Chapter 10

Soil Acidity and Liming

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Soil pH, soil acidity, and their effects on plants

The pH scale, ranging from 0 to 14, is used to indicate acidity and alkalinity. pH is a measure of the concentration of hydrogen ions (symbol = H^+) in the water contained in the soil. A pH of 7.0 is neutral, values below 7 are acidic, and those above 7 are alkaline (basic). The lower the pH, the more acid the soil. Each unit pH drop indicates ten times more acidity. For example, pH 5 has 10 times more acidity than pH 6, and 100 times more acidity than pH 7. Most Hawaii soils have pH ranging from 4 to 9. For comparison, here are the pH values of some common liquids:

- pure water, 7.0
- "city" water (tap water), 7.5–8
- clean rain water, about 5.6 (because of CO_2 presence)
- "acid rain" water, 3.5–5.5
- lemon juice, 2.2–2.4
- orange juice, 3.4–4
- vinegar, 4–4.5
- fresh milk, 6.3–6.6
- mild soap solution, 8.5–10.

Figure 10-1 describes the pH range of Hawaii soils. Soil pH affects crops in many ways. However, its effects are mostly indirect, through its influence on chemical factors and biological processes. Chemical factors include aluminum (Al) and manganese (Mn) toxicities and calcium (Ca) and phosphorus (P) deficiencies; magnesium (Mg) and molybdenum (Mo) deficiencies are also a possibility. In the soil biosphere, soil pH affects the growth and reproduction of microorganisms, which in turn can affect plants, as illustrated by the following examples:

Figure 10-1. The soil pH scale
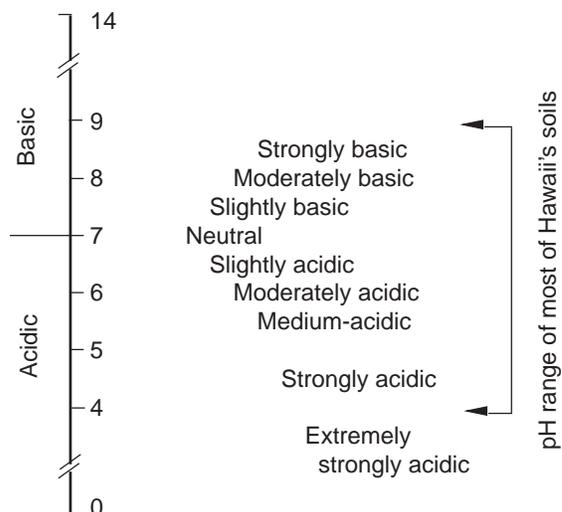
- Legumes, such as beans, peas, and desmodium forage, have nodules on their roots in which live bacteria that can take nitrogen from the air and change it to a form usable by the plant; some strains of the bacteria do not thrive at pH values below 6, thus pH 6 or above is best for the legumes that require those particular strains of the bacteria.
- Potato scab disease is more prevalent when soil pH is above 5.5; thus the recommended soil pH for optimum growth of potato is around 5.0 to 5.5, despite the fact that potato plants can grow well at higher pH.
- Plants such as azalea and camelia grow well only at pH values below 5.5 and suffer from iron (Fe) and Mn deficiencies at higher pH.

Table 10-1. Soil pH ranges for optimum growth of selected plants.

