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Lime Requirement Indices

of Alaskan Soils

by

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Introduction

Perhaps the most significant single measurement of a soil's ability to adequately support plant growth is a pH determination. If soils are too acid, reduced nutrient availability of all the macronutrients will result. Conversely with several of the micronutrients, low soil pH can increase solubilities, even to the point of causing plant toxicity. Aluminum, an element regarded as nonessential for plant growth, has been shown by numerous workers to produce toxic plant effects at low soil pH (1). High soil pH likewise is undesirable for plant growth and can result in reduced availability of several micronutrients such as boron, zinc, iron, and manganese. Phosphate fixation can occur when excessive calcium is present. Therefore, the majority of agronomic plants do best when grown in neutral to slightly acid soils in the 6 to 7 pH range.

DEGREE OF ACIDITY

The term "pH" is used to express the degree of acidity or alkalinity. The complete pH scale runs from 1 to 14 with pH 7 being neutral; however, most soils in Alaska fall in the pH range of 3.5 to 8.

The pH of a solution is defined as the negative logarithm to base 10 of the H ion activity, or the logarithm of the reciprocal of the H ion activity:

$$pH = -\log_{10} [H+] = \log_{10} \frac{1}{[H+]}$$

Thus, since pH is a logarithmic function, a soil having a pH of 5 is ten times more acid than a soil of pH 6; furthermore, a soil pH of 4 is one hundred times more acid than a pH of 6.

pH MEASUREMENT

Soil pH is determined at the Soil and Plant Analysis Laboratory (Palmer, Alaska) using one volume of soil to one volume of distilled water (23). After stirring, the soil-water suspension is allowed to stand thirty minutes prior to pH measurement. The pH is then determined using a potentiometer and a glass electrode in conjunction with a reference electrode.

The clay and organic matter fractions of most soils contain negative charges which attract cations (including the acidic cations H and A1*). When the soil-water suspension is allowed to equilibrate for thirty minutes, the acidic cations attracted by electrostatic forces to the negative-exchange sites reach an equilibrium with the soil solution; however, the majority of acidic cations remain in close association with the negative sites. Thus, during the pH determination only the H ion concentration (actually H ion activity) of the soil solution is measured. This indicates the intensity of H ions in the solution but does not determine the capacity of the soil to supply H ions. The capacity factor is related to the quantity of negative exchange sites and is referred to as the buffering capacity of the soil.

NEUTRALIZATION OF SOIL ACIDITY

An acid soil requires a certain amount of base, usually calcium carbonate, $CaCO_3$ to correct soil acidity. Both the active acidity, present in the soil solution, and the reserve acidity, associated with soil negative exchange sites, must be neutralized. Knowledge only of soil pH is inadequate to determine quantities of base required (17, 25). E. O. McLean (14) made the following paraphrased analogy:

Soil pH is an intensity rather than a capacity factor and can be related to air pressure in a tire. For example, a bicycle tire and a tractor tire may both have equal air pressure; however, the larger tire would require the addition of many more times the quantity of air than the smaller tire to achieve equal pressure.

A very similar analogy occurs in soil; the quantity of base required to neutralize acidity is a capacity-related factor determined by the buffering capacity of the soil, and is analagous to total air in the tire

* Aluminum is considered an acidic cation since H ions are released during aluminum hydrolysis.

rather than to air pressure. Hence, the quantity of base required to neutralize acidity of two soils having identical pHs may be quite different. This concept is pictorially represented in Figure 1.
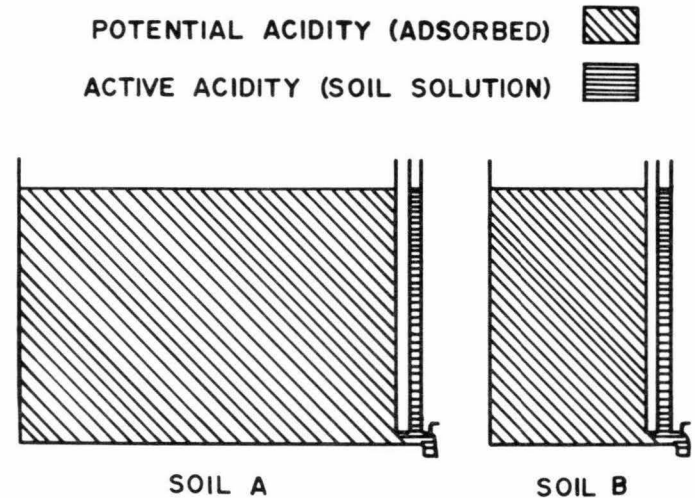
FIGURE 1. The active acidity as measured by soil pH corresponds to the fluid in the indicator tube; however during liming, both the active and potential acidity require neutralization. Therefore soil A, because it has a larger potential acidity, would require greater lime additions than soil B to achieve the same final pH.

LIME REQUIREMENT

Although numerous basic materials such as calcium hydroxide, marl, wood ashes, etc. can be used to neutralize soil acidity, the most common liming material is calcitic ($CaCO_3$) or dolomitic [$CaMg(CO_3)_2$] limestone. These two are most common due mainly to cheapness and availability of the materials. The lime requirement is defined as the quantity of agricultural-grade lime required to neutralize soil acidity and increase soil pH from an initial pH to a final desired pH. This value is commonly expressed in tons of lime required per acre. Soils having higher buffering capacities have a correspondingly higher lime requirement than those soils with low buffering capacities in order that the resulting pH in both soils be equal.

Methods and Materials

The purpose of this research was to determine the quantity of lime required to raise the initial pH of various acid soils collected throughout the state of Alaska to a final pH of 6.5. Of the 31 soils collected, 22 were determined to have pHs below 6.5 and were included in the lime incubation study. The location where each soil was obtained and the classification of these samples are indicated in Figure 2. Soils were obtained where possible from a virgin condition since the majority of potential agricultural lands within the state are not presently under cultivation.* During collection, the surface organic layer was removed and the upper six inches of mineral soil was included in the sample. This was to simulate the surface scraping required during the land-clearing operation. In instances where the mineral-organic matter interface was not abrupt, portions of the undecomposed surface duff also were included in the sample.

After arriving at the Palmer facility, a composite subsample was air dried, crushed with a wooden rolling pin, and screened through a 10-mesh stainless steel sieve, later to be used for evaluating lime-requirement indices in the laboratory. The bulk sample was passed through a ¼-inch screen and stored at 2° C in a moist condition in sealed polyethylene bags. Samples which were collected in a wet condition were partially air dried prior to screening.

Increasing increments of $<$100-mesh calcium carbonate corresponding to 0, 2, 4, and 6 tons per acre (0, 4.5, 9.0, 13.5 metric tons/hectare) were added to soils having an initial pH less than 6.5. Lime was added on a weight-to-volume basis (lime:soil). Six hundred and seventy-five cubic centimeters of soil were obtained by uniformly packing the soil into the prescribed volume. The soil was placed into a polyethylene bag, calcium carbonate added, and the soil and lime thoroughly mixed. The lime-soil mixture was then subdivided into three equal volumes and placed into 250-cc styrofoam cups.

