8 Crop Response to Lime in the Western United States

T. L. JACKSON

Oregon State University
Corvallis, Oregon

H. M. REISENAUER

University of California
Davis, California

The western states include a complex combination of geological, topographical, climatic, and vegetative features. The region extends through 1900 km of latitutde and contains three major north-south, storm-directing mountain systems. Most of the region is arid (annual precipitation < 50 cm); however, sizeable agriculturally important areas west of the Cascade and Sierra Nevada mountains, and at higher elevations along all the major mountain systems, receive substantial annual precipitation (120–200 cm). Mean annual temperatures vary from 24°C in the desert areas near our border with Mexico to 3°C in the mountain valleys of the Northwest. This wide range of climates superimposed over a variety of parent materials and landforms has favored the development of many widely differing soils. To this variety of soils and climates, farmers have introduced agricultural systems that include a large number of economically important crops grown under management systems that vary from minimal to the most intensive. As a result, acid soils and soil acidification, although not always extensive, are important in every area of the region.

I. SOILS OF THE REGION

Several factors make the soils and agriculture of the western states different from the soils and agriculture of humid areas east of the Rocky Mountains. The wide variation in soils is shown in Figure 1. First, precipitation is concentrated in the winter, and the summers are dry. Second, west of the Cascade Range, temperature variation through the year is small. July and January average temperatures generally differ < 16.7°C. Third, some areas have very high precipitation, ranging up to > 200 cm yr^{-1}. Fourth,

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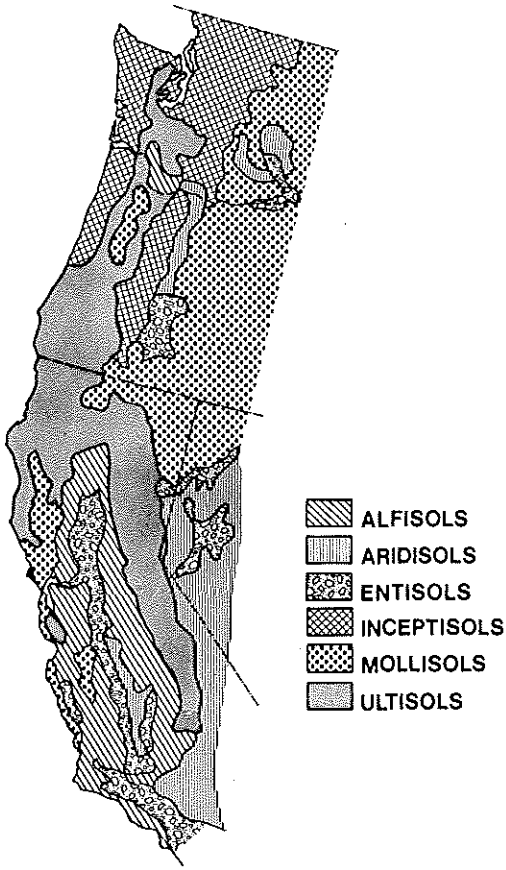

Fig. 1—Soils of the region.

volcanic ash and its weathering products are important components of the soil in many places. These factors result in wide variation in type of clay minerals, percent clay, percent organic matter, and cation exchange capacity (CEC).

A. Naturally Acid Soils

One major group of acid soils developed from alluvial and lacustrine materials in the Willamette-Puget trough, the low-lying area between the Coast Range and the Cascade Range. In the Willamette Valley, these acid soils are on broad terraces up to 50 km wide. There are floodplains and terraces in narrow strips along many of the smaller streams. Tidal areas on the east side of Puget Sound in Washington include cultivated soils that are relatively level and support a productive and intensive agriculture, including many different crops. Medium and moderately fine textures are dominant, although some soils are sandy and some are clayey. Organic matter content of surface horizons ranges mostly from 20 to 100 g kg^{-1}. Basic cation saturation levels range from 40 to 80% in surface horizons and increase with depth. Clay minerals are mostly of the 2:1 lattice type, dominantly montmorillonite and illite. The Haploxerolls, Argiaquolls, Argixerolls, and Albaqualfs are the most common great groups occurring in this area.

