

# Nutrient Mineralization Processes in Mediterranean-Type Ecosystems<sup>1</sup>

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Mineralization is a general term referring to processes that convert complex organic and inorganic materials into soluble ions available for plant uptake. Three mineralization processes are potentially important in mediterranean-type ecosystems; these are (1) pyrolysis of organic matter, (2) decomposition of organic matter, and (3) chemical weathering of inorganic minerals (fig. 1). These three mechanisms are the key processes controlling nutrient availability in terrestrial ecosystems. The rate of nutrient release through these processes is largely a function of substrate quantity and quality, temperature, and moisture.

The objectives of this review are to (1) assess the magnitude and relative importance of pyrolysis, decomposition, and weathering on macronutrient (N, P, K, Ca, Mg, S) flux in mediterranean-type ecosystems and (2) assess the importance of substrate quantity and quality, temperature, and moisture in determining nutrient flux.

## PYROLYSIS OF ORGANIC MATTER

The importance of fire as a mineralizing agent in mediterranean-type ecosystems is generally recognized (Naveh 1975, Groves 1977, Zinke 1977, Trabaud 1981). Fire can affect mineralization processes in both direct and indirect ways. The direct ashing of organic matter releases significant quantities of N, P, K, Ca, Mg, and S (table 1). The release is particularly large for

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Abstract: The objective of this paper is to assess the role of mineralization processes (pyrolysis, decomposition, and weathering) on nutrient (N, P, K, Ca, Mg, and S) release in mediterranean-type ecosystems. Decomposition is the most important process for N release. Decomposition and pyrolysis are both significant in the release of K, Ca, and Mg. Too little is known concerning the mineralization of P and S to allow generalizations. Also, generalizations about weathering are difficult because of the high site specificity of nutrient release through weathering. Environment is as important as substrate in estimating mineralization rates; these mineralization rates should be more sensitive to moisture than to temperature fluctuations.

K, Ca, and Mg. This "pulse" nutrient addition is important for the rapid reestablishment of chaparral vegetation following fire (Naveh 1975, Christensen and Muller 1975). Work in the *Quercus coccifera* garrigue has also shown that fire leads to an immediate increase in available P, K, Ca, and Mg (Trabaud 1981). The actual release depends largely on the quantity of organic matter, temperature, and moisture. Laboratory studies have shown that NH<sub>4</sub> and NO<sub>3</sub> formation begins at 200°C and peaks between 300 and 350°C; beyond 500°C, nitrogen is completely volatilized (Dunn and DeBano 1977). The formation and loss of available nitrogen depends on soil moisture content. Moist soils stay cooler during fires because the heat energy can be dissipated by evaporating moisture. As a consequence, there is generally less release of available N during fires over moist soils (table 1).

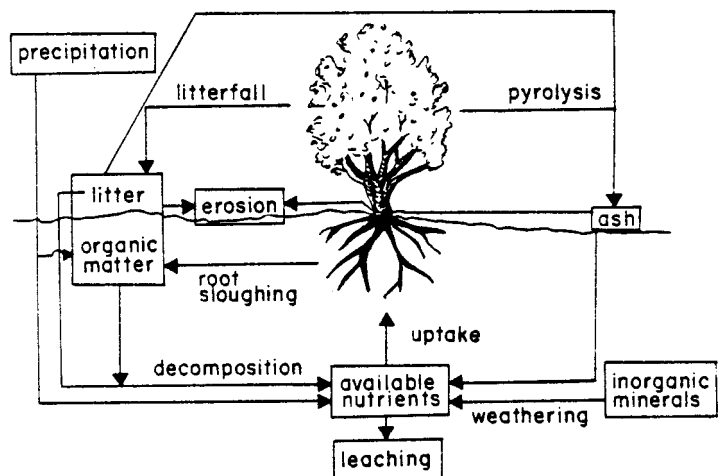


Figure 1--The ecosystem nutrient cycle.

Table 1--Nutrient mineralization from pyrolysis of organic matter in selected mediterranean-type and forest ecosystems.

