EM 9148 • AUGUST 2016

Integrated Clubroot Management for Brassicas

Nonchemical control strategies

A.L. Heinrich, A. Stone, D.M. Sullivan, J. Myers, and E. Peachey

Clubroot (*Plasmodiophora brassicae*) is a serious soilborne disease of brassica (cabbage family) crops that causes significant economic losses on western Oregon farms (see sidebar, "Western Oregon farmer experiences with clubroot," page 2). Table 1 lists susceptible crops.

Clubroot causes swellings, or "clubs," on roots (Figure 1), which reduce the ability of the infected plant to access water and nutrients. Moderate clubbing causes stunting, as well as wilting of the plant during transpiration, even when soil moisture is adequate. When severe,

Photos by Aaron Heinrich

Figure 1. Severe clubbing on turnip (left) and on broccoli roots (right). Clubbing on root crops renders the crop unmarketable.

Table 1. Clubroot-susceptible brassica crops commonly grown in the Pacific Northwest.

Crop	Genus and species
Arugula	*Eruca sativa*
Broccoli	*Brassica oleracea*
Brussels sprouts	*Brassica oleracea*
Cabbage	*Brassica oleracea*
Canola	*Brassica rapa* and *B. napus*
Cauliflower	*Brassica oleracea*
Chinese cabbage	*Brassica rapa*
Collards	*Brassica oleracea*
Kale	*Brassica oleracea* and *B. napus*
Kohlrabi	*Brassica oleracea*
Mustard greens	*Brassica juncea*
Pak choi	*Brassica rapa*
Radish	*Raphanus sativus*
Rapini (broccoli raab)	*Brassica rapa*
Rutabaga	*Brassica napus*
Turnip	*Brassica rapa*

Figure 2. Aboveground symptoms of clubroot on red cabbage (foreground), with healthy plants in the background. Clubroot often appears first in isolated patches, which spread over time. Photo by Aaron Heinrich.

Aaron L. Heinrich, faculty research assistant in soil science; Alex Stone, vegetable cropping systems specialist; Dan M. Sullivan, professor of crop and soil science; James Myers, endowed professor of horticulture; and Ed Peachey, Extension vegetable and weed science faculty; all of Oregon State University

Oregon State University

clubroot kills the plant, resulting in crop loss (Figure 2, page 1).

Both the incidence and severity of clubroot in western Oregon are increasing. Strong consumer demand has resulted in an increasing portion of vegetable farm acreage planted to brassicas, which are often grown year-round to meet demand from winter markets. With limited acreage or rotational crop options, many vegetable farmers' rotations out of brassica are short (2 to 3 years), thus increasing disease pressure until it is high enough to cause crop loss. Forage radish and turnip cover crop seed production is also increasing in this region, and clubroot likely will become a problem in these large-acreage crops over time.

Clubroot can be difficult to manage because the pathogen produces thick-walled, long-lived resting spores. Some reports suggest that clubroot spores can live for as long as 20 years, although most likely die within 5 to 7 years (Wallenhammar, 1996). Thus, the pathogen is unlikely to be eradicated once established in a field.

Clubroot control requires integration of multiple strategies, as no single strategy will provide reliable control. A successful control program includes (1) disease identification through routine scouting, (2) disease containment (minimizing pathogen spread within a field and to noninfected fields), and (3) practices that reduce disease pressure to levels that are not economically damaging. These practices include:

- Rotating out of brassica crops for 5 years or more
- Eliminating brassica weeds that are hosts to the clubroot pathogen
- Irrigation and soil management to avoid waterlogging
- Planting clubroot-resistant cultivars when available
- Liming soil to a minimum pH of 7.0 prior to planting

This guide addresses all of these strategies. It does not address chemical control measures such as the use of pesticides and fumigants.

Western Oregon farmer experiences with clubroot

STORY

"In the past 3 years [2009–2012], we have had a 25 percent loss in our brassica crops due to clubroot, costing us between $60,000 to $80,000 in lost revenue per year. We are running out of clubroot-free ground on which to rotate brassica crops."

— Mid-acreage fresh market vegetable grower, Portland, OR

"We have stopped growing brassicas on 15 percent of our land due to clubroot."

— Large-acreage processed vegetable grower, Mt. Angel, OR

"We experienced a 30 to 50 percent loss in five of our highest yielding brassica crops in 2013, totaling [an economic loss of] $20,000.… Three years ago we played out this scenario, knowing that our future looked quite bleak. So, we started to search for [organically certified] land that hadn't grown brassicas .... So far we are still looking. We need to figure out a way to grow brassicas in fields that have a high clubroot population."

— Small-acreage, diversified organic vegetable grower, Portland, OR

Key concepts

- Due to the longevity and durability of clubroot resting spores (up to 20 years), eradication is not practical. Management to keep disease pressure low is the goal.
- A 5- to 6-year rotation out of brassica family crops typically is sufficient to keep disease pressure low enough to prevent significant crop loss.
- Growing clubroot-resistant cultivars is the least expensive and easiest management strategy. However, there are a limited number of commercially available crops and varieties with proven resistance to the races of clubroot prevalent in Pacific Northwest soils.
- Liming soil to a pH of 7.0 or greater can significantly reduce disease incidence and severity. Liming has little or no benefit if a pH of 7.0 is not reached.