The second group consists of upland soils on hills in and at the margins of the Willamette-Puget trough, generally south of the terminal moraine of continental glaciation near Olympia, Washington. This group also extends south into California. Except for some tree fruits and berry crops, these soils are used less intensively than the associated alluvial soils. Organic matter content ranges from 30 to 100 g kg^{-1} in surface horizons. Soil textures are moderately fine in surface horizons and fine in the subsoil. Basic cation saturation levels, when measured with an extracting solution buffered at pH 7.0, range between 10 and 70% in surface horizons and commonly decrease with depth. The pH-dependent charge is significant on most of these soils. This group may be subdivided on the basis of the dominant clay minerals. The soils with 2:1 lattice clay minerals are usually from parent materials derived from sedimentary rock. Moderately fine-textured surface horizons and fine-textured lower horizons are most common. Haploxeralfs and Xeric Haplohumults are the dominant soils, but there are localized areas of Xererts. Alfisols and Ultisols tend to be reddish colored, highly weathered and formed predominantly from sedimentary rock. The soils with dominantly kaolinitic clays are from parent materials that are probably derived from basalt or basic, pyroclastic materials. They contain 100 to 150 g kg^{-1} of hydrous oxides of Fe and Al, are predominantly clayey textures, and are generally low in basic cation saturation.

The third group consists of soils near the Pacific Ocean, primarily in Washington and Oregon and extending into northern California. In this area, the cultivated soils are mostly on terraces, floodplains, and tidal flats, but some are on gently sloping hills. Cropping is limited largely to forages because of cool summer temperatures and excessive fog and precipitation; however, there are small areas of cranberry bogs and other highly specialized crops. Surface horizons commonly have from 100 to 200 g kg^{-1} or more of organic matter. Basic cation saturation levels range from 10 to 40% in surface horizons and generally decrease with depth. The CEC of these soils increases as they are limed from pH 5.0 to 6.0 indicating a significant pH-dependent charge (Janghorbani et al., 1975). Also, the data of Clark (1966), Pratt and Bair (1962), and Blosser and Jenny (1971) show poor relationships between pH and basic cation saturation calculated as percent of CEC at pH 8.2. The variance has been attributed to differences in reactivity of protonated organic and mineral anions. In general, soil organic matter decreases and base saturation increases from north to south. Crystalline clays are mostly of the 2:1 lattice type with some 1:1 kaolinitic clays. Chlorite-like intergrade material or partially interlayered montmorillonite is common. In addition, allophane is present, and hydrous oxide contents of 120 to 150 g kg^{-1} are common. Haplumbrepts and Humaquepts generally occupy the terraces and floodplains, and soils on marine terraces are mainly Haplorthods, Sideraquods, and Haplumbrepts. Soils on tidal flats are mainly Humaquepts and Fluvaquents. Some of the alluvial soils have higher basic cation saturation levels and are much like the alluvial soils east of the Coast Range. Some tidal flat soils contain sulfides that oxidize and lower the pH when the soils are drained. Such soils extend from Puget Sound to San Francisco.

The fourth group consists of soils from glacial till and outwash in the Puget trough around Puget Sound. These soils are commonly sandy loam in texture, or coarser, and many are gravelly. Undisturbed soils have organic matter concentrated in an organic horizon above the mineral profile. This organic matter is vulnerable to loss, and past management practices have resulted in wide variation in the organic matter content of these soils that are cultivated. Soil pH and percent basic cation saturation levels can be changed significantly by moderate rates of lime because CECs are low. Low fertility and low moisture-holding capacity levels limit the use of these soils, especially in comparison with the associated soils from alluvial and lacustrine parent materials. These soils are dominantly Durochrepts, Xerochrepts, Fluvaquents, and Xerumbrepts.

