In soil, pH is known as a master variable because it influences almost every process in the soil system. The health of crops and other important soil life, availability of nutrients, and the activity of pesticides are affected by pH.

Thirty percent of the earth’s soils are acidic. Most of these soils have been naturally acidified over geologic time. Several factors contribute to natural acidification. Climate is a main driver of natural acidification; atmospheric CO₂ slightly acidifies rainwater, and over geologic time, contributes to soil acidification. Acidic conditions are also created by removal of “base cations” such as calcium (Ca²⁺) and magnesium (Mg²⁺) from the root zone either by leaching through the soil profile or removal with harvested plant material.

A soil’s formation affects the likelihood of acidification. The soils of the iPNW are relatively younger, in a drier climate, and not typical of acidic soils. Clay content and presence of carbonates in these soils are linked to the region’s precipitation gradient, and the dominant clay minerals of mica and vermiculite correlate with the age of the soil (McDaniel and Hipple, 2010). The region had native forest or grass prairie cover, and as recently as the 1950s, soil pH was within the neutral range. Prairie soils developed in the drier part of the iPNW and tend to be higher in organic matter and concentrations of Ca²⁺ and Mg²⁺, which help to stabilize soil pH. Historically, forested soils have lower calcium and magnesium contents, lower organic matter, and higher aluminum levels. This leads to a reduced ability to buffer pH changes,

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and such soils often become acidic more quickly. Figure 1 shows the region’s precipitation gradient as cropping zones, where annual crops are grown in areas of higher precipitation, much of which historically had forest cover.

In the early 1980s, University of Idaho soil scientist, Dr. Robert Mahler, expressed concern when more than 75% of the northern Idaho soils data his group obtained from the University of Idaho Analytics Lab had a pH below 6 (Mahler et al., 1985). Today, farmers, researchers, and extension personnel are finding many sites in the iPNW with a surface soil pH below 5.0. Soil microbes convert ammonium nitrogen (NH$_4^+$) from various fertilizers into nitrate (NO$_3^-$), and this results in the release of hydrogen ions (H$^+$) into the soil solution, a process that is shown in Fig. 2 (next page). Additionally, a portion of the nitrate nitrogen leaches down through the soil profile, taking base cations with it, further accelerating soil acidification. The increasing concentration of hydrogen ions in soil solution lowers soil pH, creating an acidic environment. In conventional tillage systems, the H$^+$ is mixed throughout the tillage zone. In no-tillage systems, a band of concentrated H$^+$ often forms, creating a situation where the pH is stratified in the surface of the soil profile. This trend is shown in Fig. 3 (next page) with the Pullman site representing historically prairie soils and Rockford representing historically forested soils. In extreme cases, pH of the zone where synthetic fertilizer is commonly banded has been measured at lower than 4.0. Acidification of this zone, typically found between the 2- to 5-inch depth, has been rapidly accelerated by application of nitrogen fertilizers over the past five decades.

A pH too far from neutral, either above (alkaline) or below (acidic), makes essential plant nutrients less available. For most nutrients, optimum availability occurs near pH 6.5, and availability decreases as pH values become more extreme. Nutrient deficiencies in crops often result. In addition to decreasing nutrient availability, low pH can degrade clay minerals, like mica and vermiculite, thereby releasing the plant-toxic element, aluminum, which can interfere with root growth and function. Absorption of aluminum and other toxic elements under low-pH conditions results in yellowing, stunting, and general reduced vigor, especially in early developmental stages. The effects of

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**Fig. 1.** Agroecological classes (AECs) of the iPNW region of eastern Washington, northern Idaho, and northeastern Oregon. The AECs were derived from actual land use/cover data and largely reflect regional gradients in precipitation and temperature. The annual cropping AEC (dark green) is the region where the combination of greater precipitation, cropping intensity, and applied synthetic fertilizers have resulted in the most accelerated soil acidification. Map created by Harsimran Kaur and used with permission.
low soil pH are extensive. Low pH can negatively impact the soil microbial community, especially rhizobia symbionts of legumes. Reduced availability of certain nutrients resulting from low pH affects the growth of both crops and weeds. Pesticides, including herbicides, may be less effective and/or persist longer in low-pH soil.