Five seedlings of Weal barley were placed into the soil of each cup, the cups were put into a growth
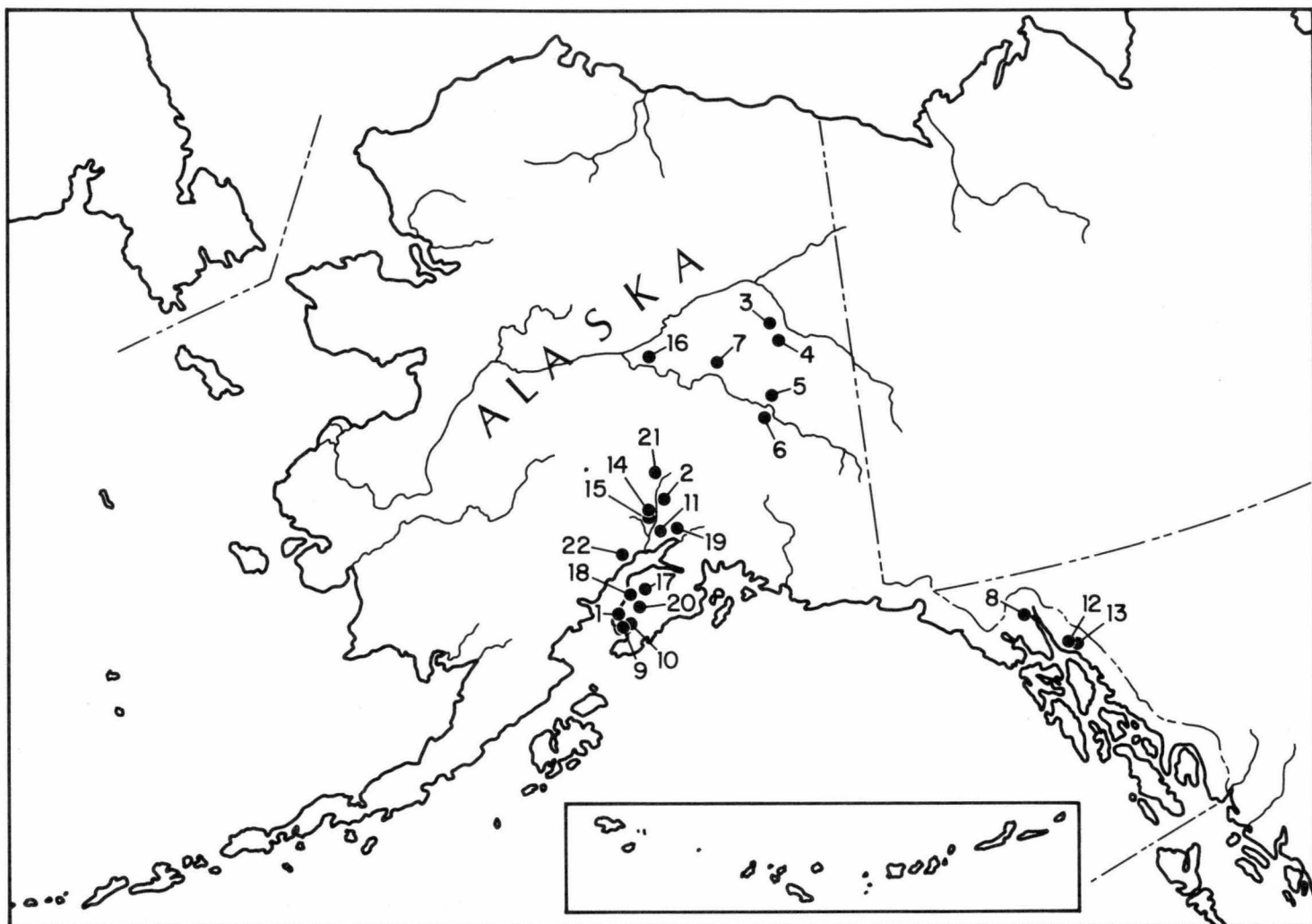
chamber, and the lime-incubation study was started (Figure 3). The growth chamber provided a combination of tungsten-fluorescent lighting at ca 2200 foot-candle intensity with 16-hour photoperiods. Daytime temperatures were maintained at 60° F (15.5° C) with night temperatures of 48° F (8.9° C). Plants were watered on alternate days with ca 30 ml of distilled-deionized water. After 6 weeks, the plants were harvested, dried at 60° C, and dry weights of the shoots were determined.

Nitrogen and phosphorus contents of the plant material were analyzed on a Technicon II Autoanalyzer following digestion with sulfuric acid, selenous acid, and hydrogen peroxide in a BD20 block digestor. Potassium, calcium, and magnesium concentrations were determined by atomic spectrophotometry.

Following plant harvest, soil from each cup was mixed and a subsample taken for pH determination;

FIGURE 3. The interior of the growth chamber with the $CaCO_3$ incubation study in progress. The unit suspended above the work table in the upper right-hand corner is the heat and light sensor.

FIGURE 2. Location and classification of soils selected for lime requirement study.

Soil No.	Series	Subgroup Classification	Legal Description	Location
1.	Cohoe	Typic cryorthods	SW¼, SW¼, Sec. 34, T4S, R15W, S.M.	Anchor Point
2.	Kashwitna	Typic cryorthods	SW¼, SE¼, Sec. 6, T21N, R4W, S.M.	Caswell
3.	1			Central
4.				Circle Hot Springs
5.				Delta-Clearwater
6.	Nenana	Typic cryochrepts	Sec. 23, T10S, R11E, F.M.	Delta Junction
7.	Fairbanks	Alfic cryochrepts	Sec. line 30, 31 east, T1N, R2E, F.M.	Fairbanks
8.				Haines
9.	Beluga	Typic cryaquepts	SE¼, SW¼, Sec. 1, T6S, R13W, S.M.	Homer
10.	Kachemak	Dystric cryandepts	SW¼, NW¼, Sec. 1, T5S, R14W, S.M.	Homer
11.	Homestead	Typic cryorthods	SE¼, SE¼, Sec. 21, T18N, R3W, S.M.	Houston
12.	Kupreanof	Humic cryorthods		Juneau
13.	Wadleigh	Cryic fragiaquods		Juneau
14.	Nancy	Typic cryorthods	SW¼, SW¼, Sec. 6, T20N, R4W, S.M.	Kashwitna
15.	Susitna	Typic cryofluvents	SW¼, NE¼, Sec. 7, T21N, R4W, S.M.	Kashwitna
16.				Manley Hot Springs
17.	Tustumena	Typic cryorthods	SE¼, SE¼, Sec. 7, T5N, R8W, S.M.	Naptowne
18.	Island	Dystric cryandepts	NE¼, NW¼, Sec. 5, T3S, R14W, S.M.	Ninilchik
19.	Knik	Typic cryorthents	SW¼, NE¼, Sec. 15, T17N, R1E, S.M.	Palmer
20.	Soldotna	Typic cryorthods	NE¼, SW¼, Sec. 20, T5N, R10W, S.M.	Soldotna
21.	Rabideux	Typic cryorthods		Trapper's Creek
22.	Mutnala	Typic cryorthods	E¼ corner, Sec. 8, T11N, R12W, S.M.	Tyonek

[1] Blank spaces indicate the information is not presently available.

the determination was made with a 1:1 distilled water to soil ratio using an Orion 601 potentiometer. The soils were then placed, in a moist condition, into polyethylene bags and stored an additional four months, for a total of six months after the initial addition of calcium carbonate. At the end of this period, pHs were again determined.

The Shoemaker, McLean, and Pratt (SMP) buffer pH was determined in duplicate on the acid soils as outlined in the original paper (29), as was the Woodruff lime-requirement procedure (31). The calcium hydroxide titration procedure allowed equilibration of aliquots of a given soil with progressively larger increments of a standard base such as $Ca(OH)_2$, followed by measuring the resulting pH change (2).

Soils were characterized to determine possible relationships between specific soil properties and quantities of lime required to obtain a desired pH correction. Cation exchange capacity (C.E.C.) was calculated by summation of a) exchangeable acidity as determined by the $BaCl_2$-triethanolamine procedure (22), and b) the exchangeable bases calcium, magnesium, and potassium extracted by NaOAc pH 4.8 (8). Readily oxidizable organic matter was determined by the Walkley-Black procedure as described by Jackson (9), and extractable A1 by the method suggested by McLean (13) using eriochrome cyanine R.

Lime Requirement Discussion

Soil is a complex, naturally occurring material in which chemical and physical properties can vary drastically over a short distance. Peech (24) stated that different rapid lime requirement methods gave widely divergent results. Certain of the methods are better suited to specific soil conditions (20). As conditions vary from location to location, the best-suited lime requirement method may change as well. Fortunately, for most agronomic crops, favorable plant response is not critically dependent upon obtaining an exact soil pH. For example, a specific crop may produce nearly as well at pH 6.2, as at pH 6.5, or at pH 6.8. Thus, the purpose of using a well-adapted lime requirement test which can be adapted to a routine soil testing program is to improve the prediction capability with which lime requirement recommendations are made, rather than to allow prediction of exact amounts of lime required for each specific soil to reach an exact final pH. Furthermore, in a state such as Alaska where soil properties are quite variable, the latter objective is not obtainable with present technology.