Plant	pH	Plant	pH
Field crops			
Alfalfa	6.5–7.5	Rice	5.0–6.5
Field corn	5.5–6.7	Sorghum	5.5–7.0
Kaimi clover	5.5–6.5	Sugarcane	5.0–6.5
Kikuyu grass	5.5–6.5	Taro	5.5–6.5
Pangola grass	5.5–6.5	Trefoil	5.5–6.0
White clover	6.0–7.0		
Flowering plants			
Anthurium	5.5–6.5	Hibiscus	5.8–6.5
Azalea	4.5–5.0	Ixora	5.8–6.5
Begonia	5.5–6.0	Jacaranda	5.8–6.5
Bougainvillea	5.5–6.8	Lantana	5.8–6.5
Camellia	4.5–5.5	Magnolia	5.5–6.5
Carnation	6.0–6.5	Marigold	5.8–6.5
Chrysanthemum	6.0–6.5	Oleander	6.0–7.0
Flame grass	5.5–6.5	Orchid	5.5–6.5
Gardenia	5.0–6.0	Poinciana	5.8–6.5
Geranium	6.0–6.5	Poinsetta	5.8–6.5
Ginger	6.0–6.5	Pomegranate	6.0–7.0
Honeysuckle	6.5–7.0	Roses	5.8–6.5
Nuts			
Coconut	6.0–8.0	Macadamia	5.0–6.5
Coffee	5.0–6.0		
Fruits			
Avocado	6.2–6.5	Lime	6.0–6.8
Banana	5.5–6.5	Lychee	5.5–6.5
Breadfruit	5.0–6.0	Mango	5.5–6.8
Date	6.5–8.0	Orange	5.8–6.5
Fig	6.0–6.8	Papaya	5.8–6.5
Grapefruit	6.0–6.8	Passion fruit	5.0–6.0
Guava	5.5–6.8	Pineapple	4.7–5.5
Kumquat	6.0–6.8	Pummelo	5.8–6.5
Lemon	6.0–6.8	Tangerine	6.0–6.8
Ornamentals			
Alamanda	5.8–6.5	Mock orange	6.0–6.8
Ficus spp.	5.8–6.7	Mondo grass	6.0–6.8
Boxwood	6.0–6.8	Monkeypod	6.0–6.8
Calinga	5.5–6.5	Moss rose	6.0–6.8
Caladium	6.0–6.5	Palms	6.0–6.8
Coleus	6.0–6.5	Pandanus	6.0–6.8
Croton	5.5–6.5	Portulaca	5.5–6.5
Eucalyptus	6.0–6.8	Sunflower	6.0–6.8
Ironwood	6.0–6.8	Stephanotis	6.0–6.8
Jade Vine	6.0–6.8		
Turf			
Bent	6.0–6.5	St. Augustine	6.0–6.5
Bermuda	6.0–6.5	Zoysia	6.0–6.5
Centipede	6.0–6.5		

Plant
Vegetables: pH 6.0–6.8 for all types listed

|		
Asparagus	Dasheen	Peas
Beets	Eggplant	Pole beans
Bell peppers	Ginger root	Potato
Bitter melon	Gourde	Radish
Broccoli	Gobo	Snap beans
Cabbage	Kai choy	Squash
Cantalopes	Leek	Strawberry
Carrots	Lettuce	Sweet corn
Cauliflower	Lima beans	Sweetpotato
Celery	Mint	Tomato
Chili pepper	Muskmelon	Turnip
Cowpeas	Okra	Won bok
Cucumbers	Parsley	Watercress
Daikon	Peanut	

Adapted from McCall (1976), Spurway (1941), and Maynard and Hochmuth (1997).

Table 10-1 lists soil pH ranges for optimum growth of selected crops.

Causes of soil acidity, and factors making acid soils infertile

Acid soils are common in humid regions. Wherever rainfall is substantial, bases and salts are leached from the soil profile, leaving behind more stable materials rich in iron and aluminum oxides, resulting in soils that are acidic and generally devoid of plant nutrients. In other words, soil acidity is a result of natural weathering processes that are accellerated in wet regions.

Soil management practices, such as regular N fertilizer application, can also acidify soils. Specifically, fertilizers that produce ammonium (NH_4^+), such as urea, anhydrous ammonia and ammonium sulfate, release hydrogen ions (H^+) through a biological process in which NH_4^+ is oxidized to nitrate (NO_3^-), according to the reaction:

$$(NH_4)_2SO_4 + 4O_2 \xrightarrow[\text{bacteria}]{\text{nitrifying}} 2NO_3^- + SO_4^{--} + 2H_2O + 4H^+$$
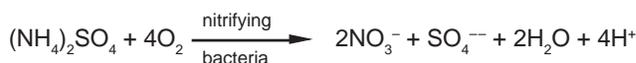
The hydrogen ions displace other positively charged ions in the soil; the ions, also called "cations" or "exchangeable bases" include the important plant nutrients Ca^{++}, Mg^{++}, and K^+. The H^+ becomes a part of the

soil's solid surface, while an equivalent amount of bases is released into the soil solution and is subject to loss by leaching, as shown in the reaction:
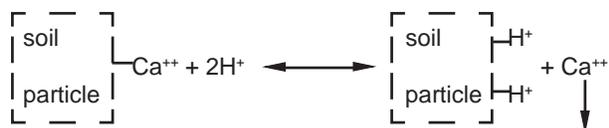
Leaching losses are especially serious in soils with variable charge, which is a characteristic of many of the highly weathered soils of Hawaii. As soil acidity increases, soil surfaces become less negatively charged, and the soil cation-retention mechanism by which exchangeable bases are held is less effective. Thus, these cation nutrients are easily moved downward by water beyond the root zone. In contrast, most negatively charged nutrient ions ("anions"), such as P and Mo, are strongly tied up by the aluminum (Al) and iron (Fe) components of acid soils, thereby becoming unavailable for plant uptake, as illustrated in the following reactions in which aluminum affects phosphate,
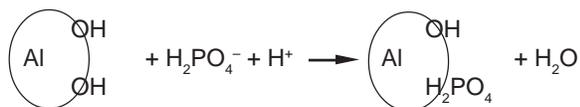

and iron affects molybdate:

$$2\,Fe(OH)_3 \ + \ 3\,MoO_4^{2-} \ + \ 6H^+ \longrightarrow \ Fe_2(MoO_4)_3 \ + \ 6H_2O$$

