Soil Acidity in Oregon:

Understanding and Using Concepts for Crop Production

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Quick facts

Nitrogen (N) fertilizer application is the predominant management practice that causes soil acidification (declining soil pH). Nitrogen fertilizers that supply N only in the ammonium (NH_4) form are the most acidifying (page 6).

Crops and varieties differ in tolerance to soil acidity. Recommended minimum pH values for a wide range of crops are listed in Table 9 (pages 18–19). Lime is recommended to maintain soil pH above recommended values.

Increased soil acidity can injure plants by a number of mechanisms, including:

- Increasing the amount of soluble aluminum (Al) and manganese (Mn) in soil to toxic levels (pages 9–11)
- Reducing the amount of plant-available phosphorus (P), calcium (Ca), and molybdenum (Mo) (pages 11–13)

Some legumes are very sensitive to soil acidity because soil acidity inhibits N fixation by bacteria of the genus *Rhizobium*. These bacteria require high soil levels of Ca and Mo, which are limited at low pH. Under acidic soil conditions, legume roots may have few nodules or their nodules may be ineffective at N fixation (page 13).

Information on pH and weed management (pages 20–21) and on soil pH monitoring (pages 7 and 15) is also contained in this publication. Neutralizing soil acidity with lime is discussed in companion publications (page 2).

Soil acidity, expressed by low pH, causes reduced crop growth and significant economic loss. It is the most commonly overlooked and poorly understood yield-limiting factor in western Oregon (Figure 1) and a developing concern in eastern Oregon (Figure 2).

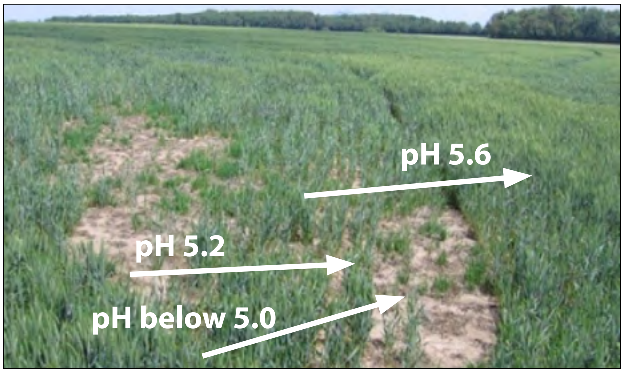

Figure 1.—Soft white winter wheat growth decreases sharply when soil pH is below the crop "threshold." The soil pH near the center of the photo (where bare soil is visible) is below 5.0. The soil pH on the right side of the photo (where winter wheat is uniform) is 5.6.

Nicole Anderson, © Oregon State University

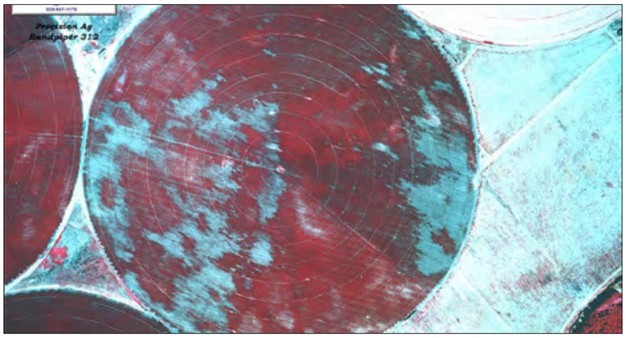

Figure 2.—Onions under center pivot irrigation, Hermiston, OR. In bare soil areas (light color), soil pH was acidic (near 5.0), killing onion seedlings. Dark areas (healthy plants) had higher pH.

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Related publications

This publication is part of a three-part series. We recommend you use them in combination.

Eastern Oregon Liming Guide, EM 9060

- Provides recommendations for lime application for dryland and irrigated cropping systems.

Applying Lime to Raise Soil pH for Crop Production (Western Oregon), EM 9057

- Describes how to estimate lime application rate and lists criteria for choosing liming materials (source), lime application method (placement), and how often to apply lime (frequency).

Declining soil pH is often overlooked because symptoms do not appear, and crop yield does not significantly decline, until a soil pH threshold is reached. Once soil pH drops below the crop threshold, a very small difference in soil pH can result in a substantial yield decrease (Figure 3). This situation differs greatly from a slight nutrient deficiency, which might cause only a 10 or 15 percent yield reduction. When soil pH is a few tenths of a unit lower than a crop's threshold, yield can decrease 50 percent or more.

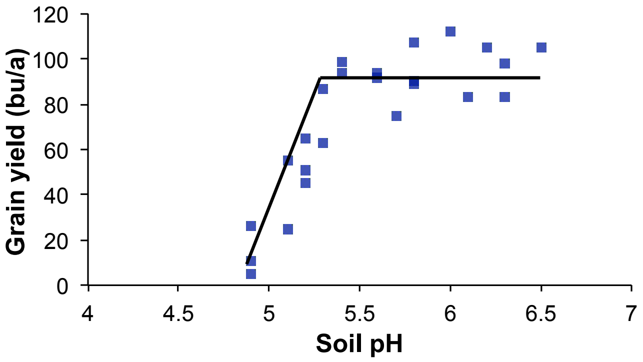

Figure 3.—Grain yield of soft white winter wheat decreases sharply when soil pH is below 5.2. Figure by John Hart. Data from Kauffman, 1977.

What is pH?

pH is a convenient way to express the amount of hydrogen (H^+) ion in solution (per liter). The more H^+ ion in solution, the more acidic the soil.

A soil with a concentration of 1.0×10^{-5} H^+ ion/L has a pH of 5. A soil with a concentration of 1.0×10^{-6} H^+/L has a pH of 6. Note that the soil with pH of 5 has a greater concentration of H^+ ion in solution (10^{-5}) than the soil with pH of 6 (10^{-6}). Thus, the soil with a pH of 5 is more acidic.

In Figure 4 we see that as the H^+ ion concentration increases, pH decreases and soil acidity increases. A pH of 7 is neutral, a pH of less than 7 is acidic, and a pH greater than 7 is basic, or alkaline.

The scale used for pH is logarithmic (base 10). In other words, it represents a 10-fold difference for each unit change. Thus, a soil pH of 5.0 is 10 times more acidic than soil pH of 6.0.

From a management viewpoint, soil pH determines whether a soil is suited to a particular crop. Lime is added to acidic soil to raise pH. Amendments such as elemental sulfur (S) are added to reduce pH.

In this publication, we will refer to H^+ simply as H for convenience, except when H^+ is shown within a chemical reaction.

Figure 4.—pH scale. As pH values decline, acidity increases. Figure by Dan Sullivan.

Soil pH thresholds are crop specific and vary considerably. The minimum recommended soil pH for Oregon crops is found in Appendix A (pages 18–19). In addition, thresholds vary among crop varieties or cultivars. For example, 'Yamhill' winter wheat is more tolerant of soil acidity than 'Goetze', 'Bobtail', or 'Stephens'.

Yield reduction from soil acidity usually results from excess aluminum (Al) or manganese (Mn); from deficiencies of calcium (Ca), magnesium (Mg), molybdenum (Mo), phosphorus (P), or nitrogen (N); or from a combination of these factors.

Lime applications should not be expected to increase yield in a manner similar to fertilizer applications. The purpose of liming fields when soil pH is above a crop threshold is to maintain adequate soil pH (keep it above the threshold), not to produce an immediate increase in crop yield. For example, winter wheat grain yields were equivalent when soil pH was above the threshold value of 5.4 (Figure 3, page 2).

When soil pH is below the crop threshold, lime is used to increase soil pH and remove growth and yield limitations. Liming to increase pH eliminates Al and Mn toxicity and increases availability of some nutrients. See Appendix C (page 22) for sources of information regarding the effects of lime on yield and tissue nutrient concentration of specific crops.

Variations in soil pH can also indirectly influence crop growth and yield through changes in weed species composition and herbicide efficacy. For more information, see "Influence of Soil pH on Weed Populations and Chemical Weed Management"(Appendix B, pages 20–21).

The soil acidification process (how soil becomes acidic)

Natural acidification

Natural soil acidification occurs slowly (over thousands of years). Acidification occurs naturally with rainfall. Rainwater absorbs and reacts with carbon dioxide as it falls through the atmosphere. This process produces dilute carbonic acid, resulting in rainfall with a pH of approximately 5.5 (see "What is acid rain?" on this page).