Disease cycle

Clubroot is caused by the pathogen *Plasmodiophora brassicae*, which is classified as a protist, an organism with plant, animal, and fungal characteristics. It is an obligate parasite, which means that it cannot grow and multiply without a living host such as a brassica crop or weed species. The life cycle of *P. brassicae* is shown in Figure 3.

The pathogen survives in the soil as long-lived resting spores (Figure 3a). If a host plant is not present, these spores remain dormant. Secretions from the growing roots of host plants (root exudates) stimulate the resting spores to germinate and produce short-lived zoospores (Figure 3b). The zoospores have tails that allow them to swim toward, and then infect, a root through root hairs or wounds (Figure 3c).

After the initial infection, the zoospore forms an amoeba-like cell. This abnormal cell multiplies and joins with other cells to form a plasmodium (a naked mass of protoplasm with many nuclei). This plasmodium is invisible to the naked eye and does not generate visible changes to the root. The plasmodium divides to form many secondary zoospores (a second generation of zoospores), which are released into the soil.

The second-generation zoospores infect the roots of the initial host or nearby plants and invade the root cortex (Figure 3d). Once in the cortex, the amoeba-like cells multiply or join with others to form a secondary plasmodium. As this plasmodium develops, plant hormones are altered, causing the infected cortical cells to swell (Figure 3e). Clusters of these enlarged cells form clubs or galls, which are typically visible 4 to 6 weeks after planting (Figure 3f). After secondary plasmodia mature, they divide into millions of long-lived resting spores. These spores are released into the soil as the clubs decompose, completing the disease cycle (Figure 3g).

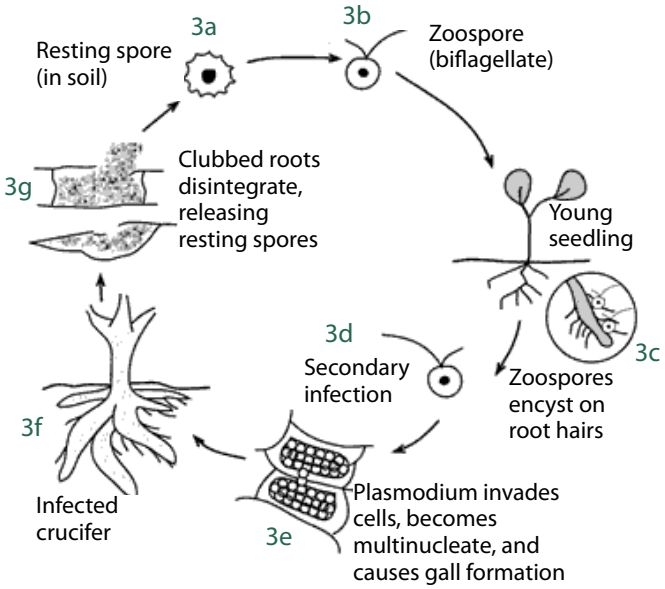

Figure 3. Life cycle of *Plasmodiophora brassicae*, the pathogen that causes clubroot. Used by permission of Ohio State University Extension, outreach arm of the College of Food, Agricultural, and Environmental Sciences.

Factors influencing infection and disease severity

Temperature

Warmer soils increase disease incidence and severity. A minimum soil temperature of approximately 57°F (14°C) is usually required for resting spore germination (Chupp, 1917), although some spores can germinate below this temperature (Thuma et al., 1983). Soil temperatures below 63°F (17°C) were shown to slow or inhibit the development of *P. brassicae* at all stages of its life cycle (Sharma et al., 2011a, 2011b), and temperatures of 73 to 79°F (23 to 26°C) resulted in the fastest development. In the Willamette Valley, the average monthly soil temperature at 4 inches in March, April, May, June, and July is approximately 50, 56, 63, 68, and 74°F, respectively.

Soil pH

The relationship between soil pH and clubroot incidence and severity is well known. Disease incidence and severity are greatest under acidic soil conditions (below pH 6.5). Clubroot risk is low when soil pH is greater than 7.0 (see "Liming," page 7).

Physical properties and water management

During the zoospore phase, when the pathogen is mobile and is moving through soil water, risk of infection is higher in soils that are overirrigated, waterlogged, or poorly drained due to environmental conditions and/or compaction. Disease severity is often greatest and most visible in low, poorly drained areas of fields. Improving

soil physical properties to facilitate drainage may reduce clubroot risk (Dixon and Tilston, 2010).

Resting spore concentration

Risk of yield loss increases as the concentration of viable resting spores increases. High concentrations increase the likelihood that crop roots will be close to spores and that galling will occur earlier in the plant's development. Plants that are infected when small produce larger galls and suffer more damage, due to greater disruption of water and nutrient flows. To reduce the risk of yield loss from clubroot, practices that reduce the concentration of viable resting spores must be adopted.

Scouting and record keeping

Scouting for clubroot is a critical part of an effective clubroot management program. If clubroot is identified early, you can take steps to contain the spread of the disease and reduce future disease severity. Clubroot may appear first in low, wet areas of a field, so scout those areas preferentially.

