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Measurement and Management of Soil pH for Crop Production in Delaware

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What is Soil pH, and Why is it Important?

Soil pH is a measure of soil acidity or alkalinity, which is a function of the presence or absence of active hydrogen ion (H^+) concentration in the soil solution and is calculated using the following equation:

$$\mathbf{pH = -log_{10} [H^+]}$$

The pH scale ranges from 0 to 14; a pH value of 7.0 is considered neutral, while pH values less than 7.0 are acidic, and pH values greater than 7.0 are alkaline. The pH values of soil usually range from pH 4.0 to pH 8.0; higher or lower pH values are very rare and are normally found only in severely disturbed soils or in soils that have been amended with some type of acidic or alkaline material.

Soil pH is one of its most important properties because it influences soil productivity, including nutrient availability, microbial activity, and pesticide efficacy. Plant growth problems are common in soils that are too acidic or too alkaline. Therefore, maintaining pH in the proper range for the desired use of the soil is critical for the successful production of agronomic and horticultural crops.

Delaware soils tend to be slightly to moderately acidic due to the nature of the parent materials from which the soils are formed. In addition, natural weathering processes in humid areas like Delaware leach base cations (e.g., Ca, Mg) from the topsoil, leaving acidic cations, particularly aluminum (Al), as the dominant exchangeable cation. Soil acidification also occurs due to organic matter decomposition (e.g., crop residues, manures, sludges), the use of fertilizers containing ammonium (e.g., ammonium sulfate, monoammonium phosphate, diammonium phosphate), or atmospheric deposition (e.g., acid rain, mist, solid particles). Management problems associated with acid soils include:

- Increased aluminum (Al) or manganese (Mn) plant toxicity
- Reduced plant availability of macronutrients, including phosphorus (P), calcium (Ca), or magnesium (Mg)
- Reduced microbial populations and activity
- Increased bioavailability of hazardous trace elements, including cadmium (Cd), nickel (Ni), and lead (Pb)
- Reduced pesticide efficiency

Soils that are too alkaline for plant growth are very rare in Delaware due to the factors described previously. Alkaline soils are mainly found in arid regions where the leaching of basic cations is greatly reduced. If excessively alkaline soil conditions are encountered in Delaware, it is likely the result of over-liming soils. Over-liming is usually caused by improper calibration of lime application equipment, but can also occur if lime applications were not based on the results of an appropriate lime requirement test. Management problems associated with alkaline soils include:

- Reduced bioavailability of micronutrients, including copper (Cu), iron (Fe), manganese (Mn), or zinc (Zn)
- Increased volatilization of surface-applied ammonium fertilizers
- Reduced availability of phosphorus (P)

Managing Soil pH

Most plants grow best in Delaware soils when pH values are between 5.5 and 7.0. As such, the first step in managing soil pH is to select the target pH. Target pH is defined as the soil pH value associated with optimum plant growth and varies based on crop type and soil characteristics. Some crops, like blueberries, grow best under more acidic conditions, while other crops, like alfalfa, grow best when soil pH is near neutral. In addition, plants grown in high organic matter (soil organic matter > 6%) often have a lower target pH than would the same plant grown on soil with a lower organic matter content. The lower target pH for high organic matter soils is related to the ability of soil organic matter to moderate some of the effects of excessive soil acidity. Seven different soil target pH values are identified for crops in the *University of Delaware Nutrient Recommendations* (available at http://www.udel.edu/008353; Shober et al., 2024) or the *Mid-Atlantic Commercial Vegetable Production Recommendations* (available at http://www.udel.edu/0012565; Wyenandt et al., 2024):

- **pH 4.8** for blueberries,
- **pH 5.2** for non-scab-resistant potatoes,
- **pH 5.6** for black, high organic matter soils in commercial production, acid loving plants,
- **pH 6.2** for some vegetable and forage crops,
- **pH 6.5** for many commercial vegetable crops, crops with a high Ca demand, commercial turf;
- **pH 6.8** for alfalfa and some herbs,
- **pH 6.0** for most other crops and soils.

Applying liming or acidifying materials will ensure that soil pH is near the agronomic target pH. Yet, it is also important to consider the critical pH before making soil pH management decisions. The critical pH is defined as "the maximum soil pH value at which liming increases crop yield" (Adams, 1984).

The critical pH is the soil pH at which acidity is likely to negatively impact plant growth. The critical pH reflects the practical and economic considerations of changing soil pH to the value most suited for plant growth. University of Delaware recommended target and critical pH values are available for agronomic crops (Table 1), fruit crops (Table 2), vegetable crops (Table 3), woody species (Table 4), and forage and hay crops (Table 5).