B. Acid Soils Caused by Cultural Practices

In addition to the naturally acid or "geologically" acid soils of the region, wide areas of both dryland and irrigated soils have been made acid by agricultural practices—notably fertilization, irrigation, and basic cation removal in harvested crops. Intense acidification from cultural practices was first noted in Washington orchards on coarse-textured soils to which $(NH_4)_2SO_4$ had been applied in the drip line of the trees (Benson & Vandecaveye, 1951; Benson & Woodbridge, 1961). In some cases, soil acidity was limiting nitrification and uptake of N by the trees. Similar results have been reported from California (Aldrich et al., 1945) and Oregon (Westwood et al., 1964) and are still observed throughout the area. Corrective practices include applications of lime and shift to nitrate sources of N, principally $Ca(NO_3)_2$, and foliar applications of urea.

Within the past few years, rapidly increasing acidity of the plow layer of the soils of the dryland, wheat-growing areas of eastern Washington and northern Idaho has been documented (Mahler, 1982). Data of the soil testing laboratories of these states indicate that the pH of the plow layer of the majority of the soils of that area has dropped from their original near-neutral reaction to values < 6. For the most part, this dramatic shift in soil pH has taken place since 1960. It is attributed to greatly increased use of NH_4^+ fertilizers and removal of basic cations by the higher yielding crops. The use of N fertilizers has expanded dramatically since 1950, with 18 000 t of N, 4% of the U.S. total, used by the three Pacific Coast states in 1950 compared with 939 000 t of N, 9% of the U.S. total, in 1980.

The agriculturally acidified soils of the region differ from the geologically (naturally occurring) acid soils in that a lower fraction of the exchange acidity (Yuan, 1959) is exchangeable Al. This is illustrated in Figure 2 as the ratios of exchangeable Al/exchange acidity for the different groups of soils. At pH 4.5, $< 50\%$ of the exchange acidity was exchangeable Al in the

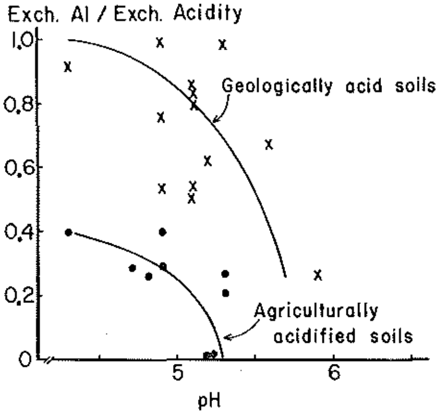

Fig. 2—Exchangeable Al as a fraction of "exchangeable acidity" for geologically acid and agriculturally acidified soils (Janghorbani et al., 1975; Brown, 1975).

agriculturally acidified soils, whereas in the geologically acid soils this fraction was > 90%. The difference is assumed to result from the low rates of accumulation of Al in the decomposition of acid clays or from the effects of the phosphate level (Lindsay, 1979) or other ligands on Al^{3+} activity. Although measurements were not made, high levels of soluble phosphate would be expected in these intensively managed, acidified soils. The relationships of Figure 2 also illustrate a source of the difficulties encountered in assessing lime requirements of the acid soils of the region.

Acidification of the intensively cropped, irrigated soils of the region is an equally serious problem and one less subject to generalization. Management practices altering soil cation levels include the acidifying effects of acid-forming fertilizers, removal of basic cations in harvested crops, and transport, with subsequent precipitation or loss, of basic cations out of the surface soil. These acidifying effects are countered by additions of alkaline carbonates in the irrigation waters or as liming materials, release of basic cations in the weathering reactions forming soil, and the use of basic fertilizers. The rate of pH change is determined by the relative contributions of these acidifying and alkalizing reactions and by the buffering characteristics of the soil.

Western farmers have a long history of preferred use of S-supplying, acidifying fertilizer materials. This choice was not without cause because western soils are inherently low in available S and responses to soil acidification are well documented (Lorenz & Johnson, 1953; Jackson & Carter, 1976). The data of Table 1 illustrate the preferred use of ammoniacal fertilizers in the Pacific states. From 1950 to 1980, fertilizer use in the region accounted for < 10% of the total U.S. consumption of N fertilizers but for about 50% of the nation's use of $(NH_4)_2SO_4$ and $(NH_4)H_2PO_4$. This usage of strongly acidifying nutrient sources has disproportionately amplified fertilizer-caused soil acidification in the region.