Scout fields for both aboveground and belowground symptoms. Aboveground symptoms of severely infected plants include stunting, yellowing of leaves, wilting on warm days even when soil moisture is adequate (e.g., following irrigation), and plant death. However, plants suffering from other diseases, pests (e.g., symphylans), or environmental stresses (e.g., water stress) may exhibit the same aboveground symptoms. Therefore, once a plant with aboveground symptoms is identified, dig the plant from the ground and inspect it for the presence of clubroot galls. Do not pull plants suspected of clubroot infection, because the galls may break off, making identification more difficult.

Clubroot galls are easily recognizable (Figure 1, page 1), as no other brassica root diseases present in western Oregon exhibit similar root symptoms. Identification becomes more difficult once galls begin to decompose, so early identification is best.

When disease severity is mild to moderate, infected plants may show no obvious aboveground symptoms or yield loss, yet future disease pressure may be increasing (see story box, "Rotation case study"). If your farm or field has a history of clubroot, but no obvious aboveground symptoms, it is recommended to walk the field after harvest and randomly dig up plants to verify the presence or absence of galls.

Document where, when, and on what crops you find galling. Maintain these records over time to document where and when clubroot has been a problem. Do not plant host crops in those fields, and avoid spreading spores to noninfested fields. Records will also help you evaluate the impact of rotation and other management strategies on clubroot incidence and severity over time.

Rotation case study

STORY

In 2013, a small, diversified organic grower experienced complete broccoli crop loss due to clubroot in a field where the disease had never previously been identified. In the 4 previous years, brassicas were grown every other year (Table 2). Clubroot severity likely was low. Thus, no aboveground symptoms alerted the farm manager to the presence of the disease.

However, each brassica crop increased the resting spore population until the level of inoculum was high enough to cause complete crop failure. Because this farm had a history of clubroot in other fields, scouting the apparently healthy brassica crops (digging up plants and examining roots) might have alerted the farm manager to the risk created by short rotations.

Table 2. Brassica rotation history for a field that suffered complete crop loss due to clubroot.

Year	Crop
2013	Spring broccoli (crop failure)
2012	Herbs, fennel, carrots
2011	Salad mix (including leafy brassicas)
2010	*Allium* species
2009	Spring broccoli
2008	Potatoes
2007	Fava bean, *Solanum* species, fallow
2006	Peas, cucurbits
2005	Peas, brassicas in west half of field
2004	Brassica in east half of field

Containment

Prevention

The best way to manage clubroot is to prevent disease establishment by never bringing clubroot spores onto the farm. To reduce the risk of introducing clubroot to your farm, identify all possible sources of pathogen transport (equipment, transplants, animals, and people), and then manage your farming system to avoid bringing the pathogen onto your farm. See the sidebar "How is clubroot spread?" for more information.

If you or others have been in an infested field, clean field equipment and footwear as follows:

1. Mechanically remove soil.
2. Wash or pressure wash to remove remaining soil.
3. Disinfect with a 2 percent bleach solution.

Minimizing within-farm spread

Once clubroot spores are present in a field, the goal is to prevent spread of the pathogen throughout the farm. Diseased roots release millions of spores into the soil as the clubs decompose (sometimes before crop maturity). These spores are then spread through the field with tillage operations or with water movement from rain or irrigation. Each subsequent tillage or runoff event further distributes the spores, and each subsequent brassica crop planted into infested fields increases inoculum levels.

Regular field scouting, especially of low, wet, or poorly drained areas, can help you detect the disease when it first occurs (see "Scouting and record keeping," page 4). If the disease is detected early in a small number of young plants, it may be possible to dig up and dispose of the diseased roots to slow the spread of the disease. Dispose of infected plants in the garbage, not in a compost pile.

If possible, "quarantine" infested fields to limit movement of spores to other locations. Plant the area to sod for at least 4 years to minimize soil movement. Clean equipment and footwear thoroughly when moving from a clubroot-infested to a noninfested field (see "Prevention").

How is clubroot spread?

Clubroot spores can be transported from an infested field to a noninfested field in several ways.

- **Machinery**. The primary mechanism for spreading clubroot is field equipment. Machinery carrying clubroot-infested soil can disseminate the disease when moved to a clubroot-free field. In farm equipment sanitation trials in Alberta, Canada, up to 330 lb of soil was recovered from large tractors with cultivation equipment (Hwang et al., 2014).
- **People/livestock**. People and livestock can spread clubroot by moving soil containing clubroot spores on footwear or feet.
- **Transplants**. Transplants grown in greenhouse flats can become infected with clubroot when placed on field soil to harden off. These plants will subsequently infest the soil into which they are planted.
- **Water**. Clubroot spores can be transported long distances by seasonal floodwaters or short distances with surface runoff caused by rain or irrigation water.
- **Wind**. Dust samplers deployed in fields in Alberta, Canada have revealed that the clubroot pathogen can be moved by wind. However, there is no conclusive evidence that these windborne spores contribute significantly to the spread of the disease (Strelkov and Hwang, 2014).

Crop production practices

Rotation

Clubroot's thick-walled resting spores are long lived. Research has shown that clubroot spores can survive for up to 20 years, although their half-life (the period of time it takes for half of the spores to die) is approximately 3.6 years (Wallenhammar, 1996). Ideally, you should wait until all of the resting spores have died before planting another host crop. Realistically, farmers cannot rotate out of brassicas for 19 years. However, as approximately half of the spores die within 4 years (and half of the remaining within the following 4 years), rotations of fewer than 8 years can be used in combination with other strategies (e.g., lime application) to keep disease pressure low enough to prevent crop loss.