The carbonic acid in rainwater adds H ions to the soil. These H ions replace the cations Ca, Mg, and K, which are attracted to or held on the surface of

What is acid rain?

Rainwater is dilute weak carbonic acid, pH 5.5. Carbon dioxide reacts with rainwater ($CO_2 + H_2O$), creating a dilute solution of weak carbonic acid (H_2CO_3). Although rainwater is acidic (pH below 7.0), in most cases it is not considered "acid rain." Acid rain forms when sulfur (S) and nitrogen (N) compounds react in the atmosphere, resulting in rainwater having a pH of approximately 4.0.

Terms related to soil pH

Ion—a molecule in which the total number of electrons is not equal to the total number of protons, giving it a net charge

Cation—a positively charged ion

Anion—a negatively charged ion

N—nitrogen

Al—aluminum

Ca—calcium

Mg—magnesium

NH_4^+-N—ammonium N

Mn—manganese

H—hydrogen

K—potassium

The cations, Al^{+3}, Mn^{+2}, Ca^{+2}, Mg^{+2}, H^+, and K^+ are used in this publication without charge designations except when used in chemical reactions.

CEC—cation exchange capacity, the sum of cations electrostatically attracted to 100 grams of soil expressed in milliequivalents (meq)

Equivalent—amount of a substance that will react with 1 gram of hydrogen

Milliequivalent (meq)—$^1/_{1,000}$ of an equivalent

CCE—calcium carbonate equivalent

Buffer—material that is resistant to pH change

Slaked lime—calcium oxide that has been mixed with water to create calcium hydroxide

Prilled or pelleted lime—finely ground agricultural lime that has been mixed into a slurry with a binding agent and pelletized. The binding agent allows pellets to disintegrate in water.

soil particles. Subsequent leaching of these cations to groundwater not only contributes to soil acidification but also makes groundwater "hard."

The material from which present-day Willamette Valley soil is formed was deposited during the ice-age Missoula floods that receded approximately 10,000 years ago. Centuries of leaching by winter rainfall have developed western Oregon's naturally acidic soils (4.8 to 6.2). Assuming the initial pH of the deposits was neutral, and the current pH of these soils is approximately 5.5, soil pH declined at a rate of 0.00015 unit/year. These naturally acidic soils limited yields for the first Euro-American farmers who settled in the Willamette Valley (Figure 5).

Columbia Basin soils have a similar age as those in the Willamette Valley, as both are the result of the Missoula floods. However, before agricultural cultivation, Columbia Basin soils have a pH of 7.8 to 8.2. The lower amount of rainfall in the Columbia Basin has resulted in slower natural soil acidification.

Agricultural practices accelerate acidification

Natural acidification usually requires a millennium or more. In agricultural systems, substantial pH changes can occur in as little as 1 year and commonly within 5 years. The application of fertilizer and irrigation water, combined with cation removal by harvest, substantially increase the rate of soil acidification.

This problem is most severe in western Oregon's naturally acidic soils, but even in eastern Oregon, the combination of irrigation with clean (low bicarbonate) river water and N fertilizer application is creating acidic soils. Soil pH levels are nearing crop acidity tolerance thresholds for peas, alfalfa, onions, and garlic. See OSU Extension publication EM 9060, *Eastern Oregon Liming Guide*, for more information.

Fertilization

As soil microbes (mostly bacteria) convert ammonium-containing fertilizer (NH_4-N) to nitrate-N (NO_3-N), soil is acidified. The process provides energy (electrons) for the microbes and produces nitrate, water, and H (acidity).The following equation illustrates the reaction:

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + H_2O + 2\,H^+$$

(Ammonium is combined with oxygen by microbes to produce nitrate, water, and hydrogen ions.)

Soil acidification from the use of N fertilizers has been documented in numerous crops and soils in Oregon for more than three decades. For example, a decrease in soil pH of 1 unit is common during a 7- to 10-year rotation of Christmas trees (Figure 6).

Likewise, during 3 years of grass seed production, surface soil pH is likely to decrease by 1 unit (Figure 7).

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Figure 5.—Increase of alfalfa yield with lime application in Lane County, 1926.

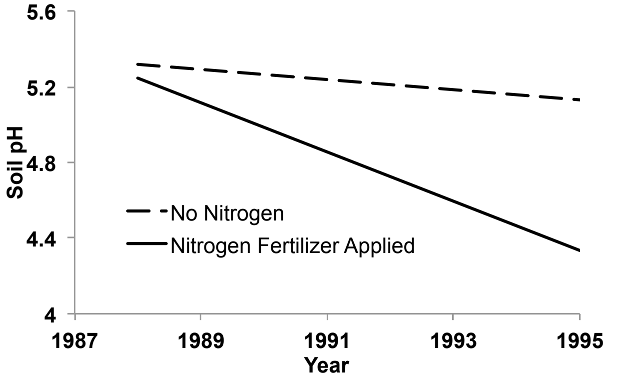


Figure 6.—Nitrogen (N) fertilizer influence on soil pH in the surface 8 inches of a noble fir Christmas tree plantation on an Alsea soil. Nitrogen fertilizer applied annually (urea-sul, 33-0-0-12) was 135 lb N/a from 1987 to 1990, 225 lb N/a from 1991 to 1993, and 450 lb N/a for the tree harvest year (1994). Data from Hart et al., 2009.

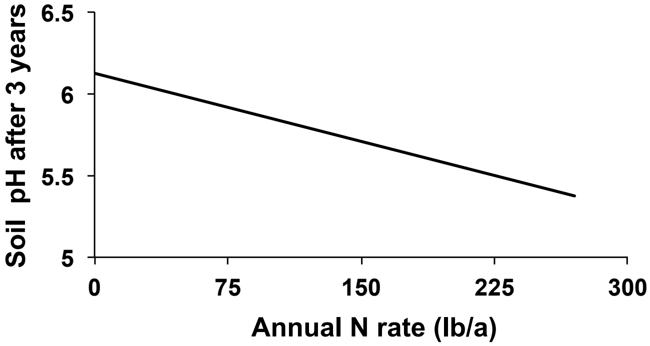


Figure 7.—Surface soil pH (0- to 2-inch depth) decreases within 3 years as nitrogen (N) rate increases on four Willamette Valley floor soils planted with perennial grass seed crops. Data from Hart et al., 2011.

Nitrogen fertilizer placement and the amount of soil with which N fertilizer is mixed by tillage or earthworms influence the depth of acidified soil and the rate of acidification. Top-dressing N fertilizer causes the surface soil to acidify faster than the soil below, creating a surface layer, or stratum, with a lower pH.

This difference in soil pH is termed stratification, and it can occur in as few as 3 years. In some situations, such as direct seeding wheat into grass seed residue, soil pH decline at the surface is sufficient to reduce the wheat stand and growth of surviving plants (see Table 8, page 15).

When urea or other sources of ammonium-N are top-dressed on naturally acidic soils of western Oregon, soil pH in the surface 2 to 3 inches decreases approximately 0.1 unit for every 100 lb N applied. This value can be used as a rule of thumb to estimate whether soil pH will be sufficient for future annual crop rotations or management of long-term perennial production systems. For more information, see Table 1 and "Soil acidification by nitrogen fertilizers" (page 6).

Some soils east of the Cascades have been acidified by N fertilizer application and, in some situations, require lime application to raise soil pH. Eastern Oregon soils buffered with carbonate will maintain soil pH above 7.5 until the carbonate is completely consumed by reaction with acid formed by N fertilizer application. See OSU Extension publication EM 9060, *Eastern Oregon Liming Guide,* for more information.

Excess N fertilizer application can also cause a loss of cations. When the nitrate form of N (NO_3, an anion) is not used by plants, it is vulnerable to loss from leaching. The leachate, or water moving through the soil profile, must be charge-balanced, so the cations K, Ca, and Mg accompany NO_3 that leaches.

Residue removal

Harvesting crops removes nutrients, including Ca, Mg, and K, from the root zone. Removal of these cations contributes to soil acidification.

Nutrient removal is greater when the entire above-ground growth of a crop is harvested than when only a portion of a crop is harvested. For example, nutrient removal is greater for alfalfa, grass hay, or peppermint than for sweet corn, green beans, or meadowfoam.

