moderately.

We concluded that the method described above provides a practical way of approximating the P storage capacity of a particular soil. Furthermore, it seems simpler than existing methods employing sorption isotherms (FOX and KAMPRATH, 1970; GARDNER and JONES, 1973) and may relate better to actual field conditions. Gardner and Jones (1973) have shown that P sorption increases as temperature increases. As a refinement, therefore, we recommend that temperatures during equilibration be maintained near the average temperatures found for specific soils in nature. Mean annual temperature at 50 cm depth is one of the standards for classifying soils under the current U.S. system (USDA SOIL CONSERV., 1970), and this temperature standard can serve as a guide for assigning equilibration temperatures. For example, both Cohasset and Sheetiron series are of the mesic family of soils, and in practice should be equilibrated at 8°C, the lower limit for their family (SOIL SURVEY STAFF, 1960). Resting a soil after sorption saturation allows a recovery of at least some of its original capacity (ELLIS, 1973), and higher temperatures would increase sorption rates (GARDNER and JONES, 1973). Consequently, our method provides a conservative test of P sorption capacity.

To use the method,

1. Identify the soil series or soil types involved and measure the surface area of the prospective treatment site.
2. Draw volume samples of known surface area to a soil depth where vertical water percolation seems impeded by hardpan, bedrock, gravel aquifers, etc. Sampling every $3\frac{1}{2}$ m provides a reasonable intensity (HEILMAN, 1971), but may be impractical for a large-scale project. The precision of the estimate--hence, the intensity of sampling--depends ultimately on project objectives.
3. Composite the volume samples and screen them to 6.4 mm (1/4-inch). Weigh and subsample to obtain ovendry weight. Calculate the mean weight of a soil column of known surface area that extends to the depth of effective water penetration.
4. Prepare an increasing P-series as outlined under Methods. Add water to bring each sample close to field capacity, and equilibrate at the appropriate temperature for one week. Determine the level of water-soluble P by the Bingham (1949) method.
5. Determine the point of P saturation graphically (Fig. 1) as the point where the calibration curve breaks sharply.

The amount of P that can be added to reach saturation is calculated as:

$$P_A = \frac{(P_s)\ (W)\ (A)}{10^3} \quad (1-R)$$

in which

P_A = the amount of P that can be applied to a treatment area in kg

P_s = the gms of P/kg of 6.4-mm fraction soil needed to reach saturation

W = the calculated mean weight in kg of a column of soil with a surface area one m^2, screened to 6.4 mm and extending to the depth of effective water penetration

A = the total surface area of the treatment site in m^2

R = the estimated proportion of rock volume (from exposed profiles, where "rocks" are any objects too large to be included in the volume sampling device).

For a hypothetical example, assume that a 2,000-m^2 area (A) of the Sheetiron series studied here with rock proportion of 0.2 (R) is being considered for an effluent treatment site. Extracting, screening, and weighing 150 volume samples, each representing a 5-cm^2 surface area, shows that the mean weight (W) of a column of soil extending to bedrock is 500 gms, or 10^3 kg/m^2. Assuming the samples had been equilibrated at 8°C, the amount of P that can be applied to the area to just reach saturation is:

$$P_A = \frac{(0.15)\ (10^3)\ (2 \times 10^3)}{10^3} \quad (1-0.2) \quad = \quad 240 \text{ kg P}$$

Thus, fertilizer P could be added periodically to a total of 1,200 kg/ha before significant increases of P should occur in the soil solution. Regarding sewage effluent, and assuming an effluent concentration of 6 ppm inorganic P--an average value for sewage in the Tahoe Basin after secondary treatment (MCGAUHEY et al., 1963), some 4×10^7 liters of effluent (20×10^4 m^3/ha) could be applied in small units before the P sorption capacity is exceeded. Such a soil, then, has a very high capacity for storing P. In time, enough information should accrue on individual soil series to allow land managers to estimate the P reserve capacity based on the current status of water-soluble P.

Risks

Application rates for aqueous materials containing P must be low enough to preclude soil clogging and surface flow, and ensure good infiltration and percolation. Thus, frozen soils and those near field capacity should be avoided. Prolonged saturation risks the conversion of ferric phosphates to more soluble ferrous forms through metabolic reduction by anaerobic bacteria (PATRICK et al., 1973). Suspended organic chelates in effluent can react with Al and Fe, thus, increasing P solubility, and should vary with the efficiency of secondary sewage treatment. Thus, our method may not be valid for sewage receiving primary treatment only. In addition, the long-term effects of sewage on soil pH are largely unknown. Since rising pH would increase the solubility of Al and Fe phosphates, soil reaction should be monitored closely. Rising pH can be a major problem if calcium phosphate fertilizers are used at heavy rates.