Ecosystem: Location (Reference)	Experimental conditions	Nutrient					
		N	P	K	Ca	Mg	S
Chamise chaparral: California (Christensen and Muller 1975)	Laboratory ashing of vegetation	0.04	0.01	5.1			0.4
	Laboratory: Burning treatments						
Chamise chaparral <u>Ceanothus</u> chaparral	Intense-dry	0.29 0.88					
Chamise chaparral <u>Ceanothus</u> chaparral	Intense-moist	0.36 0.13					
Chamise chaparral <u>Ceanothus</u> chaparral	Moderate-moist	0.17 0.14					
Chaparral: California (DeBano et al. 1979)	Field: prescribed fire	1.0-2.4					
<u>Adenostoma-Ceanothus-Salvia</u> chaparral: California (DeBano and Conrad 1978)	Field: prescribed fire			4.1	11	6.6	
Coniferous forest: Washington (Grier 1975)	Field: wildfire			3.2	31	4.5	

Fire can indirectly affect mineralization by creating a more favorable environment for mineralization processes following fire. Available  $\text{NH}_4$ ,  $\text{NO}_3$ , and P are generally higher on burned sites than on unburned sites for periods up to 2 years following fire (Christensen and Muller 1975). Factors present following fire that can lead to a more favorable microbial environment include the high content of organic N added with the ash, higher soil temperatures, more favorable moisture conditions, and the destruction of allelopathic compounds during the fire (Naveh 1975, Christensen and Muller 1975). However, the presence of high levels of available nutrients for long periods following fire is not always evidence of improved mineralization. The high available nutrient levels may simply reflect a low vegetative uptake during the establishment phase.

Although fire is generally considered a beneficial agent in releasing nutrients tied up in organic matter, there is evidence that burning too frequently can lead to site nutrient degradation (Groves 1977, Trabaud 1981, Schlesinger and Gray 1981). Frequent fires can exacerbate an already nutrient deficient situation favoring the growth of shrubby sclerophyllic species instead of the more herbaceous species and thus "deflect" succession in mediterranean-type ecosystems (Specht 1973, Groves 1977).

#### DECOMPOSITION OF ORGANIC MATTER

##### Annual Nutrient Fluxes

Decomposition of organic matter is an important process leading to the release of N, P, K, Ca, Mg, and S into forms available for plant growth. However, decomposition and mineralization are not generally synonymous. Decomposition refers to the breakdown, or disappearance, of organic matter. For a nonstructural nutrient, such as K, decomposition and mineralization are synonymous. Structural nutrients, such as N, P, and S, are frequently converted into soluble organic forms during decomposition; an additional step is required to break the organic molecules into soluble inorganic ions before plant uptake can occur. As a consequence, litter decomposition data cannot be directly used to estimate mineralization rates with the exception of K. The annual nutrient mineralization from decomposition of organic matter falls in the order:  $\text{N} \approx \text{Ca} > \text{K} > \text{Mg} \approx \text{S} > \text{P}$  (table 2). The magnitude of this release is significant with respect to plant requirements. In fact, N mineralization from organic matter is the primary source of available N for plant uptake in terrestrial ecosystems (Rosswall 1975, Ellenberg 1977).

## Nitrogen Mineralization

Nitrogen is of special importance because it is the nutrient which most frequently limits growth in terrestrial ecosystems (Ellenberg 1977, Gray and Schlesinger 1981). Substrate quantity and quality, temperature, and moisture largely control N availability. The quantity of N within an ecosystem can be easily measured; however, such point-in-time measurements are poorly correlated to N availability (Harmsen and van Schreven 1955). Soil incubations are considered the best technique for assessing substrate quality with respect to N availability (Harmsen and van Schreven 1955, Stanford and Smith 1972).

Accumulative nitrogen mineralized ( $N_t$ ) with time ( $t$ ) under optimal temperature (35°C and moisture (0.2 bar soil moisture tension) in the laboratory can be described with a three-parameter logarithmic equation:

$$\text{Log}(N_0 - N_t) = \text{Log} N_0 - kt^b \quad (1)$$

where  $N_0$  is potentially mineralizable N,  $k$  is the rate constant, and  $b$  is the time exponent (Marion and others 1981). Nitrogen mineralization parameters for chaparral and matorral soils show considerable variation between soils, particularly in the potentially mineralizable nitrogen (table 3); the latter parameter is an estimate of substrate quality.