Oregon State University researchers have monitored clubroot incidence on partner farms and examined the relationship between clubroot incidence/severity and rotation history. This farm-collected information suggests that a rotation of 5 to 6 years out of brassica crops can substantially reduce disease risk. Rotations shorter than 4 or 5 years may result in significant crop loss (see story box, "Rotation case study," page 4).

It is important to understand that rotation applies to all brassica host crops. Many diversified vegetable farmers plan for a 4- or 5-year rotation out of high-acreage brassica crops such as kale, cabbage, and broccoli. They may not realize, however, that rotation species such as brassica greens or root crops can serve as clubroot hosts and continue the disease cycle. Brassica family root crops (e.g., radish, turnip, rutabaga) and salad crops (e.g., arugula, mustard greens; Figure 4) must be regarded as clubroot hosts when designing a rotation.

Do not plant a brassica cover crop if clubroot is a current or potential problem on your farm. No evidence of clubbing has been observed on sweet alyssum, which is in the brassica family and is often planted by organic growers as an insectary planting.

Eliminating weedy hosts

When rotating out of brassica crops, it is important to control brassica crop volunteers (plants from the previous cropping season) and Brassicaceae weed species, as many weed species can be hosts (Table 3).

Figure 4. Arugula (*Eruca sativa*) with clubbed roots. Photo by Alex Stone.

Irrigation management

Clubroot risk is greater in waterlogged soils, and runoff can transport clubroot spores. Manage irrigation to avoid soil waterlogging and runoff. Fix leaks in irrigation equipment promptly. Based on conversations with farmers, drip irrigation is no more effective at reducing disease incidence and severity than are overhead sprinklers.

Resistant cultivars

Growing clubroot-resistant cultivars requires the fewest, if any, changes to a farming operation. It also gives the farmer the most flexibility regarding when and where to plant. This flexibility is important where limited acreage or a high year-round demand for brassica crops does not permit a 5- or 6-year rotation out of brassica crops. Furthermore, purchasing resistant seed is far less expensive than soil pH management with liming, which can cost hundreds of dollars per acre.

Despite the benefits of clubroot-resistant cultivars, options are limited. A limited selection of clubroot-resistant cultivars is commercially available for any particular crop, and these cultivars may not fit a farmer's market needs (e.g., size, color, growth habit, etc.) and/or planting slots (e.g., growing season or days to maturity). Also, not all available cultivars have been rigorously tested for resistance against the clubroot races predominant in the Pacific Northwest. A list of cultivars that

Table 3. Brassica family weeds commonly found in western Oregon.

Common name	Latin name
Arugula, rocket	*Eruca sativa*
Canola, rapeseed	*Brassica napus* and *B. rapa*
Money plant	*Lunaria annua*
Mustards (wild, birds' rape, white, black, Chinese, or Indian)	*Brassica* species
Shepherd's purse	*Capsella bursa-pastoris*
Western bittercress	*Cardamine oligosperma*
Wild radish	*Raphanus raphanistrum*
Yellow rocket	*Barbarea vulgaris*

have been evaluated for resistance in western Oregon is available at Oregonvegetables.com (http://horticulture.oregonstate.edu/content/vegetable-variety-selection-resources).

Repeatedly planting resistant cultivars in the same location may lead to development of a pathogen population that overcomes the main resistance genes in those cultivars (see sidebar, "Forms and durability of resistance"). Therefore, use of resistant cultivars must be part of an integrated clubroot management strategy.

Liming

Research has repeatedly demonstrated that liming soils to a pH above 7.0 can significantly reduce clubroot incidence and severity. Liming does not kill the pathogen, but it does inhibit spore germination, thereby reducing root infection.

Nonetheless, brassica producers in western Oregon have had mixed success with liming (see story box, "Mixed success with liming"). Implementing a successful liming program to control clubroot is more complicated than liming for crop production. For example, liming for crop production can be successful even if the target pH is not reached or the lime is not thoroughly incorporated, because plants can tolerate a range of soil pH and roots will grow into limed zones. With clubroot, however, the disease will not be adequately controlled if the target pH is not reached or if low-pH microsites exist due to incomplete mixing (Figure 5, page 8).

Mixed success with liming

STORY

In fall 2012, a survey was sent to 37 conventional and organic vegetable farmers in western Oregon. All were known to grow significant quantities of brassicas for fresh market and/or processing. Farmers were asked about their experience with clubroot and use of lime to control the disease.

Of the 19 respondents (51 percent), all stated that clubroot was moderately to highly important. Eighty-three percent had used lime in an attempt to control clubroot. However, only 21 percent of those using lime had aimed for a pH of at least 6.8 (the minimum pH shown to offer some level of disease control), and only 52 percent measured soil pH after liming to determine whether they had reached their target pH. Only 26 percent said that liming seemed to help control clubroot.

These results help explain why most farmers have not been successful at controlling clubroot with liming. Most have not chosen a high enough target pH, nor have they monitored pH following liming to determine whether they achieved their target pH.

