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SOIL MICROBES

Walter B. Bollen

ABSTRACT

Interactions between soil microbes and forest residues are controlled by six environmental factors: water, temperature, aeration, pH, food supply, and biological interrelationships. A change in one induces change in others. Burning drastically affects all six but is especially unfavorable in terms of nitrogen loss and effects on soil physical properties. Microbial decomposition of residues, in contrast, recycles the nitrogen and can result in improved soil physical properties. Microbial activity can be enhanced by reducing particle size of residues, by providing good contact between residue fragments and soil, and by adding nitrogen by fertilization or establishment of plants with nitrogen-fixing nodules. Petroleum products, biocides, or fire retardants appear unlikely to significantly affect soil microbial activity or residue decomposition when used at recommended rates. Forest residues combined with soil microbes offer promise for disposal of sewage waste water and decomposable garbage.

Keywords: Soil microbes, residue decomposition, nutrient cycling, chemical interaction.

INTRODUCTION

The forest soil is a basic industry resource and is important in determining sustained yields. Contributions of forest residues to this resource should be so managed that their store of nutrients can be effectively recycled and their desirable physical effects maintained. Availability, storage, and loss of nutrients in forest soils depend largely upon microbial activity. These nutrients are derived from both atmosphere and soil, but especially from the accumulation of organic residues. Forest residue treatments, therefore, will affect nutrient cycling and loss through their effects on either or both the microbes and forest floor, which provides microbial substrates. For example, as will be discussed later, the nitrogen content of slash is lost to the atmosphere by burning; if the slash is left on the ground, much of this nitrogen will be recycled to the soil through decomposition.

The microbiology of forest soil involves complex interactions between a great diversity of organisms and microhabitats. Forest soil varies from site to site, of course, and little is known about it compared with agricultural soils. Nonetheless, many of the fundamental factors affecting soil microbial activity are known and can be expected to apply to forest soils and residue situations.

Decomposition of plant and animal remains is essential to circulation of nutrients in nature, thus constituting a mineralization of organic matter. Soil micro-organisms are active in four major zones of decomposition: surface debris, turned-under residues, humus, and the rhizosphere--a narrow zone around living roots. These zones vary in extent under different conditions, may be adjacent or intermingled in time as well as in space, and vary in intensity. Each zone has peculiar significance and contains a variety of morphologically and physiologically different organisms. Fresh residues support a wide mixture of organisms able to rapidly attack the water-soluble constituents, after which they decline and are replaced by organisms adapted to more resistant substances. As decomposition proceeds to humus, other specialized bacteria that can work on the resistant lignocelluloses and nitrogen complexes take over. If no further organic additions occur, the final product is an accumulation of dead bacterial cells, high in essentially unavailable carbon and nitrogen, becoming under suitable geologic conditions a source of peat, coal, or petroleum.

FOREST SOIL AS A CULTURE MEDIUM

Soil microbes and roots live in a colloidal complex of organic and inorganic materials more or less saturated with air and water and supported by soil particles. This physical-chemical-biological complex is in unstable equilibrium with vital phenomena and is continually changing with changes in the environment. Microbes are particularly important in this medium because they transform potential fertility into active fertility that supplies nutrients in available forms. To do this, they require nutrients, which they consume more readily than do higher plants. Any food element in limited supply may be so extensively used by microbes that little or none may be immediately available to plant roots; thus the dictum, "feed the soil, then the plant."

Infiltration of the end products of surface decomposition influences soil formation and soil morphology. Treatments that incorporate residues and fertilizers into soil hasten mineralization of organic matter to the advantage of plant growth. Humus under natural conditions is distributed from the soil surface downward in decreasing concentration, proportionately affecting the distribution and activity of the native microflora. In soil supporting living plants, microbial populations and activities are especially concentrated in the rhizosphere and extend downward on old dead roots.

ENVIRONMENTAL FACTORS

The entire ecosystem is in a state of dynamic balance with six environmental factors that affect growth and activities of soil microbes: water, temperature, aeration, pH, food supply, and biological factors. These are all interrelated; a change in one induces change in others. The production of forest residues and treatment of those residues can influence each of these factors drastically. As a result, the entire soil microbiota can shift in another direction.

1. Water. The optimum for microbial activity is almost 50 percent of soil water-holding capacity. As moisture decreases, growth slows until, in air-dry soil, the organisms become inactive. Excessive moisture reduces air supply and retards microbial metabolism. The kind of forest residue present on a site and, more important, the way it is treated can greatly affect this factor, especially the rapidity with which the upper soil layers dry out during the summer. Obviously, the rate of drying is affected by climate and vegetation as well as residue treatments. Residues in wet spots may remain saturated much of the year and decompose extremely slowly. Soil moisture loss in summer would have a greater impact on microbial activity under ponderosa pine (*Pinus ponderosa* Laws.) than similar loss under Sitka spruce (*Picea sitchensis* (Bong.) Carr.).

2. Temperature. Each micro-organism has an optimum temperature for growth and a range outside of which growth ceases; the optima can vary within certain limits, depending on other environmental factors. The population of soil organisms in any given forest would be comprised primarily of those well adapted to the prevailing temperature regime. Radical changes of the forest soil temperature regime resulting from clearcutting or residue treatments, such as burning, can engender equally radical changes in microbial populations. Such effects are likely to be most pronounced in the uppermost soil layers, where temperatures are strongly influenced by solar radiation exchange.

3. Aeration. Free oxygen (O_2) and carbon dioxide (CO_2) are vital in microbial metabolism. Although all bacteria require at least a trace of CO_2 to initiate growth, the compound is also produced as a respiration product which, accumulated in excessive amounts in the soil, can retard microbial activity. Gaseous nitrogen (N_2) is used by N_2-fixing bacteria and algae; an adequate supply of air in soil is important to maintenance of soil fertility. Good soil ventilation is required for satisfactory exchange of these gases with the atmosphere. Any residues that impede aeration and any residue treatments that compact or encrust the soil surface will reduce microbial activity, not only by restricting O_2 supply but also by allowing accumulation of toxic concentrations of CO_2.

Deep accumulations of duff,[1/] unless compacted or waterlogged, are unlikely to inhibit aeration sufficiently to impede microbial action. Abundant microbial development was found in unusually deep duff layers under a virgin Sitka spruce stand close to the Oregon coast by Bollen and Wright (1961). There would seem to be no limit to the desirable amount of duff accumulated normally. Neither would a layer of slash chips be likely to interfere with aeration if it was distributed by blowing.

4. pH. Soil microbial activity is strongly related to soil acidity or basicity (usually expressed as pH value). Forest soils are typically acid, i.e., have a pH of less than 7. Some micro-organisms thrive only in a very narrow pH range, whereas others tolerate extremes. The micro-organisms of a forest soil will be predominantly those adapted to the acidity of that soil. Radical changes in soil acidity, such as after burning of forest residues, or excessive leaching, can result in strong shifts of microbial populations. Microbes with a narrow pH

1/ The term, "duff," is used more or less loosely to designate the surface accumulation of litter and often includes some of the immediately underlying decomposing material, especially when dry (see fig. 2, p. B-9). In older reports, components of the forest floor are designated "litter," "duff," and "leaf mold."

tolerance will be largely replaced by those with a wide tolerance plus those whose narrow pH range encompasses the new pH of the soil. This could cause some changes in physiological activities. Functions of the replaced organisms would, in general, be similar, if not the same, as those taking their place.

5. Food supply. Microbes require the same essential nutrient elements as do higher plants but often in quite different proportions. The quantities required, in keeping with the minute size of microbes, are correspondingly small per individual except for relatively large amounts of energy sources. Bacteria are comparatively inefficient in using energy; they waste much in the form of heat and incomplete oxidation. Almost any substance can be attacked by some microbe under favorable conditions. Forest residues, of course, expand the food base for microbial activities. The long-term results--nutrient recycling, breakdown of organic matter and its incorporation into the soil--will most often be beneficial. Deleterious, short-term effects can also develop, however. Although an abundant source of carbon is desirable, markedly expanded activity by organic matter decomposers can cause a temporary, severe deficiency of readily available soil nitrogen. The nitrogen is used in production of microbial cells and is not released for use by higher plants until death and decomposition of the cells outpaces new cell formation. For optimum rate of decomposition the ratio of readily available carbon-to-nitrogen should be about 25:1 (Bollen 1969). In tree residues, the ratio is much wider but most of the carbon is in resistant ligno-celluloses (table 1) that are attacked very slowly and exert only a

Table 1.-- *Proximate analyses of Douglas-fir bark, wood, and needles compared with alfalfa hay and wheat straw*

(In percent, ovendry basis)

Chemical characteristic	Bark	Sapwood	Heartwood	Needles	Alfalfa hay	Wheat straw
Total carbon	53.97	49.36	51.51	55.75	43.15	44.70
Kjeldahl N	.11	.09	.12	.96	2.34	.12
C/N ratio[1]	491:1	548:1	429:1	58:1	18:1	373:1
Hot-water extractives	2.50	2.70	4.20	12.10	16.90	5.00
Cold-water extractives:						
Total	1.90	1.00	4.80	22.00	23.10	7.80
Reducing sugars	.79	.14	.77	5.65	2.70	3.98
Kjeldahl N	.04	.09	.13	.16	1.13	.48
C/N ratio[2]	1,250:1	556:1	385:1	313:1	44:1	04:1
Ash	.50	.30	.30	5.60	8.80	8.50
Alcohol extractives	13.70	3.50	8.10	36.60	15.70	8.00
Alcohol-benzene extractives	.20	.10	.30	.30	.60	.40
Holo-cellulose	42.20[3]	52.20	60.60	20.50	29.80	62.90
Klason lignin	41.60[3]	37.40	25.90	20.30	14.30	13.50
Crude protein	.70	.60	.80	6.00	14.60	.80

[1] *Not expressed as percent.*

[2] *Approximate: based on C = 50 percent.*

[3] *Not typical wood cellulose or lignin.*

correspondingly slow nitrogen demand that can be supplied by slow release from humus and decomposing dead microbes. This means that for rapid decomposition of most residues, except those which are high in nitrogen like alfalfa (table 1), fertilizer nitrogen must be added to satisfy needs of microbes involved. Alfalfa contains more than enough nitrogen so that the excess soon is released as ammonium. On the other hand, humus and soils, although having a narrow carbon-to-nitrogen ratio (table 2), decompose very slowly because the organic matter is already highly decomposed and the residue is resistant to further microbial attack.