In determining lime requirements for soil, the most precise procedure would be to add increasing increments of lime in the field and observe pH changes as a function of time; however, one of the big problems with field techniques is sampling. The need for determining the lime requirement of soils more rapidly under a wider range of conditions has led to development of the incubation method (14). Perhaps the most widely accepted laboratory method currently available for determining lime requirement is $Ca(OH)_2$ titration (2). However, this method requires three days for equilibration, and thus for routine soil testing, has a drawback similar to the incubation and field-study procedures in that the method is not sufficiently rapid to be practical for daily use.

Two rapidly determined indices of lime requirement are the SMP and the Woodruff buffer procedures. Both procedures are based on similar principals; i.e. a given quantity of soil is equilibrated with a highly buffered salt solution followed by determination of the exchangeable acidity in the extract by measuring a pH decrease. Further, the decrease in the buffer solution pH is proportional to the acidity present and thus is proportional to the quantity of lime required to obtain a final desired pH.

Lime Requirement Results

Characteristics of the 22 soils considered in the study are presented in Table 1. Soil pHs initially were as low as 4.45. Note that the volume weight of the soils ranged from 0.59 to 1.24 g/cc. Volume weight of soils was determined following grinding and screening using the scooping method suggested in Recommended Chemical Soil Test Procedures for the North Central Region, 1975 (21). These weights would not relate directly to bulk densities determined in the field on undisturbed sites, but perhaps would, to some degree, represent soil in the field following the necessary cultivation and packing preparatory to seeding.

Lime is customarily surface applied and tilled or disced to a 6- or 8-inch depth. Thus, lime is added to a given volume of soil rather than to a given weight of soil; i.e. lime added to the surface six inches of soil on an acre basis would be added to 21,780 cu. ft. of soil. Considering the differences that exist in volume weights of Alaskan soils, lime was added in the incubation study on a volume rather than a weight basis. Other workers have assumed an acre-furrow-slice of soil weighs 2,000,000 pounds (B.D. = 1.34 g/cc), and have had good success basing their calculations on a weight basis (11, 29, 33). Woodruff (31), however, pointed out that in determining lime requirements by buffer pH a volume measure is preferable to a weight measure if the soil is not highly aggregated since the weight of an acre-plow-depth is not constant. Presumably, the greater variation occurring in volume weights of soils analyzed by a specific soil testing laboratory, the more important this point becomes.

During a lime incubation test, McLean (15) observed that salt accumulation during the incubation period, especially from high organic matter soils, caused serious error in the indicated pH. Since microbial activity is intense under incubation conditions, salts, particularly nitrates of calcium, magnesium, potassium, etc. (14), accumulate in the soil and tend to lower indicated pH. To minimize this effect in the present study, barley seedlings were planted in the soil prior to incubation to remove nutritive salts as they accumulated. Additionally, the barley seedling

SELECTED PHYSICAL AND CHEMICAL PROPERTIES OF ACID SOILS
COLLECTED FROM VARIOUS LOCATIONS THROUGHOUT ALASKA

Soil No.	Initial Soil pH	Volume Weight	Organic Matter	Exchangeable Acidity	Extractable Al	Cation Exchange Capacity	Base Saturation
	1:1 H_2O	g/cc	%	meq/85 cc [1]	meq/85 cc [1]	meq/85 cc [1]	%
1	5.30	0.71	11.6	32.1	4.9	35.7	10.0
2	5.11	0.66	16.0	38.8	6.6	40.1	3.3
3	5.78	0.80	4.8	12.3	0.4	23.0	46.8
4	6.24	1.24	2.8	5.7	0.1	14.3	60.1
5	5.96	0.76	8.7	17.8	0.4	30.6	41.7
6	6.04	0.89	2.2	11.8	1.3	15.5	23.8
7	5.03	0.71	13.6	27.0	3.5	32.1	15.7
8	5.20	0.68	20.5	32.6	0.8	52.6	38.4
9	5.34	0.77	9.5	21.0	1.0	33.0	36.5
10	4.45	0.59	25.2	49.8	5.3	51.3	2.8
11	5.16	0.72	9.5	30.2	5.8	31.2	3.3
12	5.84	0.70	37.0	32.1	0.4	58.1	44.7
13	5.07	1.01	13.1	39.3	9.3	40.2	2.3
14	5.09	0.73	14.4	42.2	6.9	43.5	3.0
15	5.39	1.08	2.0	12.1	0.8	20.7	41.5
16	5.51	0.76	8.7	17.8	0.4	30.6	41.7
17	5.36	0.73	14.6	25.5	1.4	37.2	31.5
18	5.06	0.64	14.4	36.1	3.9	40.9	11.6
19	5.65	0.84	11.5	18.8	0.5	33.9	44.4
20	4.97	0.86	12.3	39.9	6.9	41.5	3.9
21	5.21	0.70	13.7	34.2	5.8	38.2	10.3
22	4.53	0.66	20.2	48.3	5.5	49.9	3.2

[1] g/cc x meq/100 g x 0.85/0.85 = meq/85 cc

provided means to evaluate, on a relative scale, the natural fertility of these mainly virgin soils and, further, provided means to evaluate the effects on plant growth due solely to lime additions.

Soil pHs were determined two months after addition of lime, immediately following harvest of barley seedlings. To ensure that the < 100-mesh calcium carbonate had completely reacted, the soils were allowed another 4-month incubation period, while stored at 2° C (to minimize microbial activity), and pHs were again determined. Differences of several tenths of a pH unit were observed between the 2- and 6-month readings. In general, those treatments without lime additions tended to be one- to two-tenths lower in pH (perhaps due to the salt effect) and those treatments with lime addition tended to be a few tenths higher (perhaps due to continued neutralization of soil acidity); however, this effect was not consistent over all treatment units. In reconstructing the titration curve, incubated lime addition versus soil pH at 6 months, and comparing those results with the 2-month data, the shifts in indicated lime were minimal. Early field work in Ohio by Schollenberger and Salter (28) indicated 100-mesh calcite limestone was completely reacted in three months. To ensure complete lime reaction due to the cool conditions of the study, $CaCO_3$—indicated lime requirement pHs were reported at six months.
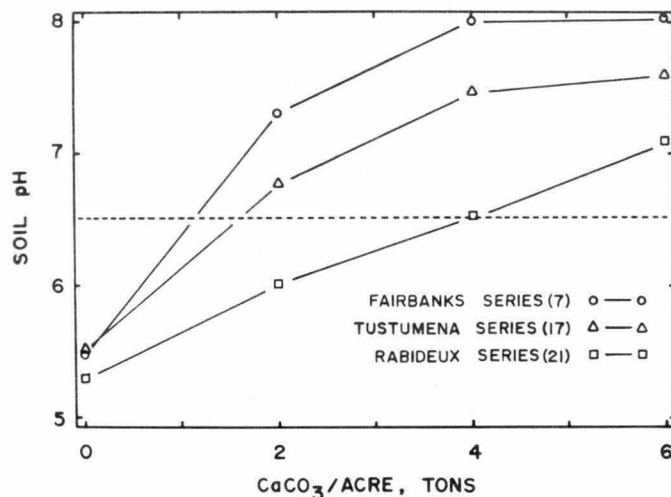
LIME REQUIREMENTS OF ALASKAN SOILS EXPRESSED AS POUNDS PER ACRE PURE CALCIUM CARBONATE AS DETERMINED BY VARIOUS LIME REQUIREMENT INDICES TO OBTAIN A FINAL pH OF 6.5