Forms and durability of resistance

Resistance to clubroot was found in turnip and cabbage in the early 20th century by J.C. Walker of the University of Wisconsin. The resistant cabbage source was incorporated into the OSU vegetable breeding program. Other sources of clubroot resistance were discovered by European breeders, so that genetic resistance is now available for most brassica crop species.

The genetics of resistance varies among species. In *dominant resistance*, only one parent needs to carry resistance. With *recessive* (or *quantitative*) *resistance*, both parents must carry the appropriate resistance alleles. When developing hybrids, brassica breeders prefer the dominant forms of resistance since they make it easier to achieve resistance. However, dominant resistance has the disadvantage of being race-specific and potentially easier to overcome than recessive resistance.

Dominant, race-specific resistance is found in *Brassica rapa* and *B. napus*, while predominantly recessive, race-nonspecific resistance is found in *B. oleracea*. Resistance breeding in *B. oleracea* was impeded because of the recessive nature of the trait. After many years of selection and numerous setbacks, Walker released the kraut cabbage 'Badger Shipper' in 1956 with recessive, race-nonspecific resistance. Jim Baggett of Oregon State University released several broccoli and cabbage inbreds with recessive resistance (1976, 1983, and 1985). More recently, breeders transferred the dominant forms of resistance from *B. napus* (rutabaga) and *B. rapa* (turnip) into *B. oleracea* (Diederichsen et al., 2009).

Although resistant cultivars are important to clubroot management, the race- or pathotype-specific nature of most genetic resistance means that resistance can break down when virulent races increase in the pathogen population. Therefore, resistant cultivars should be used carefully in combination with other methods of clubroot control.

Research conducted from 2013–2016 in western Oregon has demonstrated that liming can be an effective management strategy in this region (Heinrich and Stone, 2014, 2015). Under field conditions, liming is unlikely to achieve 100 percent suppression of the disease. However, the liming program described in this publication, if carefully followed, will minimize yield and crop loss, both in the current and in future seasons. By limiting the number of galls formed, which can infect future host crops, you can reduce disease pressure to a level that is not economically damaging. See the sidebar "Key liming concepts."

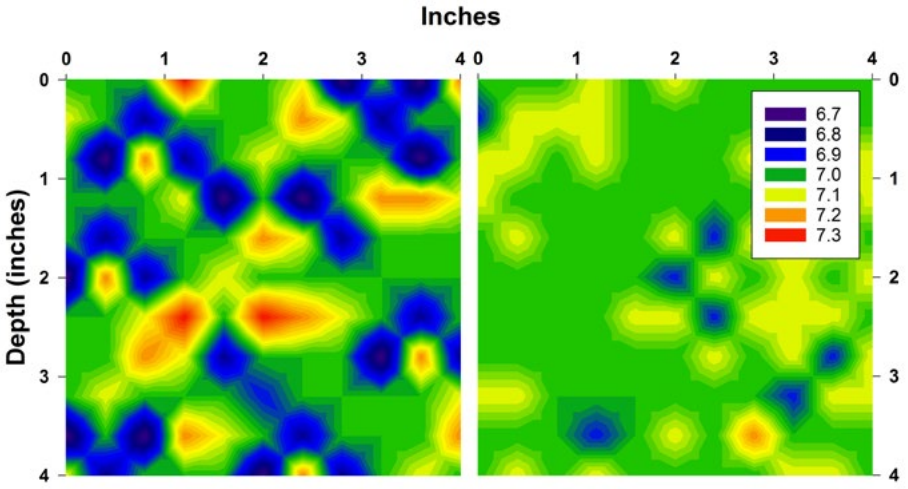

Figure 5. Conceptual illustration of lime mixing and pH uniformity in soil. Both soils have the same average pH of 7.0 in the surface 4 inches. However, the soil on the left has zones where pH is below 7.0. In these zones, clubroot is not suppressed, and root infection may occur. These low-pH microsites are the result of incomplete lime mixing. When lime is thoroughly mixed, many of the low-pH microsites are eliminated (right).

A successful clubroot liming program consists of seven steps (Figure 6). This section describes each step in detail. In this publication, soil pH is based on a 1:2 soil-to-water pH analysis.

Step 1. Soil sampling and lab analysis

Before starting a liming program, collect a soil sample and have it analyzed by a commercial lab for initial soil pH (1:2 or 1:1 soil-to-water) and lime requirement buffer test value. The buffer test (SMP or Sikora) is used to calculate the amount of lime required to increase soil pH to a desired level. Interpretation for the two methods is the same.

Collect soil samples that are representative of the field 2 to 6 months before lime application. If the field has multiple soil types or differences in topography, divide it into zones and collect

Key liming concepts

- Liming will not completely suppress clubroot in the field, but it can significantly reduce infection rate and disease severity when done correctly.
- Unless a target pH of 7.0 is reached, liming has little or no effect on clubroot.
- Liming for clubroot control typically requires higher rates than liming for crop production. Lime rate calculations given in this guide are not appropriate for calculating liming for crop production. For crop production, use OSU Extension publication EM 9057, *Applying Lime to Raise Soil pH for Crop Production: Western Oregon*.
- Apply and incorporate lime at least 1 month prior to planting; longer is better.
- Thorough lime incorporation is critical for achieving a uniform soil pH and eliminating low-pH zones (below 7.0) where infection can occur.