The far-reaching effects of soil acidification underscore the importance of its influence on crop production and soil quality. These effects also make it difficult to diagnose acidic soils as the root of the problem. It has been common for growers or professionals in the area to see yellowing stunted plants in their field and attempt to diagnose the issue. Depending on the environmental conditions, symptoms of Al toxicity can look like winter-kill, water-logged soil, too-dry soil, pathogens, herbicide carryover, wireworms, nutrient deficiency, and numerous other issues. Developmentally stunted winter wheat from Rockford, WA, is shown in Fig. 4. These disorders not only stand alone but can interact and increase the complexity of diagnostics. This has led to many professionals and growers in the region to calling it the “low-pH complex.”

Researchers and extension professionals at Washington State University (WSU), University of Idaho (UI), and USDA-ARS are collaborating in an effort to understand how the low-pH complex uniquely affects the soils of this region and make that information available to producers. This work includes launching a set of interlinked web-based extension modules that address a variety of issues surrounding low-pH soils. Low soil pH affects beneficial soil microbes and pathogens, herbicide activity, and crop and variety selection. Soil sampling and testing on low-pH soils in this region, as well as nutrient management and development of a liming program, are all important components of working with the “pH complex.”

The effect of low pH on the microbial community

Soil microbiologist at WSU, Dr. Tarah Sullivan, has been interested in the impact of low soil pH on the microbial community, especially those that form mutually beneficial (symbiotic) relationships with crop plants. She has found that soil health, through the combined influence of pH on overall soil chemistry, including Al toxicity, is having a profound effect on the structure and function of two very important components of the plant-associated soil microbial community: rhizobia and mycorrhizae.

In general, bacterial growth and biomass in the soil are largest when pH is above 6.9. Rhizobia, a specific type of bacteria that forms symbiotic relationships with legumes and provides nitrogen to the plant, are no different than other bacteria in regard to pH. While some rhizobia can still grow below neutral pH, it is understood that soil pH
below 5.0 is detrimental for nodulation and nitrogen fixation. Low soil pH reduces nodule numbers on the roots of legume crops by more than 90% and nodule dry weight by 50% (Ferguson, 2012). The reduced numbers of rhizobia contributes to a reduction in nitrogen provided to the plant.

Attachment of rhizobia to plant root hairs requires Ca$^{2+}$ for adhesion (Ferguson, 2012). However, Ca$^{2+}$ is limited in acidic conditions and impairs the association between the bacteria and the crop. This is especially important in the iPNW where grain legumes (chickpea, dry pea, and lentil) are common rotational crops and the area has been showing increasingly lower soil pH values. Figure 5 shows the N-fixing rhizobia nodules on chickpea roots.

Many soil bacteria, like rhizobia, do not tolerate acidic conditions well, while most fungi are acid tolerant and are commonly found in acid soils. This results in acidic soils being favored by fungal communities. One type of plant–symbiotic fungi, called mycorrhizae, have been found to decrease Al toxicity by improving nutrient absorption, accumulating Al in the fungal biomass away from the plant roots, and by producing chelating compounds (Seguel et al., 2013). An experiment by Lux and Cumming (2001) showed that non-mycorrhizal plants had 51 to 210% more Al in their tissues than plants with these symbiotic relationships. Mycorrhizal fungi are known to be associated with many of the crop species found throughout the Palouse, but nothing is known about their capacity to buffer Al toxicity for these crops in these soils (Seguel et al., 2013).

The effect of low pH on common pathogens

In the mid-2000s, USDA-ARS plant-pathologist, Dr. Tim Paulitz, was approached by growers and extension agents trying to diagnose the “pathogen” that was causing yellowing and root stunting in their fields. Dr. Paulitz was able to determine that the symptoms in this case were not caused by a pathogen, but by Al toxicity from low-pH soils. He has also noted that because of the shifts that happen in the microbial community when pH changes, some pathogens are more likely to cause problems under low-pH conditions.