Biomass removed and nutrient concentrations, especially Ca, are higher for forage legume crops than for seed crops such as grass seed and wheat. For example, 1 ton of alfalfa contains 40 to 60 lb of cations. A typical annual yield for irrigated alfalfa in Oregon is 6 to 9 t/a. Thus, harvest removes 250 to 500 lb cations/a annually.

In western Oregon dryland alfalfa production systems, where 4 to 5 t/a yields are achieved, 200 to 300 lb cations/a are removed each year. This is approximately double the amount removed by harvesting grass seed and straw.

Two years of irrigated alfalfa production removes the equivalent of more than 1½ tons of lime. Western Oregon dryland alfalfa hay production removes the equivalent of 1 ton of lime in 3 years. Baling grass seed straw removes cations equivalent to 1 ton of lime in approximately 4 years.

continues on page 8

Table 1.—Lime required to neutralize soil acidity from nitrogen (N) fertilizers.

N fertilizer	**Abbreviation**	**Analysis ($N-P_2O_5-K_2O-S$)**	**Lime to neutralize acidity ($lb\ CaCO_3/lb\ N$)[a]**
Calcium nitrate	CN	9-0-0	0
Anhydrous ammonia	AA	82-0-0	3.6
Urea	—	46-0-0	3.6
Ammonium nitrate	AN	34-0-0	3.6
Urea ammonium nitrate	UAN	32-0-0	3.6
Ammonium polyphosphate	APP	10-34-0	7.2
Ammonium sulfate	AS	21-0-0-24S	7.2
Mono-ammonium phosphate	MAP	11-52-0	7.2
Ammonium thiosulfate	ATS	12-0-0-26S	10.8
Manure or compost	—	Varies	Varies

[a] Lime requirement is expressed as pounds of 100-score lime per pound of N applied. Lime requirement is based on chemical reactions that convert fertilizer N to nitrate-N in soil, generating H. Actual soil acidity produced in long-term field trials typically is about half of the values listed here.

Soil acidification by nitrogen fertilizers

Figure 8 shows the series of transformations in soil that produce acidity.

The form of N present in N fertilizers determines the amount of acidity generated per pound of N used or applied. Figure 9 shows the net chemical reactions and acidity produced per unit of various N fertilizers.

Table 1 (page 5) shows the amount of lime needed to neutralize the acidity produced by various fertilizers. The greater the "net acidity" generated by N fertilizers, the more lime is needed.

Theoretical acidity values for various N fertilizers can be calculated using chemically equivalent weights ($CaCO_3$ = 50; N = 14). To neutralize acidity from urea, ammonium nitrate, or anhydrous ammonia, the calculation is:

50 lb $CaCO_3$/14 lb N

(3.6 lb $CaCO_3$/lb N)

For these fertilizers, each formula or molecular weight of N applied produces one formula weight or molecular weight of acidity (Figure 9).

Soil acidity produced in long-term field trials typically is about half of the values in Table 1 (page 5). In field situations, the form of N used by crops (NH_4 or NO_3) affects acidity production. So, acidity estimates given in Table 1 should be used only to assess relative acidity produced by various N fertilizers, not to make liming recommendations.

Manures and composts supply N as a mixture of organic, ammonium, and nitrate forms. The conversion of manure organic N to NH_4-N consumes H (increases pH). Long-term trials generally show that N supplied by manure or compost is less acidifying than urea. Soil pH in acidic soils that are heavily amended with compost (e.g., gardens) typically reach values of 5.6 to 6.0. Compost is generally ineffective in increasing soil pH above 6.0, even when very high rates are applied.

Soil acidity resulting from municipal biosolids application is typically about the same per pound of plant-available N as urea. Additional details on the effect of municipal biosolids on soil pH are found in publication PNW 508, *Fertilizing with Biosolids*.

The S in thiosulfate (S_2O_3) is another source of acidity. The sulfate (SO_4) in ammonium sulfate does not produce acidity.

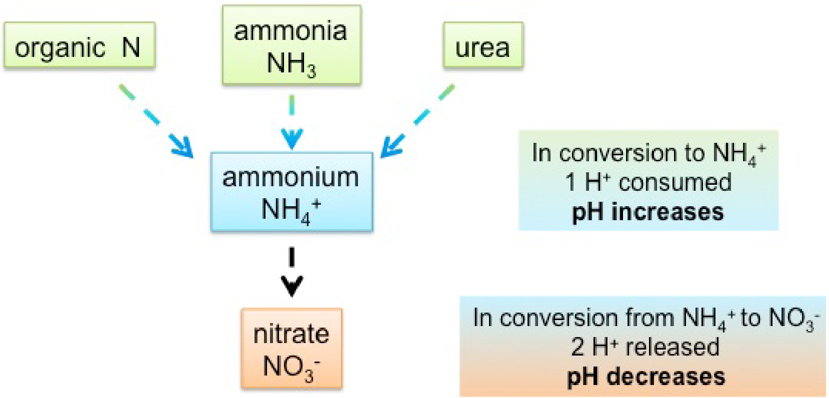
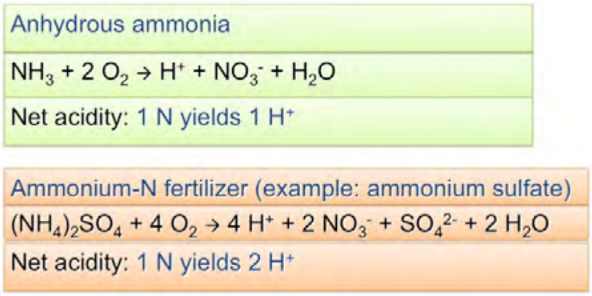


Figure 8.—Microbial conversion of nitrogen (N) fertilizers in soil. First, microbes convert urea, organic N, or ammonia to ammonium-N, thereby increasing pH. Second, ammonium is converted to nitrate. This step (nitrification) is responsible for acidity production. Thus, N fertilizers that contain N as NH_4 produce the most acidity per unit of N. Nitrogen fertilizers that supply only NO_3-N do not produce acidity. Figure by Dan Sullivan.



Anhydrous ammonia

$NH_3 + 2\ O_2 \rightarrow H^+ + NO_3^- + H_2O$

Net acidity: 1 N yields 1 H^+

Ammonium-N fertilizer (example: ammonium sulfate)

$(NH_4)_2SO_4 + 4\ O_2 \rightarrow 4\ H^+ + 2\ NO_3^- + SO_4^{2-} + 2\ H_2O$

Net acidity: 1 N yields 2 H^+

Figure 9.—Soil acidity produced by two nitrogen (N) fertilizers. The most acidifying N fertilizers supply all of the N in ammonium form (e.g., ammonium sulfate). When N is supplied via other N forms (e.g., anhydrous ammonia), less acidity is produced. Figure by Dan Sullivan.

Measuring and monitoring soil pH

Soil pH can be measured in a laboratory or in the field. The pH values provided by field measurement should be used only to estimate soil pH. If an in-field measurement indicates that soil pH might be above or below the range given for a crop, or if the accuracy of the measurement is questionable, send a soil sample to a laboratory for analysis.

Laboratory soil pH analysis

Laboratory analysis provides the most accurate soil pH measurement and is recommended for monitoring soil acidification and determining when lime is needed. Any laboratory that performs standard soil test analyses can determine soil pH quickly and inexpensively.

Soil pH is measured by inserting a hydrogen ion electrode into a mixture (paste or slurry) of soil and water. A consistent soil:water (weight/volume) ratio is important. Diluting soil from a ratio of 1:1 (soil:water) to a ratio of 1:2 generally causes soil pH values to increase (Gavlak et al., 2003). Recommendations in this publication are based on a 1:2 soil:water ratio.

In other areas of the world, soil pH is measured by mixing soil with a dilute salt solution (usually calcium chloride) rather than deionized water. This method is used by some laboratories in the United States, usually in addition to the traditional measurement in water. A salt solution typically yields a soil pH that is 0.5 to 1.0 pH unit lower than that measured with deionized water. Do not use a salt solution pH measurement to determine lime need, as tables in this guide and recommendations in companion publications are based on soil pH determination with a 1:2 soil:water ratio.