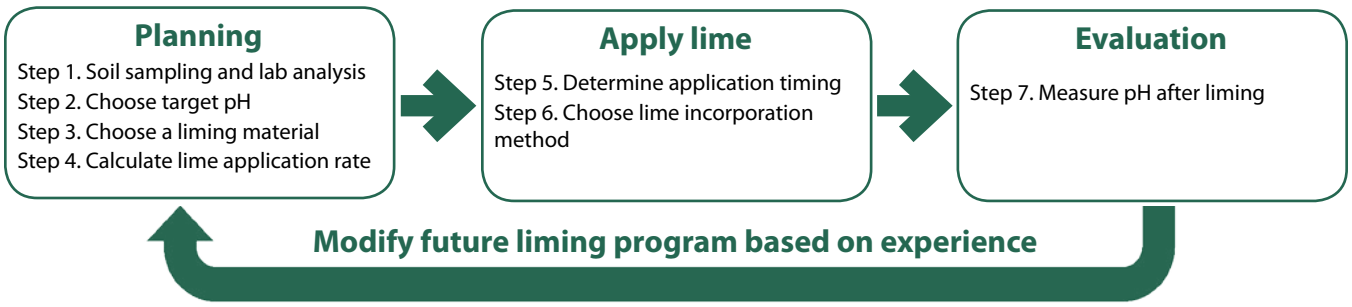

Figure 6. Steps in a successful clubroot liming program

samples from each zone. Use Table 4 to determine the number of samples needed to obtain a representative sample. Take soil samples randomly throughout the field or zone to the depth of lime incorporation, typically 6 to 8 inches, although depth depends on the tillage equipment used.

Table 4. Suggested number of subsamples to obtain a representative composite sample based on field size.

Field size (acres)	Number of subsamples
Less than 5	15
5–10	18
10–25	20
25–50	25
More than 50	30

Adapted from University of Idaho Cooperative Extension Bulletin 704, *Soil Sampling*.

Thoroughly mix all of the samples from a single field or zone and take a 1-pound subsample (about a pint). Send this subsample to a commercial lab for pH and lime requirement buffer analysis. The results of these analyses will be used in Step 4.

We discourage in-field pH measurement using hand-held pH meters, color kits, or pH probes, due to the potential for poor accuracy. Commercial laboratories use trained personnel, well-maintained equipment, reference samples, and consistent sample handling protocols, all of which result in a more accurate pH reading. The cost of pH analysis by a commercial lab is minimal, and turn-around time is usually rapid.

Step 2. Choose a target pH of 7.0 or greater

Although some research has shown that increasing the soil pH to at least 6.8 reduces clubroot infection rate and disease severity, adequate control was not achieved in western Oregon field trials until pH was 7.0 or greater. In the Salinas Valley of California (a major brassica-producing region), the recommended target pH is 7.5. This target eliminates the presence of low-pH microsites where infection can occur (Figure 5, page 8). However, liming western Oregon's acidic and well-buffered (heavier textured) soils to a pH of 7.5 is unlikely to be economical, given the large quantities of lime required to do so. If possible, choose a target pH above 7.0, because it is better to overshoot your target than to fall short.

Step 3. Choose a liming material

When choosing a liming material, consider the following factors: cost, product availability, reactivity (speed of acid neutralization), organic certification, worker safety, and ease of application using available equipment (see sidebar, "Equipment for applying lime on small acreages"). Liming materials are available as powder, granules

Equipment for applying lime on small acreages

Farmers with large-acreage fields hire a commercial applicator to apply lime. For small-acreage fields or plantings (0.25 to 2 acres), this may not be economical or practical. In this case, drop and spin spreaders can be used to spread pelleted lime (Figures 7 and 8). Both are commonly found on small-scale farms or can be rented. The disadvantage of using a spin spreader with powdered lime is the creation of lime dust (Figure 8).

Figure 7. Powdered lime applied with a drop spreader. Photo by Aaron Heinrich.

Figure 8. Powdered lime applied with a Willmar 150 spin spreader. Photo used by permission of Sauvie Island Organics.

(prill), or fluid (liquid). Given the typically high rates of lime required to raise the pH to 7.0 or greater, fluid lime is not economical, so this material is excluded from the following discussion.

A list of lime products and their relative reactivity and cost is given in Table 5. See Extension publication EM 9057, *Applying Lime to Raise Soil pH for Crop Production,* for additional information on liming materials.

Powdered lime. Traditional *agricultural lime* (also called aglime, lime, ground limestone, flour lime, or calcitic lime) is a finely ground material derived primarily from calcitic (calcium carbonate) limestone. It neutralizes soil acidity quickly when thoroughly incorporated into moist soil. *Dolomite* (dolomitic limestone) contains both calcium carbonate and magnesium carbonate. Dolomite reacts more slowly than agricultural lime, so apply it farther in advance of planting. The more finely a lime product is ground, the faster it will react in the short term (3 months or less).

Hydrated lime (calcium hydroxides and oxides). These products (also known as quick lime and burnt lime) are manufactured by heating agricultural lime. They have several advantages. They react very quickly (days versus weeks or months for other products) and have a high lime score, resulting in lower application rates. The soil pH response to these products is linear (see Appendix A, page 17).