The laboratory nitrogen mineralization equations can be used to estimate field nitrogen mineralization by adjusting for suboptimal moisture and temperature. Stanford and others (1973) found a  $Q_{10}$  of 2.0 for the N mineralization rate constants ( $k$ ; table 3); that is, the rate constant is halved for every 10°C drop below 35°C. Stanford and Epstein (1974) found that relative N mineralization with respect to moisture (N mineralized at field moisture/N mineralized at optimum moisture) was equal to relative moisture content [field moisture content/optimum moisture content (approximately field capacity)]. Nitrogen mineralization under optimal moisture and temperature for the Cieneba-mixed soil (table 3) is 5.4 ppm N/week. Using the above relationships to adjust the optimal equation (table 3) to field temperature and moisture (measured at the Echo Valley research site), one can calculate the relative effect of field temperature and moisture on N mineralization (fig. 2). Moisture is optimum for N mineralization during the winter months; temperature optimums for N mineralization are reached in the summer. However, the relative N mineralization attributable to temperature fluctuates by a factor of less than three, while the relative N mineralization attributable to moisture fluctuates by a factor of ten (fig. 2). As a consequence, the combined moisture and temperature curve, which assumes that moisture and temperature are acting independently, more closely follows the moisture fluctuations.

Table 2--Nutrient mineralization from decomposition of organic matter in selected mediterranean-type and forest ecosystems.

Ecosystem: Location (Reference)	Material	Nutrient					
		N	P	K	Ca	Mg	S
		$\text{g m}^{-2} \text{ yr}^{-1}$					
Coastal sage: California (Gray and Schlesinger 1981)	Litter			<sup>1</sup> 1.1			
<u>Ceanothus</u> chaparral: California (Gray and Schlesinger 1981)	Litter			<sup>1</sup> 3.4			
Chamise chaparral: California (Mooney and Rundel 1979)	Soil and litter	3.3					
Mixed chaparral: California (Marion et al. 1981)	Soil and litter	8.0					
<u>Banksia</u> scrub: Australia (Maggs and Pearson 1977)	Litter			<sup>1</sup> 0.9-2.1			
<u>Quercus ilex</u> forest: France (Lossaint 1973)	Litter	2.6	0.2	0.7	5.3	0.3	
Deciduous forest: U.S.A. (Likens et al. 1977)	Soil and litter	7.0		2.0	4.2	0.6	0.6

<sup>1</sup>Calculated from litterfall data assuming the ecosystem litter is in a steady state (input = output).

Table 3--Nitrogen mineralization parameters for the equation,  $\text{Log}(N_0 - N_t) = \text{Log} N_0 - kt^b$ , determined under optimal conditions for temperature (35°C) and moisture (0.2 bar moisture tension) (Marion et al. 1981).

Location: soil	Horizon	Total nitrogen	Potential mineralizable nitrogen ( $N_0$ )	Rate constant (k)	Time exponent (b)	$r^2$
		%	ppm	week <sup>-1</sup>		
San Diego County, California, U.S.A.:						
<sup>1</sup> Cieneba-chamise	A	0.043	9.8	0.141	0.61	0.94
	C	0.016	0.4	<sup>2</sup> 0.39	<sup>2</sup> 0.70	---
<sup>1</sup> Cieneba-mixed	A	0.098	24.5	0.109	0.72	0.77
Tollhouse	A	0.083	14.8	0.104	0.65	0.96
	AC	0.035	4.0	<sup>2</sup> 0.50	<sup>2</sup> 0.70	--
La Posta	A	0.186	50.7	0.070	0.73	0.95
	C	0.075	11.9	0.142	0.69	0.97
Las Posas	A	0.123	54.0	0.104	0.87	0.99
	B	0.040	3.0	0.147	0.62	0.94
Sheephead	A	0.107	20.3	0.127	0.73	0.98
	C	0.050	3.4	<sup>2</sup> 0.87	<sup>2</sup> 0.70	--
Fundo Santa Laura, Chile:						
Ridgetop--near ravine	A	0.223	73.0	0.027	1.09	0.94
Ridgetop	A	0.141	37.6	0.082	0.87	0.99

<sup>1</sup>The Cieneba-chamise and Cieneba-mixed are Cieneba soils under pure chamise and mixed chaparral vegetation, respectively.