Table 2.--*Chemical analyses of soil under red alder and conifer stands on Astoria silty clay loam soil (samples taken in April)*

Stand layer, horizon	Water	pH	Nitrogen				Total carbon	C:N ratio
			Ammonium	Nitrite	Nitrate	Kjeldahl		
	Percent		- - - - - - - - -	-	*P/m*	- - - - - -	*Percent*	
Alder stand:								
L	--	--	--	--	--	1.83	51.13	28
F	239.1	3.7	190	0.07	283	2.22	40.23	18
A11	162.1	3.5	45	1.20	164	1.48	25.18	17
A12	109.0	3.9	5	.18	91	.76	13.47	18
B	83.5	4.5	5	.05	19	.35	5.92	17
Conifer stand:								
L	--	--	--	--	--	1.30	42.34	33
F	158.1	5.0	120	1.43	89	1.06	26.31	25
A11	92.0	4.8	30	.39	74	.84	18.39	22
A12	101.5	4.8	8	.19	66	.69	14.92	22
B	102.0	5.1	5	.05	15	.69	14.26	21

6. Biological factors.--Interactions between organisms are prominent features of the soil microbial complex. Competition for water and nutrients is continuous and sometimes limits development of certain species. As noted above, changes in the soil microhabitat from timber harvest or residue treatment can change competitive relationships. Many soil organisms produce products that inhibit others; penicillin and streptomycin are classic examples. On the other hand, byproducts of one species often provide food for others. Parasitism of one micro-organism on another is a common phenomenon, e.g., by bacterial viruses and predaceous fungi. Residues and residue treatments will exert indirect effects insofar as they influence the establishment of higher plants. For example, establishment of *Alnus* or *Ceanothus* species following burning will provide host roots for symbiotic, nitrogen-fixing organisms. Treatments that encourage herbaceous plants or brush species such as *Acer* or *Rubus* will similarly encourage development of roots for rhizosphere organisms and for host tissue for endomycorrhizal fungi in the family *Endogonaceae*. Like other root-inhabiting fungi, their mycelial extensions into the soil extend the nutrient absorbing power of their host plant roots.

Any one of the foregoing factors may become inhibiting when varying from an optimum range. For example, nitrification as well as general microbial activity and leaching would be limited by low summer rainfall; in winter, when temperature is low or ground is covered with snow, leaching can occur but nitrification is inhibited and all micro-organisms are only slowly active.

Cardinal values applicable in general for the environmental factors are shown in table 3.

Table 3.--*Factors of environment and their approximate cardinal values for general microbial activity in soil*[1/]

Factors	Minimum	Optimum	Maximum
Moisture	5 percent[1/]	50 percent[1/]	80 percent[1/]
Temperature	2° C	28° C	40° C
Aeration	varies	at 50 percent[1/] H_2O	varies
pH	4	7	10
Food supply	varies	balanced, C/N = 25/1	varies
Biological	--	symbiosis; limited antibiosis	--
Inhibiting	Positive or negative extremes of other factors		

1/ Of moisture capacity.

KINDS AND NUMBERS OF MICRO-ORGANISMS IN SOIL

Almost any kind of microbe may be found in the soil (Benjamin et al. 1964). Microbes differ widely in size and shape and range from ultramicroscopic viruses to relatively gigantic fungi with spores easily visible to the unaided eye. A variety of these forms often is found in the same physiological group, producing similar chemical transformations with characteristic end products.

Bacteria are important components of the soil microflora because they grow and transform matter more rapidly than other soil organisms. Certain actinomycetes are important as the endophytes, or plant-inhabiting microbes, of nitrogen-fixing root nodules, and many species produce potent antibiotics. Soil molds are prominent in decomposition processes; many species produce antibiotics, and some are important parasites on other fungi. Mycorrhizal fungi are root symbionts of higher plants and play vital roles in nutrient absorption by their hosts. Several molds and higher fungi are root pathogens.

These organisms occur in phenomenal numbers in the soil. Table 4 and figure 1 give examples of populations in a silty clay loam soil under different

Table 4.--*Approximate masses of organisms in a fertile soil*

Organism	Live weight per acre to 6-2/3-inch depth[1]	Relative numbers
	Pounds	*Percent*
Bacteria	1,000	80-20
Actinomycetes	1,000	20-70
Molds	2,000	1-10
Algae	100	1
Protozoa	200	2
Total	4,300	
Dry weight =	1,000	
Nematodes	50	
Insects	100	
Worms	1,000	
Plant roots (dry weight)	[2]2,000	

[1] Nominally 2,000,000 pounds.

[2] Varies widely with kinds and numbers of plants, and soil type.

stands at Cascade Head. The highest populations in forest soils occur in the F horizon, the "fermentation layer" where leaves, twigs, and other residues are undergoing active microbial decomposition (Lu et al. 1968) (fig. 2). This horizon or layer may range from a small fraction of an inch to approximately 2 feet, varying with forest stand, soil type, and climate. Microbes are most abundant and most rapidly acting here. The surface layer of mineral soil may contain 10 million to 100 million bacteria (including actinomycetes) per gram and 1,000 to 100,000 molds per gram. These estimates are conservative, especially for molds, because available methods fail to detect many forms present. Numbers decrease rapidly in lower horizons.

The total living microbial mass, more significant than numbers, of the top 6 inches (15.24 cm) of an acre (0.4 ha) of fertile soil has been estimated to approach 1,000 lb (453.6 kg) each of bacteria and actinomycetes and 2,000 lb (907.2 kg) of molds, dry basis (table 4) (Bollen 1959).

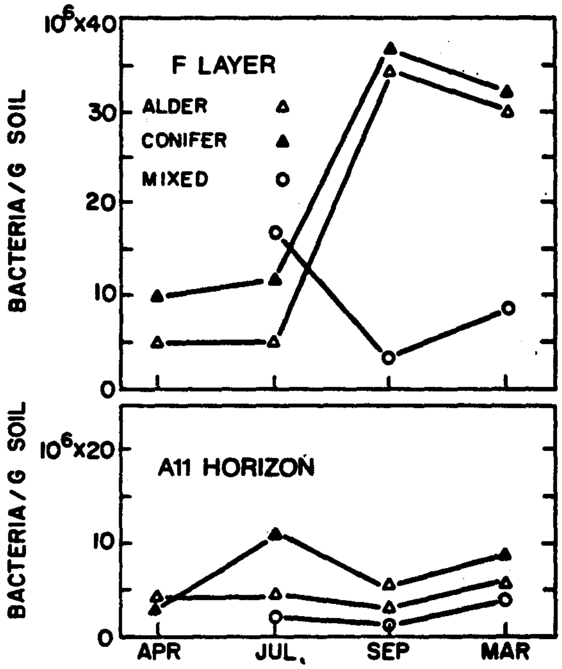


Figure 1.--Seasonal changes in numbers of bacteria in F and A11 horizons under three different stands on Astoria silty clay loam soil.

Similar populations may be found in agricultural soils; but they are influenced more by a variety of cropping, tillage, and cultural practices.

These values represent average conditions; they would differ under different ground covers, climatic conditions, and soil types (table 5) (fig. 1). More extensive examples, encompassing 12 different soils and showing wide differences between soil types and climates, have been presented by Bollen and Wright (1961). Bollen et al. (1967) reported comprehensive seasonal changes in microbial and chemical properties in different horizons under conifer, alder, and mixed stands on Astoria silty clay loam soil at Cascade Head, Oregon.

Other organisms in forest soils deserve mention as "partners" of microbes. Nematodes, insects, and worms of various kinds are generally common in soils. They participate with microbes in decomposing organic matter, mixing it with the soil, and rendering it more susceptible to microbial attack. Their waste substances are utilized by microbes, they transport microbes on or within their bodies, and they enhance microbial activity by increasing soil permeability (Jacot 1936, Macfadyen 1968). Earthworm activity mixes surface material with the mineral soil and increases aeration and drainage. Certain larger insects, such as wood borers and bark beetles, contribute to residue deterioration, not only directly but also by transporting microbes into the channels made. Bacteria are often linked with tree-destroying fungi (Anonymous 1972b). Fungi and minute insects are important in the preliminary deterioration of forest residues. The role of higher fungi is discussed by Aho (1974); biological and sequential aspects are covered.

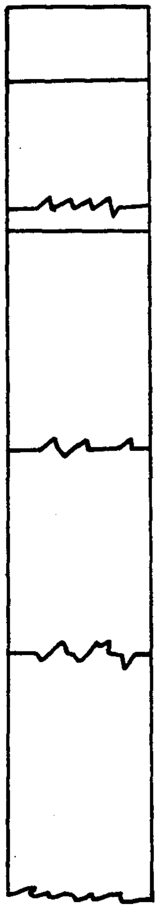
Roots deserve special consideration as a biological component of the soil. A narrow zone, designated as the rhizosphere, approximately 1 mm wide and surrounding living roots, is especially favorable to development of bacteria; 75 to 90 percent of the total microbial population of a soil occurs in this zone.

Table 5.--*Molds in F layer and A11 horizons under three different stands on Astoria silty clay loam soil*

Stand and layer, horizon	Water	Water-holding capacity	Loss on ignition	pH	Molds					
					Total	*Mucors* 1/	*Aspergilli*	*Penicillia*	*Trichoderma*	Others
	- - - - - *Percent*	- - - - -			2/*M/g.*	- - - - - - - - - - *Percent*	- - - - - - - - - -			
Alder stand:										
F	193	418.8	62.4	3.6	225	0	0	33	67	0
A11	98	196.3	30.4	3.9	73	13	0	40	37	10
Conifer stand:										
F	135	292.5	44.0	5.1	709	27	0	41	0	32
A11	105	205.8	34.1	5.3	195	19	8	39	0	34
Mixed stand:										
F	135	303.3	45.0	3.9	291	20	3	54	0	23
A11	90	184.5	28.6	4.3	79	23	5	49	0	23

1/ Included *Rhizopus*, *Mucor*, *Mortierella*, and other genera of the Mucorales.

2/ Thousand per gram of soil.



O1 Invertebrate fauna, microbes, and higher fungi active (L),[1/] (litter)[1/]

O2 Region of greatest microbial activity (Aoo),[1/] (F),[1/] (fermentation)[1/]

H Featureless, highly decomposed organic matter; found in mor soils of cold regions. Not in mull soils. Mor humus. Characteristic of Podzols. Limited microbial activity.

A Mineral horizons. May be subdivided into A1, A2, etc., according to transitional features and humus concentrations. Top soil. Microbial activity decreases with depth.

B Subsoil. Contains illuvial concentration of clay, iron, aluminum, or humus, alone or in combination. May be subdivided into transition zones B1, B2, etc. Minimum microbial activity. Acts as a microbial filter.