Due to such reactions releasing cations or binding anions, nutrient impoverishment results. Because of warm temperatures and high rainfall in many tropical and subtropical areas such as Hawaii, acid soils often contain very little Ca and can "fix" P in large quantities. Thus, Ca and P deficiencies are likely problems in acid soils of Hawaii and similar areas. Many soils on Kauai (e.g., the Halii, Kapaa, and Pooku soil series) and Oahu (the Kaneohe, Manana, and Paaloa series) are well known for Ca and P deficiencies if they are not amended.

Other serious problems in acid soils are the abundance of soluble aluminum and manganese ions (Al^{3+} and Mn^{2+}) because of mineral dissolution by acidity. For example, as soils weather, clay minerals such as kaolinite decompose with increased soil acidity to yield soluble Al^{3+} according to the reaction:

$$Al_2Si_2O_5(OH)_4 \ + \ 6H^+ \longrightarrow \ 2Al^{+++} \ + \ 2Si(OH)_4 \ + \ 2H_2O$$
(kaolinite)
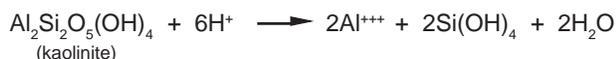
Solid MnO_2 can also be converted to soluble Mn^{2+} according to the reaction:

$$MnO_2 \ + \ 4H^+ \ + \ 2\ electrons \longrightarrow \ Mn^{++} \ + \ 2H_2O$$

High levels of aluminum and manganese are toxic to plants. Aluminum toxicity usually first damages the root system. Aluminum-affected roots tend to be shortened and swollen, having a stubby appearance. In plant shoots, Al levels above 100 ppm (100 mg/kg) would be detrimental to most crops. For example, we have found critical leaf tissue Al levels of 30 ppm for some *Sesbania* (legume) species[x], 75–80 ppm for the forage legume *Desmodium intortum* and for pigeon pea (*Cajanus cajan*)[y], and 275–300 ppm for the relatively tolerant macadamia nut tree (*Macadamia integrifolia*)[z] (see the references [x]Poolpipatana and Hue 1994, [y]Hue 1992, and [z]Hue et al. 1987).

Manganese toxicity first shows up in plant tops rather than in roots. The symptoms vary widely among plant species and are often specific to a particular species. For example, stunted, crinkled, and chlorotic leaves are the Mn toxicity symptoms in soybean. Such affected leaves contain about 600 ppm Mn (Vega et al., 1992). On the other hand, macadamia can accumulate Mn and may contain as much as 1000 ppm Mn in its leaf tissue without noticeable adverse effects.

Correction of soil acidity

Although planting crops tolerant of soil acidity is a reasonable option for dealing with acid soils, liming is traditionally used to correct soil acidity and to improve soil productivity. Common liming materials are the oxides, hydroxides, carbonates, and silicates of Ca or Ca-Mg mixtures. When lime (e.g., $CaCO_3$) is added to a moist soil, the following reactions will occur:
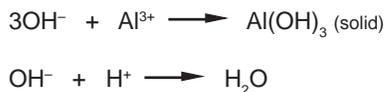
(1) Lime is dissolved (slowly) by moisture in the soil to produce Ca^{2+} and hydroxide (OH^-) :

$$CaCO_3 \ + \ H_2O_{\ (in\ soil)} \longrightarrow \ Ca^{++} \ + \ 2OH^- \ + \ CO_2\ _{(gas)}$$

(2) Newly produced Ca^{2+} will exchange with Al^{3+} and H^+ on the surface of acid soils:
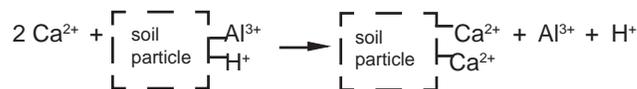
(3) Lime-produced OH^- will react with Al^{3+} to form solid $Al(OH)_3$, or it will react with H^+ to form H_2O :

$$3OH^- + Al^{3+} \longrightarrow Al(OH)_{3 \text{ (solid)}}$$

$$OH^- + H^+ \longrightarrow H_2O$$

Thus, liming eliminates toxic Al^{3+} and H^+ through the reactions with OH^-. Excess OH^- from lime will raise the soil pH, which is the most recognizable effect of liming. Another benefit of liming is the added supply of Ca^{2+}, as well as Mg^{2+} if dolomite $[Ca,Mg(CO_3)_2]$ is used. Calcium and Mg are essential nutrients for plant growth, yet they are often deficient in highly weathered acid soils.