Table 1. Target and critical pH values used by the University of Delaware Soil Testing Laboratory to calculate lime requirements, mineral soils – Agronomic and fruit crops.

Crop	Target pH	Critical pH
Barley	6.0	5.5
Corn	6.0	5.5
Kenaf/Hemp	6.0	5.5
Oats	6.0	5.5
Rye	6.0	5.5
Sorghum	6.0	5.5
Sunflower	6.0	5.5
Wheat	6.0	5.5

Table 2. Target and critical pH values used by the University of Delaware Soil Testing Laboratory to calculate lime requirements, mineral soils – Fruit crops.

Crop	Target pH	Critical pH
Apples	6.5	6.0
Blackberries	6.2	5.5
Blueberries	4.8	4.2
Cherries	6.5	6.0
Nectarines	6.5	6.0
Peaches	6.5	6.0
Pears	6.5	6.0
Plums	6.5	6.0
Raspberries	6.2	5.5
Strawberries	6.2	5.8
Watermelons	6.2	5.5

Table 3. Target and critical pH values used by the University of Delaware Soil Testing Laboratory to calculate lime requirements, mineral soils – Vegetable crops.

Crop	Target pH	Critical pH
Asparagus	6.8	6.2
Beets	6.5	6.2
Broccoli	6.5	6.2
Brussels Sprouts	6.5	6.2
Cabbage	6.5	6.2
Cantaloupes	6.5	6.0
Carrots	6.0	5.5
Cauliflower	6.5	6.2
Celery	6.5	6.0
Collards	6.5	6.2
Cucumbers	6.5	6.0
Eggplant	6.5	6.0
Endive - escarole	6.5	6.0
Horseradish	6.5	5.5
Kale	6.5	6.2
Kohlrabi	6.5	6.2
Leeks	6.5	6.0
Lettuce	6.5	6.0
Lima Beans	6.2	6.0
Mixed Vegetables	6.5	6.0
Muskmelons	6.5	6.0
Okra	6.5	6.0
Onions, Bulb and Scallions	6.5	6.0
Parsley	6.5	6.0
Parsnips	6.5	6.0
Peas	6.5	6.0
Peppers	6.5	6.0
Potatoes, Sweet	6.2	5.5
Potatoes, White, Non-scab Resistant	5.2	5.0
Potatoes, White, Scab Resistant	6.2	5.5
Pumpkins	6.5	6.0
Radishes	6.5	6.2
Rhubarb	6.5	5.5
Rutabaga	6.5	6.2
Snap Beans	6.2	6.0
Spinach	6.5	6.0
Squash	6.5	6.0
Sweet Corn	6.5	6.0
Tomatoes	6.5	6.0
Turnips	6.5	6.0

Table 4. Target and critical pH values used by the University of Delaware Soil Testing Laboratory to calculate lime requirements, mineral soils – Woody species.

Crop	Target pH	Critical pH
Acid-loving Shrubs	5.6	5.0
Broadleaf Evergreens	6.0	5.5
Christmas Trees (Concolor Fir, Douglas Fir, Blue Spruce, Balsam Fir)	6.5	6.0
Christmas Trees (Scotch Pine, White Pine, Norway Spruce, Fraser Fir, Canaan Fir)	6.0	5.5
Deciduous Shrubs	6.0	5.5
Deciduous Trees	6.0	5.5

Table 5. Target and critical pH values used by the University of Delaware Soil Testing Laboratory to calculate lime requirements, mineral soils – Forage and hay crops.

Crop	Target pH	Critical pH
Alfalfa	6.8	6.0
Alfalfa/Grass mix	6.8	6.0
Annual or Italian Ryegrass	6.5	5.8
Bermudagrass	6.5	5.8
Big Bluestem	6.2	5.5
Eastern Gamagrass	6.5	5.8
Grass/Brassica mix	6.2	5.5
Grass/Chicory Mix	5.6	5.0
Indiangrass	6.2	5.5
Kentucky Bluegrass	6.5	6.0
Lespedeza/Sericea	6.2	5.5
Little Bluestem	6.2	5.5
Mixed Grass/Legume	6.2	5.5
Orchardgrass	6.5	5.8
Perennial Ryegrass	6.5	5.8
Red Clover	6.5	5.8
Reed Canarygrass	6.5	5.8
Smooth Bromegrass	6.5	5.8
Switchgrass	6.2	5.5
Tall Fescue	6.5	5.6
Timothy	6.5	5.8
White Clover	6.5	5.8