Despite these advantages, few farms use these products. They are corrosive to farm equipment; few, if any, commercial applicators will apply them; they may not be available in bulk; and they require the use of worker protective safety equipment.

The USDA's National Organic Program rules list hydrated lime as a synthetic material, but it is approved for use on certified organic farms for control of plant diseases such as clubroot. Check with your certification agency to confirm that use of hydrated lime is allowed. If planning to apply hydrated lime, see Appendix A for specific information.

Prilled lime. Both calcitic and dolomitic lime are also available in prilled form. Prilled lime (also called granular or pelleted lime) is ground limestone that is held together with a binder, typically lignosulfonate or bentonite clay. When moistened by soil moisture, rain, or irrigation water, these materials fall apart (slake) rapidly, dispersing the lime (Figure 9).

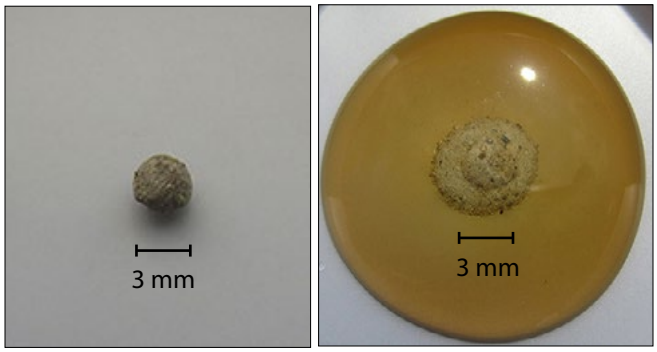

Figure 9. A lime prill (left) and a slaked (dispersed) prill 2 minutes after adding water (right). The coloring of the water is due to the dissolved binder that holds the dry prill together. Photos by Aaron Heinrich.

Table 5. Characteristics of commonly used powdered and prilled liming materials.

Material	Lime score	Relative short-term reactivity[1]	Relative cost
Agricultural lime ($CaCO_3$)			
Standard	90–100	Moderate	$
Superfine[2]	95–100	Fast	$$
Dolomitic limestone ($CaCO_3 + MgCO_3$)	95–110	Slow	$
Hydrated lime	120–135	Very fast	$$
Prilled calcitic limestone[3]	80–90	Slow	$$$

[1]Reactivity over 3 months. Over a longer period of time, differences between products are less distinct.

[2]Superfine materials are defined in this publication as those in which 90 percent or more of the particles will pass through a 200-mesh sieve (75 µm).

[3]See sidebar, "Using prilled lime," page 11.

Prilled products are more expensive than powdered lime, but they have the advantage of being easily applied by a wider range of farm equipment (e.g., spin or drop spreaders). Handling and application are relatively dust-free. Their disadvantage is a lower lime score. Compared to powdered lime, they neutralize less acid per unit weight. Thus, they require higher application rates to achieve the same pH. If using prilled lime, see sidebar, "Using prilled lime."

Step 4. Calculate lime application rate

The quantity of lime required to achieve a target pH of at least 7.0 is soil specific. Soil properties such as clay content, mineralogy, organic matter content, and pH determine how much lime is required.

When the target pH is 6.4 or less, OSU publication EM 9057, *Applying Lime to Raise Soil pH for Crop Production,* provides excellent liming guidance for western Oregon. There is little or no economic benefit to raising pH above 6.4 for most crops, however, so EM 9057 does not provide recommendations for liming to a higher pH. Above pH of 6.4, recommendations also become less reliable, because most soils exhibit a nonlinear response to agricultural lime at higher pH, requiring higher rates to change the pH (Figure 11).

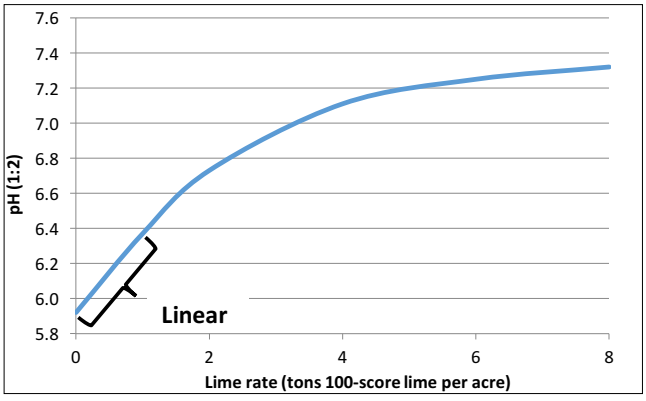

Figure 11. Lime response of a Sauvie fine sandy loam soil to agricultural lime in a laboratory incubation (4 weeks following lime addition). In most soils, the response to agricultural lime is linear to approximately pH 6.4. In most Willamette Valley soils, each pH unit increase from 6.4 to approximately 7.3 requires 1.4 times the amount needed for each unit increase up to pH of 6.4.