<sup>2</sup>Calculated indirectly because of too few points for a statistical fit.

Nitrogen mineralization is more sensitive to moisture than to temperature fluctuations in this mixed chaparral ecosystem; this high sensitivity to moisture conditions agrees with previous chaparral work (Schaefer 1973, Mooney and Rundel 1979). Nitrogen mineralization should theoretically peak in the winter and be at a minimum in the summer. The simulated weekly N mineralization ranged from 3 to 27 percent of the optimal amount (5.4 ppm N). Clearly, quantification of the mineralization environment, particularly temperature and moisture, is as important as quantification of substrate quantity and quality in estimating N availability in terrestrial ecosystems.

These field temperature and moisture effects are based on a theoretical model of the N mineralization process developed from laboratory studies. There exists field data to support this theoretical model. Using the N mineralization equations for optimal conditions (table 3), the previously mentioned relationships to adjust N mineralization to field moisture and temperature, and field moisture and temperature measurements, one can calculate the annual N mineralization by integrating the mineralization equations at weekly time steps over the plant rooting zone. The predicted annual N mineralization for a

chamise and a mixed chaparral ecosystem were 3.2 and 7.4 g N m<sup>-2</sup> yr<sup>-1</sup>, respectively; these estimates agree reasonably well with independent estimates using a mass balance equation of 3.3 and 8.0 g N m<sup>-2</sup> yr<sup>-1</sup>, respectively (Marion and others 1981).

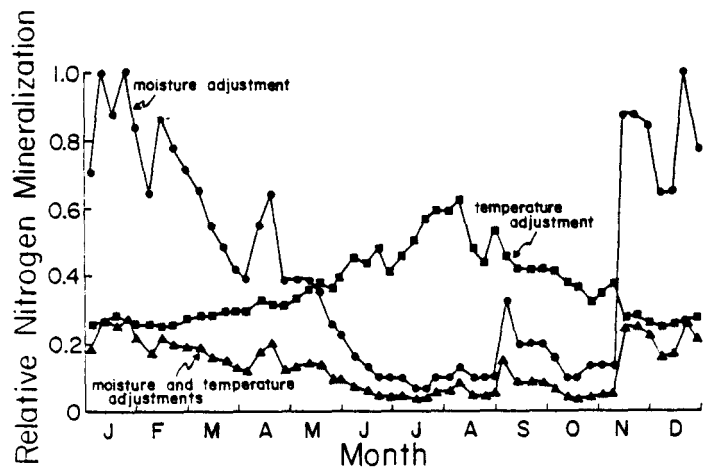


Figure 2--The simulated effect of seasonal field soil temperature and moisture on relative nitrogen mineralization for a surface soil in a mixed chaparral ecosystem.

Table 4--Nutrient mineralization from chemical weathering in selected mediterranean-type and forest ecosystems.

Ecosystem type: Location (Reference)	Rock type	Nutrient				
		P	K	Ca	Mg	S
		$\text{g m}^{-2} \text{yr}^{-1}$				
Fynbos: South Africa (Day 1981)	Sandstone	0.025	6.0	3.5	2.0	
Oak-pine forest: New York, U.S.A. (Woodwell and Whittaker 1967)	Outwash sands		1.0-1.2	2.3-2.6	0.7-1.0	
Scrub pine-oak forest: Maryland, U.S.A. (Cleaves et al. 1974)	Serpentinite		tr	tr	3.4	
Forest: Maryland, U.S.A. (Cleaves et al. 1970)	Shist		0.23	0.13	0.17	
Oak-beech forest: Luxembourg (Verstraten 1977)	Shale		0.02	0.87	1.6	
Northern hardwood forest: New Hampshire, U.S.A. (Likens et al. 1977)	Moraine/gneiss		0.71	2.1	0.35	0.08
Douglas-fir forest: Oregon, U.S.A. (Fredricksen 1972)	Tuffs/breccias		0.16	4.7	1.2	
Northern hardwood forest: Michigan, U.S.A. (Adams and Boyle 1979)	Outwash sands		0.1-0.3	0.1	0.1	

Table 5--The primary minerals and mean annual temperature and precipitation for five selected sites within mediterranean-type ecosystems.