Other significant acidifying actions influencing the soils of the region include crop removal of basic cations and the transfer of basic cations from

Table 1—Fertilizer use in Pacific states (Scholl & Wallace, 1950; Hargett & Berry, 1981).

Year	Fertilizer	Pacific states Usage	Pacific states Fraction of U.S. total
		$t \times 10^3$	%
1949–1950	Ammonium sulfate	111	62
	Ammonium phosphate	82	58
	All N	20	4
1959–1960	Ammonium sulfate	245	45
	Ammonium phosphate	157	26
	All N	382	14
1969–1970	Ammonium sulfate	440	56
	Ammonium phosphate	237	37
	All N	646	9
1979–1980	Ammonium sulfate	346	41
	Ammonium phosphate	273	46
	All N	1036	9

surface to subsoil layers with percolating waters. Crop removal of basic cations is significant principally with crops for which a large fraction of the plant is removed at harvest, e.g., hay, silage, and pasture. An 18 t ha^{-1} crop of alfalfa hay removes an average of 23.2 mmol of basic cations (+) dm^{-2} (Pierre & Banwart, 1973). This is an important loss of cations from western soils, because animal feed crops occupy up to 15% of the cultivated acreage. Acidification from transfer of basic cations (largely as NO_3^- salts) to subsurface layers is difficult to evaluate. Efficient use of irrigation water involves an extended dry-down period between applications during which plant uptake of water occurs mostly from the upper portions of the rooting depth. Under the high evaporative demand of desert regions, as many as 10 to 12 irrigations yr^{-1} are required for long-season crops. These regular, efficient transfer actions with subsequent plant uptake of the translocated NO_3^- leave the surface depleted of bases while the subsoils are enriched with lime and other less soluble salts. These acidifying actions are further enhanced by the low buffering capacity of many of the soils common to the region's intensive agriculture.

Basic cations are added to western soils as alkaline carbonates in irrigation waters and liming materials, by weathering of rocks, and by applications of basic fertilizers. Irrigation waters, though generally recognized as a source of accumulating salts and nutrients such as N and S, are not commonly considered as a source of basic salts. The titratable alkalinity (CO_3^{2-} plus HCO_3^-) of western irrigation waters varies from trace amounts to levels exceeding 20 mmol (−) L^{-1}. Most surface-derived waters contain 1 to 3 mmol (HCO_3^-) L^{-1}, whereas well waters may contain as much as 5 to 10 mmol L^{-1}. An average seasonal irrigation (Stewart, 1975) of 1 m of a water containing 1 mmol (HCO_3^-) L^{-1} supplies 10 mmol of basic cations (+) dm^{-2} (equivalent to 500 kg ha^{-1} of $CaCO_3$). Thus, water characteristics may be a dominant factor in assessing potential pH changes in irrigated soils. The rate of basic cation inputs via soil weathering should also be included in evaluating the effects of management systems on soil properties. This contribution can be expected to vary widely over different parent materials and climates. As estimated by the mean of the values reported by Barshad (1964), Cole et al. (1967), and Silkworth and Grigal (1982), weathering of minerals releases 5.3 ± 1.3 mmol of basic cations (+) dm^{-2} yr^{-1}.

For an established alfalfa field producing 18 t ha^{-1} of hay, the approximate cation balance sheet would be:

Acid or base source	Amount produced [mmol (+) or (−) dm^{-2}]
Excess bases in harvest crop	23.2 of acid
NO_3^-, 100 kg of N ha^{-1}, from organic sources	7.2 of acid
Rock weathering	5.3 of base
Net effect	25.1 of acid

The bases needed to avoid soil acidification could be supplied by irrigation water containing at least 2.5 mmol (+) dm^{-2} as HCO_3^- salts or by liming materials. Estimates for other crops can be made similarly. In most cases, some transport of NO_3^- salts out of the surface soil should be anticipated.

The factors contributing to agricultural acidification of arid soils have also intensified soil acidity problems on intensively managed, naturally acid soils. Grass seed fields of the Willamette Valley are frequently found with soil pH values of 4.5 and 2 to 3 cmol of [½ (Ca + Mg)] kg^{-1} of soil where 100 to 150 kg of N ha^{-1} yr^{-1} has been used for 30 to 40 yr.