Summarizing those differences, he says that diseases caused by soilborne pathogens of wheat and barley can be classified into two groups: those that are not influenced greatly by pH and those that are. The first group includes the root-rotting pathogens *Pythium* and *Rhizoctonia*. These are considered to be generalist types of pathogens that quickly kill and rot the plant tissue. The second group includes the crown-rotting pathogens *Fusarium* and *Gaeumannomyces* (take-all). These initially infect and colonize the root without causing massive tissue death and later move into the crown when the plant is older. These two diseases show opposite trends; take-all is reduced under acid conditions, while Fusarium crown rot may be increased. Low pH favors the fungal community in soil; thus, prominent diseases seen under low-pH conditions are often caused by fungi. Of all the diseases influenced

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**Fig. 4.** Winter wheat in late spring displaying symptoms of chlorosis (yellowing) and general reduced vigor that are typical indications of the “the pH complex,” especially aluminum toxicity. The soil pH was near 4.5 as measured with a field pH meter.

**Fig. 5.** Rhizobia nodules on a chickpea plant from research plots that received surface application of lime.
by pH. Cephalosporum stripe, a vascular disease that presents as yellow stripes on the leaves, shows the strongest trend toward greater severity in acid soils.

**The effect of low pH on herbicides**

When attempting to diagnose yellowing and reduced vigor in crops as symptoms of low-pH soils and Al toxicity, it is common for those symptoms to look like herbicide injury. As part of the challenge of the low-pH complex, herbicide injury, resulting from unexpected activity or persistence, can also be fostered under low-pH conditions. Alan Raeder, a WSU Ph.D. candidate in weed science, explains that decreasing soil pH is a major concern related to the cases of herbicide persistence in the iPNW. Soil pH can have substantial effects on the activity and persistence of herbicides in soil, especially at pH extremes below 4.5 and above 7.5. In order to understand how soil pH affects the activity and persistence of herbicides, a knowledge of the charge (ionic) and polarity properties associated with herbicides is needed.

There are five categories based on the charge and polarity properties by which herbicides can be classified: weak acid, weak base, cationic, nonionic polar, and nonpolar. Of the 49 herbicide active ingredients used in the iPNW, 34 are classified as weak acids. Products (WSSA and HRAC mode of action groups in parenthesis, respectively) such as Assure II (Group 1, A), Beyond (Group 2, B), Pursuit (Group 2, B), GoldSky (Group 2, B and 4, O), PowerFlex HL (Group 2, B), Everest 2.0 (Group 2, B), 2,4-D (Group 4, O), WideMatch (Group 4, O), Huskie (Group 27, L and 6, C3), Roundup PowerMax (Group 9, G), and Sharpen (Group 14, E) all contain weak acid active ingredients. The activity and persistence of some herbicides classified as a weak acid will likely not be affected by decreasing soil pH due to a short soil half-life or lack of herbicidal activity in the soil; however, other weak acid herbicides are known to persist in soil with continued activity. In the latter cases, decreasing soil pH may be a major factor determining persistence if it alters the charge and, therefore, altering the sorption and water solubility properties of the herbicide. Imidazolinones and triazolopyrimidines are weak acids and will persist longer in lower pH soils. As the soil pH decreases, both imidazolinones and triazolopyrimidines become more hydrophobic (water-hating) and are more likely to associate with the soil organic matter fraction rather than the water, making the herbicide less active and less available for microbial degradation.

There are 13 nonionic polar active ingredients used in the iPNW, and they are found in products such as Lorox (Group 7, C2), Valor (Group 14, E), Axiom (Group 15, K, and 5, C3), and Zidua (15, K). Many of the nonionic active ingredients are primarily degraded by soil microbes, mostly bacteria and fungi. Many factors affect the rate at which microorganisms degrade herbicides, and these factors include soil temperature, moisture, and pH.

Weak base and cationic herbicides have drastically different activities and persistence in soil. In the iPNW, there is one weak base active ingredient commonly used, metribuzin, and one cationic active ingredient used, which is paraquat. Soil pH has no effect on the activity and persistence of paraquat, and the activity of metribuzin decreases with decreasing soil pH. A majority of metribuzin will be positively charged at lower soil pH and adsorbed tightly to the negatively charged soil particles, unavailable for absorption by plant roots.