C Parent material from which the soil profile is formed. Unconsolidated rock, sand, peat, etc. Essentially no microbial activity.

[1/] Alternate or obsolete designations.

Figure 2.--Forest soil horizons. Depth of horizons or layers which constitute the profile vary by forest type, vegetation, drainage, climate, and parent material. For complete descriptions, see Glossary of Soil Science Terms, Soil Science Society of America, Madison, Wis., 33 p., illus., 1973.

This is attributable to the enormous extent of root systems and their root hairs, which have a calcium-pectate surface layer, and to the metabolites liberated at the surfaces. These metabolites include sugars, organic acids, and other compounds that provide readily available nutrients for many micro-organisms. On the other hand, some of the exudates liberated by roots of white pine (*Pinus strobus* L.) may be inhibiting to certain microflora (Slankis et al. 1964). Significance of these interactions, especially in root pathogens, deserves further study.

The extent of root systems and their surface exposure is little appreciated. An exhaustive study by Dittmer (1937) of one rye plant grown in 2 ft^3 (56.6 dm^3) of a silt loam soil revealed the following:

13,800,000 roots: total length, 387 miles (622.7 km); surface area 2,554 ft^2 (237.4 m^2)

14 x 10^9 root hairs: total length, 6,600 miles (10,619 km); surface area, 4,320 ft^2 (401.5 m^2).

Compared with the total external surface of shoots and leaves, which was 51.38 ft^2 (4.78 m^2), the root exposure was 130 times that of the aerial parts.

The 2 ft^3 (56.6 dm^3) of soil, 145 lb (65.8 kg), had a total particle surface of 70 x 10^6 ft^2 (1,607 acres (650.4 ha)). Thus the total root surface was only 0.01 percent of the surface available in the soil, indicating roots make little contact with the soil.

The few studies made on forest tree roots have been less comprehensive. However, for white spruce (*Picea glauca* (Moench) Voss) 10,000 linear feet (304.8 m) of root in a sandy loam soil was related to 10 ft^3 (0.28 m^3) of volume in the trunk; in clay the relationship was 5,000 ft (1,524 m) of root to 10 ft^3 of trunk (Anonymous 1967). McMinn (1963) reported 464 ft of roots greater than 1 cm in diameter for a 55-year-old dominant Douglas-fir.

Dead roots are important because they support microbes active in decay and mineralization in deeper soil strata. After decay is complete, the root channels provide drainage and aeration.

ORGANIC MATTER AND NITROGEN--CARBON AND NITROGEN CYCLES

Organic matter is the cream of the soil. It is a storehouse of available and potential nutrients, improves soil structure, increases water-holding capacity, buffers against changes in pH, and adsorbs cations, such as ammonium (NH_4^+) and calcium (Ca^{++}), against leaching even though they remain available to microbes and roots.

Bacteria and other microbes which attack plant and animal remains break them down into simple substances plants can use. Like animals, they are destructive feeders. They bring about decomposition or decay, which is an essential sequel to life. From the standpoint of plant nutrition, this may be considered a predigestion of plant food. It is performed by many unspecific bacteria and by a few specialized bacteria capable of attacking particular substances. In some instances, the bacteria act as scavengers in decomposing materials that might be toxic to plants.

Forests annually contribute about 16 x 10^9 metric tons (17.6 tons) of carbon as organic matter (Riley 1944) to the global production on the soil as shown in figure 1. Thus forest residues account for nearly 75 percent of the total carbon recycled each year from the total land surface.

Building-up processes in the soil are brought about by those bacteria which may be considered constructive feeders. Two types may be recognized: autotrophs--strictly mineral feeders which, like plants, build their organic substance from carbon dioxide and water and semimineral feeders or nitrogen-fixers, which require complex carbonaceous food but can utilize nitrogen in elemental form. The significance of strictly mineral feeders lies in their ability to obtain energy by oxidizing simple mineral substances--such as hydrogen, methane, ferrous iron, and especially ammonia--to nitric acid and sulfides or sulfur to sulfuric acid. This action not only changes decomposition products to available plant food but also dissolves soil minerals, rendering them available.

The ecological significance of these two groups can be appreciated from a brief consideration of the cycles of carbon (fig. 3) and nitrogen (fig. 4) (Bollen 1959, 1967). In the carbon cycle, carbon dioxide from the atmosphere is converted by autotrophs into organic compounds of high energy content. Photosynthetic organisms obtain energy for this transformation from the sun's rays. The autotrophic bacteria derive energy from oxidation of certain elements, such as sulfur or hydrogen, or from oxidation of simple compounds such as ammonium, hydrogen sulfide, or carbon monoxide. Heterotrophs consume organic energy-containing substance previously synthesized by autotrophs and other heterotrophs; this biological material is used for both structure and energy, the greater proportion being oxidized for energy and therefore yielding much carbon dioxide, which returns to the cycle. During photosynthesis, CO_2 is consumed and O_2 is evolved. Thus all green plants, and forests especially, make it possible for us to live here. Also, all living cells give off CO_2 during respiration, and this is returned by trees and other green plants to the atmosphere during dark periods. Due to the supply of juvenile CO_2 from volcanoes and mineral springs, which supply over 90 percent of the CO_2 in our atmosphere, and to the $CO_2 + CaCO_3 + H_2O \rightleftharpoons Ca(HCO_3)_2$ buffer action in the oceans, the supply of CO_2 is maintained remarkably constant at 0.04 percent by weight. This and the O_2 supply and other chemical factors in the environment are additionally subject to biological control by reciprocal interactions of organisms and their external conditions (Redfield 1958).

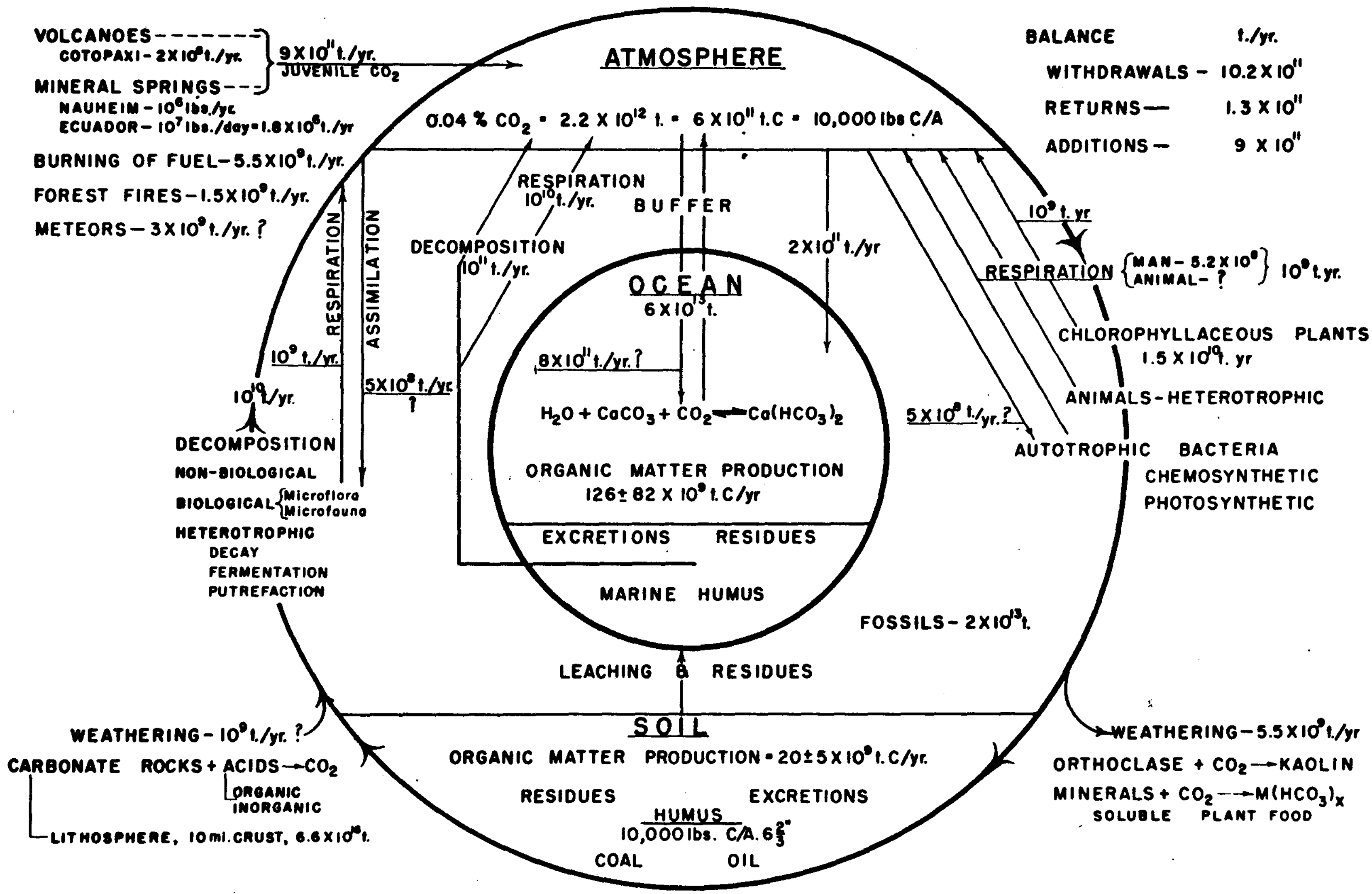
An additional phase (not illustrated in fig. 3) of the carbon cycle involves CO. This is discussed under "Burning."

In the nitrogen cycle, proteins yield ammonia (NH_3), upon decomposition by a wide variety of bacteria, actinomyces, and molds. NH_3 rapidly combines with water to become NH_4OH, yielding ammonium (NH_4^+). Ammonium is oxidized to nitrite (NO_2^-) and nitrate (NO_3^-) by autotrophic nitrifying bacteria. Nitrite occurs in a very limited concentration, rarely more than 2 p/m, in soils. It is converted by nitrifying bacteria to NO_3^- more rapidly than NH_4^+ is oxidized to NO_2^- by nitrosofying bacteria. Nitrification is especially rapid under red alder (*Alnus rubra* Bong.) (Bollen and Lu 1968). Only when nitrifiers are absent, which is rare, or when NH_4^+ concentrations exceed about 100 p/m and become toxic to nitrifiers does NO_2^- accumulate to any extent. High concentrations of NO_2^- become toxic to plants under most conditions.

Examples of the influence of stand and season on the nitrogen transformations in F and All horizons are given in figure 5. Table 2 shows differences in all horizons for samples taken in spring. Nitrate, as well as some NH_4^+, is assimilated by plants and microbes and converted to amino acids (H_2N-R-COOH) (where R represents CH_3^- or other organic groups), then to proteins, which are highly complex polymers of amino acids, thus completing the cycle. Protein metabolism by animals extends the cycle without greatly altering the fundamental mechanism.