Various liming materials are sold. The cost of the liming material increases with the fineness of its particles, which determines its rate of reaction with the soil. The initial soil pH, the degree of mixing with the soil, and the chemical nature of the material itself also influence the reaction rate. For example, oxides and hydroxides react more rapidly than carbonates. Adequate soil moisture is necessary for the reaction to occur.

Commonly used liming materials and their relative neutralizing values are given in Table 10-2. The neutralizing value, or calcium carbonate equivalent (CCE), is defined as the amount of acid a given quantity of the lime will neutralize when it is totally dissolved. The relative neutralizing value is expressed as a percentage of the neutralizing value of pure $CaCO_3$, which is given a value of 100.

The relative neutralizing value is dependent upon the purity of the liming material used. An example of calculating this value is

pure $Ca(OH)_2$ (formula weight = 74 g)
pure $CaCO_3$ (formula weight = 100 g, or a neutralizing value of 100)
$\quad\quad$ X $\quad$ = neutralizing value of $Ca(OH)_2$
$\quad$ X / 100 $\quad$ = 100 / 74
$\quad\quad$ X $\quad$ = 135

Thus, each ton of $Ca(OH)_2$ can neutralize as much acid as 1.35 tons of $CaCO_3$. In other words, you can replace 1 ton (2000 lb) of $CaCO_3$ with 0.74 ton (1480 lb) of $Ca(OH)_2$.

Liming is not effective unless the liming material is thoroughly mixed with the soil. It should be applied

Table 10-2. Common liming materials

Liming material	Chemical name	Relative neutralizing value
Calcitic limestones	calcium carbonate ($CaCO_3$)	100
Quicklime	calcium oxide (CaO)	150–175
Hydrated lime	calcium hydroxide ($Ca(OH)_2$)	120–135
Dolomitic lime	calcium-magnesium carbonate	95–108
Slag	calcium silicate ($CaSiO_3$)	50–70

evenly and worked in to 6 inches (15 cm) deep, if possible. Lime recommendations are often based on a plow depth of 6 inches. Thus, if the soil is plowed to different depths (e.g., 4 or 8 inches), then adjustment of the amount of liming material should be made proportionately to reach the same target pH.

Lime requirements of acid soils in Hawaii

Nearly all acid soils in Hawaii belong to three soil orders: Andisols, Oxisols, and Ultisols. Table 10-3 lists common pH ranges (in the unlimed state) of some agriculturally important soils of Hawaii. Because these soils, as their classification implies (see Chapter 5), differ widely in properties ranging from mineralogy to organic matter content, their lime requirements—the amount of lime required to raise soil pH to a given value—are expected to vary from soil to soil. Thus, lime requirement curves should be constructed for individual soils. CTAHR soil scientists have determined lime requirement curves for 22 acid soils of Hawaii; these are given in Table 10-4 and drawn in this chapter's Appendix 3 (reproduced from Hue and Ikawa 1994). The data for these curves were obtained after equilibrating 0, 0.25, 0.5, 1, 2, 4, and 8 g $CaCO_3$ with 100 g soil at field moisture capacity. Then the soils were air-dried gradually for one week, re-moistened, and dried again, so that the lime had enough time to react with the soil acidity. At the end of the second week, soil pH (20 g soil in 20 ml water) was measured. The utility of these curves can be illustrated in the following examples.

(1) You wish to determine the amount of lime required to raise the pH of a soil in the Helemano area, Oahu (the Paaloa soil) from 4.5 to 6.2. You would look up the lime requirement curve of the Paaloa soil (graph

**Table 10-3. Common pH ranges of selected agricultur-
ally important soils of Hawaii (under unlimed conditions).**

Soil series	Soil order	Soil pH range[z]
Akaka	Andisol	4.8 – 5.8
Haiku	Ultisol	4.8 – 5.5
Hilo	Andisol	4.8 – 5.8
Kapaa	Oxisol	5.0 – 6.0
Kula	Andisol	5.2 – 6.0
Leilehua	Ultisol	4.8 – 5.8
Lihue	Oxisol	5.0 – 5.8
Lualualei	Vertisol	7.2 – 8.2
Paaloa	Ultisol	4.5 – 5.2
Wahiawa	Oxisol	4.5 – 5.5
Waialua	Mollisol	6.5 – 7.3
Waikaloa	Andisol	5.5 – 6.5

[z]Measured with soil-water ratio of 1:1.