Soil No.	$CaCO_3$ Incubation	$Ca(OH)_2$ Titration	SMP Buffer Indicated	Woodruff Buffer Indicated	$BaCl_2$-Triethanolamine Buffer Indicated	Base Saturation to 62%	(6.5-Initial pH) X 4,300
1	4,600	4,600	13,700	6,900	20,500	13,200	5,200
2	5,500	6,800	14,800	8,100	24,800	16,900	6,000
3	900	1,400	1,400	2,800	7,900	1,700	3,100
4	300	400	400	1,700	3,600	—	1,100
5	1,400	800	2,600	3,100	11,400	2,200	2,300
6	1,500	800	1,400	2,200	7,600	4,100	2,000
7	1,800	3,300	12,700	7,100	17,300	10,200	6,300
8	10,000	8,800	15,900	8,200	20,900	7,500	5,600
9	4,400	6,000	8,600	5,400	13,400	5,100	5,000
10	13,500	10,700	20,000	9,700	31,900	21,700	8,800
11	5,900	5,800	12,700	7,000	19,300	13,200	5,800
12	4,100	3,300	10,700	6,100	20,500	5,200	2,800
13	12,500	10,200	17,900	9,900	25,200	17,200	6,100
14	7,400	8,000	16,700	8,700	27,000	18,400	6,100
15	4,800	2,800	5,600	4,200	7,700	2,400	4,800
16	3,100	2,000	4,400	4,100	11,400	3,500	4,300
17	3,000	4,200	9,600	5,700	16,300	7,300	4,900
18	5,500	5,500	14,900	8,100	23,100	14,400	6,200
19	2,300	3,600	8,600	5,400	12,000	3,100	3,700
20	7,900	8,600	17,900	8,800	25,500	17,300	6,600
21	7,900	6,100	12,700	7,500	21,900	14,000	5,500
22	11,800	10,900	22,100	10,500	30,900	21,100	8,500

Data of Table 2 indicate seven methods of determining lime requirements for 22 Alaskan soils. The $CaCO_3$ incubation lime requirement was derived from a goodness-of-fit line relating the lime requirement indicated by $CaCO_3$ addition (plus moist incubation) to change in soil pH after 6 months. The lime requirement (L.R.) was calculated at pH 6.5 (Figure 4). The $Ca(OH)_2$ titration was calculated as milliequivalents of base added per unit volume of soil, and was then related to an acre-furrow-slice basis. SMP

buffer lime requirement was related to a decrease in buffer pH as indicated by Shoemaker, McLean, and Pratt (29). Decrease in Woodruff buffer from pH 7

FIGURE 4. Lime-response curve of three soils initially having a similar pH but responding much differently to lime additions. Incubation lime requirements were evaluated by following the response curve to pH 6.5 and then determining the corresponding lime addition; for example, the Fairbanks series required approximately 1 ton/acre to pH 6.5 while the Rabideux series required 4 tons/acres.

was adjusted for 1,000 pounds limestone per 0.1 pH unit (31). To adjust this to pure $CaCO_3$ as suggested by McLean, Dumford, and Coronel (15), the limestone values were divided by 1.4.

Peech (24) stated that the more accurate lime requirement methods are based on exhaustive leaching of the soil with a buffered salt solution. Further, he stated that the $BaCl_2$-triethanolamine was suitable for routine determination of L.R. As suggested by Peech, the calculated rates in Table 2 equal 80% of the theoretical L.R. as determined by this method. Additionally, the recommendation was adjusted to a volume basis of soil rather than to an assumed weight of 2,000,000 pounds per acre. The following formula was used for calculations, L.R. = meq/85 cc x 800 x 0.8; whereas 1 meq acid/85 cc equals 800 pounds $CaCO_3$ per acre 6-inch volume.

Although pH determinations are widely used for making liming recommendations, the reliability of this method is determined largely by the accuracy with which the relationship between soil pH and percent base saturation (% B.S.) of the soil has been established (24). Figure 5 indicates the relationship between % B.S. and initial pH of the collected soils; note that the relationship does not fit a straight line but is presumably related to differences in type of minerals in the soil or to differences in the organic components present. The linear regression equation of Figure 5 (pH = 0.028% B.S. + 4.75) indicated the expected base saturation at pH 6.5 equals 62%.

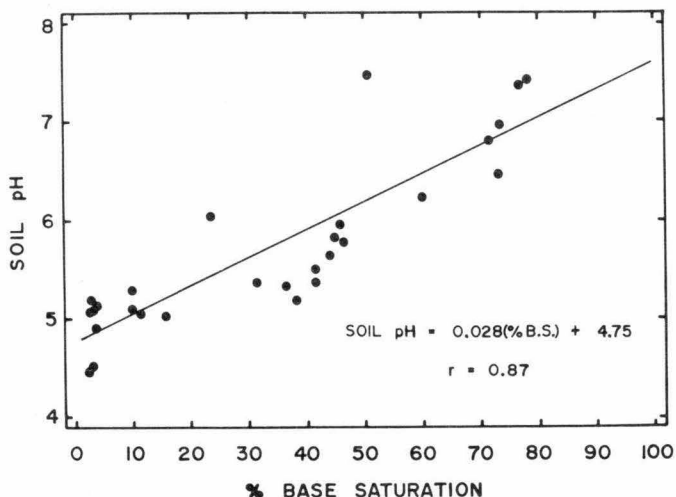Thus, lime requirement in pounds per acre to 62% base saturation was calculated by L.R. = (62-%B.S.) x Cation Exchange Capacity x 800. (Cation exchange capacity was calculated per 85 cc of soil rather than per 100 g soil to agree with the earlier discussion that lime requirement for Alaskan soils is better estimated on a volume rather than a weight basis.) From a graph presented by Peech (24) for New York soils, it appeared B.S. at ca 72% is equal to a 6.5 pH. This indicates Alaskan soils require a lower base saturation for comparable pHs. Mehlich (18) observed that soils dominated by organic matter reached a given pH at a lower % base saturation than those dominated by montmorillonite or illite clays.

Sequential increments of lime have been shown to cause straight-line increases in soil pH between ca 4.8 and 6.2 (9, 29). Assuming a linear or nearly linear lime response curve to pH 6.5, data of Table 3 indicate on the average that 4,300 pounds lime per acre were required to increase soil pH one unit. Based on this information, the lime requirement of the test soils was calculated by the formula: L.R. = (6.5-initial soil pH) x 4,300. Note additionally from Table 3 that the range in L.R. per unit pH change varied from 1,200 to 7,700 pounds per acre, or approximately a sixfold difference. Thus, it is easy to conclude, as Mehlich did working in North Carolina in 1939 (17), that use of soil pH as a single predictor of L.R. for Alaskan soils is hazardous.

Information in Table 2 emphasizes the need for an adapted L.R. test for Alaskan conditions; indicated L.R. varies considerably according to the method of prediction. Coleman and Thomas (4) stated that, in many ways, the uncertainties attributed to measuring L.R.s reflect the lack of accurate information on the nature of the acid-soil system. Although the field study of L.R. is ideal, due to inhibitive costs and time requirements of field methods, the $CaCO_3$ moist-incubation method has been considered as a standard for comparative purposes with buffer indicated L.R. by numerous researchers (11, 15, 19, 29, 33). Regression equations in Table 4 relate $CaCO_3$ incubation L.R. with six other L.R. indices. The best predictive index is $Ca(OH)_2$ titration (r = 0.95); this is in agreement with observations by McLean, Dumford, and Coronel (15) in that lime-water titration or $Ca(OH)_2$ equilibration followed by carbonation is a widely accepted reference method. But as noted earlier, this method has a serious drawback for routine soil testing since three days are required for equilibration.

The Woodruff and SMP buffer methods are both well adapted to routine soil testing operations, and

FIGURE 5. The relationship between % base saturation and corresponding pH for 22 Alaskan soils.