In-field soil pH measurement

In-field pH measurements provide a way to rapidly determine soil pH when attempting to diagnose crop problems. In-field soil pH measurement tools include color kits, probes, and portable pH meters. Portable pH meters are compact versions of laboratory instruments that can be calibrated or standardized and measure pH in a 1:2 soil:water ratio. Soil pH probes are a sealed unit with no ability to calibrate or standardize and are designed to be pushed into moist soil and to instantly provide a pH measurement.

How accurate are these tools?

In a university study, four in-field methods were used on three soil samples from a national quality control program (Table 2). The portable meter produced results closest to the average from 82 laboratories. The pH probe provided the same soil pH for all three samples. Results from the color kit were intermediate between the pH probe and the portable meter.

Table 2.—Soil pH comparison of three in-field methods with results of a laboratory quality control program.

Method of pH measurement	Soil 1	Soil 2	Soil 3
Laboratory average[a]	7.9	6.3	5.6
Portable pH meter	7.7	6.3	5.5
Color kit	8.0	6.5	5.5
pH probe	6.0	6.0	6.0

[a] Average from 82 participating laboratories. Data from Stevens et al., 2001.

In summary, **color kits** can be effective for determining which samples to send to a laboratory. Soil pH, as determined by color kits, is typically within 0.5 to 1.0 unit of the pH determined by laboratory analysis. However, because plants can respond to differences of 0.1 or 0.2 pH unit, a more accurate laboratory analysis should be used to compare pH levels in “good’ and “bad” areas of a field (in situations similar to those shown in Figures 1 and 12).

Color kit solutions often degrade with time and exposure to heat and should be replaced frequently.

Soil pH probes provide rapid pH measurement. Studies show that they are unable to reliably measure pH (Table 2). Thus, they are not useful for diagnosis of soil pH problems.

Portable pH meters can be accurate, but only when correctly calibrated and maintained. We do not recommend purchase of a meter without technical training or support for maintenance.

Irrigation

Irrigation creates the potential for higher yield, which increases the demand for N fertilizer. As a result, acidification due to N fertilizer application is often accelerated by irrigation. Also, clean water pumped from rivers or from shallow alluvial wells leaches soil Ca, Mg, and K, accelerating the soil acidification process.

Conversely, irrigation water from deep wells can be a significant source of lime input (pH increase). Irrigation well water analysis is recommended to determine water pH and liming potential (carbonate + bicarbonate content). Calculations to estimate the liming effect of high bicarbonate irrigation water are found in OSU Extension publication EM 9060, *Eastern Oregon Liming Guide*. Irrigation water that contains high concentrations of bicarbonate can be detrimental to plants requiring acidic soil such as blueberries, azaleas, rhododendrons, sweet gum trees, and maple trees.

Soil properties that influence acidification rate

Soil pH buffering capacity determines the rate at which soils acidify. In acidic soil, the buffering capacity is primarily a function of cation exchange capacity (CEC). In basic or alkaline soil, the amount of precipitated calcium carbonate or lime also buffers soil from acidification.

The CEC varies with clay and organic matter content. The higher the clay and organic matter content, the higher the CEC and buffering capacity. As soil buffering capacity increases, the soil acidification rate decreases since more H ions are needed to change pH. Thus, a sandy soil with low CEC has a faster acidification rate than a soil with moderate to high clay content and CEC.

For example, soil acidification proceeds faster in Madras sandy loam (eastern Oregon) compared to a Nekia silty clay loam (western Oregon). The acidification rate was almost 0.2 pH unit/year for Madras sandy loam compared to about 0.1 pH unit/year for Nekia silty clay loam (Figure 10).

Irrigated crop production areas of Umatilla and northern Morrow counties, as well as Deschutes, Jefferson, and Crook counties, are primarily located on low organic matter sandy soils, such as the Madras series. These soils have low buffering capacity, resulting in rapid acidification.

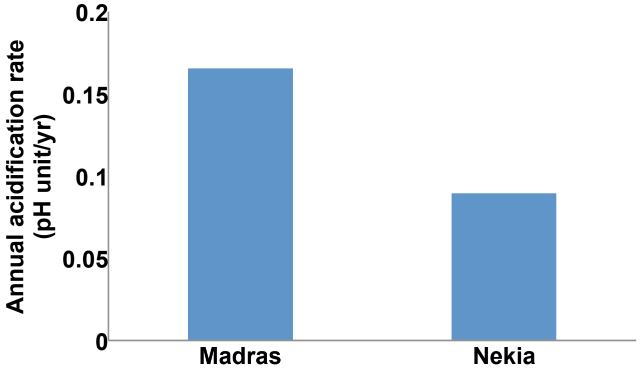


Figure 10.—The pH of Madras sandy loam decreases faster than that of Nekia silty clay loam. Buffering capacity, which is based primarily on cation exchange capacity (CEC), produces the difference in acidification rate. Figure by John Hart. Data from Doerge and Gardner, 1985a.

Problems caused by soil acidity

Soil pH plays a major role in regulating solubility and/or availability of elements in soil solution. A change in elemental solubility may create growth-limiting soil conditions. The result of soil pH below the crop threshold can be abrupt and disastrous (Figure 3, page 2).

Soil acidity limits plant growth in the following ways:

- Aluminum solubility increases. Even small concentrations of Al in soil solution can be toxic to root apical meristems (the growing tip). A reduction in root growth limits the ability of a plant to obtain water and nutrients such as P.
- Plant-available Mn can increase to levels that inhibit shoot growth.
- Phosphorus availability (solubility) decreases. Decreased P solubility is of limited agronomic importance. Rather, acidity usually creates P deficiency through Al-induced reduction in root growth.
- Exchangeable cations—Ca, Mg, and K—decline, as exchange sites are occupied by H and Al. The displaced nutrients, especially Mg, can become deficient.
- Molybdenum solubility decreases, creating deficiencies in some crops, especially in legumes.

- Symbiotic N fixation by Rhizobia on legume roots is reduced, resulting in N deficiency in legumes.
- The soil bacteria responsible for nitrification are inhibited, slowing the rate of conversion of ammonium-N to nitrate-N. Crops that take up primarily the nitrate form of N may respond more slowly to application of ammonium-N fertilizers in acid soils (pH below 5.5).

Depending on species and variety, plants vary in sensitivity or tolerance to acidic soil conditions (see Appendix A, pages 18–19). Plants are most susceptible to low pH during the seedling stage.

If you suspect a pH-related growth problem, check Appendix A for the recommended minimum soil pH for your crop. When soil pH is below the value in Appendix A, crop growth will likely be limited. Typical symptoms and causes are given in Table 3.

Metal toxicities

Reduced crop growth from soil acidity is principally caused by toxicity of Mn and Al. As soil pH decreases, solubility of these metals increases sharply (Figure 11). A slight difference in soil pH, as little as 0.1 unit, can substantially reduce plant survival at germination. Fields rarely have a uniform soil pH. Thus, when a field's overall Al concentration approaches a toxic level, slight differences in soil pH allow some plants to grow while others die (Figures 12 and 13, page 10).

Soil pH and manganese solubility

As pH decreases and soil solution Mn concentration increases, plant accumulation of Mn increases, sometimes to levels that are toxic to the plant. Usually, plant Mn toxicity occurs at a higher pH than does Al toxicity. In most mineral soils, Al toxicity does not occur until the soil pH is below 5.0. To prevent Mn toxicity, however, the soil pH for some crops (e.g., spinach) should be 6.0 or higher. Unfortunately, no definitive soil pH threshold for Mn toxicity exists, as sensitivity to Mn varies with crop and variety.

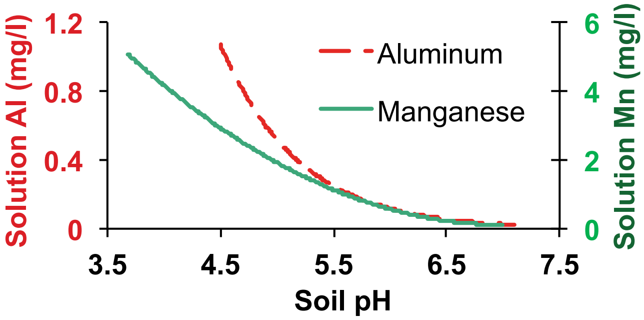


Figure 11.—As soil acidity increases (pH decreases), soil solution concentrations of aluminum (Al) and manganese (Mn) increase (Woodburn soil, Willamette Valley, Oregon). Figure by Don Horneck. Data from Horneck, 1994.