An additional, important phase is biological dinitrogen fixation. This converts free nitrogen (N_2) to NH_4^+, amino acids, and cell protein. Assimilation

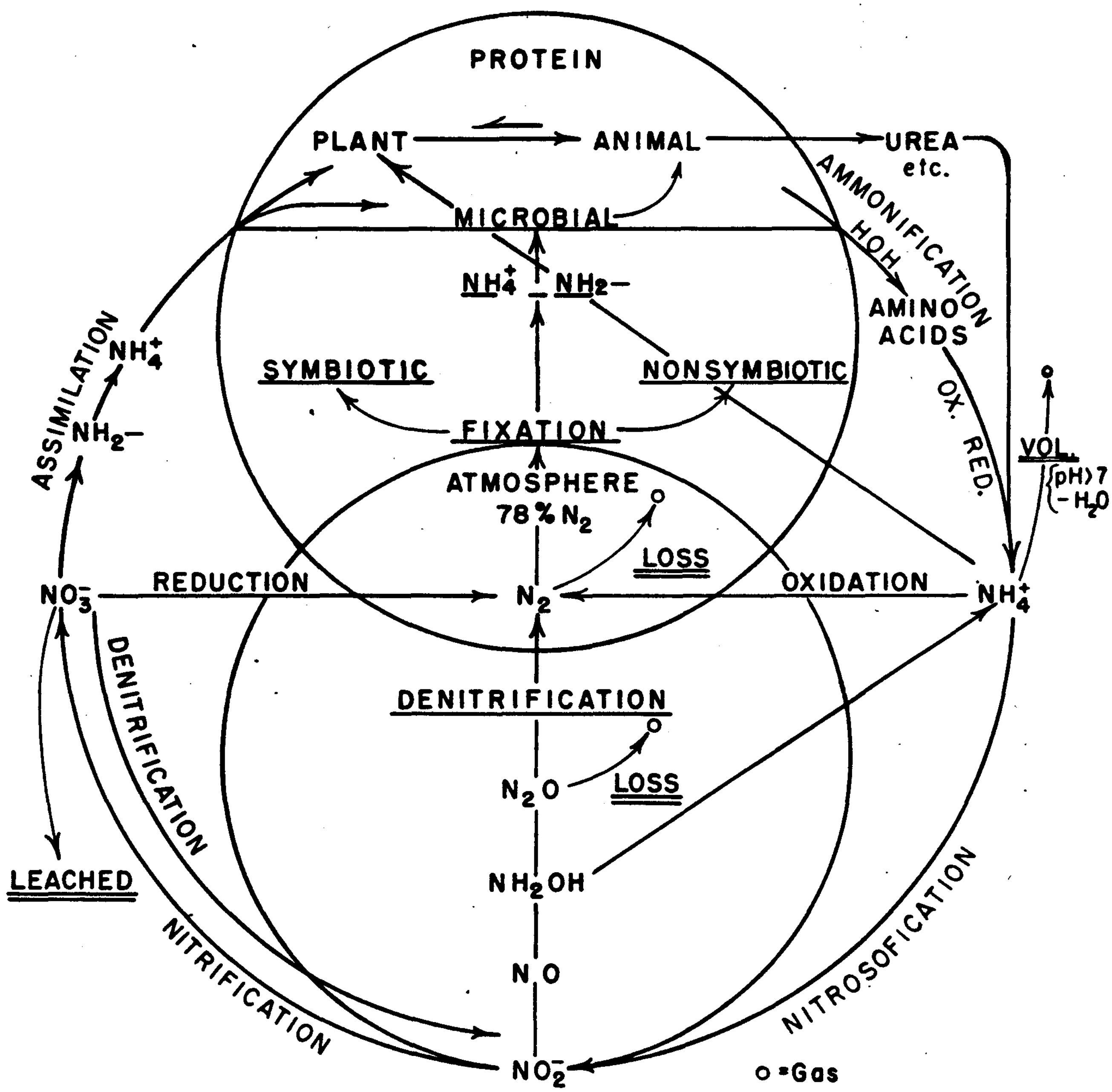
Figure 3.-- **THE CARBON CYCLE**



Data In Metric Tons CO_2 Except C As Indicated

W. B. BOLLEN, 1958

Figure 4.-- NITROGEN CYCLE



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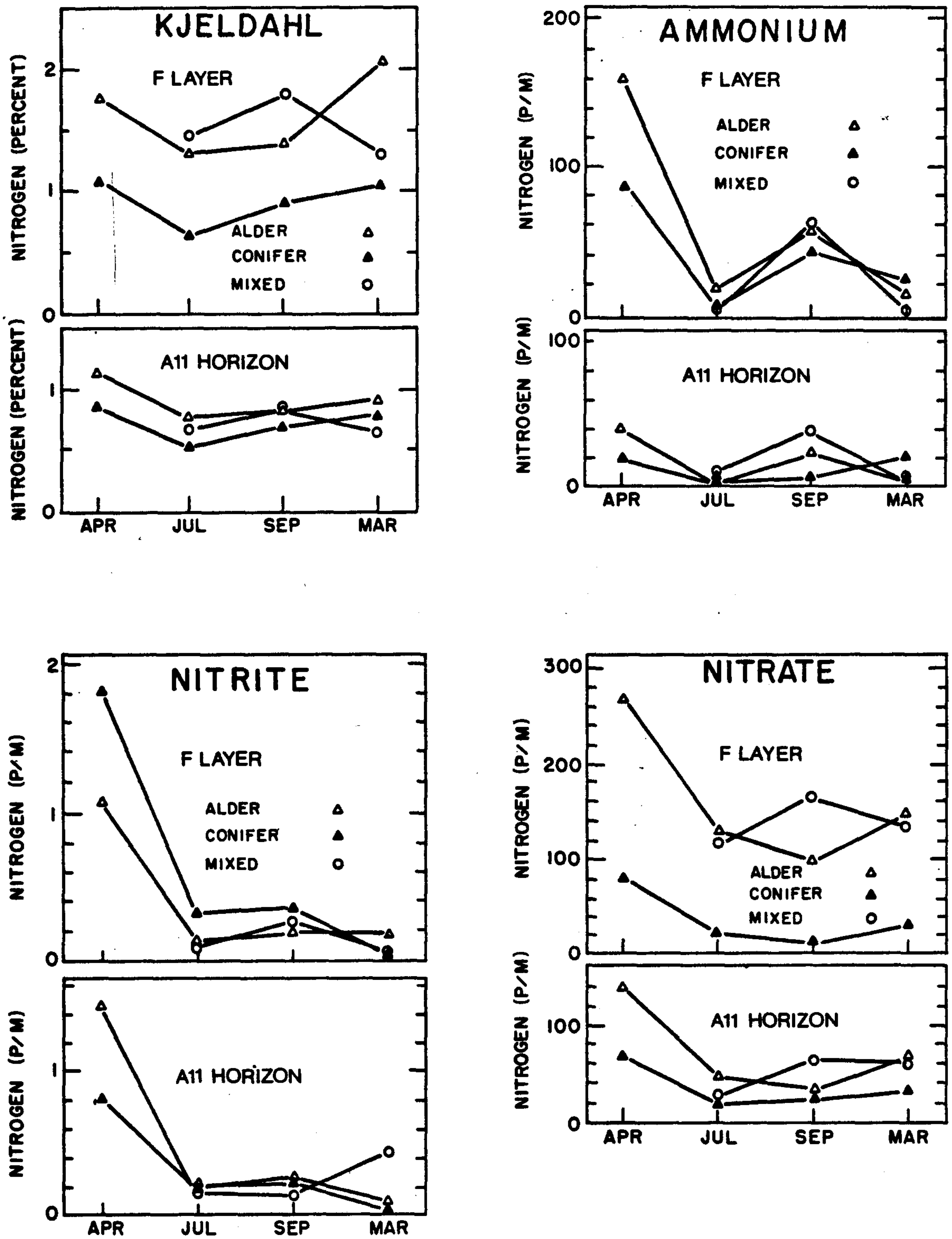

Figure 5.--Seasonal changes in nitrogen status in F and A11 horizons under three different stands on Astoria silty clay soil.

of elemental nitrogen is an ability possessed only by a few bacteria, mainly heterotrophs, and by certain blue-green algae. Nonsymbiotic fixation is carried on by *Azotobacter* and certain species of *Clostridium*. Upon death of the cell, the protein reenters the cycle and becomes subject to ammonification. Species of *Rhizobium* carry on fixation only when living symbiotically in nodules on roots of leguminous plants--much of the fixed nitrogen being NH_4^+ and amino acids, immediately available to the host. Of the total nitrogen-fixation by both *Azotobacter* and *Rhizobium*, a considerable part is liberated in soluble extracellular organic form during the life of the cell; some ammonium is also liberated. Thus nitrogen-fixing bacteria convert the generally unavailable gaseous nitrogen into immediately available compounds as well as into nitrogenous tissue which must be decomposed later by other organisms before becoming active in fertility.

Were it not for these bacteria, the vast supply of N_2 in the atmosphere would not become available to other organisms. Trace amounts are converted to NO_3^- by lightning and other electrical discharges, and traces of NH_4^+ are formed by some nonbiological processes, but the amounts are minor compared with biological fixation. Most of the combined nitrogen in the atmosphere comes from the combustion of fuel. The total amount of NO_3^- and NH_4^+ brought to the earth by precipitation averages about 5 lb/acre (5.6 kg/ha) N-equivalent per year. Nonsymbiotic fixation varies with soil type, cultural practices, and climate. The average N_2 fixation is near 5 lb/acre (5.6 kg/ha) per year and may only offset leaching losses. Symbiotic fixation by cultivated leguminous plants, such as alfalfa, may exceed 200 lb (224 kg/ha), whereas fixation by alder ranges from 50 to 185 lb/acre (56 to 207 kg/ha) per year (Tarrant 1968, Bollen and Lu 1968).

N_2 fixation by the symbiotic association of microbes with plants is undoubtedly the most important source of fixed nitrogen in nature. However, the broad distribution of free-living N_2 fixers, especially certain blue-green algae and photosynthetic bacteria, is an important contribution to soil fertility. Estimates range from 5 to 20 kg/ha (4.5 to 18 lb/acre) per year (Dalton and Mortenson 1972) for agricultural soils. The significance of nonsymbiotic N_2 fixation in forest soils should be investigated.