TABLE 3:
QUANTITIES OF CaCO₃ REQUIRED BY INDIVIDUAL
SOIL TO INCREASE SOIL pH BY ONE UNIT [1]

Soil No.	Initial Soil pH	CaCO₃ Incubation Lime Requirement Pounds Per Acre	Lime Requirement Per Unit pH Increase Pounds Per Acre
1	5.30	4,600	3,800
2	5.11	5,500	4,000
3	5.78	900	1,300
4	6.24	300	1,200
5	5.96	1,400	2,600
6	6.04	1,500	3,300
7	5.03	1,800	1,200
8	5.20	10,000	7,700
9	5.34	4,400	3,800
10	4.45	13,500	6,600
11	5.16	5,900	4,400
12	5.84	4,100	6,200
13	5.07	12,500	8,700
14	5.09	7,400	5,200
15	5.39	4,800	4,300
16	5.51	3,100	3,100
17	5.36	3,000	2,600
18	5.06	5,500	3,800
19	5.65	2,300	2,700
20	4.97	7,900	5,200
21	5.21	7,900	6,100
22	4.53	11,800	6,000
		Av.:	4,300
		Range:	1,200-7,700

[1] Calculated by dividing CaCO₃ Incubation Lime Requirement by difference in pH (6.5-initial pH).

TABLE 4:
REGRESSION STATISTICS FOR LIME REQUIREMENT INDICATED BY CaCO₃
INCUBATION VERSUS OTHER L.R. INDICES FOR 22 ALASKAN SOILS

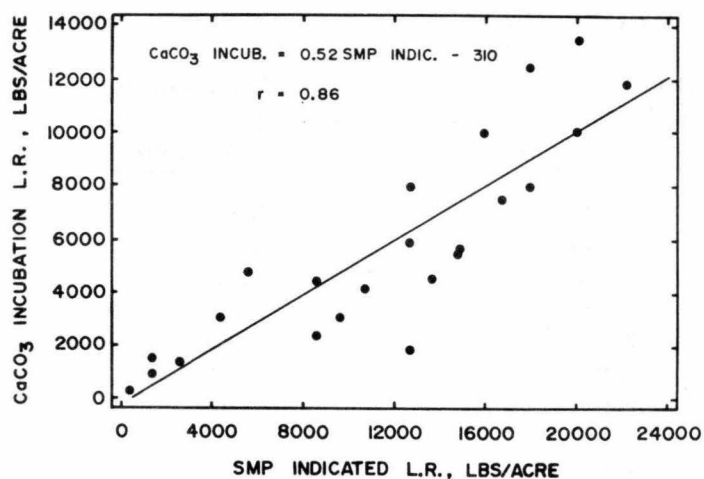|	Independent Variable (Y)	Dependent Variable (X)	Equation	Regression Coefficient (r)
a)	CaCO₃ Incubation	Ca(OH)₂ titration	$Y = -290 + 1.10\ X$	+0.95
b)	CaCO₃ Incubation	Woodruff L.R.	$Y = -2,900 + 1.30\ X$	+0.87
c)	CaCO₃ Incubation	SMP L.R.	$Y = -310 + 0.52\ X$	+0.86
d)	CaCO₃ Incubation	BaCl₂-Trieth. L.R.	$Y = -1,900 + 0.41\ X$	+0.84
e)	CaCO₃ Incubation	To 62% Base Saturation L.R.	$Y = +1,000 + 0.45\ X$	+0.81
f)	CaCO₃ Incubation	pH 6.5-Initial pH X 4,300 L.R.	$Y = -2,600 + 1.60\ X$	+0.81

FIGURE 6. Relationship between SMP indicated and $CaCO_3$ incubation lime requirements.

reported that up to 68% of the C.E.C. can be dominated by exchangeable Al in certain soils.

The nature of soil acidity, whether predominantly H or Al, may affect buffer pHs. McLean et al. (16) observed the change in SMP buffer pH to be greater with H ions from HCl than with soil acidity based on equal milliequavelant additions. Furthermore, Shoemaker, McLean, and Pratt (29) indicated the SMP buffer method would predict more lime required if the amount of acidity were large and H ions predominated instead of Al. In soils where organic matter is an important contributor to C.E.C., it appears that a higher proportion of the exchangeable acidity is H (32). It is of interest to note McLean et al. (15) found regression lines relating the SMP buffer-indicated and incubation-measured L.R.s, based on pH of unleached soils in water, had slopes of 0.90, 0.82, and 0.77 for Ohio, North Central regional, and U.S.A. soils, respectively. Therefore, the tendency was to decrease the slope relationship in going from the more highly weathered Ohio soils to the North Central regional to the U. S. soils. Since prediction at low L.R.s is good, and considering that ca one-half (0.52 from equation C, Table 4) the lime is required as indicated by the buffer L.R., the SMP method appears suited to routine use in the Palmer Soil Testing Laboratory for evaluation of Alaskan soils.

The BaCl$_2$-triethanolamine and the base saturation to 62% methods gave a similar slope in the regression equation as did the SMP method: 0.41 and 0.45 respectively, compared to 0.52 for SMP. This would indicate that all three procedures were measuring comparable forms of soil acidity. The regression coefficients, however, for the two former procedures were somewhat lower than for the SMP method.

The best-fit linear regression equation comparing $CaCO_3$ incubation with difference in initial soil pH from 6.5 indicated a negative y-axis intercept of 2,600 pounds per acre, and a regression coefficient of 0.81. Although other means of predicting L.R. provided higher correlations, this method offers the advantage of simplicity. Inclusion of organic matter into the regression equation, (pH 6.5 - soil pH) x %O.M., as suggested by Keeney and Corey (12) resulted in a regression coefficient of 0.72. The organic matter in these soils was in various stages of decomposition; some of the material in certain soils was quite fibrous and undecomposed.

both gave similar regression coefficients, 0.87 and 0.86, respectively. However, at low lime requirements the Woodruff buffer overestimated L.R. by greater than one ton as indicated by the regression equation; however, the indicated slope of 1.3 suggested that both Woodruff buffer and $CaCO_3$ incubation L.R. were measuring similar components of soil acidity. Woodruff (31) reported this buffer gave a slope of 1:1 for Missouri soils. The SMP buffer, on the other hand, estimated more closely low lime requirements falling only 310 pounds below the X-Y intercept at pH 6.5 (Figure 6). However, the slope of the regression equation did not approach unity as did the Woodruff buffer. This indicates that the nature of Alaskan soil acidity differs significantly from that of the the fourteen Ohio soils for which the SMP buffer pH depression was originally correlated with lime requirement (29). McLean (15) found the SMP buffer method to be well adapted for soils requiring > 4,000 lb of lime per acre, having pH < 5.8, containing <10% organic matter, and having appreciable quantities of solube (extractable) Al. Data of Table 1 indicate extractable Al is variable in Alaskan soils but is relatively low compared to total acidity; this presumably reflects low clay content of soils and little weathering of primary soil minerals as influenced by a cold-dominated climate. Kamprath (11)

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The Liming Factor

The factor by which the L.R., as determined under laboratory conditions, must be multiplied to get the same soil pH in the field is called the liming factor. Dunn (6) found the liming factor for Washington soils to range from 1.0 to 1.6. Pierre and Worley (26) obtained an average liming factor of 1.5 for 77 soils held under greenhouse conditions. Many soil and climatic conditions affect the action of lime in soils. Russell (27) concluded that the factor may be as high as two or three for some soils yet be unity for other soils. Conditions such as the evenness and depth with which the limestone is incorporated into the soil, the rate at which it dissolves in the soil solution and reacts with the soil particles, the neutralizing value and fineness of grind of the limestone, and the quantity of rainfall are presumably important factors in explaining the observed differences.

Data of Table 5 indicate the liming factor of several of the soil series under consideration. Note that numerous observations are available for four of the series; however, five of the series are represented by less than three field studies. Nevertheless, this is the only known data available on these soils. The liming factor of soils with corresponding field data ranged from 1.1 to 2.8, which is in the range suggested by Russell (27). Further note that the average liming factor was 1.8.