Measuring Soil pH

Once a target pH is selected for the appropriate crop-soil pair, the next step is to determine the soil pH. For conventional tillage systems, we recommend soil pH measurements should be taken on a soil composite sample that was collected from the top 8 inches ("plow depth"), although measurements may also be taken on a 6-inch sample. For fields under reduced tillage, we also recommend measuring soil pH on a 2-inch composite sample. (Note, a 6- or 8-inch composite sample may also be needed to determine management for reduced tillage systems.) As always, be sure to collect enough core samples to ensure that the sample is representative of the management area. Soil testing laboratories typically offer soil pH as part of a routine soil test. When soil samples are submitted for analysis, the laboratory will measure soil pH using an electronic pH meter that is inserted into a soil-water or soil-weak salt slurry. The University of Delaware Soil Testing Program (and other regional laboratories) uses the soil-water slurry (water pH) method with a 1:1 soil-to-solution ratio (Table 6). It is important to note that other soil testing laboratories may use different soil-to-solution ratios (1:2) or different solutions (e.g., weak salt solutions such as 0.01M $CaCl_2$) to measure soil pH. Make note of the soil pH method used by the soil testing lab that you choose, as the soil pH method will impact management decisions for liming or acidification.

Portable pH meters and inexpensive hand-held "pH pens" are also available and can provide reasonably accurate estimates of soil pH in the field. Field measurements of pH are especially useful in reduced tillage systems to spot-check soil pH levels. If soil pH in a 2-inch (surface) composite sample is at or below the critical pH for the specific crop or soil type (Tables 1-5), we also recommend collecting a 6-or 8-inch composite sample and submitting that sample to a regional laboratory for soil pH analysis.

The use of indicator dye kits to measure soil pH is not recommended for making soil pH management decisions because of the difficulty in obtaining accurate, reproducible pH values with these color-based procedures.

Interpreting Soil pH Results

If the measured soil pH is below both the target pH and critical pH: The soil testing laboratory will run the lime requirement (buffer pH) test and provide a lime recommendation.

If the measured soil pH is between the critical pH and the target pH: The soil testing laboratory will run the lime requirement (buffer pH) test and may provide a lime recommendation. If you receive a lime recommendation, you may choose to wait to apply lime and continue to monitor until the pH approaches the critical level. Waiting to apply lime until the soil pH is closer to the critical pH can be a good strategy for crops that are sensitive to micronutrient deficiency (e.g., small grains or soybean) or if current field conditions prohibit the application of lime.

If the measured soil pH is at or above the target pH: The soil test lab will not provide a lime recommendation. However, if the soil pH is above the target pH, it may be prudent to reduce the soil pH for certain types of plants, such as blueberries or non-scab-resistant potatoes. Acidification is difficult on a large-scale basis and is only recommended if growing acid-loving plants.

Determining the Lime Requirement

When soil pH (1:1 soil-to-water ratio) is below the target pH, regional soil testing laboratories will also measure soil pH in a buffer solution. The soil pH in the buffer solution provides an indication of how easily the pH can be changed (also known as the "the buffering capacity of the soil").

The University of Delaware Soil Testing Laboratory uses the **Adams-Evans buffer pH** test to determine the lime requirement. The Adams-Evans buffer was specifically developed for the coarse-textured, poorly buffered soils of the Atlantic Coastal Plain, including those in Delaware. The Adams-Evans buffer can detect small changes in lime requirement on soils which can be easily over-limed, thus resulting in problems with plant growth such as micronutrient deficiency (Sims & Eckert, 2011). Calibration of the Adams-Evans buffer test was conducted by Sims and Dennis (1989) using 20 Delaware soils. Other regional soil testing laboratories use the Mehlich, Modified Mehlich, Sikora, or SMP buffer test (Table 6). The SMP and Sikora buffer tests are also listed for use in the Northeastern U.S. However, the Sikora and SMP buffer tests were designed for heavier soils of the Northeastern and North Central US (i.e., soils with higher CEC, higher buffering capacity, and higher lime requirements). Use caution when applying lime at rates based on the Sikora or SMP buffer test, as overliming is possible on Delaware's sandy loam and loamy sand soils. Lime recommendations based on the Adams-Evans, Mehlich, or Modified Mehlich buffers are better suited to Delaware soils (Sims & Dennis, 1989).

The water pH value is typically listed as "soil pH" on the soil test report. The buffer pH may also be reported on the soil test report as the "buffer pH" or "buffer index". In lieu of listing the buffer pH value, laboratories that use the Mehlich or Modified Mehlich buffer test may report exchangeable acidity (meq/100 cm^3); exchangeable acidity is calculated based on the pH of the soil in the Mehlich buffer (Hardy, 2014).