Table 3.—Potential problems caused by soil acidity.

Legume			**Non-legume**		
Situation	**Possible reason**	**Page**	**Situation**	**Possible reason**	**Page**
Yellow and/or stunted plants	Ineffective nodulation	13	Stunted growth in allium species (onion and garlic) with little bulb development	Mn toxicity	9–10
Yellow and/or stunted plants	Low Mo availability	13	Brassica stems do not develop leaves	Low Mo availability	11
New leaves cup, crinkle, and are smaller than normal with chlorotic edges	Mn toxicity	9–10	New leaves cup, crinkle, and are smaller than normal with chlorotic edges	Mn toxicity	9–10
Dark brown spots appear after chlorosis; leaves dry and fall	Mn toxicity	9–10	Dark brown spots form after chlorosis; leaves dry and fall	Mn toxicity	9–10
			New stand is uneven; roots of plants may be stubby	Al toxicity	11
			Plants are purple and stunted with adequate P soil test	Al toxicity	11, 12–13

Sensitive crops. For most plants, a sufficient foliar tissue Mn concentration ranges from 15 to 25 ppm. In crops sensitive to Mn accumulation, such as garlic, yield reduction occurs when Mn concentration exceeds 50 ppm. Garlic plants with more than 100 ppm tissue Mn in May produced little to no marketable yield as shown by the "no lime" garlic in Figure 14.

Green, snap, or bush beans also have limited tolerance to Mn. The recommended soil pH for bean production in western Oregon is 5.5 to 6.0. Bean yield is substantially reduced when soil pH is below 5.5 (Table 4).

Table 4.—Effect of soil pH on the yield of beans.

Soil pH	Bush bean yield (t/a)
4.9	2.6
6.6	7.0

Data from Jackson et al., 1966.

Bean leaf tissue Mn increases as soil pH decreases (Table 5). A concentration of more than 300 ppm Mn in the youngest fully expanded trifoliate of beans is considered high (Reuter and Robinson, 1997). Tissue Mn concentration of 700 to 900 ppm in mature trifoliate leaves is toxic.

Table 5.—Effect of soil pH on the manganese (Mn) concentration of bean leaves.

Soil pH	Mn (ppm)
4.9	605
5.2	360
6.0	225

Data from Jackson et al., 1966.

Tolerant crops. Douglas-fir Christmas tree needles naturally have a much higher Mn concentration than many crops. Thus, although Mn concentration in Christmas tree tissue increases as soil pH decreases (Figure 15, page 11), trees show no symptoms of Mn toxicity until needle concentration exceeds 7,000 ppm (Kaus and Wild, 1998).

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Figure 12.—Very acidic soils that contain high concentrations of soluble aluminum (Al) can cause localized plant death. To determine whether acidic soil is a likely cause for poor plant performance, collect separate soil samples from "good" and "bad" areas of the field. Collection of a single soil sample would mix areas with adequate soil pH and areas of inadequate soil pH, masking the low pH associated with stunted or dead plants.

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Figure 13.—Low soil pH, 4.6, disrupts perennial ryegrass establishment, creating an uneven stand.

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Figure 14.—Manganese (Mn) toxicity in garlic causes cloves to have loose, leafy internal structures ("no lime"), while bulbs grown in limed soil developed normally.

Soil pH and aluminum toxicity

Like Mn, Al in soil solution increases as pH declines. A small decline in pH can result in a large increase in soluble Al (Figure 11, page 9). Excess Al causes malformed, thick (stubby) roots, reducing a plant's ability to obtain nutrients and water (Figure 16). Soil Al concentration can easily reach levels that are toxic to plants, causing stunted growth or even death.

Sensitive crops. Severe yield decline resulting from Al toxicity is observed in many crops when soil pH declines below 5.0. For example, root and top growth of tall fescue was poor in strongly acidic soil (Figure 16).

"Tolerant" crops. Some crops have genetic tolerance to soluble Al, so crop yields do not decline as precipitously when pH drops below 5.0.

For example, annual ryegrass has some tolerance to soluble Al in soil. Field research in Linn County on poorly drained soil showed that seed yield for unlimed soil (pH = 4.5) was about 75 percent of that produced in a limed soil with a pH of 5.5 (Hart and Mellbye, 2010). Reduced seed yield when soil pH was below 5.0 was associated with higher soil test Al.

Banding lime with seed for annual ryegrass production is recommended on leased ground where growers are unsure of having sufficient time to obtain a return on investment from a conventional lime application. Banding lime with seed to combat Al toxicity in soils with pH below 5.0 has not been evaluated on other crops. For more information, see publications EM 9057, *Applying Lime to Raise Soil pH for Crop Production (Western Oregon)*, and EM 8854, *Annual Ryegrass Grown for Seed (Western Oregon) Nutrient Management Guide*.

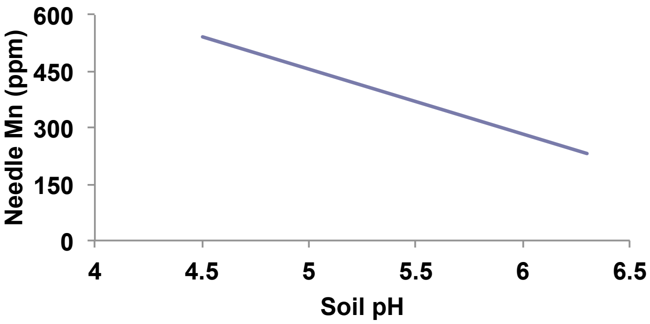


Figure 15.—The relationship between Christmas tree needle manganese (Mn) concentration and soil pH. Data collected from 32 plantations in western Oregon and Washington in 2002. Data from Hart et al., 2009.

Nutrient deficiencies— Non-leguminous crops

The solubility and supply of the micronutrients Mn, Zn, Fe, and Mo change with soil pH. Soil acidity affects Ca, Mg, and K concentration through a different mechanism. The addition of H ions accompanying soil acidification replaces these cations and allows them to be leached below the root zone. In the case of P, the reduced root growth caused by metal toxicities is more important in limiting P supply to plants than is the direct effect of soil pH on P solubility.

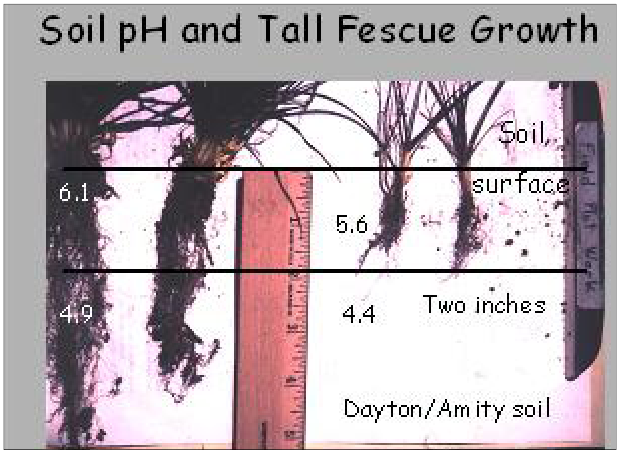
Molybdenum and other micronutrients

The amount of Mo required differs considerably among crops. Dicots, especially legumes and brassicas (e.g., cabbage and cauliflower), have a high Mo requirement compared to monocots (e.g., wheat, corn, and other grasses). Mo availability decreases as soil pH declines. Therefore, lime applied to an acidic soil to raise pH increases plant Mo supply.

In contrast, the plant-available supply of Fe, Zn, and Mn increases as soil pH decreases. Thus, lime applied to an acidic soil to raise pH decreases the availability of these nutrients. It does not, however, cause deficiency of these nutrients in most plants.

Calcium

The amount of exchangeable cations, especially Ca and Mg, decreases as exchangeable H replaces exchangeable Ca, Mg, and K during the soil acidification process. Even though exchangeable Ca



Mark Mellbye, © Oregon State University

Figure 16.—Tall fescue root growth is restricted by low soil pH, 4.4 (right). Root growth is adequate in soil with pH 4.9 (left).

decreases as soil pH decreases (Figure 17), Ca deficiency is rare in most crops.