II. CROPS OF THE REGION

The wide range of soils and climates of the region, along with extensive irrigation, allows production of over 200 commercial crops. Pasture, grain, hay, and seed crops dominate the dry-farmed areas. In contrast, the irrigated areas produce a wide variety of crops, including fruit, nuts, vegetables, grapes, alfalfa, cotton, sugar beet, grain crops, and irrigated pasture. Production of irrigated crop is especially favored by the mediterranean-type climate of the area, which facilitates cultural and harvest operations unhampered by inclement weather. The nonfarmed areas provide forest products, range, and recreation and include desert and brush lands.

The production of processing crops is concentrated on the recent alluvial and the older, valley floor soils that are well drained. Almost all of this acreage is irrigated. Berries, tree fruits, and nuts have been important crops for this area for many years. Although the total area occupied by these crops is relatively small, they are of major economic importance to the area due to the high per-hectare return. Tree fruits, potato, hops, sweet corn, and onion are intensively grown, irrigated crops of major importance east of the Cascades. Vineyards have long been a major California crop and are emerging as an important crop in central Washington.

The agriculture of California is particularly diverse, producing over 200 different crops on its varied soils and climates. Over two thirds of its more than 3 million ha of irrigated farmlands are in the central valley, producing a wide variety of crops, many in double-crop rotations. The Imperial Valley in southern California, with its year-long frost-free growing season, produces many off-season, high-value crops. Production of cool-season vegetable crops, quality wine grapes, pasture, and timber products is allowed by the sea-moderated climates of the coastal valleys. Individual crops, listed in order of decreasing cash farm income for 1980, were cotton, grapes, alfalfa, nursery products, almond, tomato, rice, flowers and foliage, lettuce, wheat, and orange (California Dep. of Food and Agric., 1981).

Crop rotations are seldom followed in the Pacific Northwest or in California. Grain farmers in the area between the Cascades and the Rocky Mountains typically have grain as the single major cash crop. Winter barley and wheat are grown in sequence with tomato and other row crops in many central California areas. Pea is used as an alternate cash crop for a portion of the acreage in the foothills of the Blue Mountains and in the Palouse area of eastern Washington and northern Idaho. Potato production is concentrated in the semiarid soils that have been brought under irrigation in the Columbia Basin in central Washington, the Klamath Basin in south-central Oregon and northern California, the irrigated areas in central Oregon, and the Snake River Valley in southern Idaho. Early-harvest potato is concentrated in central and southern California.

Forage crops are produced for livestock throughout the West. Dairy enterprises are concentrated in western Oregon and Washington and in the irrigated areas of central Washington, southern Idaho, and California. The northeastern parts of Washington and northern Idaho support mixed livestock enterprises, cereal production, and grass seed production. Poor nodulation and low production of legumes have been problems on the moderately acid soils throughout this latter area for many years (Harder et al., 1962; Reisenauer, 1963; Pumphrey & Moore, 1973).

In the areas west of the Cascades, crimson and red clover seed crops are generally produced in a cropping sequence with winter wheat. Oat and grass seed crops followed by winter wheat minimizes wheat diseases and has developed as a good crop sequence in western Oregon. The farmers that produce small fruits and vegetable crops frequently specialize in intensive crops and do not follow rotations. Winter annual cover crops are often grown in association with the more intensive, annual processing crops for erosion control and soil organic matter maintenance. Vegetable crops followed by winter wheat has developed as a very desirable crop sequence for those vegetable growers with enough hectares of cultivated soils to allow efficient wheat production. Root disease problems are minimized on both crops, weed problems are reduced, and the fertilizer carryover from the vegetable crop results in maximum wheat yields with relatively low production costs.

A major portion of the lime that is applied in the Pacific Northwest is for the production of vegetable crops and forage legumes. Alfalfa, red clover, crimson clover, white clover, and subterranean clover are the main legumes grown in this area.