Determining the Base Lime Requirement

Lime requirement is determined based on the mathematical relationships between the soil pH (1:1 soil to water) and pH in the buffer solution (or exchangeable acidity when using the Mehlich or Modified Mehlich buffer test). Given the complexity of the lime requirement equations, we prepared tables that identify the base lime rate (tons/ac) of agricultural-grade limestone based on water pH and buffer pH. Lime requirement tables are available for all target pH values for both 6- and 8-inch soil sampling depths using the appropriate mathematical equations for the Adams-Evans (Soil and Plant Analysis Council, 2000), Mehlich/Modified Mehlich (Hardy, 2014), and Sikora/SMP (Ritchey & McGrath,

Table 6. Methods for water and buffer pH tests used by regional soil testing laboratories.

Laboratory	**Soil pH Method**	**Lime Requirement Method**
University of Delaware	Water (1:1)	Adams-Evans
AgroLab	Water (1:1)	SMP
Brookside Laboratories, Inc.	Water (1:1)	SMP/Sikora
Penn State University	Water (1:1)	Modified Mehlich
Rutgers University	Water (1:1)	Adams-Evans
Spectrum Analytical Laboratories	Water (1:1)	Sikora
Virginia Tech	Water (1:1)	Modified Mehlich
Waters Agricultural Laboratories, Inc.	Water (1:1)	Adams-Evans (KY location); Mehlich (NC location)
Waypoint Analytical	Water (1:1)	Mehlich; SMP (by request only)

2000) buffer tests. (**http://www.udel.edu/0013618**) The lime tables should be used to determine the appropriate base lime application rate for a 6- or 8-inch composite soil sample as follows:

- Conventional tillage: Run the lime requirement test and determine the appropriate base liming rate from the lime recommendation tables.
- Reduced tillage: If the soil pH of the 2-inch composite sample is below the critical pH, run the lime requirement test on an 8-inch composite sample (Beegle and Ligenfelter, 2014).
  - If lime is recommended for the 6- or 8-inch composite sample, determine the appropriate base liming rate for conventional tillage systems.
  - If lime is not recommended for the 6- or 8-inch composite sample, surface apply 1.5 tons/ac of agricultural-grade limestone.

More detailed information on the different lime requirement tests and the equations used to determine the lime requirement for regional buffer pH tests is available in *A Comparison of Methods to Determine Lime Requirement* (available at http://www.udel.edu/0013612).

Adjusting the Base Lime Requirement to Account for Past Lime Applications

The base lime requirement obtained from these tables can be used if no additional lime was applied within the last 18 months. If lime was applied within the last 18 months prior to the current soil test, then the base lime requirement must be adjusted to account for previous lime recommendations because limestone reacts relatively slowly in the soil to neutralize soil acidity. In fact, it can often take up to two years for lime to be fully effective. As a result, soils tested for lime requirement within two years of a lime application may still show a need for pH adjustment even though enough limestone was applied initially. Applying the full rate of lime recommended by the current soil test could easily result in over-liming of Delaware's poorly buffered, low organic matter soils and lead to problems such as Mn or Zn deficiency.

To avoid the risk of over-liming soils, the University of Delaware calculates a lime credit for soils limed in the previous 18 months. This credit (reported in tons/ac) is based on the previous liming rate and time since application and calculated using the equation:

Lime credit (ton/ac) = Previous lime rate (ton/ac) × Lime availability factor

The previous lime rate (tons/ac) refers to the amount of any liming material applied within 18 months of the soil sampling event and the lime availability factor is based on the length of time since last application (Table 7). The **net lime requirement** is determined by subtracting the lime credit from the base lime recommendation, as determined from the current soil test by the following equation:

Net lime requirement (tons/ac) = Base lime requirement (ton/ac) × Lime credit (ton/ac)

Table 7. Availability factor used to adjust lime rates when liming materials were applied within 18 months of the current soil test.

Time Since Last Lime Application (months)	Lime Availability Factor
0-6	0.75
7-12	0.50
13-18	0.25
>18	0.00

Recommendations for Applying Lime

Lime is most effective when it is mixed with the soil. Therefore, lime should be applied and incorporated into soils by plowing prior to planting pastures or converting an operation to conservation tillage or Repeated, smaller applications of lime to the surface of soils managed under conservation tillage, no-till, or pasture will be effective at maintaining soil surface pH near the target pH in subsequent years. The University of Delaware recommends applying no more than 2 ton/ac of lime per surface application under conservation tillage, no-till, or pasture.