**Table 10-4. Selected Hawaiian soils used in constructing
lime requirement curves, and their corresponding equa-
tions (Hue and Ikawa 1994).**

Soil series	Soil order	Equation for lime requirement[z]
Alealoa	Ultisol	$pH = -0.85e^{-0.98X} + 7.7$
Haiku	Ultisol	$pH = -2.6e^{-0.46X} + 7.3$
Halii	Oxisol	$pH = -2.0e^{-0.62X} + 6.5$
Hamakuapoko	Ultisol	$pH = -1.3e^{-0.43X} + 7.1$
Hilo	Andisol	$pH = -1.5e^{-0.33X} + 7.0$
Honolua	Ultisol	$pH = -2.8e^{-0.21X} + 7.5$
Kahanui	Oxisol	$pH = -2.5e^{-0.40X} + 8.1$
Kaipoioi	Andisol	$pH = -1.5e^{-0.12X} + 7.2$
Kaiwiki	Andisol	$pH = -2.0e^{-0.33X} + 7.0$
Kalapa	Ultisol	$pH = -2.8e^{-0.29X} + 7.6$
Kaneohe	Ultisol	$pH = -2.0e^{-0.39X} + 6.8$
Kapaa	Oxisol	$pH = -1.65e^{-0.63X} + 6.9$
Kokee	Ultisol	$pH = 0.20\,X + 4.9$
Leilehua	Ultisol	$pH = -3.2e^{-0.23X} + 7.7$
Mahana	Oxisol	$pH = -2.0e^{-0.49X} + 6.5$
Makawao	Ultisol	$pH = -2.09e^{-0.33X} + 7.7$
Manana	Ultisol	$pH = -2.7e^{-0.33X} + 7.7$
Niu	Oxisol	$pH = -2.3e^{-0.98X} + 7.7$
Olinda	Andisol	$pH = -2.1e^{-0.15X} + 7.6$
Paaloa	Ultisol	$pH = -4.9e^{-0.10X} + 9.4$
Piihonua	Andisol	$pH = -1.28e^{-0.27X} + 6.4$
Tantalus	Andisol	$pH = -1.9e^{-0.34X} + 7.1$
Wahiawa	Oxisol	$pH = -3.66e^{-0.23x} + 7.89$
Generalized	—	$pH = -2.56e^{-0.25X} + 7.4$

[z]X = tons (2000 lb) of $CaCO_3$ per acre

no. 20 in Appendix 10-3), and from that curve it is clear that 4 tons/acre of $CaCO_3$ is needed to raise the soil pH from 4.5 to 6.2.

(2) What if your soil of interest (say, the Akaka soil of the Big Island) is not one of those shown? Then substitute the curve of another Andisol with similar properties, such as the Kaiwiki soil, to estimate the lime requirement. Alternatively, if your soil is listed among the lime titration curves developed by Matsusaka and Sherman (1950) and shown in Appendix 10-1, then use that curve to estimate the lime requirement.

(3) What if your soil is unknown, in terms of series name or location? Then use the generalized lime requirement curve (Appendix 10-3, graph no. 23). This curve was constructed by combining data from 22 Hawaii soils; it is not exactly correct for any real soil, but it is not far wrong either. Be sure to keep in mind that the lime requirement estimated from this curve is just a first approximation. Use it with caution!

(4) Finally, what if your soil has an initial pH of 4.3 instead of 4.8 as the generalized curve illustrates? Well, as long as your target pH is around 6.5, you can draw a curve parallel to the generalized curve, but start at 4.3, and read the lime requirement from that newly drawn curve. Alternatively, you can use the equation listed in Table 10-4 and solve for the amounts of lime (X) corresponding to pH 4.3 (a negative value, X_1) and also for the target pH (a positive value, X_2); then $X_3 = [X_2 - X_1]$ is the quantity of lime needed.

Additional lime requirement curves for soils and ornamental mixes

The importance of liming acid soils of Hawaii has long been recognized. Matsusaka and Sherman (1950, 1964) used sodium hydroxide (NaOH) solution to develop titration curves for a large number of Hawaii soils (Appendix 10-1). Given the fact that a strong base like NaOH may inadvertently dissolve certain minerals and organic components in soils, Matsusaka and Sherman's method might not be desirable by current analytical standards. Yet their lime titration curves are still useful because they cover many soil orders and wide pH ranges.