III. LIMING PRACTICES

A. Lime Use and Method of Application

Records from the state departments of agriculture in Oregon, Washington, and California show that annual consumption of lime has averaged about 225 000 t yr^{-1} in Oregon and about 135 000 t yr^{-1} in Washington and 150 000 t yr^{-1} in California. Minimal usage of lime in the region has been attributed to its comparatively high cost and the use of phosphate fertilizer to moderate the acid soil problems of intensively cropped areas. A major portion of the limestone marketed in the Pacific Northwest is calcitic limestone. A small tonnage of dolomitic limestone is shipped to Washington and Oregon from Oakland, California, for use on soils that are low in Mg.

Lime is most frequently broadcast before or during the latter stages of seedbed preparation and worked into the seedbed with a disk. Mixing of lime throughout the upper 15 to 30 cm of soil is achieved during seedbed preparation and cultivation operations for the production of succeeding crops.

Recent research in western Oregon (Kauffman & Gardner, 1978) has shown that limited mixing of low lime rates in the surface 5 to 10 cm of soil results in pockets of soil with a desirable pH and maximizes yields with limited expense for the immediate crop. However, subsequent tillage operations provide more thorough mixing and reduce responses from low rates, e.g., 1 t ha^{-1} applications. In some cases, plowing to a depth of 25 to 30 cm for the next crop, following a surface lime application and light disking, will place most of the lime at the bottom of the plow furrow, leaving the surface 20 cm at the original low pH and with the original soil acidity problems for seedling establishment.

Low rates of lime combined with minimum soil mixing may be an alternative production practice where land is rented and only one crop is produced every 4 to 5 yr that has a low tolerance for acid soils (e.g., lettuce, spinach, table beet, and cabbage family crops).

More than one plowing plus disking is necessary to provide complete mixing of lime with the soil. If complete mixing is important, it may be preferable to apply lime 6 months to 1 yr before planting to allow time for additional tillage operations during normal crop production practices to mix lime throughout the soil.

The frequency with which lime should be applied has not been established for western conditions. The lack of definite rotations that have a fairly specific lime requirement and the wide variation in the amount of acid-forming fertilizers applied make it difficult to establish a recommendation for frequency of application that would cover the range of conditions encountered. It is presently recommended that farmers submit soil samples from each field to a soil testing laboratory every 2 to 6 yr for an estimation of the lime that should be applied for the specific crops or crop rotation to be used. It is important to recognize that where intensive agricultural production is being followed with high N rates (100–200 kg of N ha^{-1} yr^{-1}) as NH_4^+-N, animal manure, or sewage sludge, decreases in soil pH of 0.5 to 1.0 unit in 6 to 7 yr with a corresponding reduction in basic cations throughout the surface 25 to 30 cm of soil should be expected where pH values are already < 6.0.

B. Soil Acidity and Lime Recommendations

Soil pH, exchangeable Ca^{2+}, and percent basic cation saturation have been used as a basis for recommending application of lime in this area. However, no single measurement has proved to be a reliable criterion for predicting response from liming under a wide range of soil conditions. This would be anticipated when the range of soil acidity conditions, soils, and the range in the tolerance of different crops to soil acidity factors are considered. Responses to lime in the region have been associated with reduction of excessive quantities of Mn, Fe, and Al in the soil (Jackson et al., 1966; Janghorbani et al., 1975; Lingle et al., 1961; Stephenson, 1929), increased availability of soil P, and correction of Mo deficiency (James et al., 1967; Reisenauer, 1955; 1963).

Extension workers, consultants, and most growers recognize that lime recommendations are not precise and that soil acidification is a continuing process. Whenever a visual response from lime is observed, crops with comparable tolerance to soil acidity have been suffering reduced yields on that field for a number of years. Recommendations normally are made to apply enough lime to achieve a specific soil pH or percent base saturation, depending on the crops that will be grown. The most common rates recommended for one application are 3 to 5 t of lime ha^{-1}. Rates of 6 to 10 t ha^{-1} are sometimes required for alfalfa on hill soils that have not been limed previously and where growers want to raise soil pH to 6.0 or higher to help control clubroot on cabbage, broccoli, and cauliflower and to produce vegetable crops with limited tolerance to soil acidity.