Larger lime applications are feasible during tillage operations. However, there is little benefit to applying lime at a rate >4 ton/ac in a single application. If the net lime requirement is >4 ton/ac, the University of Delaware recommends splitting the total amount of lime into 2 to 3 smaller applications for best results. Applications should be made more than 6 months apart or (at a minimum) by tillage operation. When a single lime application is 3-4 ton/ac, the University of Delaware recommends applying half the recommended rate prior to plowing and then disc the remainder of the lime in after plowing.

Selecting a Liming Material

The selection of a liming material is dependent upon several factors including the need to increase soil Ca or soil Mg concentrations, economics, material availability, desired speed of reaction, and ease of use. In this section, lime type selection will be discussed solely in terms of whether to use calcitic ("Hi-Cal") or dolomitic ("Hi-Mag") agricultural-grade limestone. Agricultural limestone is assumed to be 67% as effective as pure calcium carbonate. For a more detailed discussion of liming material selection and application, see *Liming Materials and Management* (available at http://www.udel.edu/0013552).

In most cases, the lime requirement of the soil can be adequately met by applying either calcitic or dolomitic agricultural-grade lime. Growers can make their choice of agricultural grade limestone based on availability and cost. However, in certain situations, it may be desirable to choose one or the other to have the added benefit of increasing either the soil Ca or soil Mg concentrations without applying additional Ca or Mg fertilizers.

Choose calcitic ("High-Cal") lime when:

- Soil test Mg > 100 UD-FIV (based on Mehlich 3)
- Soil test Mg is between 50 and 100 UD-FIV and is > soil test Ca levels

Choose dolomitic ("High-Mag") lime when:

- Soil test Mg < 100 UD-FIV (based on Mehlich 3)
- Soil test Mg is between 50 and 100 UD-FIV and is < soil test Ca levels

Note: Soil test Ca and Mg are based on extraction with Mehlich-3, where University of Delaware fertility index value (UD-FIV) of 50 is equivalent to 131 lb/ac (65.5 ppm) for Mg and 1,000 lb/ac (500 ppm) for Ca. A UD-FIV of 100 is equivalent to 262 lb/ac (131 ppm) for Mg and 2,000 lb/ac (1000 ppm) for Ca.

Soil Acidification

Soil acidification is difficult to achieve on a large scale. As such, it may be better to choose a different crop if the soil pH is more than 1.0 unit higher than the target pH. However, if acidification is desired, the University of Delaware recommends ground elemental sulfur (S) as the acidifying material. While other materials are capable of acidifying soils (e.g., aluminum sulfate, peat), they are often more difficult to manage or less effective than elemental S. For example, aluminum sulfate can be used as an acidifying agent but can cause phytotoxicity if over-applied. Peat moss is sometimes used as a short-term solution to acidify soil in the root zone of newly installed plants, but results are less predictable than with elemental S.

The quantity of acidifying agent required to reduce soil pH in a given soil depends upon two factors: the desired change in soil pH and the buffering capacity of that soil. Soils that are more strongly buffered against changes in pH (e.g., fine-textured, high CEC, high OM soils) require more S to achieve the same pH change than those less strongly buffered (e.g., sandy, low CEC, low OM soils). The rate of elemental S required to cause the desired change in soil pH is available in Table 8.

Rates are expressed as a function of the pH unit decrease and soil type. The pH unit decrease is the difference between the current soil pH and the desired soil pH; hence, if the present soil pH is 6.5 and the desired soil pH is 5.5, the pH unit decrease would be 1.0. Because of differences in soil buffering capacity, a silt loam soil would require an application of 1,000 lb/ac of elemental S to achieve a 1.0 pH unit decrease, while application of 320 lb/ac of elemental S would be required to achieve the same 1.0 pH unit decrease for a sandy loam soil. If aluminum sulfate is the desired acidifying agent used rate in Table 8 (elemental S rate multiplied by 6).

Table 8. Elemental S (ton/ac) required to reduce soil pH as a function of pH unit decrease and soil type. Black soils have a soil organic matter content >6.0.

Desired pH Unit Decrease	Loamy sands, Sandy loams	Black loamy sands, Black sandy loams	Silt loams, Loams	Black silt loams, Black loams
3.0	0.5	0.62 - 0.76	1.4	1.76 - 2.10
2.5	0.4	0.50 - 0.60	1.2	1.50 - 1.80
2.00	0.3	0.38 - 0.46	0.9	1.12 - 1.34
1.5	0.24	0.32 - 0.36	0.7	0.88 - 1.06
1.0	0.16	0.20 - 0.24	0.5	0.62 - 0.76
0.5	0.08	0.12 - 0.16	0.2	0.24 - 0.30

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