Recently, N_2-fixing bacteria have been isolated from decay caused by fungi on white fir (*Abies concolor* (Gord. and Glend.) Lindl.) trees (Seidler et al. 1972) Possibly these bacteria supply the fungi with nutritional forms of nitrogen. If so, then development of some means of inhibiting the bacteria or their N_2-fixing capability could provide a control of the fungi. Discovery of these bacteria suggests that the possibility of N_2 fixation by other bacteria occurring in living trees (Bacon and Mead 1971) should be examined. Cornaby and Waide (1972) found N_2-fixing bacteria in decaying chestnut logs; they suggest that nitrogen fixed by organisms inhabiting decaying woody tissue is an important part of the total nitrogen input to forest ecosystems.

Losses of nitrogen from the soil occur by erosion, leaching of nitrate, or by volatilization of ammonia under moist, nonacid conditions, by assimilation by plants, and by denitrification. These losses are especially important because available nitrogen is most frequently the limiting plant nutrient in soils. In this connection, the cation exchange capacity (CEC) is significant. It consists of organic matter and colloidal clay. The organic matter is especially

...tant because it comprises a major fraction of the CEC of soils. Different ... and residues vary in CEC largely because of differences in organic matter ...t. Examples are shown in tables 6 and 7. Importance of the CEC lies in ...acity to hold nutrient cations, particularly NH_4^+, against leaching ...gh they are readily available for assimilation by roots and microbes. ...ate, being an anion, is not held and can be rapidly leached.

...ble 6.--*Lime requirement, exchangeable cations, and available boron in A11 horizon under three different stands on Astoria silty clay loam soil*

Stand and pH	Lime requirement to pH 6.5	Cation-exchange capacity						Available boron
		H+	Ca++	Mg++	K+	Sum of cations	Total	
	Tons/acre	*Milliequivalents per 100 grams of soil*						*P/m*
...der stand: 3.9	25	45.1	3.8	8.6	8.1	65.6	68.1	1.19
...ifer stand: 5.3	11	30.4	12.5	16.0	5.2	64.1	69.0	1.83
...ed stand: 4.3	17	40.6	2.3	8.2	9.3	60.5	65.4	1.79

The forest floor may have a higher total CEC than several inches of the ...lying mineral soil (Wells and Davey 1966). For the forest floor from ...ferent Douglas-fir plant communities in the Oregon Coast Ranges, Youngberg ... found CEC values ranging from 54.4 to 75.8 meq/100 g, the differences ... associated with different understory vegetation.

...enitrification occurs when available oxygen (O_2) in the soil becomes ...ted and NO_3^- or NO_2^- and oxidizable substances are present. Under these ...tions, certain anaerobic and facultatively anaerobic bacteria use the ... NO_2^- as oxidants to catabolize oxidizable substrates and obtain energy ... growth. Nitrate is reduced to NO_2^-, NO_2^- to nitric oxide (NO, gas), then ...droxylamine (NH_2OH) which becomes reduced to nitrous oxide (N_2O, gas) ...ally N_2 (gas). The gases are lost to the atmosphere. The sequence ... in various combinations. In some cases it stops at NO_2^-; if O_2 ... available loss does not then occur, and nitrification can reoxidize ... to NO_3^-. Limited amounts of denitrification can occur even in well-... soils, where there always are microclimates of anaerobiosis ... within groups of O_2 consuming aerobes surrounding particles of ...ate.

Table 7.--*Cation exchange capacity (CEC) of some organic residues and soils*

Material	Mesh size[1/]	CEC
		Meq/100 g
Douglas-fir:		
Bark	+5	44.8
Bark	-10+40	39.7
Bark	-40	60.5
Wood	-10+40	39.5
Wood	-40+100	28.2
Wood	-100+200	15.0
Red alder:		
Bark	-10+40	40.4
Wood	-10+40	59.0
Wood	-100+200	7.5
Ponderosa pine wood	-10+40	13.5
Wheat straw	-10	39.4
Delhi loamy sand	-10	2.7
Walla Walla silt loam	-10	18.6
Chehalis silty clay loam	-10	24.3

1/ Tyler standard sieves.

Soil nitrogen is depleted only by leaching, denitrification, and assimilation by microbes and plants. Nitrogen tied up by microbes is eventually returned when they die and become decomposed by succeeding generations. Nitrogen assimilated by plants is lost to the system where the trees or other plants are removed from the site. When these or their residues decay on the site, their nitrogen returns to the soil as decomposition products and in dead microbes that effected the decomposition.

Table 8 shows some of the important physiological groups of bacteria, their functions, and range of typical numbers.

Table 8.--*Kinds, numbers, and significant functions of microbes in soil*[1]

Kinds	Numbers/gram	Functions	Remarks
	Millions		
Heterotrophs:			
Oxidative	10-100	Completely oxidize organic matter	Active only in presence of free O_2
Fermentative	10-100	Partially oxidize organic matter	Active in absence of O_2; may be facultatively oxidative
Proteolytic	10-100	Decompose proteins to amino acids	
Ammonifiers	10-100	Oxidize amino acids to NH_4^+	Aerobic, anaerobic, and facultative. Include most proteolytic species
Denitrifiers	1-10	Oxidize organic matter with NO_3^- or NO_2^-. Release N_2 or gaseous N oxides. Assimilate N_2	Function in absence of O_2
Nitrogen fixers	1-10		Aerobic species often limited by pH<5.5. Anaerobes less sensitive. Symbiotic species adapted to pH of host
	Thousands		
Autotrophs:			
Nitrosofiers	1-10	Oxidize NH_4^+ to NO_3^-	Often inhibited by pH<5
Nitrifiers	1-10	Oxidize NO_2^- to NO_3^-	Sensitive to acidity; inhibited by excessive NH_4^+
Sulfur oxidizers	1-100	Oxidize H_2S, S, etc., to $SO_4^=$	Most species favored by or tolerate very low pH

[1] Table generalized and necessarily incomplete for the present discussion. The various groups not only occur simultaneously but more or less overlap according to substrate and environmental conditions.

For a more complete discussion of the carbon cycle see Bolin (1970); for the nitrogen cycle, Delwiche (1970). Other elements undergo similar cycles, but some different microbes are involved. An extensive description of the sulfur cycle is given by Kellog et al. (1972). Mineral cycles are described by Deevey (1970). Oxygen, originally derived from photosynthesis, is fundamentally important in energy-yielding reactions. Its cycle has been well described by Cloud and Gibor (1970). All these cycles occur simultaneously and often involve the same substrates where a great variety of organisms carry on their life functions.

KINDS OF FOREST RESIDUES AND MICROBIAL ACTIVITIES

Particle size, nitrogen content, presence of microbial-resistant compounds, moisture content, and aeration are particularly critical factors in rate of forest residue decomposition. The finer the particle, the greater is its surface exposure to microbial attack (Neal et al. 1965). An optimum size particle is difficult to define. Too fine a particle restricts aeration and percolation; too large retards decomposition. An ideal product would be a mixture of shapes and sizes ranging from one-fiftieth to one-eighth inch (approximately 32- to 6-mesh screen size). The importance of size and shape of particles in relation to use on the soil has been discussed in a previous paper (Bollen 1969; p. 8, 15, 18).

The higher the nitrogen content, within reasonable limits, the greater is the potential for microbial activity and reproduction. Thus for a given particle size, leaves, with their relatively high nitrogen content, are more rapidly decomposed than wood which has a low nitrogen content and contains resistant lignocellulose complexes (Bollen and Lu 1957). Wood, in turn, decomposes faster than bark (Bollen 1969, Bollen and Glennie 1961). Water-soluble materials (tables 1 and 9) are decomposed rapidly, but ligneous materials are attacked slowly by specialized bacteria and fungi. Composition of residues--particularly nitrogen, water-solubles (table 9), cellulose, and lignin--influence rates of decomposition under any given conditions (compare with table 1). Bark contains more nitrogen than wood, has generally less water-soluble material, and the lignocelluloses are different, accounting for slower decomposability.

Total nutrients in residues (table 10) indicate potential returns to the soil upon complete decomposition, though not necessarily the rate of return. The rate is determined by quality, which depends upon proximate analyses (table 1).

Young and Guinn (1966) give comprehensive analyses for nitrogen and ash constituents, including trace elements, in needles or leaves, branches, trunks, and roots of four conifers and three hardwood species of Maine. Pitchwood seams remain intact long after the other wood has disintegrated; the limiting factor in this case is probably aeration, since finely divided pitch is rapidly attacked (Bollen and Glennie 1961). Under similar conditions, different species of barks and woods decompose at different rates (table 11) (Allison 1965, Bollen 1969).

In the Pacific Northwest, moisture-temperature relationships are critical in controlling rates of microbial activity on residues. During the winter and spring, residue moisture contents are good for microbial activity but temperatures are below optimum. During the summer and autumn, temperatures may be optimum for

Table 9.--*Analysis of cold-water solubles in bark and wood*

Species	pH		Water soluble[1]		Kjeldahl nitrogen		C:N ratio	
	Bark	Wood	Bark	Wood	Bark	Wood	Bark	Wood
			Percent					
Western redcedar:								
Untreated	3.2	3.5	2.95	6.99	0.14	0.06	378:1	810
Extracted	4.5	4.6	--	--	.13	.06	392:1	835
Redwood:								
Untreated	3.2	4.4	2.35	1.67	.11	.07	473:1	753
Extracted	4.8	5.6	--	--	.11	.06	457:1	876
Red alder:								
Untreated	4.6	5.8	11.64	1.43	.72	.13	71:1	377
Extracted	5.0	6.0	--	--	.81	.15	62:1	320
Western hemlock:								
Untreated	4.1	6.0	3.95	3.47	.27	.04	212:1	1,234
Extracted	4.4	4.4	--	--	.24	.03	223:1	1,618
Ponderosa pine:								
Untreated	3.8	4.4	4.35	2.68	.12	.04	422:1	1,297
Extracted	3.9	4.2	--	--	.13	.06	429:1	895
Sitka spruce:								
Untreated	4.9	4.1	10.89	1.27	.41	.04	130:1	1,214
Extracted	6.4	6.4	--	--	.40	.04	127:1	1,194
Douglas-fir:								
Untreated	3.6	3.4	5.49	4.65	.12	.04	471:1	1,268
Extracted	3.8	3.3	--	--	.11	.04	513:1	1,242
Sour sawdust	--	2.0	--	12.81	--	.06	--	893
Moss peat:								
Untreated	3.8		1.04		.83		58	
Extracted	4.4		--		--		--	

[1] *Total solids in 12 successive 1:10 water extractions, 24 hours each.*

Table 10.-- *Major plant nutrients in bark and wood (sawdust)*

(In percent, dry basis)

Material	N	P	K	Ca	Mg
Bark:					
Douglas-fir	0.12	0.011	0.11	0.52	0.01
Ponderosa pine	.12	.003	.11	.25	.01
Redwood	.11	.011	.06	.29	.00
Red alder	.73	.153	.24	1.25	.18
Sawdust:					
Douglas-fir	.04	.006	.09	.12	.01
Ponderosa pine	.04	.008	.12	.16	.02
Redwood	.07	.001	.01	.20	.02
Red alder	.37	.013	.12	.18	.04
Moss peat	.83	.030	.02	.50	.12

many microbes but low moisture becomes limiting. Wagener and Offord (1972) reported in a northern California study that unburned logging slash on two mixed-conifer sites decayed at a much slower rate than any previously studied. High summer temperatures and low summer and fall precipitation were thought to be the major limiting factors. Since the soil retains moisture, which ameliorates temperature extremes, close contact of residues with the soil can normally be expected to extend the season of most active microbial attack.