For liming ornamental growing mixes, such as black cinders and peat moss, Appendix 10-2 shows curves developed by Kawabata et al. (1975). However, two points should be mentioned: (1) acidity caused by

the presence of hydrogen ions (H^+) does not itself adversely affect the growth of many plants until pH drops below 4.0; (2) since ornamental growing mixes contain very little or no aluminum, most plants can grow well in these mixes at much lower pH (between 4.5 and 5.5) than in mineral soils, where such pH levels often are associated with aluminum toxicity.
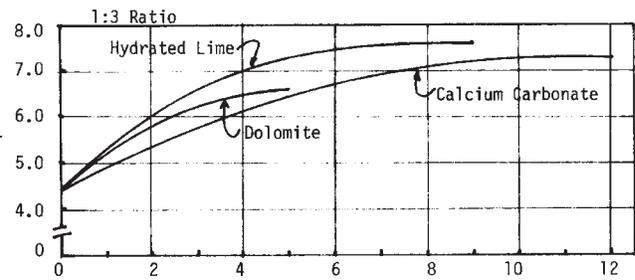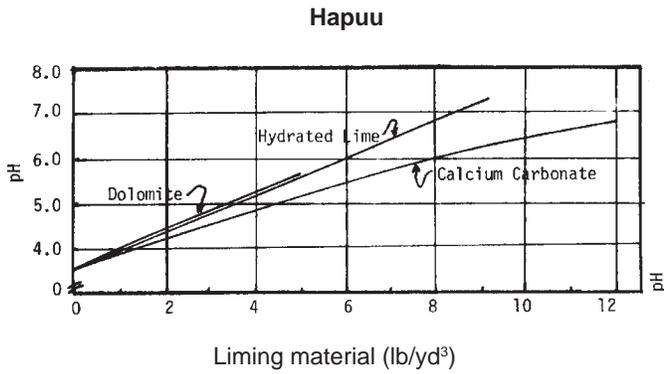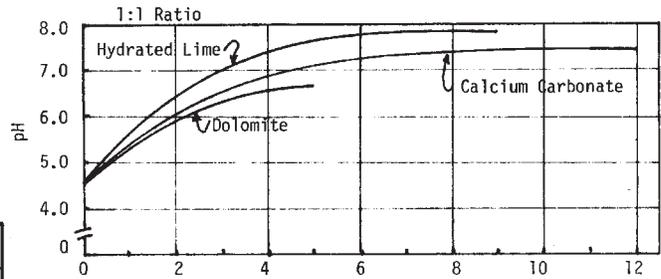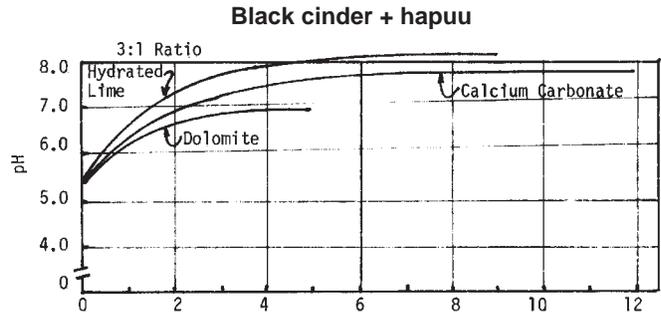