Soil pH in the iPNW poses unique challenges for agricultural professionals in the region. In order to minimize the risk of herbicide injury or carryover to succeeding crops, it is important to know your soil characteristics, including soil pH. Refer to the herbicide label for region-specific guidelines for use rates and rotation restrictions for your soil conditions.

**Research on lime and lime requirement**

Amending soils with agricultural lime is the most common and effective strategy to correct soil acidity. Inevitably, a liming program that addresses soil acidification will be used by most farms in the iPNW. Correcting soil acidification with lime is certainly not new to agriculture, but it is new to the region and will require that we develop effective strategies for our unique soils and conditions. This has brought up some key questions that are being asked by growers in the iPNW:

- What are the best methods to diagnose the severity of a soil acidification problem?
- What liming materials are best suited to address a particular situation?
- How will the optimal amount of lime, time of application, and placement be determined?

Currently, these questions are being addressed by the combined efforts of university, industry, and agency experts often working collaboratively with producers. USDA-ARS soil scientist based at WSU, Dr. Dave Huggins, describes some of the research that is being done in the iPNW to help answer some of these questions:

“We are testing liming strategies in no-till systems that might correct stratified acidity. The low-pH zone seems to be relatively easy to target, perhaps with lower amounts of lime. One study is looking at unincorporated surface applications of two different lime sources: a very finely-ground fluid lime as well as sugarbeet by-product lime were applied at rates from 200 to 2,000 lb/ac calcium carbonate equivalent (CCE). Materials were applied in fall 2013 at two sites before spring planting chickpeas (Pullman) and canola (Rockford), with the idea that ultra-fine liming materials might be physically moved by winter precipitation and
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Determining how much lime to apply

Developing a liming program will be a relatively new management consideration for growers and consultants in the iPNW. Several important decisions will have to be made regarding application materials, methods (equipment, placement), amounts, and timing. How much lime to apply depends on the starting soil pH, the target pH, the soil's buffering capacity, and the type of liming material used. There are a variety of liming materials available in the iPNW, including fluid lime, prilled lime, crushed limestone, and "sugar lime"—a sugarbeet by-product with a high percentage of calcium carbonate. These materials are not abundant locally and the cost of transport can be high, so it is important to make sure that you are getting the best value for the investment.

An important thing to consider when comparing liming materials is their calcium carbonate equivalent (CCE) and lime score (LS). The term CCE represents how the acid-neutralizing power of the product compares with pure calcium carbonate. Lime score is a term used in the PNW and is officially required on liming products registered in Oregon. The lime score accounts for CCE but also how much moisture is in the product as well as its fineness because finer particle-sized lime reacts more efficiently. A higher LS typically indicates a higher quality liming product. Lime requirement reports from analytical labs are given in units of pure calcium carbonate and must be adjusted based on material.

An example: a soil test report recommends 6,000 lb/ac of calcium carbonate to achieve a target soil pH, and there are two (hypothetical) materials available. If Product 1 has a lime score of 89 and costs $75/ton and Product 2 has a lime score of 67 and costs $62/ton, how much should be applied and which is the better value?

The formula (J. Hart, 1998 FG 52) for adjusting the recommended rate to the material is:

\[
\frac{\text{Recommended rate}}{\text{lime score}} \times 100 = \text{rate of material to apply}
\]

Product 1

\[
\frac{6,000}{89} \times 100 = 6,741 \text{ lb of Product 1 to apply the recommended rate}
\]

\[
6,741 \text{ lb Product 1/2000 lb/ton} = 3.37 \text{ tons} \times \$75/\text{ton} = \$253/\text{ac}
\]

Product 2

\[
\frac{6,000}{67} \times 100 = 8,955 \text{ lb of Product 2 to apply the recommended rate}
\]

\[
8,955 \text{ lb of Product 2/2,000 lb/ton} = 4.48 \text{ tons} \times \$62/\text{ton} = \$278/\text{ac}
\]