At any given pH, exchangeable Ca varies with CEC. For example, a Chehalis silty clay loam soil with a pH of 5.0 contains more exchangeable Ca than either a Latourell or Alsea loam soil (Figure 17) at the same pH. This difference is a result of the lower CEC of loam soils compared to silty clay loam soil; fewer cations, including Ca, are attracted to loam soils.

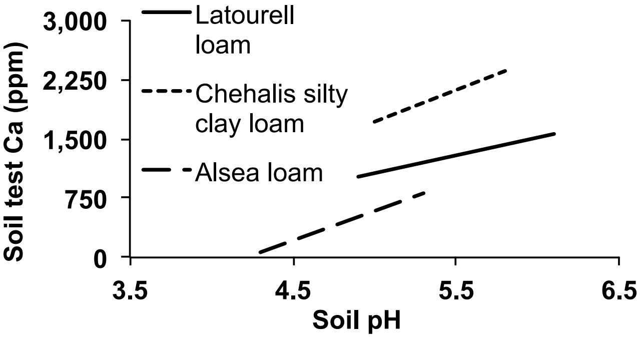


Figure 17.—The relationship between exchangeable calcium (Ca) and soil pH in three western Oregon soils. At a given pH, a silty clay soil (Chehalis) contains more Ca than a loam soil (Latourell or Alsea). Data from Hart et al., 2009.

Phosphorus

Liming an acidic soil to the recommended pH value (Table 9, pages 18–19) often increases plant growth and P uptake. Liming acts indirectly, since at a higher pH, less soluble Al is present, and root growth is improved.

This principle is illustrated in a case study from a western Oregon silage corn field where growth was uneven. Shorter plants had purple leaves and were approximately half the size of plants with green leaves (Figures 18 and 19).

Soil test P from both areas was above 30 ppm, a value at which no P fertilizer is recommended (Table 6). The surface soil pH in the area with short corn and purple leaves (4.8) was at the threshold of Al toxicity, while surface soil pH was higher (5.2) for the green corn plants.

Table 6.—Soil analyses from two areas of a silage corn field.[a]

Leaf color	Soil depth (inches)	pH	Soil test P (ppm)
Purple	0 to 6	4.8	87
Green		5.2	95
Purple	7 to 12	5.5	49
Green		5.6	61
Sufficient values		Above 5.5	Above 30

[a] One area with adequate growth (green plants) and one area with poor growth (purple plants). Figure 18 shows poor growth and purple color of corn. Figure 19 shows normal coloration.


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Figure 18.—Silage corn showing typical phosphorus (P) deficiency symptoms—purple coloration of lower leaves. Refer to Table 6 for soil test data.


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Figure 19.—Silage corn showing normal coloration. Phosphorus (P) uptake is adequate, so leaves do not show deficiency symptoms. Refer to Table 6 for soil test data.

Plants with purple leaves were deficient in P, while plants with green leaves had sufficient plant tissue P (Table 7). For this corn development stage, 0.25 percent whole plant tissue P should be sufficient.

Table 7.—Tissue analyses from silage corn field.

Leaf color[a]	Tissue P (%)
Green	0.28
Purple	0.14

[a]Plants are shown in Figures 18 and 19.

Thus, the corn plants with purple leaves had adequate soil test P, deficient tissue P, and low soil pH. Al toxicity, rather than inadequate soil P, likely caused the P deficiency symptoms. The reduced root growth caused by Al toxicity reduced the plant's ability to accumulate P, even though soil test P was adequate.

When both soil pH and soil test P are low, the application of lime (to raise pH) and P fertilizer are both needed to optimize yield. A lime application will not compensate for low soil test P.

Nutrient deficiencies—leguminous crops

The plant-available supply of Ca and Mo is critical to N fixation, the mechanism by which most legumes obtain N. The first step of N fixation is formation of a root nodule, followed by transformation of atmospheric N to a plant-available form. Soil acidity reduces both nodule formation and conversion of atmospheric N.

Calcium

Nitrogen fixation begins when bacteria of the genus *Rhizobium* penetrate a legume root. In response, the plant forms a nodule. This step depends on Ca supply. For example, nodules on greenhouse-grown alfalfa roots increased from 35 to 70 per plant when soil pH increased from 5.3 to 5.8 and soil Ca increased (Figure 20).

Molybdenum

After nodule formation, an ample supply of Mo is needed for creation of the nitrogenase enzyme, which is used for N fixation. Low soil pH results in decreased Mo availability. Increased alfalfa growth after application of lime to alfalfa fields with acidic soil is often associated with higher leaf Mo, an indicator of increased soil Mo solubility (Figure 21).

The combination of nodule formation and subsequent N fixation influences both legume seed and forage yield. In some situations, the yield increase is linear with soil pH increase (Figure 22).

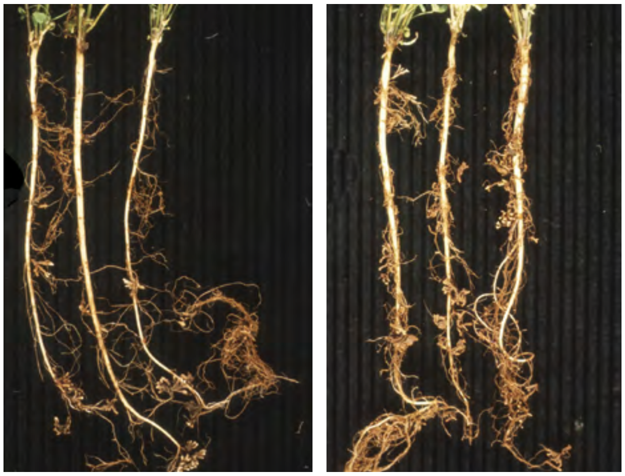

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Figure 20.—Roots and nodules of greenhouse-grown alfalfa in a Woodburn silt loam with soil pH 5.3 (left) and 5.8 (right).

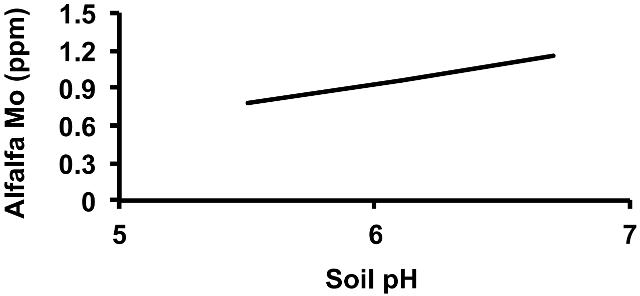

Figure 21.—Relationship between molybdenum (Mo) concentration in alfalfa tissue and soil pH. Figure by John Hart. Data from Doerge et al.,1985.

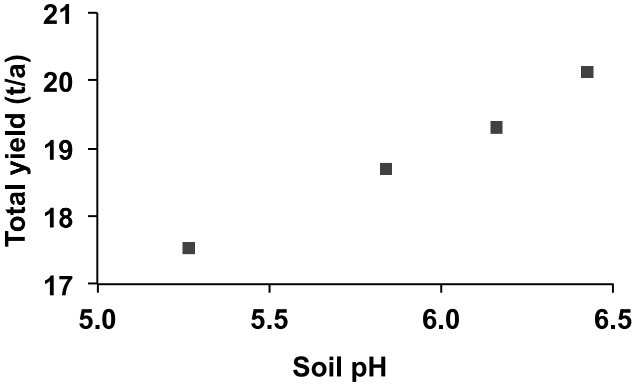

Figure 22.—The relationship of soil pH (depth 8 inches) and total yield for 3 years in a central Oregon alfalfa field. The Deschutes sandy loam soil at this site was neutral to slightly alkaline before acidification. Figure by John Hart. Data from James, 1988.

The effect of low pH and reduced Mo availability on alfalfa are illustrated in the series of photos in Figure 23.

Interactions among factors

Yield decline when soil pH is below the crop threshold is usually caused by more than one factor. Sometimes, multiple factors interact, resulting in a "perfect storm." In such instances, crop yield decline is especially severe. For example, the toxic effect of Al on root growth can be greater when other factors, such as soil compaction, drought, root disease, or low soil P also limit root growth.

Managing soil pH

The pH at which yield is diminished is not precise, and it varies among production areas. However, when soil pH drops below the threshold for a given crop, yield decline can be sudden and drastic (Figure 3, page 2). This effect is often described as falling over a waterfall or off a cliff. The goal of managing soil pH is to avoid falling off the production cliff or slipping over the waterfall. Thus, lime application is not expected to increase yield, but rather to prevent a decrease in yield by maintaining soil pH above the crop threshold.