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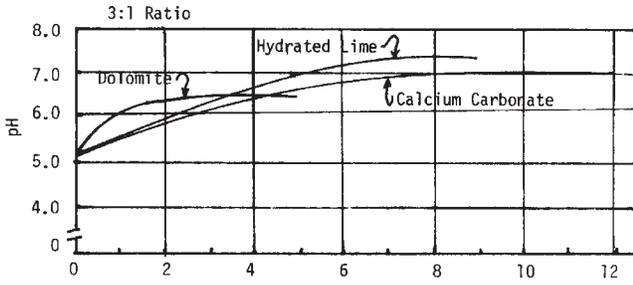
Appendix 10-1. Liming curves developed by Y. Matsusaka and G.D. Sherman (1950) for various soil series of Hawaii.
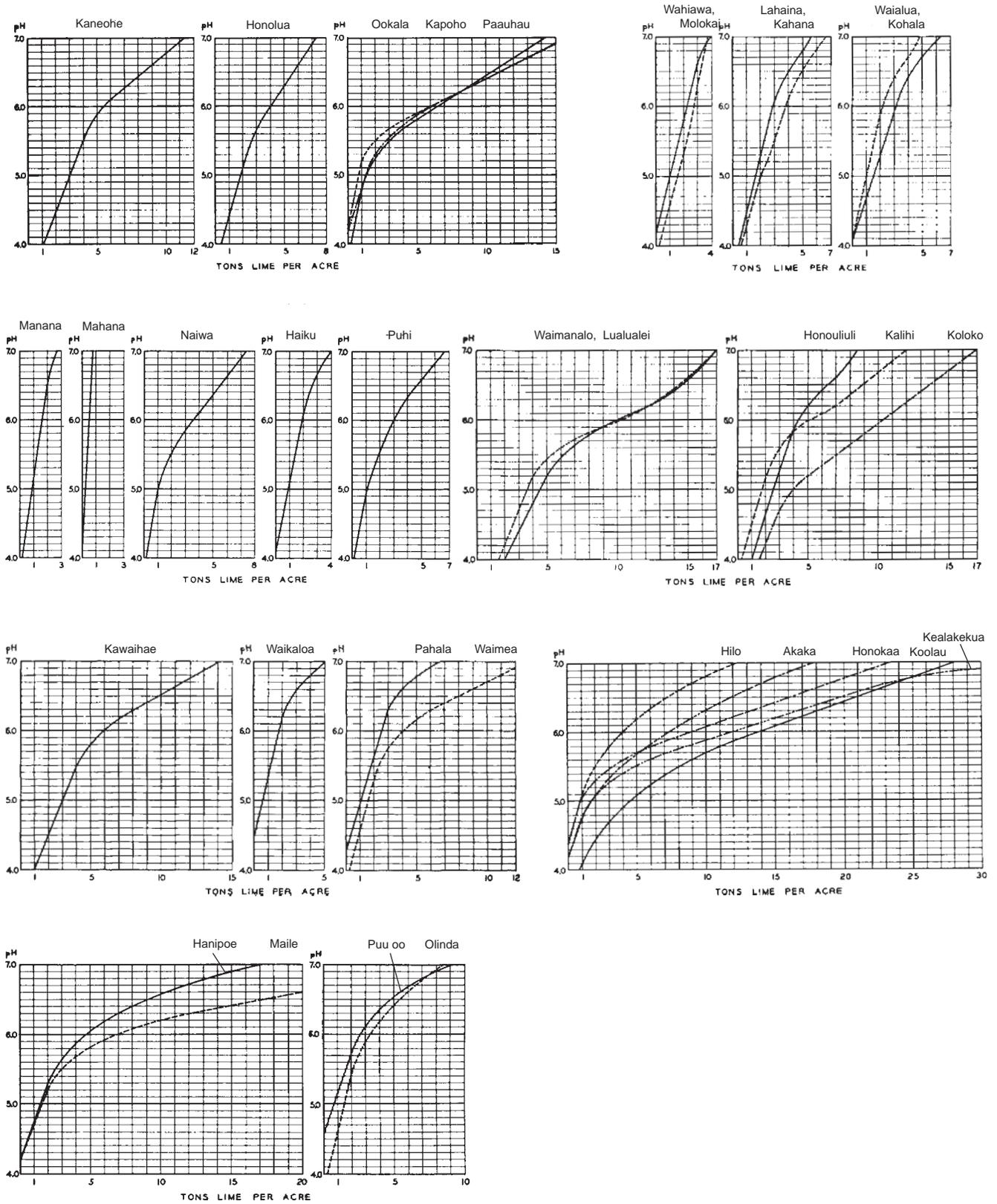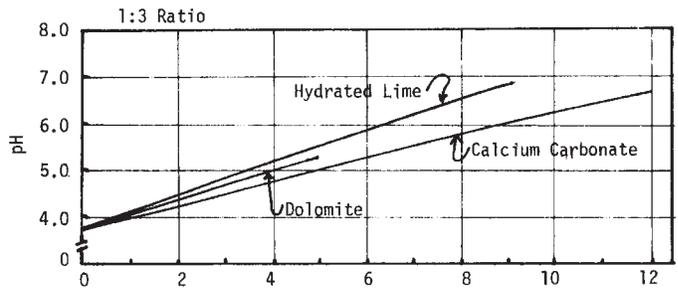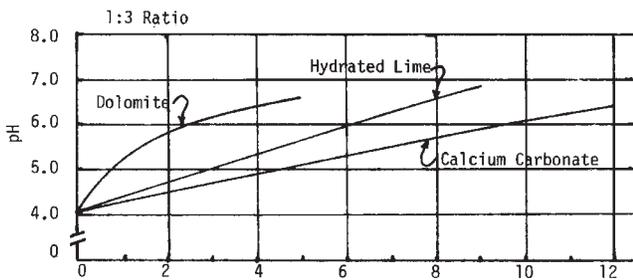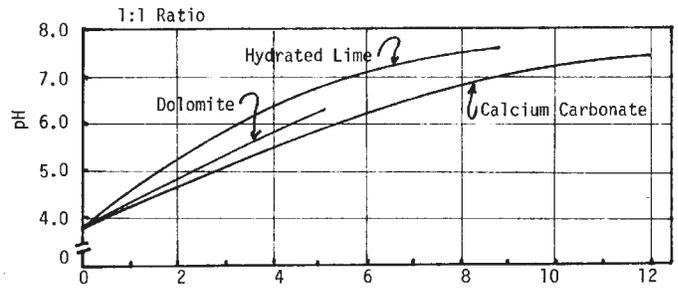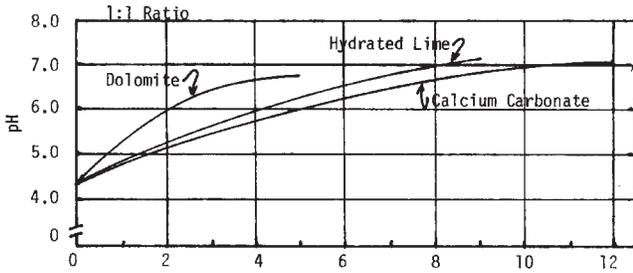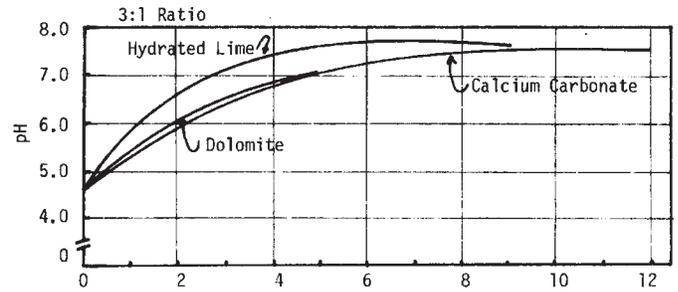
Appendix 10-2. Lime requirement curves for potting media mixes including black volcanic cinder, peat moss, perlite, sphagnum peat moss, and hapuu fern (Kawabata et al. 1975).