The quantities of less than 100-mesh $CaCO_3$ required to obtain a final pH of 6.5 as indicated in Table 2, also as indicated in Appendix 1, likely underestimate the actual field requirements expressed as agricultural-grade limestone. A better estimate could be obtained by multiplying the less than 100-mesh $CaCO_3$ requirement by the factor 1.8. For example, a soil of the Soldotna series with an initial pH of 4.97 (Table 1) requires 7,900 pounds $CaCO_3$ per acre (Table 2) as determined by $CaCO_3$ incubation to reach a final pH of 6.5. Under field conditions using agricultural-grade lime, the best estimate currently available would be 14,220 pounds (7,900 x 1.8), or seven tons per acre.

TABLE 5:
CALCULATION OF LIMING FACTOR APPROPRIATE FOR CONVERSION OF INCUBATION LIME REQUIREMENTS TO FIELD CONDITIONS.[1]

| Soil Series | No. field[2] Observations | Tons lime required to[3] increase pH one unit | | Liming factor[4] |
		Field	Laboratory	
Cohoe (1)	3	3.9	1.9	2.1
Kashwitna (2)	11	3.2	2.0	1.6
Kachemak (10)	9	3.6	3.3	1.1
Homestead (11)	15	3.0	2.2	1.4
Nancy (14)	24	4.4	2.6	1.7
Tustumena (17)	2	3.7	1.3	2.8
Island (18)	1	3.2	1.9	1.7
Knik (19)	1	3.4	1.4	2.4
Mutnala (1)	1	4.5	3.0	1.5

Av.: 1.8

[1] Sincere appreciation is expressed to Dr. Winston M. Laughlin, Agricultural Research Service, United States Department of Agriculture, Palmer, for providing the necessary field data for determination of the liming factor.

[2] Represents the number of field studies in which averages were derived to calculate the effect of liming on soil pH. The purpose of a number of these studies was to observe the liming effects in combination with fertilizer and management treatments.

[3] The field lime requirement was calculated by dividing lime addition by change in pH at the end of one growing season or following one year after lime application. Values for laboratory lime requirements were obtained from Table 3.

[4] The liming factor was obtained by dividing field lime requirement by the laboratory lime requirement.

Plant Responses

Soil factors influencing plant growth and mineral nutrition represent a complex relationship. When soils are limed, many facets of the soil environment are changed. Responses of crops to lime generally have been attributed to changes in the soil environment with regard to: 1) solubilities of toxic substances, aluminum and manganese being those most frequently implicated; 2) availabilities of calcium and magnesium; 3) availabilities of phosphorus and potassium; 4) solubilities or availabilities of trace elements; or 5) populations and activities of soil microorganisms (3).

Most vegetables and field crops perform best at a soil pH in the range 6.0-7.0. Barley, however, is a low-acid tolerant crop. Doll (5) confirmed this for mineral soils in Michigan stating best results can be expected in the 6.5 to 7.8 pH range. Figure 7 indicates the dry weight of barley produced per pot as influenced by soil pH. Bear in mind that these yield data are from virgin soils and represent an average over all the pH ranges indicated. Yield drops off sharply below pH 5.5. Since yield in the 5.5 to 6.0 group represents only six observations, the height of the bar may be misleading. In the groups 6.0 to > 7.5, ca twenty observations were averaged for each

bar height. These data indicate maximum barley growth in these soils occurs near soil neutrality, pH 7.0.
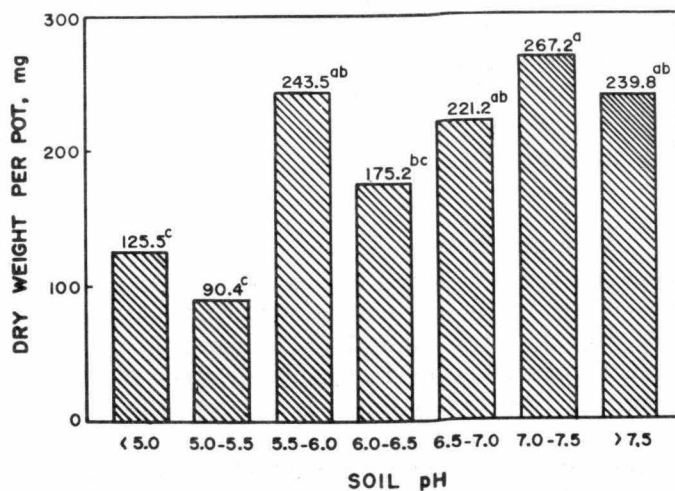

FIGURE 7. Barley response versus soil pH for 22 Alaskan limed and unlimed soils. Means followed by the same letter are not statistically different at the 0.05 level (Duncan's Multiple Range Text).

Dry-yield response to lime varied tremendously between individual soils. The majority of soils, however, with an initial pH of 6.0 or below did show a positive liming response. Several of the more responsive soils are depicted in Figure 8; pH and dry-weight response to liming for each soil along with percent shoot composition of N, P, K, Ca, and Mg is presented in Appendix 1. Visual responses of the Cohoe, Haines, and Susitna series are presented in Figure 9 (note: numbers depicted in the photographs correspond to the original field inventory of soils and not to the alphabetized location list used in this bulletin and shown beneath each photograph.

Cohoe Series (1)

Haines Soil (8)
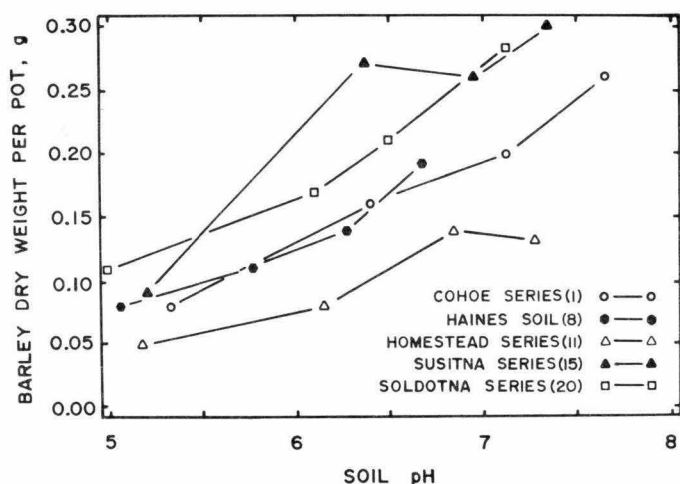
FIGURE 8. Barley dry-weight response due only to lime additions on several responsive soils. Responsive soils were determined by considering dry-weight production on unlimed soils and comparing those results with the results from soils receiving increasing increments of added lime.

Why are these soils responsive to lime? Aluminum in the soil solution has been identified as a factor responsible for poor growth in many acid soils (12, 30). In fact, Kamprath (11) suggested that liming only to neutralize exchangeable Al was a reasonable approach for determining L.R.s for Ultisols and Oxisols. Several of the soils high in extractable Al (Table 1) did show a marked yield increase with liming. Other soils, however, that had low extractable Al levels also responded to lime additions.

Dr. Jackson (10) stated that a number of soil parameters change as the acidity is altered, and this hinders our ability to determine with certainty the precise factor responsible for poor growth of a specif-
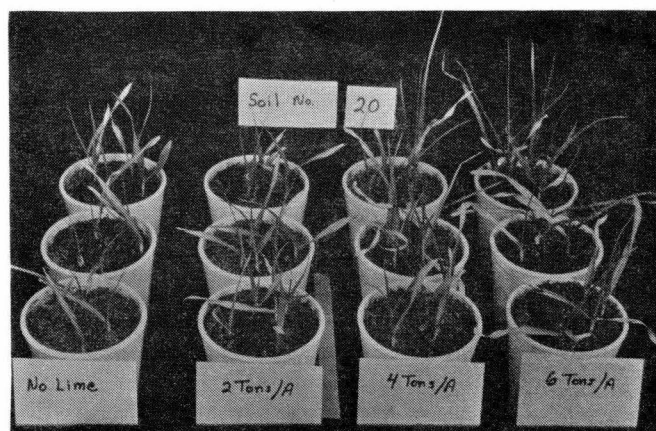
Susitna Series (15)

FIGURE 9. Visual response of barley to lime additions on three responsive soils.

ic plant under acid conditions in a given soil. Numerous workers have shown that major and secondary nutrients become more available to plants as acid soils are limed. This may be a strictly chemical occurrence, or result indirectly via biological activity. For example, if liming increases the organic matter decomposition rate of acid soils (which is well documented), the mineralized nutrients then become available to growing plants. This may be a short-term response, however, and only be active the first several years following liming as the more readily degraded soil components are mineralized.