Reduced growth or yield from soil acidity does not always occur immediately. When perennial legumes, such as alfalfa, are planted in a soil with adequate pH, acidity can reduce forage yield, protein, and root nodulation as the stand ages. Woody perennial crops such as Christmas trees and nursery stock are established by transplanting. The nutrient concentration of the transplant stock is much higher than that required for initial growth. Therefore, low soil pH might not reduce growth for 1 or 2 years after transplanting.

A complicating factor in soil pH management is soil variability. If soil samples are collected from areas with adequate and inadequate soil pH, the composite soil pH could indicate adequate conditions for crop growth. In this case, plants will grow in some areas and not in others (Figures 24 and 25, page 15).

Soil sample collection techniques—such as sampling zones within the field—reduce variability in soil pH measurements. Zones should be based on

Photos by Hugh Gardner, © Oregon State University

Figure 23.—Evidence of legumes' need for molybdenum (Mo) and the reduced availability of Mo in acidic soil: (A) Alfalfa growth was poor in a soil with pH of 5.5; (B) addition of Mo increased alfalfa growth when soil pH was 5.5; (C) application of nitrogen (N) to a low-pH soil allowed normal alfalfa growth, indicating that N fixation is limited by Mo deficiency in acidic soil; (D) increasing soil pH to 6.5 increased Mo availability, N fixation, and alfalfa growth.

soil textural class (an estimation of CEC and buffering capacity), which can be estimated from Natural Resources Conservation Service (NRCS) soil maps, grid sampling, or soil electrical conductivity mapping. Nonetheless, even these techniques will not eliminate variability in soil pH measurement. Soil sampling methods are discussed in publication PNW 570, *Monitoring Soil Nutrients Using a Management Unit Approach*.

Soil pH also varies seasonally, with regional differences in the patterns of seasonal variation:

- In western Oregon, soil pH commonly fluctuates 0.3 pH unit or more during a calendar year. The highest pH is measured in late winter, and the lowest in late summer.
- In eastern Oregon, soil pH can fluctuate by more than 1 unit in sandy soils that do not


Maryna Serdani, © Oregon State University

Figure 24.—Spinach growth varies with soil pH. The plant on the left was growing in a soil with pH of 5.8, and the plant on the right was growing in the same field with a soil pH of 5.5. Soil pH was measured in July.


Nicole Anderson, © Oregon State University

Figure 25.—Spinach field showing stand variability within and between rows caused by low soil pH. Arrow points to the area that was the source of the small plant shown in Figure 24.

Soil sample collection

Soil sample collection technique, primarily sample depth, influences soil pH. When N fertilizer is top-dressed without tillage, the surface 1 to 2 inches of soil acidify much faster than soil below the surface. Conversely, because of its limited mobility, lime can raise the pH in the surface soil when top-dressed (Table 8).

Table 8.—Stratification of soil pH in two no-till fields. Top (wheat): Acidification at soil surface as the result of top-dress N fertilizer. Bottom (grass seed): Higher pH at soil surface resulting from liming.

Crop	Sample depth (in.)	Soil pH
Wheat	0 to 2	4.3
(three fields)	2 to 6	5.5

Crop	Sample depth (in.)	Soil pH
Grass seed	0 to 0.25	6.3
(one field)	0.25 to 0.5	5.2
	0.5 to 6	4.9

Both of these scenarios result in an uneven distribution of soil pH that will not be apparent in a soil sample collected at the standard depth of 0 to 6 or 8 inches. Acidification at or below the soil surface can severely inhibit crop growth and result in substantial yield loss.

Collection of soil samples from multiple depths (stratified sampling) helps identify pH throughout the rooting zone. Consider stratified sampling if you top-dress fertilizer and (1) produce a woody perennial crop or orchard crop, (2) manage pasture, (3) produce peppermint, grass for seed, or another perennial field crop, or (4) establish crops by direct seeding.

To collect a stratified sample, insert a soil probe 6 to 8 inches into the soil. Separate the top 2 inches of soil from the remaining depth and analyze the two samples independently. For no-till cropping systems, pastures, and fields where perennial crops have been grown for 3 or more years, wait 2 or 3 years after establishment to begin stratified sampling.

See OSU Extension publication EM 9014, *Evaluating Soil Nutrients and pH by Depth*.

contain carbonate. The highest seasonal soil pH is measured in late winter or early spring after soil is leached by winter rain. Soil pH is lowest or most acidic in spring after fertilizer application.

To minimize variation in soil pH test results, maintain a consistent sampling protocol, including sampling depth and timing.

Maintenance of an adequate soil pH creates an environment in which plants can grow in response to other inputs such as fertilizers and pesticides. Monitoring soil pH through careful sample collection, consistent collection timing, and appropriate analytical procedures is necessary. Addition of lime is recommended to maintain soil pH in a range considered adequate for the crop (Table 9, pages 18–19). When managing soil pH, consider an entire rotation plan and apply lime well ahead of the most acid-sensitive crop or when tillage may occur in perennial or reduced-tillage cropping systems.

Recommendations for lime application rates, method of application, liming materials, and time of application are provided in companion publications EM 9057, *Applying Lime to Raise Soil pH for Crop Production (Western Oregon),* and EM 9060, *Eastern Oregon Liming Guide.*

Tissue analysis as an indicator of soil pH

Soil and seasonal variability make measurement of small pH changes difficult. Especially in woody perennial crops, plant tissue analysis can detect soil pH changes more easily than can soil samples.

Plant tissue Mn increases as soil pH decreases. For example, in Christmas trees, an increase in Mn needle concentration of 150 to 200 ppm represents a soil pH decrease of approximately 1 unit. Tissue Mn increases very rapidly when soil pH falls below 5.2.

For more information

The following OSU Extension Service publications are available online at http://extension.oregonstate.edu/catalog/

Annual Ryegrass Grown for Seed (Western Oregon) Nutrient Management Guide, EM 8854

Applying Lime to Raise Soil pH for Crop Production (Western Oregon), EM 9057

Christmas Tree Nutrient Management Guide for Western Oregon and Washington, EM 8856

Eastern Oregon Liming Guide, EM 9060

Evaluating Soil Nutrients and pH by Depth in Situations of Limited or No Tillage in Western Oregon, EM 9014

Fertilizing with Biosolids, PNW 508

Monitoring Soil Nutrients Using a Management Unit Approach, PNW 570

Soft White Winter Wheat (Western Oregon) Nutrient Management Guide, EM 8963

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The authors thank Mark Mellbye for his contributions to this publication. In addition to photos, some of the data Mark collected about soil pH management in western Oregon grass seed cropping systems during his tenure as an OSU Extension agent are used in this publication.

We thank Gale Gingrich, OSU area Extension agronomist emeritus, for supplying photos.

Appendix A. Recommended Crop Threshold Soil pH for Oregon Crops

Liming is a management practice that prevents crop damage from acidity. The frequency and amount of lime needed to maintain pH above the injury threshold (Table 9) depends on soil buffering (primarily CEC), N fertilizer source and rate, and tillage.

Regular monitoring of soil pH will help you determine the need for lime.

For seed crop production, use the soil pH requirement for the primary crop production purpose. For example, sugar beet production as a field crop requires a minimum soil pH of 6.0, as does sugar beet seed production.

The soil pH values in Table 9 are for soils with less than 10 percent organic matter. In high organic matter soils, Al–organic matter complexes reduce the concentration of Al in the soil. Consequently, in soils with more than 10 percent organic matter, threshold soil pH values are usually 0.5 unit lower than those given in Table 9. High organic matter soils are found in the glacial Lake Labish area of Marion County, in the Gaston area of Yamhill County, in coastal pastures of Tillamook County, and in lake areas of Klamath County.

Table 9.—Recommended minimum soil pH for Oregon crops.