Ecosystem: Location (Reference)	Rock type: Primary minerals	Mean annual	
		Temperature	Precipitation
		$^{\circ}\text{C}$	$\text{mm}$
Chaparral: Echo Valley, California (Thrower and Bradbury 1977)	Quartz diorite: plagioclase, quartz, orthoclase	17	440
Matorral: Fundo Santa Laura, Chile (Thrower and Bradbury 1977, Miller et al. 1973)	Andesite: plagioclase, augite. Quartz diorite: Hornblende quartz, plagioclase, biotite	16	550-600
Garrigue: Montpellier, France (Lossaint 1973)	Limestone: calcite	14	770
Fynbos: Jonkershoek, South Africa (Kruger 1977, 1979)	Quartzite: quartz	16	1270
Heath: Dark Island Soak, Australia (Specht and Rayson 1957)	Aeolian sand: quartz	15	460

CHEMICAL WEATHERING OF INORGANIC MINERALS

Many igneous, metamorphic, and sedimentary rocks were formed under high temperatures, high pressures, and in the absence of air and water; their exposure to the low temperatures, low pressures, and the presence of air and water at the Earth's surface causes their chemical breakdown into stable secondary minerals. A by-product of this chemical transformation is the release of essential nutrients for plant growth. Primary mineral weathering is an important process releasing Ca, Mg, and K, and to a lesser extent, P and S for plant growth.

Watershed level studies using mass balance techniques provide the best estimates of nutrient release from rock weathering (Clayton 1979). A mass balance equation can be written as:

$$\text{precipitation} + \text{weathering} = \text{plant uptake} + \text{leaching} + \Delta \text{ soil storage} \quad (2)$$

Accurate estimates of weathering rates require accurate estimates of precipitation, plant uptake, leaching, and changes in soil storage. Although there are a few gaged watersheds within mediterranean-type ecosystems, none have been used to estimate rock weathering rates. The only estimate of nutrient release from rock weathering in a mediterranean-type ecosystem was developed by assuming a weathering rate of 1 cm/100 years for a sandstone (table 4); since details of this estimate are not available, it is impossible to critically assess its validity. However, the weathering data from forested ecosystems are adequate to demonstrate the high inherent variability likely to be found from site to site (table 4). Under the right circumstances, significant amounts of K, Ca, and Mg can be released, but generalizations are difficult because of the highly variable mineral suites (tables 4 and 5).

Both temperature and moisture affect weathering rates. The weathering diagram (fig. 3) depicts the relative effect of temperature and moisture on chemical weathering intensity. At the average temperature and precipitation typical of mediterranean-type ecosystems, the chemical weathering intensity should be weak to moderate (fig. 3). Because moisture regimes are more likely than temperature regimes to be different between sites within mediterranean-type ecosystems (fig. 3), differences in chemical weathering intensity between sites are more likely to be due to moisture than to temperature. Climate also plays an indirect role on weathering intensity through its effect on vegetative growth. Carbon dioxide from root and microbial activity in the soil can react with water to form carbonic acid which can react with primary minerals. Carbon dioxide levels may ultimately control weathering in soils (Johnson and others 1975, Routson and others 1977).