Application rates of 1.0 to 2 t ha^{-1} of lime are recommended for strawberry plants where soils are low in Ca and are acid (Kirsch & Jackson, 1959). Dolomitic lime is recommended where soils are low in Mg or have questionable Mg levels (Mortensen et al., 1961).

IV. LIME AND PLANT NUTRIENT INTERACTIONS

Lime-phosphorus interactions have been observed over a wide range of soil and cropping conditions. Increasing the pH of acid soils for legume production increases both P and Mo availability. Increased N_2 fixation by rhizobia is associated with higher levels of P and Mo; also, the soil pH range for optimum efficiency of some N_2-fixing rhizobia is generally recognized as 6.0 to 8.0. All of these factors complicate the problem of identifying specific cause and effect relationships associated with crop response to liming.

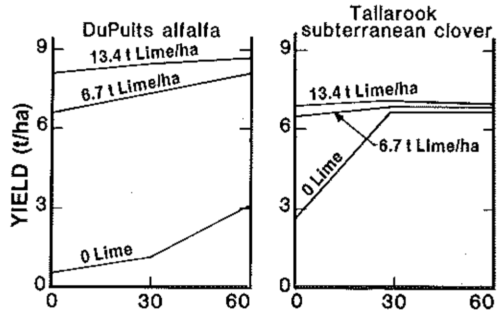

Fig. 3—Lime and P effects on yield of alfalfa and subterranean clover, Red Soils Exp. Stn., 1956–1961.

Responses of alfalfa and subterranean clover to liming illustrate (Fig. 3) the marked differences in tolerance to soil acidity of different legume species (Jackson et al., 1964). Response to liming and lime-P interactions for white and red clover are generally similar to that for subterranean clover.

A number of vegetable crops, with limited tolerance to both Al and Mn, frequently show marked increases in P uptake following lime application in western Oregon. Table beet, lettuce, and spinach are some of the less acid-tolerant crops that exhibit this response pattern (Jackson et al., 1974; Hemphill & Jackson, 1982). Rutabaga represents the response of more acid-tolerant root crops (Table 2).

The marked increases in yields of table beet and spinach to liming are associated with increases in P concentration of leaf samples and marked decreases in Mn concentrations. Rutabaga response from lime was much smaller and the leaves showed smaller changes in P and Mn concentrations. The decrease in Ca concentration in table beet and spinach leaves is associated with marked increases in yield and is a dilution of the Ca content of low-yielding plants. This decrease in leaf-Ca concentration with the first

Table 2—Chemical analyses of leaf samples and yield with different rates of lime, North Willamette Exp. Stn. (Jackson et al., 1974).

Crop	Treat-ment†	pH	Ca	Mg	P	K	Zn	Mn	Yield
			g kg^{-1}				mg kg^{-1}		kg m^{-1}
Table beet	L_0	5.8	20.4	12.4	5.1	69.1	71	328	1.34
	L_9	6.3	17.7	9.3	6.3	70.8	57	78	1.88
	L_{18}	6.6	21.9	9.5	6.5	67.5	45	71	1.77
Spinach	L_0	5.8	19.5	11.7	4.6	63.0	164	204	0.06
	L_9	6.3	18.2	10.8	6.7	78.0	137	70	0.25
	L_{18}	6.6	20.8	9.4	6.8	76.2	113	63	0.25
Rutabaga	L_0	5.8	21.8	2.8	5.3	51.1	34	70	1.11
	L_9	6.3	24.5	2.5	5.2	57.8	31	42	1.22
	L_{18}	6.6	22.8	2.2	5.8	47.0	32	42	1.29

† kg × 10^3 ha^{-1} of lime applied.

increment of lime applied emphasizes that very few lime responses are associated with deficiencies of Ca as a nutrient.

A range of yield responses were reported for snap bean, carrots, and lettuce (Hemphill & Jackson, 1982) on this same soil series. Lettuce response was comparable to that of spinach, whereas response of carrot tended to follow the rutabaga response discussed earlier. Snap bean was intermediate in response. There was a 25 to 30% yield increase when the soil pH was increased from 5.1 to 5.6 or 5.7, but yield increase was limited with additional application of lime. Lettuce yields were increased 30 to 50% when the soil pH was increased from 5.6 or 5.7 to > 6.0 with applications of lime. These increases in yield were associated with significant increases in leaf P and decreases in leaf Mn. Calcium concentrations in lettuce leaf samples were consistently decreased when the first increment of lime increased yields two to three times. In contrast, moderate increases in snap bean and carrot yields from liming resulted in small, but consistent, increases in leaf-Ca concentrations.