	Crop	Recommended (minimum) soil pH
Field crops	Barley	5.8
	Oats	5.8
	Silage and grain corn	5.5
	Sugar beets	6.0
	Triticale	5.8
	Wheat—all market classes	5.4
Oil crops	Camelina	5.7
	Canola	5.4
	Meadowfoam	5.8
	Peppermint	5.6 to 6.0[a]
Grasses for seed	Annual ryegrass	5.5
	Bentgrass	5.0
	Fine fescue	5.5
	Kentucky bluegrass	5.5
	Orchardgrass	5.8
	Perennial ryegrass	5.5
	Tall fescue	5.5
Legumes	Alfalfa	6.5
	Crimson clover	5.5
	Peas	5.5
	Red clover	6.0
	Subterranean clover	5.2
	Vetch	5.5
	White clover	5.8
Small fruits	Blueberries	4.5
	Caneberries	5.6
	Cranberries	4.5
	Strawberries	5.4

continues on page 19

Table 9.—Recommended minimum soil pH for Oregon crops.

	Crop	Recommended (minimum) soil pH
Tree and vine crops	Apples	5.6
	Christmas trees	5.0
	Filberts (hazelnuts)	5.6
	Hops	5.7
	Peaches, pears, prunes	5.6
	Rhododendrons and azaleas	4.5
	Shade, ornamental, fruit, other bare-root stock[b]	5.5
	Sweet cherries	5.6
Vegetable crops	Asparagus	6.0 to 6.5[c]
	Broccoli, Brussels sprouts, cabbage, cauliflower	6.3
	Carrots	5.6
	Cucumbers, melons, squash, pumpkins	5.8
	Garlic	6.5
	Green or snap beans	5.8
	Onions	6.0 to 6.5[c]
	Peas	6.0
	Potatoes	5.5
	Radish	6.0
	Rhubarb	5.5
	Spinach	6.0 to 6.5[c]
	Sweet corn	5.8
	Table beets	5.8
	Turnips[d]	5.8 to 6.0[c]
Other crops	Grass legume pastures	5.5[e]
	Grass pastures	5.5

[a] Use pH 6.0 for preplant pH and 5.6 for established stands.

[b] Maximum soil pH for red maple should not exceed 6.0.

[c] A range is used since data and references provide conflicting values. The safest approach is to use the higher value. Your experience or local experience may prove the lower value to be satisfactory.

[d] No local data are available for forage turnip seed production. Minimum soil pH from other areas varies from 5.5 to 6.0. For vegetable production, pH 6.0 or higher is recommended.

[e] Species choice determines the minimum soil pH. Use the species with the highest pH requirement to determine whether soil pH is adequate or lime is needed.

Appendix B. Influence of Soil pH on Weed Populations and Chemical Weed Management

Small changes in soil pH (tenths of a pH unit) can have large ramifications on crop growth and yield. The impacts of soil pH on weed management are no different. Soil pH can shape the species composition of weed populations as well as influence the efficacy and persistence of commonly used herbicides.

Effect of pH on weed species composition

The influence of soil pH on weed species composition in agricultural fields has not been studied in great detail. Often, reports about the relationship between weed species vigor and soil pH are anecdotal and conflicting, in addition to varying by geographic location. Soil type and crop management practices (crop rotation, weed seed bank size, and past weed management strategies) usually play a greater role than soil pH in shaping weed species composition.

Nevertheless, scientific data do exist that indicate a relationship between weed species and soil pH. Several species show no preference for either high or low soil pH, or are generally unaffected by soil pH as long as pH is within normal agricultural production ranges. Canada thistle and some smartweed species are examples.

In other cases, data indicate that some weed species are well adapted to high or low soil pH. In fact, certain species can be reasonably thought of as "indicator" species for either low or high soil pH (Table 10).

Table 10.—Weed species commonly found in Oregon annual cropping systems and their general association with acidic (low pH) or basic (high pH) soil conditions.

Weed species associated with low soil pH	Weed species associated with high soil pH
Dock spp.	Common velvetleaf
Field horsetail	Pigweed spp.
Knapweed spp.	Dandelion
Common mullein	Clover spp.
Plantain spp.	Mustard spp.
Field bindweed	
Hawkweed spp.	

Effect of pH on herbicide efficacy

Soil pH can influence longevity and efficacy of several important herbicides, including those within the imidazolinone, sulfonylurea, and triazine families.

Herbicides are degraded by soil microbes and by chemical processes (e.g., acid hydrolysis). This degradation results in reduced herbicide efficacy and persistence. Chemical degradation tends to be more rapid when herbicides are tightly bound to soil particles. Microbial degradation is more rapid when herbicides are less tightly bound to soil particles.

In neutral or slightly acidic soil, herbicides are more likely to be tightly bound to soil particles and degrade primarily from chemical reactions. The opposite is true in basic soil. In these soils, herbicides are less likely to be tightly bound to soil particles. Thus, they are less subject to chemical degradation and more likely to degrade via microbial activity.

Herbicides with increased efficacy at high pH. Common **sulfonylurea** herbicides with substantial soil activity are listed in Table 11. In general, when soil pH is above 7, these herbicides are less tightly bound to soil particles. The result is twofold:

- The herbicides are more available for plant uptake, making them more effective at weed control but also more likely to cause crop injury.
- They are less subject to chemical degradation, so they last longer in the soil.

Table 11.—Common sulfonylurea herbicides with substantial soil activity.

Herbicide	Herbicide
chlorsulfuron	halosulfuron
metsulfuron	prosulfuron
rimsulfuron	sulfosulfuron
sulfometuron	nicosulfuron

Soil-applied **triazine** herbicides, including atrazine, metribuzin, hexazinone, and mertibuzin, behave in a similar fashion at high pH values.

In lower soil pH conditions (pH less than 6), the activity of herbicides in these chemical families decreases. Triazine herbicides, for example, become more tightly bound to soil particles, thus increasing their chemical degradation rate and making them less available for plant uptake. Thus, herbicides such as atrazine and metribuzin are less active (lower risk of crop injury, but less weed control efficacy) at a given application rate in low pH soil than where soil pH is higher.

If utilizing herbicides within these two chemical families (triazine and sulfonylurea), plan to lime soils to raise pH values to approximately 6 to maximize weed control performance.

Avoid liming above pH 6.8, as the risk of herbicide carryover (damage to the following crop) from these herbicides increases. If soil pH is naturally high, avoid using products in these chemical families or use them only in crop rotations where the risk of carryover to the next crop is minimal.

Herbicides with increased efficacy at low or neutral pH. Conversely, for soil-active herbicides in the **imidazolinone** chemical family, low soil pH (less than 6) increases the potential for longevity in the soil. Herbicides in this family include imazamox, imazapic, and imazethapyr. These herbicides are primarily degraded by soil microbes.

In acidic soil conditions, these herbicides are tightly bound to soil particles, thus decreasing the microbial degradation rate. This effect is opposite that for the sulfonylurea and triazine families, where being tightly bound to soil particles increases the chemical degradation rate. Maintain a slightly acidic to near-neutral pH to maximize weed control efficacy of imidazolinone herbicides, while limiting the potential for herbicide carryover.

Use pesticides safely!

- Wear protective clothing and safety devices as recommended on the label. Bathe or shower after each use.
- Read the pesticide label—even if you've used the pesticide before. Follow closely the instructions on the label (and any other directions you have).
- Be cautious when you apply pesticides. Know your legal responsibility as a pesticide applicator. You may be liable for injury or damage resulting from pesticide use.

Appendix C. Crop Yield and Nutrient Concentration with Lime Application

Changes in yield and nutrient concentration from lime application have been documented for many Oregon crops.

Data in the following publications were used to establish recommended minimum soil pH requirements in this publication (Table 9) and pH recommendations in other OSU Extension Service publications.

Lime–fertilizer interactions affecting vegetable crop production

http://hdl.handle.net/1957/35414

Dill for oil

The Effect of Lime on Yield of Dill, 1974
http://hdl.handle.net/1957/35413

Bentgrass for seed, fine fescue for seed, garlic, and mint—central Oregon

1977 Annual Report: Soil Fertility Trials. Annual Report to Tennessee Valley Authority, 1977
http://hdl.handle.net/1957/35532

Garlic

Effects of Lime and Nitrogen Fertilization on Solids Content in Garlic, 1973
http://hdl.handle.net/1957/35449

Table beets, carrots, cauliflower, lettuce, spinach, sweet corn, bush bean

Lime Fertilizer Interactions Affecting Vegetable Crop Production, 1983
http://hdl.handle.net/1957/35414

Table beets, spinach, turnip, rutabaga

Oregon Vegetable Digest, Volume 23, No. 2, 1974
http://hdl.handle.net/1957/11619

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