Beyond the problem of P mobility in the soil solution is the effect of high soil P on natural vegetation. The concentration of water-soluble P in surface horizons of the coniferous forest soils of California averages about 0.3 ppm (COLWELL, 1960) and does not seem to range much beyond 3 ppm. Increasing P solubility past this level carries an unknown risk of inducing secondary deficiencies of Cu and Zn through interaction of P with these nutrients. Serious P-micronutrient interactions have been reported by many workers for agronomic crops on acid soils (BINGHAM, 1966) and in some cases, micronutrient toxicities have developed (WALLACE et al., 1974). We have noted that growth of seedlings of Abies concolor (Gord & Glend.) Lindl. and Pinus ponderosa (Laws.) is depressed when the level of soil P approaches saturation (POWERS, 1974). In addition, effects of heavy metals often found in sewage wastes on the metabolism of forest vegetation are not known fully. As Rolfe (1973) has shown in studies of lead, high levels of P may precipitate certain heavy cations, thus reducing their absorption by plants and their transfer in the food chain to higher animals. But a strong case exists for natural or introduced organic chelators raising solution concentrations of heavy metal ions several-fold (ELLIS, 1973).

Clearly, research must be directed to all trophic levels in studying the circulation of minerals and matter in forest ecosystems. As an interim guide, we urge caution in fertilizing forest soils, such as the Sheetiron series, that are already near P-saturation capacity. And though our test did not include sewage effluent, we recommend choosing effluent treatment sites on moderately-deep, well-drained soils where the vegetation has low commercial value and low palatability to wildlife, and where loss of vegetative cover would not create an erosion hazard.

Bibliography

BINGHAM, F. T.: Calif. Agr. 3, 11 (1949).

BINGHAM, F. T.: In: H. D. Chapman (ed.). Diagnostic Criteria for Plants and Soils. Univ. Calif. Div. Agr. Sci., 324 (1966).

COLWELL, W. L., JR.: Abstr. West. Soc. Soil Sci. Pac. Div. AAAS, Univ. Oreg., Eugene. 15 (1960)

ELLIS, B. G.: In: W. E. Sopper and L. T. Kardos (eds.). Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. Penn. State Univ. Press, Univ. Park. 46 (1973).

FOSTER, H. B., JR., P. C. WARD, and A. A. PRUCHA: J. Sanit. Engin. Div., Proc. Amer. Soc. Civil Engin. 91, 1 (1965).

FOX, R. L., and E. J. KAMPRATH: Soil Sci. Soc. Amer. Proc. 34, 902 (1970).

GARDNER, B. R., and J. **P. JONES: Comm. Soil Sci. Plant Analy.** 4, 83 (1973).

HEILMAN, P.: Coop. Ext. Serv., Coll. Agr., Wash. State Univ. EM3549. 14 pp (1971).

HUTCHINSON, G. E.: A Treatise on Limnology. Vol. I. John Wiley and Sons, New York, 1015 pp (1957).

LOUCKS, O. L.: In: J. A. Behnke (ed.). Challenging Biological Problems. Oxford Univ. Press, New York, 297 (1972).

MCGAUHEY, P. H., R. ELIASSEN, G. ROHLICH, H. F. LUDWIG, and E. A. PEARSON: Engin.-Sci., Inc., San Francisco, Ca. 157 pp (1963).

PATRICK, W. H., JR., S. GOTOH, and B. G. WILLIAMS: Sci. 179, 564-565 (1973).

PENNYPACKER, S. P., W. E. SOPPER, and L. T. KARDOS: J. Water Pollut. Cont. Fed.,285 (1967).

POWERS, R. F.: Proc. Servicewide Silvic. Work Conf., USDA Forest Serv., Wash., D.C., 124 (1974).

ROLFE, G. L.: J. Environ. Qual. 2, 153 (1973).

ROY, D. F., and P. M. MCDONALD: In: Silvicultural Systems for the Major Forest Types of the United States. USDA Agr. Hndb. 445, 28 (1973).

SCHINDLER, D. W.: Sci. 184, 897 (1974).

SOIL SURVEY STAFF: Soil Classification, a Comprehensive System, 7th Approximation. USDA Soil Conserv. Serv. 265 pp (1960).

STATE OF CALIFORNIA: Sewage disposal in mountain areas. A summary report. State Calif., Dep. Pub. Health, Bur. Sanit. Engin. 11 pp (1971).

ULRICH, A., L. JACOBSON, and R. OVERSTREET: Soil Sci. 64, 17 (1947)

U.S.D.A. FOREST SERVICE: Current Info. Rept. 8, Wash., D. C. 17 pp (1972).

U.S.D.A. SOIL CONSERVATION SERVICE: Soil Taxonomy of the National Cooperative Soil Survey, ch. 3. Wash., D. C. (1970).

WALLACE, A., A. A. ELGAZZAR, J. W. CHA, and G. V. ALEXANDER: Soil Sci. 117, 347 (1974).