The important relationship between soil pH and response to P applications was illustrated in greenhouse experiments with 448 different California soils of pH 5.0 to 8.0 (Jenny et al., 1950). Growth response of 'Romaine' lettuce to applications of N and P was evaluated. Lettuce responded to P applications in about 80% of the soils of pH < 5.0. Response occurred in 40% of the soils of pH about 6.5 and in 30% when pH was 7.0 to 7.3. Obviously, residual P also influenced response from P, but the soil pH-P response relationship was striking.

The increase in soil P availability associated with liming acid soils requires a moderate to high P soil test value. Guerrero et al. (1967) found that actual increases in yield of 10 different grass species from P application were greater on two acid grassland soils after these soils were limed. There was a response from both P and lime; the lime plus P treatments yielded five to eight times more than the lime-zero, P-zero treatment in these experiments.

V. MANGANESE TOXICITY

Recent research to evaluate crop production practices on poorly drained soils in the Willamette Valley has shown that Mn toxicity is one of the major factors limiting production of certain crops on these soils. This work (Jackson et al., 1966) indicated Mn toxicity occurred in bush snap bean when the most recently matured trifoliate leaf contained 600 to 800 mg kg^{-1} or more of Mn. Liming poorly drained soils from pH 4.9 to 6.3 reduced the Mn content of snap bean leaves from 1010 to 620 mg kg^{-1}. Improved drainage and aeration also reduced the levels of exchangeable Mn^{2+} and the amount of Mn taken up by bean plants grown on these soils. Thus, Mn toxicity on acid soils is accentuated by restricted drainage.

When alfalfa is grown on different western Oregon soils, marked differences have been observed in the relationship between soil pH, or percent basic cation saturation, and response of alfalfa to lime. This range in response from lime has been related, in part, to differences in levels of exchangeable and readily reducible Mn^{2+} in these soils (Dawson, 1958). About 40 mg kg^{-1} of NH_4OAc-exchangeable Mn^{2+} were present in two soils where there was a marked reduction in Mn content of alfalfa associated with the increases in yield from liming in greenhouse experiments. The Mn content of the alfalfa foliage was 100 to 130 mg kg^{-1} with 60% base saturation and 49 to 55 mg kg^{-1} with 100% base saturation. Other research has also identified that excessive Al levels limit alfalfa production on a number of these soils (Janghorbani et al., 1975; Vlamis & Williams, 1962).

Benson and Vandecaveye (1951) reported Mn toxicity on 'Delicious' apple trees where surface soils were below pH 5.0 and Mn content of leaves collected in midsummer or later was 500 mg kg^{-1} or more. The critical level for Mn toxicity in Delicious apple leaves collected in midsummer or later was later revised downward to 300 mg kg^{-1} by Benson and Woodbridge (1961). These authors pointed out that all orchards with surface soils of pH 5.0 did not result in Mn toxicity and that waterlogging also contributed to increased availability of soil Mn. They recommended adding enough lime to raise the soil pH to 6.0 on the area within a 2-m radius of young trees showing Mn toxicity. A comprehensive evaluation would be required to identify the relative contribution of low soil pH and reduced drainage to Mn toxicity, especially where low soil pH is associated with drip line applications of acid-forming fertilizers. Relatively high levels of hydrous oxides of Fe and Al have undoubtedly contributed to the response observed from application of lime in some of these situations.

VI. SUMMARY

We tend to think of the calcareous soils in the western United States with micronutrient deficiency problems associated with high soil pH levels. However, there are extensive areas of naturally occurring acid soils west of the Cascade mountains, in or associated with other mountain ranges, along the California coast, and where the use of acidifying materials on intensively managed soils have decreased the soil pH and induced soil acidity problems. There is a definite need for increasing the application of liming materials in many parts of the region.

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