Spaghnum peat moss

Liming material (lb/yd³)

Black cinder + hapuu

Liming material (lb/yd³)

Hapuu

Liming material (lb/yd³)
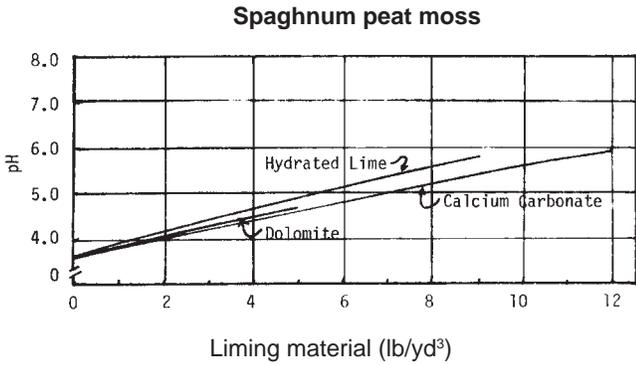
Black cinder + peat moss

Perlite + peat moss

3:1 Ratio

Hydrated Lime

Dolomite

Calcium Carbonate

3:1 Ratio

Hydrated Lime

Dolomite

Calcium Carbonate

1:1 Ratio

Hydrated Lime

Dolomite

Calcium Carbonate

1:1 Ratio

Hydrated Lime

Dolomite

Calcium Carbonate

1:3 Ratio

Hydrated Lime

Dolomite

Calcium Carbonate

1:3 Ratio

Hydrated Lime

Dolomite

Calcium Carbonate

Liming material (lb/yd³)

Liming material (lb/yd³)

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Appendix 10-3. Lime requirement curves for selected soils of Hawaii (Hue and Ikawa 1994); equations for the curves are given in Table 3.

Tons CaCO$_3$/acre

(13) Kokee

(14) Leilehua

(15) Mahana

(16) Makawao

(17) Manana

(18) Niu

(19) Olinda

(20) Paaloa

(21) Piihonua

(22) Tantalus

(23) Generalized

Soil pH

Tons CaCO$_3$/acre

Tons CaCO$_3$/acre