In the example above, adjusting for the actual pH neutralizing capability of the product demonstrates that the cheapest material available (per ton) may not be the best value. It is important to consider the quality of the liming material as well as the cost when determining which product and how much to apply.

correct near-surface soil acidity. Our spring soil sampling indicated that the lime effects had not gone beyond the surface inch of soil, and acidification at 3 to 4 inches remained uncorrected. Consequently, no crop response was measured in 2014. Preliminary soil data from fall 2014 suggests a reduction in KCl-extractable Al through the 2-inch depth with lime treatment. We are continuing to monitor surface liming effects. Other strategies for addressing stratified acidity include placement of lime with the seed at planting and surface broadcast lime combined with shallow tillage. We are also developing a new applicator that injects fluid lime behind V-sweeps at the 3- to 4-inch depth.

“In many regions, a soil pH buffer test is used in combination with initial soil pH values, and a target final pH of between 6 and 7 is used to determine how much lime is required. Common soil buffer tests include Adams and Evans, SMP, and Woodruff. Soil is mixed with the buffer solution, and the change in solution pH is correlated to how much lime is needed to reach a given target soil pH. The tests are typically calibrated for the unique properties of soil by region.

“In an example from the Cook Agronomy Farm in Pullman, we found that 6-inch-deep soil samples from across the farm indicated that 3 to 6 tons/ac CCE was required to raise the soil pH to 6.5. The range in lime requirement recommendations is due to wide field variability in soil pH. These tests are not well calibrated for our region and are likely over-predicting the lime actually needed to correct our soil pH. Consequently, our research is currently evaluating lime requirement tests that will be calibrated for our unique soils and will provide a more realistic lime requirement.

“Another dimension of our research effort is assessing field variability in soil pH and seeing if variable-rate lime applications are practical. Many fields have shown soil pH tests ranging often 2 or more units. If the range in lime requirement is from 1 to 4 tons/ac, then targeting lime to match the spatial variability in soil pH may be advisable.
Otherwise, an initial application of 1 ton/ac could be followed by soil testing and variable lime applications to locations that still need a pH correction.

Other lime-related research and demonstration projects that are underway include:

- Testing different materials and rates incorporated under reduced tillage (Dr. Kurt Schroeder, University of Idaho)
- On-farm lime demonstrations evaluating variable-rate strategies and different materials (Tabitha Brown, Latah Soil and Water Conservation District and WSU)
- Soil acidification and liming effects on grain legumes and county-level assessment of soil acidification and associated soil tests (Dr. Paul Carter and co-workers, WSU).

While farmers and researchers experiment with different facets of liming program options in the iPNW, producers can plant crops and varieties more suited for production on acidic soils to reduce yield penalties associated with growing on low-pH soils.

Crop and variety selection for low-pH conditions

Paul Froese (M.S., crop science), from the wheat breeding program at WSU, has found that not all crop species, nor varieties within species, respond the same to acidic soil. Of the crops commonly grown in eastern Washington and northern Idaho, legumes are the most sensitive to soil acidity while wheat and barley are less so, followed by triticale and grass hay/seed crops, which can tolerate more acidic soil. Canola and buckwheat also fare better on acidic soils than legumes and some wheat varieties.

The response of a particular crop to acidic soil will also depend on soil characteristics other than pH, such as soil fertility, microbiology, organic matter content, concentration of available aluminum (Al), etc.; so it is difficult to determine an absolute pH cutoff value under which a certain crop or variety will begin to lose productivity, and at what pH point yield loss will become economically important.