Kowal (1969) found that leached needles of *Pinus echinata* decomposed much more rapidly than unleached ones. This effect had been observed previously by King and Heath (1967) and was attributed to the removal of polyphenols by the leaching. From this it is evident that decomposition of needles in the forest floor under pine will be additionally favored during periods of heavy rainfall or snowmelt.

Thinnings, prunings, and slash are all subject to the foregoing considerations. For untreated logging residues especially, of considerable diameter and length, the surface exposure and contact with the soil are much less than for litter fall; and tremendously greater amounts of substance are left. On Douglas-fir clearcuts, coarse logging residues range from about 2,500 to nearly 20,000 cubic feet per acre (75 to 1,200 m^3/ha), weighing from approximately 30 to 230 tons (67 to 516 metric tons/ha) (Dell and Ward 1971). In western Oregon and Washington, about 63 percent of all net residue volume is in pieces 12 feet (3.66 m) or more in length, while about 82 percent is 8 feet (2.44 m) and

Table 11.--*Decomposition of bark, wood, and other organic materials in silt loam soil incubated at 28° C and 50 percent of water-holding capacity*

Material	Carbon released as CO_2 in 50 days	
	Bark	Wood
	- - - - *Percent* - - - -	
Douglas-fir:		
Young growth	26	30
Old growth	18	--
Red alder	18	40
Western hemlock	16	27
Ponderosa pine	21	33
Western redcedar	8	33
Dextrose[1/]	58	
Wheat straw[1/]	48	
Moss peat[1/]	4	

1/ Standards for comparison.

longer. In western Washington National Forests, the diameter of half of the residue pieces was 15 inches (3.8 dm) or more (Howard 1971). Such residue would require years to decompose if not burned, salvaged, chipped, or otherwise treated. As long as it remains intact, slash constitutes a fire hazard and interferes with reforestation, not to mention its undesirable appearance.

Breakdown of slash in the Sierra Nevada of California required about 30 years to transform the fire hazard from extreme, immediately after logging, to a low rating comparable to the undisturbed forest (Wagener and Offord 1972). By contrast, such a span in fire hazard conditions in the South was 6 years for hardwoods. In the Douglas-fir region of the Pacific Northwest, tops and small logs under 2 feet in diameter showed 90 percent of wood volume decayed after 16 years (Wagener and Offord 1971).

Although decomposition of residues is due largely to soil microbes, bacteria--some of which may be N_2 fixers, already present in living trees--may disposed of in a manner favorable to the establishment of new trees and decomposition and recycling of nutrients.

BURNING

Severe burns, such as wildfire and slash pile burns, can sterilize the upper soil and change soil properties (Neal et al. 1965). However, reinoculation by windblown dust and debris soon follows; and when moisture is sufficient, microbial populations can increase for a few weeks until an equilibrium is reached. Insofar as burning changes the soil properties, the microbes having advantage in a burned soil will differ from those having the advantage before burning, since for the most part effects of fire are indirect through the physical and chemical changes induced. These changes vary in degree and duration by intensity of burn, soil and climatic characteristics of the site, and kind of vegetation that invades an area after the burn.

When combustion of organic matter is complete, the end products are largely carbon dioxide, water, and ash, plus some nitrogen oxides derived from nitrogenous materials. With both wildfires and prescribed burning, oxidations in much of the affected area are usually incomplete and produce a wide variety of products (Hall 1972). Many of these, including carbon monoxide and hydrocarbons, are like those entering the atmospheres from trees and other plant life and from microbial decomposition of vegetative remains. In effect, fire compresses these normally occurring processes into a shorter time. Most of the residual products, including carbon monoxide and hydrocarbons, are consumed by certain species of bacteria and microfungi; and the elements are eventually recycled in the biosphere.

Although the contributions of carbon monoxide and hydrocarbons from slash fires to the atmosphere are appreciable (Fritschen et al. 1970), the emitted quantities add little compared with natural sources. Scientists of Argonne National Laboratory, Argonne, Illinois, have shown that at least 10 times more carbon monoxide enters the atmosphere from natural sources, including oxidation of methane and decay and growth of chlorophyll, than from all industrial and automotive sources combined (Anonymous 1972C, Maugh 1972).

Charcoal residues are highly resistant to decomposition. Pieces are commonly found in many soils. Bollen (unpublished 1931 data) found that, when 1,000 p/m of 60-mesh Douglas-fir charcoal was added to a soil in the laboratory, 14.9 percent was decomposed in 312 days, as shown by CO_2 evolution. However, most of this CO_2 was probably derived from microbial oxidation of the adsorbed hydrocarbons.

Keep in mind that most of the nitrogen is in fallen and decaying leaves of the duff; much less nitrogen is in wood and bark (table 1). Broadcast burning that consumed the duff would result in loss of most of the nitrogen to the atmosphere, largely in the form of nitrogen oxides. DeBell and Ralston (1970) found that 62 percent of the nitrogen in pine litter and green needles was released by burning. They theorized that since only minor amounts of ammonia and other nitrogen compounds appeared in the combustion gases, the majority of the nitrogen was volatilized as nitrogen gas. Piled burning and pit burning would leave much of the duff, with its greater nitrogen content subject to microbial transformation to ammonium and nitrate, which would be available to plant roots. These forms of nitrogen would disappear from the soil only by assimilation and, in the case of nitrates, by leaching.

play a role (Bacon and Mead 1971, Shigo 1967). Present information is insufficient to assess the significance of these organisms.

INTERRELATIONSHIPS OF SOIL MICROBES WITH RESIDUE TREATMENTS

The return of forest organic matter to the soil, whether by standing trees or by their residues after harvest, includes potential nutrients and also increases the capacity of the soil to store nutrients. Microbes are important in this phenomenon because they render the potential nutrients slowly available, so that either or both the soil adsorptive colloidal-organic complex and assimilation by roots and microbes can absorb the nutrients before they are susceptible to loss in drainage or runoff.

RESIDUES FROM DIFFERENT HARVESTING PRACTICES

In addition to tree residues from timber harvest the forest floor has considerable volume and contains significant amounts of nutrients. Youngberg (1966) found that the forest floor in Douglas-fir stands from the Oregon Coast Ranges varied from 20,000 to 76,000 lb/acre (22 to 85 metric tons/ha) and contained from 0.71 to 1.52 percent total nitrogen. Whatever the method of logging, the soil is disturbed and residues are left. When trees are removed, when fires occur, and when vegetation is destroyed by herbicides, the release of nutrients from the soil is accelerated. In part this is due to the resulting microclimate being more favorable to rapid mineralization by the soil microflora (Bormann et al. 1968). Likens et al. (1969) demonstrated that nitrates and other anions in stream water were considerably increased by removal of all vegetation from a forested watershed. The rate of loss is not long sustained, however, and nutrient outflows are small compared with the total nutrient reserve in the soil (USDA Forest Service 1971).

Clearcutting obviously disturbs the soil most and leaves the most residue, calling for postharvest treatment. Chunks and broken pieces could be picked up by relogging for salvage. Prelogging to remove 6- to 30-inch (15.2- to 76.2-cm) diameter trees valuable for pulp, before big trees are logged, can be done with lighter equipment and avoids the damage caused by harvesting big logs. Progressive logging in old growth removes windfalls and sound snags before the green trees are cut, reducing breakage in falling. Thinning and partial harvesting of young-growth stands and harvesting of individual selected trees, as in uneven-aged pine forests, leave much less residue and disturbs the soil less. Shelterwood systems involve less area and have less effect on soil environment. Where even-aged forests are block-logged by area selection, impact is maximum but not widespread.

Greatest damage is done when skid trails and roadways remove all topsoil, causing erosion and increasing susceptibility to leaching and runoff.

Prelogging, thinning, and shelterwood methods not only conserve timber, improve utilization of old-growth stands, and result in clean-logged areas low in fire hazard, but also cause less slash and more rapid decomposition and recycling.

As young-growth trees replace harvested virgin timber, the transition involves changes in forest residue regimes. Old-growth residues should be

Severe burns usually occur in small scattered patches. Only here will all organic matter be destroyed to a depth of several inches. Knight (1966), from burning experiments in the laboratory, reported 25- to 64-percent loss of nitrogen from forest floor material at temperatures of 300°-700° C. Nitrogen concentration of residual material increased, but the total amount of nitrogen decreased. Decay fungi will be destroyed in burned areas but can survive in underlying roots.

Neal et al. (1965) found that slash burning on Astoria silt loam soil significantly reduced water-holding capacity during the 1 year of study. Soil pH was increased in amounts ranging from 0.3 to 1.2 units. Increases in ammonium nitrogen were found up to 6 months after burning, but nitrate nitrogen was low at all times during the 1 year of study. Kjeldahl nitrogen declined, but total carbon increased by 1 to 2 percent; thus the C:N ratio appreciably widened. Numbers of bacteria significantly increased but fluctuated with seasonal changes. Percentage of *Streptomyces* among the bacteria was not markedly influenced. The mold population, however, was significantly reduced. At least the initial effects of slash burning on physical, chemical, and microbial properties of the soil appeared beneficial to fertility.