Plants growing in a number of the soils (see Appendix 1) showed increased N content in the shoots after liming. Soils which clearly indicated this response included the Cohoe series, the Central soil, the Delta-Clearwater soil, the Nenana series, the Nancy series, the Susitna series, the Tustumena series, the Island series, the Soldotna series, the Rabideux series, and the Mutnala series. The increased % N in the shoots is somewhat misleading since most of the plants grown on these soils also showed a yield increase with liming. Perhaps a better indicator of available soil N would be total plant uptake (% N times dry weight of the shoots). Consider the Nancy series for example. The % N in the shoots increased from 0.9 to 1.7% with liming; this represented a 1.9X increase. However, the total N uptake increased from 0.9 mg to 3.9 mg per pot, a 4.3X increase. The range of % N in the shoots over all soils was 0.8 to 2.1%. Visual observations during the study indicated shoots with under ca 1.0-1.1% N showed symptoms of N deficiency.

Contrary to N, concentration of P in the shoots of plants grown on several soils decreased with higher rates of lime addition. This indicated that the increase in dry-matter production was greater than the increased P availability from liming. Additionally for the majority of soils, total plant uptake of P in soils receiving six tons lime per acre versus soils receiving no lime was similar. In fact, only plants grown in four soils showed greater than 1.5X increase in P uptake with soils receiving six tons than with no lime addition; these were the Beluga series (ratio of 1.88), the Kachemak series (ratio of 1.70), the Knik series (ratio of 2.16), and the Rabideux series (ratio of 3.56). Thus, based on plant uptake, it appears liming

had a more decisive influence on increasing N availability to plants than on increasing P availability. The P concentration of shoots ranged from 0.08 to 0.33%. The P level, to express deficiency symptoms, was ca 0.10%. Note that the Kachemak, the Susitna, and the Tustumena series all produced shoots with low P levels; it appeared P was the major nutrient limiting further production in these soils. Fine and Carlson (7) in a greenhouse study of barley reported shoots at the dough stage containing 0.14% P to be in the low range, while shoots containing 0.07% P showed definite deficiency symptoms.

The influence of liming on % K in the shoots was not consistent from soil to soil; content increased in some soils, decreased in others, and apparently varied at random in still others. However, on the majority of soils, total K uptake increased with liming when considering both % nutrient in the shoots and the total dry-weight production. Certain of the soils appeared to be critically short of this nutrient; plants having under 0.3% K in the shoots showed severe K deficiency. These soils included the Kachemak, Island, Soldotna and the Mutnala series—all soils from the Kenai or Alaskan Peninsula. The percent K composition of shoots from the 22 Alaskan soils varied from 0.1 to 2.0%, a twentyfold difference.

The addition of a liming agent such as $CaCO_3$ not only increases percent base saturation of a soil but also provides the plant nutrient calcium. Note from the data in Appendix 1, that plants grown in a number of unlimed acid soils had an initial Ca content of 0.4%; further note, that the first lime addition (2 tons/acre) increased Ca content to near maximum levels obtained at all higher rates of liming. This indicated that after the addition of two tons lime per acre, that further liming served only to correct an unfavorably low % base saturation and did not increase percent composition in the shoots. Calcium composition of the shoots varied from 0.3 to 1.4%.

The effect of liming on Mg content of the shoots was similar to that of K: wide differences occurred between soils. The Circle Hot Springs soil, the Manley Hot Springs soil, the Tustumena series, and the Rabideux series all, in general, produced shoots with under 0.20% Mg. Magnesium content of shoots varied from 0.10 to 0.44%.

Summary and Conclusions

The majority of the 22 Alaskan soils included in this study which had an initial pH below 6.0 responded to lime additions with increased yields of barley. Dry-weight yields at the conclusion of the six-week incubation period on the average, over all soils, were greater than twice as high on the limed than on the unlimed soils; this ranged from no response to lime (Central soil) to a 3.5X response to lime additions (Kashwitna series).

Several indices for lime requirement prediction which were thought to have application for Alaskan soils were evaluated, and results were compared by regression equations to actual lime requirement as indicated by $CaCO_3$ moist incubation. The $Ca(OH)_2$ titration method provided the most reliable index to actual lime requirement ($r = 0.95$); however, for routine use in a soil–testing laboratory, the required three-day equilibration period seemed excessive. Furthermore, this procedure had a higher labor and glassware requirement which additionally proved unfavorable compared to other methods.

The SMP and Woodruff procedures both were readily adaptable to routine laboratory use; however, the Woodruff method overestimated low lime requirements. The SMP buffer did an adequate job of estimating lime requirement compared to the $CaCO_3$ incubation method ($r = 0.86$), although the slope of the regression equation comparing SMP buffer and $CaCO_3$ incubation was ca 0.5. For reasons undetermined in this study, the SMP buffer, as originally correlated on the more highly weathered acid soils of Ohio, overestimated lime requirement by approximately twofold. This is probably related to the forms of acidity or higher contents of organic matter present in Alaskan soils. Nevertheless, since the correlation is high and the predictive equation indicates good agreement at low lime requirements, with an appropriate adjustment, the SMP method appears best suited to predict the lime requirement of Alaskan soils (Appendix 2).

Nutrient composition of plant shoots grown on limed and unlimed soils revealed that liming increased N and Ca content of shoots; however, P percentage tended to decrease with liming. It further appeared that liming stimulated plant growth more readily than it stimulated P uptake. The K and Mg composition of shoots was unrelated to liming treatment.

As production agriculture and interest in small-plot food production increases in Alaska, more demands are being made on the Agricultural Experiment Station and other research and information agencies within Alaska to provide technical assistance. A well-adapted soil–testing program with adequate response data is essential for Alaskans to better utilize and understand limitations of their natural resources.

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Appendix 1

Soil response data to pH change and nutrient composition of Weal barley as a function of lime addition on 22 individual Alaskan soils. Soil pH and dry-matter production represent the average of 3 replications. Nutrient composition represents analyses made on a composite sample from the 3 replications.

To compensate for uniformity of mixing and to adjust for agricultural grade lime, the quantities of lime as indicated in this appendix should be increased by a factor of 1.8 to approximate expected field responses.

		Barley (6 weeks)					
Tons Lime/Acre	Soil pH	Dry Wt g/pot	N %	P %	K %	Ca %	Mg %
Soil: Cohoe Series, Anchor Point, No. 1							
0	5.33	0.08	1.0	0.27	1.0	0.4	0.36
2	6.40	0.16	0.9	0.15	0.8	0.9	0.30
4	7.13	0.19	1.1	0.10	1.0	0.9	0.27
6	7.65	0.26	1.3	0.10	0.6	0.9	0.23
Soil: Kashwitna Series, Caswell, No. 2							
0	5.18	0.04	1.3	0.50	0.4	0.5	0.32
2	6.30	0.07	1.2	0.30	0.5	1.3	0.29
4	6.79	0.14	1.1	0.18	0.3	1.2	0.26
6	7.34	0.12	1.4	0.22	0.3	1.3	0.20
Soil: Central, No. 3							
0	5.87	0.08	0.9	0.26	0.7	1.0	0.32
2	7.80	0.07	1.1	0.29	0.7	1.4	0.30
4	8.08	0.07	1.2	0.24	0.7	1.4	0.30
6	7.94	0.08	1.2	0.31	0.7	1.4	0.30
Soil: Circle Hot Springs, No. 4							
0	6.30	0.25	0.9	0.18	1.0	0.4	0.10
2	7.92	0.25	0.7	0.21	1.1	0.6	0.13
4	8.01	0.26	0.8	0.20	1.1	0.6	0.13
Soil: Delta-Clearwater, No. 5							
0	5.97	0.21	0.9	0.14	1.1	0.6	0.28
2	7.20	0.28	1.2	0.12	1.1	0.8	0.28
4	7.87	0.21	1.5	0.14	1.1	1.1	0.31
6	7.97	0.23	1.7	0.14	0.9	1.0	0.28
Soil: Nenana Series, Delta Junction, No. 6							
0	5.62	0.10	0.9	0.19	1.1	0.6	0.32
2	7.40	0.16	1.1	0.19	1.3	0.9	0.27
4	7.96	0.11	1.2	0.15	1.0	1.1	0.29
6	7.85	0.16	1.0	0.15	1.1	1.0	0.29