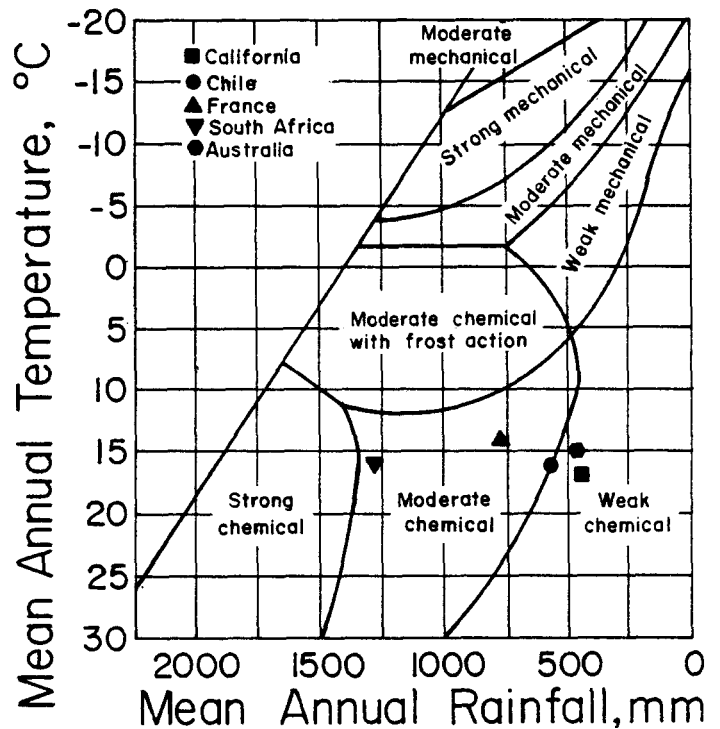


Figure 3--Relative mechanical and chemical weathering rates as influenced by mean annual temperature and rainfall (adapted from Peltier 1950).

An alternative to the empirical measuring of chemical weathering rates is to develop a theoretical model based on chemical thermodynamics. Adequate thermodynamic data exist to develop such models (Sillen and Martell 1964, Robie and Waldbaum 1968, Wagman and others 1968, Lindsay 1979). The solubility of simple compounds, such as calcite and gypsum, have been used in theoretical soil models (Dutt and others 1972). More complex primary mineral weathering models have been developed for arid watersheds (Routson and others 1977) and humid watersheds (Cleaves and others 1970, 1974); however, it remains to be seen whether or not equilibrium thermodynamic relationships can be used to quantitatively predict the release of nutrients from complex suites of primary minerals.

SUMMARY

Decomposition is the most important process rendering N available for plant growth in mediterranean-type ecosystems. Although important quantities of available N are added through pyrolysis (0.04-2.4 g m<sup>-2</sup> yr<sup>-1</sup>), more available N can be expected through decomposition on an annual basis (2.6-8.0 g m<sup>-2</sup> yr<sup>-1</sup>). The pulse addition through pyrolysis of K, Ca, and Mg (3.2-31 g m<sup>-2</sup> yr<sup>-1</sup>) will probably exceed annual additions through either decomposition or weathering (tr-6.0 g m<sup>-2</sup> yr<sup>-1</sup>); however, release of K, Ca, and Mg through decomposition will

certainly play an important role in cycling of these nutrients. It is difficult to generalize about chemical weathering release of K, Ca, and Mg because of the highly variable primary mineral suites present in the different mediterranean-type ecosystems (table 5) and the highly variable moisture regimes (fig. 3). Decomposition and chemical weathering both can play an important role in the cycling of P; however, because of the highly immobile nature of P, it is quite difficult to separate decomposition and weathering releases. Too little is known about S release to allow generalizations at this time.

Although substrate quantity and quality play an important role in the mineralization processes, the environment in which these transformations take place is of equal importance (figs. 2 and 3). Although both temperature and moisture are important, both organic matter decomposition and chemical weathering rates in mediterranean-type ecosystems are more likely to be influenced by moisture fluctuations than by temperature fluctuations (figs. 2 and 3).

Two serious gaps exist in our current understanding of nutrient mineralization processes in mediterranean-type ecosystems. Phosphorus limits growth in many mediterranean-type ecosystems (Gray and Schlesinger 1981, Read and Mitchell 1981). In part, because P is highly immobile in soils and, in part, because of the many processes controlling P availability, our understanding of the controls on P availability is not good. A simple P mineralization model relating substrate quantity and quality, temperature, and moisture, analogous to the N mineralization model, does not exist. More complex P models exist (Cole and others 1977), but they generally require too much information to be useful for practical purposes. Our current understanding of the importance of chemical weathering in mediterranean-type ecosystems is poor. Experimental work on chemical weathering would be a valuable contribution to furthering our understanding of nutrient cycling in mediterranean-type ecosystems.

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