Accumulation of residues in forests from which fire has been excluded constitutes a fire hazard. For this reason, very light burns may be made periodically. Burning of surface material occurred naturally at intervals of about 5 to 15 years in sequoia and ponderosa pine forests before white man. Prescribed burning to remove the Aoo horizon (duff or surface litter of needles, leaves, twigs, etc.) is practiced at about 5-year intervals in pine plantations of the South. Prescribed burning in conjunction with clearcutting has been used to prepare seed beds for loblolly pine (*Pinus taeda* L.) in the Upper Piedmont of South Carolina and in mixed stands of shortleaf pine (*P. echinata* Mill.) and hardwoods. After leaffall was complete and when the duff had sufficient moisture to prevent exposure of the mineral soil, burning stimulated natural regeneration of yellow-poplar (*Liriodendron tulipifera* L.) (Shearin et al. 1972). Effects of such light burning are: (1) it stimulates germination of seeds of certain species, (2) it removes the competitive herbaceous understory, and (3) the ash is a source of newly available nutrients. Although nitrogen of the burned duff is lost to the air, this loss may be compensated for through nitrogen fixation by *Azotobacter* and other nitrogen-fixing bacteria when the ash is leached into the soil.

Annually burned loblolly pine stands in the lower coastal plain of South Carolina showed an increase in nitrogen of 23 kg/ha/yr (20.5 lb/acre/yr). Fixation rate in burned forest floor samples increased with moisture to above field capacity and with temperature from 25° to 35° C (77° to 95° F) (Jorgensen and Wells 1971).

From a study of microbial characteristics of a South Carolina forest soil after 20 years of prescribed burning, Jorgensen and Hodges (1970) found there were few indications that the burning adversely altered the composition of the saprophytic, sporeforming microfungi, or reduced the number of bacteria and actinomyces to the extent that soil metabolic processes were impaired.

Prescribed burning in a jack pine (*Pinus banksiana* Lamb.) stand on a sandy loam soil immediately decreased numbers and activity of most micro-organisms, but these increased abruptly after the first rainfall (Ahlgren and Ahlgren 1965). Depth and extent of burned area and the effects were influenced by intensity of fire and moisture conditions. Numbers and activity of organisms were generally lower the second growing season after burning, and some effects, especially a greatly increased *Streptomyces* population, were still evident the third growing season.

Greene (1935) found that 8 years of annual grass-burning under a longleaf pine (*Pinus palustris* Mill.) stand in Mississippi increased soil organic matter and nitrogen, originating chiefly from roots rather than from tops of plants. Growth of grass and leguminous plants on burned areas was more than twice that on unburned areas.

Pit burning, used where space and time are at a premium and residue pieces are large, produces a hot fire and completely destroys all organic matter and micro-organisms in the immediate area. To replant the area, the pit must be filled in with fresh soil, preferably with topsoil piled aside during construction of the pit. Portable burning bins, used for smaller amounts of fuel, cause little damage to the soil.

Use of an air cushion logging raft (Anonymous 1972a) (tracked vehicle with directed high velocity air blower) instead of a bulldozer to push slash to a spot for burning would cause less disturbance of the soil. However, the air-blast would transfer more fine residues to the pile or pit. These finer organic particles could better be left on the soil as a mulch, both as a protection for seedlings and as an eventual source of nutrients.

Effects of burning on soil chemical and physical properties are discussed in detail by Moore and Norris (1974) and Rothacher and Lopushinsky (1974). Some examples of changes particularly important to microbial activity deserve mention. Burning of foliage, litter, and F-horizon material can result in loss into the atmosphere of a substantial portion of the nitrogen contained in forest floor material (Knight 1966). Obviously, the surface organic matter is also reduced. Soil pH and the carbon-to-nitrogen ratio can increase (Neal et al. 1965), and the mineral nutrients can be either redistributed or removed by leaching (Smith 1970). Soil bulk density can increase, and soil water-holding capacity and rate of moisture movement can decrease (Tarrant 1956, Neal et al. 1965).

The net effect of burning-induced changes on microbial activity has been studied in only a very few cases and is complicated by seasonal as well as long-term changes. Six months after Douglas-fir slash had been burned in Oregon, the numbers of soil bacteria were significantly greater than at an unburned site, but mold populations were reduced. Ammonium nitrogen also increased in soil of the burned site during this period (Neal et al. 1965). This may have resulted from partial sterilization which eliminated certain competitions or antagonists, and residual humus, perhaps thermally altered, became a suitable substrate. Some available carbon and nitrogen could have been contributed by rainfall and windblown organic matter.

Prescribed burning of a stand of jack pine in Minnesota resulted in an immediate decrease in numbers and activity of most micro-organisms, but these abruptly increased after the first rainfall. Some effects of burning on the soil microbiota were still evident in the third growing season after burning (Ahlgren and Ahlgren 1965). Too little is known about effects of burning and all the variables involved to generalize about either short-term or long-term effects on soil microbes. The net results, however, are not necessarily deleterious.

LEAVING RESIDUES UNBURNED

Decomposition of residues under forest conditions is particularly dependent on moisture, temperature, residue size, and an adequacy of available nitrogen. The closer each of these approaches optimum, the faster will be the rate of decomposition and resultant nutrient cycling. From present knowledge, we assume the native micro-organisms will carry on their essential functions.

In standing forests, the rotting remains of earlier events could be left undisturbed to play their natural role in the ecosystem. Where concentrated, however, the remains could be crushed and scattered to distribute their nutrient potential and minimize undesirable effects.

By any method other than burning, natural disposal of forest residues left on the site will be slow, usually requiring many years. Methods for faster decomposition must be developed. To prolong the coincidence of moisture and temperature ranges most favorable to decomposition, the residue must be in close contact with or, preferably, embedded in the soil. Chipping, crushing, and burying are options where heavy equipment can be used. Chipping and crushing reduce particle size, important in attaining more rapid decomposition. Ideal is approximately 32- to 6-mesh screen size (equivalent to particle sizes of slightly less than 1/32 inch and 1/6 inch, respectively). The pieces should be blown or otherwise spread as uniformly as practicable over the ground and rolled, treaded, or churned to insure maximum contact with soil. Excessive compaction should be avoided. The layer of chips or crushed material should not be too deep; more than 6 inches could retard aeration of the lower strata and underlying duff or soil. A thinner layer allows more complete inoculation with decomposers distributed from dust or soil by wind and rain spatter.

Some chipped or crushed residues can be advantageously used as an erosion-retarding mulch on roadbanks or skidways.

BURYING

Disposal of slash, thinnings, and brush by burying may be feasible (Schinke and Dougherty 1966) where bulldozers could push the slash into pits about 10 to 12 feet wide, 50 to 100 feet long, and up to 10 feet deep (3 to 3.5 m wide, 15 to 30 m long, and up to 1 m deep), and then cover the slash with about a foot (30 cm) of soil. Enough soil for inoculation would be mixed with the material during transfer and enough moisture would be held under the soil cover to allow fairly rapid decomposition. Addition of nitrogen fertilizer or establishment of dinitrogen-fixing plants would be desirable (Bollen 1969). Nitrogen must be added to avoid temporary nitrogen deficiency of tree regeneration if residue particles are incorporated into the soil (Cochran 1968). Depending on soil type, phosphate and sulfur fertilizers may be required.

Burying should not take place in heavy, poorly aerated soils or where there may be poor drainage and a high water table. In such cases, the material will ferment, decomposition will be incomplete, and acids and other undesirable end products will accumulate. Sufficient heat may be retained from the microbial and chemical reaction to cause spontaneous combustion and thus create a fire hazard (Bollen and Lu 1970).

Some compaction from use of equipment could be desirable to insure favorable contact with inocula and active surfaces, but repeated compaction over the same area could retard aeration. Some disturbance of the natural soil by any method involving heavy equipment is inevitable. As long as this is confined to the surface soil and does not admix much of the subsoil, the results should not be damaging.

OTHER USES OF RESIDUES

Availability of chips from residues offers potential for solving some of the other waste disposal problems of civilization. Application of sewage plant waste water to forest land has shown promise (Pennypacker et al. 1967). This involves functioning of the litter and F layer as biological and chemical filters and the long-term capability of the soil to act as a physical filter. Microbes decompose and metabolize biodegradable organic materials rapidly under favorable conditions of aeration and temperature; most of the sludge would be decomposed within a month if water relations were managed to avoid anaerobiosis, which would result in gas production, odor, and unsanitary conditions. Potentially toxic or ecologically undesirable compounds such as pesticides and phenols would be decomposed with sufficient residence time. Forest growth is promoted by water and nutrients from sewage plant effluents, and deer populations have increased in treated areas. Site and management are critical factors in obtaining good results.

After several years' study of sprinkler irrigation of sewage effluent in a mixed oak stand, a red pine (*Pinus resinosa* Ait.) plantation, and an old open field area planted with white spruce, Sopper and Kardos (1972) concluded that diversion of such waste water to the forest ecosystem should help to eliminate or alleviate many disposal and pollution problems. Secondary benefits observed were an increased recharge of ground-water reservoirs, increased growth of vegetation, and amelioration of unproductive sites. Detergent residues did not accumulate, suggesting complete degradation by soil micro-organisms. Extractable phosphate and exchangeable sodium increased in the sewage irrigated soil, but no other particular cation or group of cations appeared to be adsorbed or released. There were no significant qualitative or quantitative microbiological differences between the control and irrigated areas. Total nitrogen did not accumulate in the soil; apparently the effluent nitrogen was absorbed by the vegetation.

Biotoxic elements in compounds of heavy metals, including cadmium, copper, lead, nickel, and zinc, are present in sewage sludge in concentrations greater than in normal soils (Anonymous 1973) and may build up to undesirable concentrations from long-continued applications of sludge or, perhaps, even from waste water. A monitoring system to keep track of such metals thus added to soils and taken up by plants is desirable.

The Forest Service as well as the Corps of Engineers and several university experiment stations are involved in projects seeking feasible methods for the most efficient and beneficial methods for disposal and utilization of sewage plant waste.

A series of papers from a symposium on Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland has recently been published. (Sopper and Kardos 1973). Topics covering waste water and sludge include chemical and biological quality; the soil as a physical, chemical, and biological filter; waste water quality changes during recycling; soil, vegetation, and other ecosystem responses; examples of operating and proposed systems; and research needs.

Bark or chips might be suitable for primary biological filters. Microbial decomposition would be enhanced by the addition of moisture and nutrients. Perishable garbage might also feasibly be disposed of in areas where residues can be chipped. A mix of residue, garbage, and soil, with added nitrogen when needed, would improve decomposition of both forest and city residues by increasing aeration and available nutrients. It would offer additional benefits of esthetics and odor suppression.

Agricultural uses of ground bark and wood residues should not be overlooked in localities where feasible (Bollen 1969), even though the current demand is supplied by sawmills and wood-processing plants.

MICROBIAL INTERACTIONS WITH CHEMICALS

Pesticides including herbicides, fire retardants, fertilizers, and petroleum products are all associated with production or treatment of forest residues. Any of these various chemicals are capable of destroying at least certain soil microbes under certain conditions, but this hazard is appreciable only when rates of application far exceed those generally used (Bollen 1961, Martin 1963).