| Tons Lime/Acre | Soil pH | Barley (6 weeks) | | | | | |
		Dry Wt g/pot	N %	P %	K %	Ca %	Mg %
Soil: Fairbanks Series, Fairbanks, No. 7							
0	5.48	0.08	0.9	0.24	1.1	0.5	0.30
2	7.28	0.10	1.1	0.25	0.5	0.5	0.23
4	8.00	0.16	1.1	0.21	0.9	0.8	0.29
6	8.12	0.15	1.1	0.19	1.1	0.9	0.30
Soil: Haines (Lewis Nelson), No. 8							
0	5.06	0.08	0.9	0.26	1.1	0.5	0.32
2	5.77	0.11	0.8	0.18	1.1	0.6	0.29
4	6.28	0.14	1.0	0.13	1.3	0.6	0.27
6	6.67	0.19	1.3	0.09	1.6	0.7	0.23
Soil: Beluga Series, Homer, No. 9							
0	5.05	0.21	0.8	0.20	1.3	0.4	0.29
2	6.44	0.33	0.7	0.20	1.2	0.6	0.29
4	7.07	0.40	0.9	0.19	1.2	0.7	0.25
6	7.49	0.42	0.9	0.19	1.1	0.7	0.26
Soil: Kachemak Series, Homer, No. 10							
0	4.36	0.16	1.4	0.11	0.1	0.4	0.19
2	5.40	0.25	1.3	0.09	0.2	1.0	0.24
4	5.62	0.35	1.4	0.07	0.1	1.1	0.24
6	6.26	0.33	2.1	0.09	0.1	1.1	0.28
Soil: Homestead Series, Houston, No. 11							
0	5.17	0.05	1.1	0.44	0.3	0.5	0.31
2	6.14	0.08	1.1	0.27	0.8	1.0	0.23
4	6.84	0.14	1.1	0.17	0.8	0.9	0.20
6	7.27	0.13	1.7	0.18	0.8	1.1	0.18
Soil: Juneau (State Correction Institute), No. 12							
0	5.90	0.23	0.9	0.26	1.0	0.7	0.33
2	6.48	0.27	0.9	0.24	1.0	0.7	0.30
4	6.98	0.27	0.9	0.23	0.8	0.8	0.26
6	7.34	0.29	0.9	0.24	0.8	0.7	0.24
Soil: Juneau (Walt McPherson), No. 13							
0	5.03	0.06	1.1	0.48	0.4	0.4	0.15
2	5.69	0.14	0.9	0.18	1.0	1.1	0.26
4	6.03	0.19	1.1	0.17	0.6	1.1	0.26
6	6.40	0.16	1.8	0.20	0.6	1.5	0.26
Soil: Nancy Series, Kashwitna, No. 14							
0	4.83	0.10	0.9	0.26	0.4	0.3	0.26
2	5.94	0.16	1.0	0.19	1.0	1.0	0.26
4	6.63	0.16	1.3	0.18	0.8	1.0	0.27
6	6.87	0.23	1.7	0.13	0.8	1.0	0.23

Tons Lime/Acre	Soil pH	Barley (6 weeks)					
		Dry Wt g/pot	N %	P %	K %	Ca %	Mg %
Soil: Susitna Series, Kashwitna, No. 15							
0	5.21	0.09	1.1	0.24	1.0	0.5	0.36
2	6.37	0.27	1.0	0.09	1.5	0.7	0.28
4	6.94	0.26	1.5	0.09	1.5	1.0	0.28
6	7.34	0.30	1.8	0.09	2.0	0.9	0.27
Soil: Manley Hot Springs, No. 16							
0	5.57	0.45	0.9	0.16	1.3	0.4	0.18
2	6.76	0.62	0.9	0.16	1.3	0.5	0.15
4	7.68	0.69	1.1	0.13	1.5	0.6	0.17
6	7.84	0.71	1.1	0.13	1.6	0.6	0.15
Soil: Tustumena Series, Naptowne, No. 17							
0	5.51	0.30	1.0	0.07	0.7	0.5	0.21
2	6.77	0.39	1.1	0.07	0.7	0.6	0.18
4	7.46	0.39	1.4	0.07	0.7	0.7	0.20
6	7.59	0.31	1.6	0.07	0.6	0.7	0.15
Soil: Island Series, Ninilchik, No. 18							
0	5.24	0.05	1.0	0.47	0.3	0.8	0.32
2	6.31	0.07	1.2	0.31	0.2	1.4	0.30
4	6.83	0.07	1.8	0.35	0.2	1.1	0.20
6	7.27	0.11	1.7	0.21	0.3	1.3	0.23
Soil: Knik Series, Palmer, No. 19							
0	5.76	0.09	0.9	0.27	1.1	0.7	0.27
2	6.99	0.17	0.9	0.25	1.3	0.8	0.27
4	7.74	0.17	1.0	0.23	'1.2	0.8	0.26
6	7.83	0.22	1.0	0.24	1.1	0.9	0.31
Soil: Soldotna Series, Soldotna, No. 20							
0	4.95	0.11	1.4	0.24	0.2	0.6	0.23
2	6.09	0.17	1.3	0.11	0.2	1.2	0.27
4	6.49	0.21	1.9	0.15	0.2	1.2	0.21
6	7.12	0.28	2.0	0.12	0.2	1.1	0.23
Soil: Rabideux Series, Trapper's Creek, No. 21							
0	5.29	0.23	0.8	0.14	0.6	0.3	0.18
2	6.00	0.25	1.2	0.18	1.1	0.7	0.20
4	6.52	0.35	1.4	0.19	1.0	0.9	0.20
6	7.10	0.60	1.4	0.19	0.6	0.9	0.19
Soil: Mutnala Series, Tyonek, No. 22							
0	4.68	0.09	0.9	0.29	0.2	0.4	0.23
2	5.54	0.11	1.1	0.16	0.2	1.0	0.28
4	6.08	0.11	1.3	0.18	0.2	1.2	0.28
6	6.53	0.15	1.6	0.15	0.2	1.1	0.30

Appendix 2

Suggested agricultural lime additions for SMP buffer pH for Alaskan soils. This appendix is based on the data of Shoemaker, et al. (29) as adjusted by equation C Table 4 of the text and considering a liming factor of 1.8. Values are expressed as tons of agricultural-grade lime[1] required to adjust soil pH to the indicated pH based on an acre 6-inch volume of soil.

	Final Soil pH		
Buffer pH	6.0	6.5	7.0
6.9	0	0	0
6.8	0.3	0.5	0.6
6.7	0.7	1.0	1.2
6.6	1.1	1.4	1.7
6.5	1.5	1.9	2.3
6.4	1.9	2.4	2.9
6.3	2.3	2.9	3.5
6.2	2.7	3.3	4.0
6.1	3.1	3.8	4.5
6.0	3.5	4.3	5.2
5.9	3.9	4.8	5.8
5.8	4.2	5.2	6.3
5.7	4.6	5.8	6.9
5.6	5.0	6.2	7.4
5.5	5.5	6.8	8.0
5.4	5.9	7.2	8.6
5.3	6.2	7.6	9.2
5.2	6.6	8.2	9.8
5.1	7.0	8.6	10.4
5.0	7.4	9.2	11.0
4.9	7.8	9.6	11.6
4.8	8.2	10.2	12.1

[1] Amounts of lime are based on agricultural-grade limestone (95% through 8-mesh and 40% through 100-mesh sieve, and 90% $CaCO_3$ equivalent).