The dominant cool season crops of the region, wheat and barley, are more tolerant of acidity than legumes, but yields even of relatively tolerant options will still be compromised by low-pH soils in eastern Washington and northern Idaho. A major growth-limiting factor in acidic soil is Al toxicity. Immediately following seed germination, cell walls in emerging root tips are bound by Al in acidic soil solutions and become prematurely stiff and brittle, resulting in root stunting. Stunted roots access less water and mineral nutrition than healthy roots, and thus support less crop growth and yield. Wheat variety testing by spring and winter wheat breeders at WSU has identified, within adapted germplasm, moderately tolerant lines suitable for cultivation on many of the iPNW’s low-pH soils. Of the spring wheat varieties tested on acidic, aluminum-toxic soil, ‘Whit’ and ‘Babe’ (soft white), ‘SY Steelhead’ (hard red), and ‘LCS-Atomo’ (hard white) all demonstrated tolerance. Of the winter wheat tested, ‘Whetstone’ and ‘Norwest 553’ (hard red), ‘Coda’ and ‘Cara’ (soft white club), and ‘WB 528’ and ‘ARS Amber’ (soft white) were notably tolerant. Other spring and winter varieties also showed promising tolerance, and the development of superior tolerance in adapted germplasm by breeding and selection is expected. As Cephalosporium stripe disease of winter wheat is aggravated in acidic soil, lines with some level of acidity tolerance and Cephalosporium stripe resistance (e.g., Cara and ‘Finch’*) are preferred when cropping on acidic soils infested with *Cephalosporium gramineum*.

Managing soils to reduce acidification

Strategies for reducing the rate of soil acidification and restoring the health of low-pH soils can be used to reduce the amount of lime required. Crop residues should be left in the field to minimize the removal of base cations from the soil and increase soil organic matter content, which helps buffer pH changes. Though legumes still produce acidity, they do not require the supplemental N fertilizer that contributes the most to soil acidification. If it is possible to grow legumes despite low-pH conditions, they are a good addition to crop rotations. Nitrogen fertilizers acidify soil, and studies have shown that more N results in more acidification, meaning that practices
Follow these steps to sample accurately

1. Create a map of soil sampling areas, using GPS if possible to allow for sampling of these same sites in following years. Use landscape position, exposure, soil type, management history, and crop performance as a starting point.

2. Collect soil cores in a sampling area and split by sampling depth.
   a. Remove surface residues from the coring site and root material from the sample. Use stainless steel or nickel-plated soil sampling equipment.
   b. When pH stratification is suspected, divide the top foot into 0- to 3-, 3- to 6-, and 6- to 12-inch increments.
   c. Collect one or two cores from at least six sites of the dominant soil condition of each sampling area. More cores will improve accuracy.
   d. Blend cores from across the sample area for each depth.

3. Keep samples cold before delivery for analyses or freeze if delayed more than a few days.

4. Submit soil samples in bags labeled with: name, date of collection, field, and depth. Visit the North American Proficiency Testing Program website (www.naptprogram.org) to locate a standardized soil testing laboratory near you.

Optimizing N use efficiency also reduces the rate of soil acidification. Calcium nitrate is the least acidifying nitrogen fertilizer; unfortunately, using it is rarely seen as being economically competitive with ammonia-based fertilizers. Another practice is calculating how much lime is needed to compensate for the acidity being released by fertilizer annually and applying enough lime to neutralize the acidity input. This strategy is more effective if the soil starts from a desirable baseline pH.

It is critical to measure and understand the extent of the soil pH problems within fields, across farms, and throughout the region. Spatial variability of pH within fields means that typical soil sampling is not providing the necessary information needed to identify the severity of soil acidity. Appropriate soil sampling and analysis are important first steps to identifying a soil pH problem. Wayne Thompson, WSU Extension Faculty based in Walla Walla County, WA, recommends an effective soil sampling plan that divides farms and fields into distinct areas with minimal variation in aspect or landscape position, similar management history, and uniform crop performance. Sampling should characterize soil chemistry, available water, and nutrient status of a sampling area. It is important to keep in mind that pH, in particular, varies seasonally, so the most effective way to compare pH values over time is to take soil samples at the same time every year.

Identifying and managing the various components of the “pH complex” is an emerging challenge for the farmers and professionals of the iPNW and is being addressed through communication, research, and collaboration across the region. Implementing strategies to stabilize and reverse acidification will be essential to achieving optimal crop yields in the short term and critical for the long-term maintenance of soil health and productivity in the iPNW.

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