PESTICIDES

Some of the pesticides, e.g., the chlorinated hydrocarbons, are quite resistant to microbial attack. Their degradation by microbes and plant roots is slow (Mehendale et al. 1972), so that much can be leached or volatilized to become widely distributed in the biosphere. Others, such as the organic phosphates, are readily decomposed and may even stimulate microbial activity (Bollen et al. 1970, Bollen and Tu 1971). In general, the presence of most pesticides on forest residues is not likely to impede decomposition.

Similarly, residues produced by responsibly applied herbicides will likely be as readily decomposed by microbial attack as "natural" residues. To the extent they have been studied, organic herbicides have proven to be rapidly degraded and have little effect on microbial populations or activities (Bollen 1962, Norris 1966, Tu and Bollen 1969). Even arsenic compounds, such as cacodylic acid or monosodium methanearsonate (MSMA) used as silvicides in thinning operations, are degraded by soil organisms (Von Endt et al. 1968). Research in progress at the Forestry Sciences Laboratory, Corvallis, Oregon, indicates that these compounds applied at rates as high as 1,000 p/m arsenic equivalent have no appreciable effect on common forest soil microbes or on their general physiological activity in forest soil or litter.

Effects of pesticides on the forest ecosystem are more extensively discussed in this volume by Moore and Norris (1974).

FIRE RETARDANTS

Chemicals used in fire control operations now include diammonium phosphate, ammonium sulfate, and ammonium pyro (poly) phosphate (Handleman 1971). These have high fertilizer values of available nitrogen, and the phosphates also supply phosphorus. Sulfur from ammonium sulfate would be valuable on soils of humid regions and on soils derived from basalt because these are typically low in sulfate. Only when the concentration might be high enough to produce osmotic effects would these chemicals retard microbial action. However, such effects would disappear upon dilution by rainfall or snowmelt. Leaching from heavy concentrations could cause eutrophication in streams and lakes (Lotspeich and Mueller 1971). Aside from direct fertilizing value, the added nutrients would enhance desirable microbial action in the soil and on tree residues.

Other chemicals included in the retardant formulations include (1) thickeners, such as clays and gums; (2) corrosion inhibitors; (3) ferric oxide color; (4) stabilizers; and (5) flow conditioners. These are present in relatively minor concentrations and therefore would have very little effect on soil microbes.

Studies now in progress at the Forest Research Laboratory in Corvallis, Oregon, indicate that as much as 100 lb/100 ft^2 of Phos-Chek, a diammonium phosphate based fire retardant, has little effect on decomposition of organic matter and nitrification.

FERTILIZERS

Forest fertilization, especially with sources of nitrogen, commonly a limiting nutrient element in soils, is practiced to increase tree growth and to enhance early development of introduced native vegetation after fires. The need for fertilizers has been extensively discussed by Maki (1966). Aside from benefiting the plants, fertilizers promote microbial decomposition of forest residues and soil organic matter. Nitrogen fertilizers are subject to losses by leaching and by denitrification. Nitrate forms are subject to these losses directly; ammonium fertilizers and urea, only after nitrification.

Urea pellets, because of high nitrogen content (46 percent) and consequent lighter weight than ammonium sulfate or ammonium nitrate, are preferred for aerial application, usually at the rate of 200 pounds of nitrogen per acre (224 kg/ha). This is rapidly transformed to ammonium nitrogen (NH_4^+) by microbes in the soil, is then subject to assimilation by plant roots and microbes, or may be oxidized by nitrifying bacteria to nitrate (NO_3^-). Nitrate is generally not desirable because it is subject to leaching and to loss of nitrogen gases by denitrification. Whether or not NO_3^- may be a preferable form for assimilation by plants is questionable, but McFee and Stone (1968) found that Monterey pine (*Pinus radiata* D. Don) and white spruce seedlings exhibited greater growth and nitrogen uptake with an ammonium source than with nitrate. Ammonium is assimilated by most kinds of plants, the preference being determined by a combination of factors, including kind and age of plant, pH, assortment of other ions, and environmental factors (Prianishnikov 1942). The effect of forest fertilization on water quality has been discussed by Moore (1972). Total amounts of fertilizer nitrogen entering surface streams after aerial application of urea to forested watersheds were minor and below toxic levels.

Sulfur fertilizers are beneficial in humid regions where sulfate ($SO_4^=$) is readily leached, and also on soils derived from basalt, which is low in sulfur. Fertilizers carrying $SO_4^=$, as in ammonium sulfate ($(NH_4)_2SO_4$) or gypsum ($CaSO_4.2H_2O$), provide this nutrient. They could therefore promote decomposition and recycling of forest litter and residues. Pumice soils supporting stands of ponderosa pine have shown response to gypsum (Will and Youngberg 1972). Flour sulfur (S), preferably in pellet form for aerial application, becomes available after oxidation in the soil by *Thiobacillus thiooxidans* and related species. Phosphate fertilizers may be needed in some cases to supply available phosphate. Forest management operations that remove surface soil will seriously lower the N, P, and S status of the site, and the use of fertilizers will be essential.

PETROLEUM PRODUCTS

Hydrocarbon fuels, oil, grease dropped from mechanical equipment, and oil carriers of biocidal sprays are not likely to harm microbial decomposition of residues. About a hundred species of bacteria, yeasts, and molds, many indigenous to the soil, attack hydrocarbons, even those considered to be antiseptic (Zobell 1946, Jones and Edington 1968). Asphalt and rubber also are slowly attacked. Applications of crude oil to soil result in increased microbial populations and, in many cases, improve soil fertility.

CONCLUSIONS

RECOMMENDED PRACTICES

Any burning of forest residues results in immediate losses of nitrogen from the ecosystem. Hard burns can be deleterious to soil physical properties. Such adverse effects of burning can be avoided by taking advantage of present knowledge about soil microbes and their interactions with residues. Desirable microbial activity, including rapid decomposition of residues, gradual release of bound nitrogen and other nutrients for tree growth, and improvement of soil physical properties by humus development can be enhanced by proper treatment. Incorporation of rotted wood as well as leaves and comminuted thinnings and slash could improve aeration, drainage, and moisture retention properties. Such treatment entails (1) reducing residue particle size by chipping or crushing, (2) assuring good contact of residue particles with soil, and (3) fertilizing with nitrogen to overcome early nitrogen deficiency caused by rapid microbial population buildup. Because the nitrogen in residues and assimilated fertilizer is gradually released by death of microbial cells, relatively little is lost from the ecosystem. Technology now exists to conserve and increase fertility on many sites, although better, more economical methods can doubtless be devised. The long-term potential benefits of improved site productivity must be kept in mind when costs of the treatment are reckoned. Residue and fertilizer treatments can be designed to serve as site preparation for regeneration as well. Forests, if not abused, tend to improve fertility of the soil, especially if use can be made of soil-ameliorating trees such as alder (*Alnus* spp.) and black locust (*Robinia pseudoacacia* L.).

RESEARCH NEEDED

So little research on soil microbial relationships of forest soils has been done that virtually all aspects need further work. High priority needs in relation to residues and residue treatments include (1) research techniques; (2) evaluation of long-term as well as short-term effects of treatments; (3) development of more economical and more widely applicable methods to hasten residue decomposition; (4) studies on specific situations, including combinations of tree species, climate, soil type, and residue; (5) more efficient methods of evaluating effects of residue treatments on microbial activity--existing methology may serve the purpose, but it needs to be better adapted for easy field use, and the interpretive value for results needs to be confirmed; (6) soil respiration determinations for evaluating effects of different residue treatments on microbial activity; (7) studies on long-term effects--the short-term effects of some residue treatments on nitrogen cycling in ecosystems have been studied to some degree. Microbial decomposition of residues is an integral feature of the cycling process, controlling the rates and times of nitrogen release. We must learn how the process is influenced by varying the major factors that affect microbial activity before we can quantitatively predict long-term effects of residue treatments. Long-term effects must be reasonably predictable in order to compare the net benefits of treatment alternatives.

More effective and efficient means of hastening microbial decomposition of residues and nitrogen recycling probably can be developed--certainly few have been tried to date. Nitrogen-fixing plants such as legumes, alder, and ceanothus have been effectively used in forests in lieu of nitrogen fertilization. These nitrogen fixers offer many benefits in terms of enhanced microbial activity, residue decomposition, and continuing nitrogen input (Tarrant and Trappe 1971). At the same time, they present silvicultural problems that need to be overcome. (8) studies of nitrification inhibitors. Outflow of nitrogen from ecosystems could conceivably be stemmed by applications of nitrification inhibitors and more strategic placement of residue fragments. The potential of multiple benefits from use of fragmented residues in sewage waste water and garbage disposal on forest land should be explored. (9) evaluation of differential response to ammonium fertilizers of different tree species in different situations, including deficiency of other nutrients, to obtain maximum response from nitrogen sources. In this connection the possible value of nitrification inhibitors should be investigated. (10) working out the technology of sewage waste water and garbage disposal, evaluating first the microbiological and other ecosystematic factors.

EQUIPMENT DEVELOPMENT

Equipment that combines fragmentation of residue and scattering or mixing with soil, nitrogen fertilization, and possibly even seed broadcasting into a single operation could substantially increase efficiency of residue treatment. Development of such equipment and also equipment for fragmenting residues on steep slopes should receive high priority.

RELATED INVESTIGATIONS IN PROGRESS

1. At the Forestry Sciences Laboratory, Corvallis, Oregon.

Effect of fire retardants on microbial activities in forest litter and soil, with emphasis on organic matter decomposition and nitrification. W.B. Bollen.

Decomposition of litter in different forest stands. Kermit Cromack, Jr.

2. In the Coniferous Forest Biome. Ecosystem Analysis, International Biological Program. 1973-1974.

Decomposers on living twigs and foliage. G.C. Carroll, C. Driver.

Decomposer process studies. W.C. Denison, G.C. Carroll.

Further studies on the characterization of primary decomposition of the wood components of the Douglas-fir ecosystem. D.H. Driver, W.C. Denison.

Energy flow as determined by rates of litter decomposition. C.M. Gilmour, C.T. Youngberg.

A coordinated study of movement of elements from vegetation to soil in coniferous ecosystems. C.C. Grier.

Role of microfauna in biogeochemical cycling. H.J. Jensen, G.W. Krantz.

Coordinated nutrient cycling and litter decomposition study. D.P. Lavender, W.C. Denison, J.R. Sedell.

Fixation, uptake, and release of nitrogen by epiphytes. L.H. Pike.

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