Using prilled lime

When wetted, pelleted lime prills break apart rapidly (Figure 9, page 10). However, if incorporated before wetting, the soil will prevent the lime from dispersing, even though the binder is no longer holding the prill together (Figure 10). As a result, soil pH increases only around the prill, resulting in localized zones of high pH surrounded by lower pH soil. If prilled lime is used, one of the following methods must be used to maximize its benefit:

- **Method 1**. After surface application, wet the prills (irrigate or wait for rain) to cause the prills to fall apart (Figure 9). Then incorporate thoroughly (see Step 6, page 14).
- **Method 2**. After surface application, incorporate the prills:
  - — If sufficient soil moisture is present, the binder will no longer hold the prill together, but the surrounding soil will keep the prill intact. Till again to break the prills apart and distribute the lime throughout the soil.
  - — If soil is dry, wet the soil to the incorporation depth following the first tillage. Then follow with a second tillage.

Figure 10. Lime prills 9 months after banding. Although the binder is no longer holding the prill together, the surrounding soil supports the prill, preventing lime dispersal. Photo used by permission of Romulo Pisa Lollato.

Two methods for estimating the lime required to achieve a target pH of 7.0 or greater are presented below. These methods provide a "best estimate" that should get you close to your target pH. To fine tune your liming program, keep detailed records of application rates and monitor changes in soil pH following lime addition. Adjust future application rates, timing, and incorporation methods based on experience.

Method 1: Using the lime requirement buffer test to calculate lime requirement. The buffer test (SMP or Sikora) is used to determine the amount of lime required to reach a target pH. These tests do not work as well on sandy soils with low cation exchange capacity (CEC).

Use Worksheet 1 to calculate lime requirement based on buffer test results. *The target pH for this method is 7.0.* This method is appropriate for all lime materials, including hydrated lime.

Clubroot on cauliflower. Photo by Aaron Heinrich.

WORKSHEET 1. Estimating lime requirement based on lime requirement buffer test results (SMP or Sikora)[1]

Line no.		Your value	Example	Unit
1	Buffer test value from lab analysis		6.2	—
2	Lime required to reach pH 7.0 (from Table 6)		5.4	t/a[2]
3	Product lime score		95	—
4	Depth of lime incorporation		8	inches
5	Amount of lime product to apply, adjusted for depth of incorporation and lime score: *(100* x *line 2* ÷ *line 3)* x *(line 4* ÷ *6)*		7.6	t/a lime product

[1]Either the SMP buffer test or the Sikora buffer test may be used. Interpretation for the two tests is the same.

[2]100-score lime incorporated to a depth of 6 inches.

Table 6. Lime requirement to reach a target pH of 7.0 (6-inch incorporation depth).

Buffer test value	Lime requirement (t/a)[1]
6.8	1.1
6.7	1.8
6.6	2.4
6.5	3.1
6.4	4.0
6.3	4.7
6.2	5.4
6.1	6.0
6.0	6.8
5.9	7.7

Adapted from McLean, 1982.

[1]100-score lime.

Method 2: Using the soil series. This method is based on the lime response of selected Willamette Valley soils for which data have been collected (Table 7). If your field's soil series is not listed, use Method 1. *If you are using hydrated lime, see Appendix A* (page 17).

Table 7. Lime requirement for a 1-unit pH increase (up to pH 6.4) of soil series found in the Willamette Valley of Oregon.[1]

Soil series	Lime requirement for 1-unit pH increase (t/a)[2]
Newberg	2.2
Woodburn, Chehalis, Willakenzie	2.7
Steiwar, Laurelwood, Cascade	3.3
Malabon, Dayton, Powell	3.7
Sauvie, Amity	4.1
Bashaw, McBee, Nekia, Jory	4.5
Salem	5.3

Data extracted from Peterson, 1971.

[1]The agricultural lime response of most soils is linear up to pH 6.4 (Figure 11, page 11). Above this pH, each pH unit increase (up to a pH of approximately 7.3) requires 1.4 times the amount of lime needed for each unit increase up to pH of 6.4.

[2]Based on 100-score lime and 6-inch incorporation depth.

Clubroot on rutabaga. Photo by Aaron Heinrich.

WORKSHEET 2. Estimating lime requirement based on soil series

Line no.		Your value	Example	Unit
1	Soil series		Woodburn	—
2	Target pH (7.0 to 7.5)		7.1	—
3	Initial pH (if greater than 6.4, skip to line 5)		6.0	—
4	Lime required (100-score) to increase pH by 1 unit (from Table 7)		2.7	t/a/unit pH change[1]
5	Lime required to reach pH of 6.4: *(6.4 – line 3)* x *line 4*		1.1	t/a[1]
6	Lime required to increase pH from 6.4 to target pH: *(line 2 – 6.4)* x *(line 4* x *1.4)*		2.6	t/a[1]
7	Total lime required to reach target pH: *line 5 + line 6*		3.7	t/a[1]
8	Product lime score		95	—
9	Depth of lime incorporation		8	inches
10	Amount of lime product to apply, adjusted for depth of incorporation and lime score: *(100* x *line 7 ÷ line 8)* x *(line 9 ÷ 6)*		5.2	t/a lime product

[1]100-score lime incorporated to a depth of 6 inches.

Step 5. Determine application timing

To allow time for lime to react and for soil pH to reach your target, apply and incorporate lime at least 1 month before planting, longer if possible. The finer the lime particles and the more thoroughly you mix the lime with soil, the faster it will react.

Lime will not react in the absence of water. Therefore, if applying lime to dry soil, irrigation may be necessary before planting. Prilled products require additional steps (see sidebar, "Using prilled lime," page 11). If using hydrated lime, see Appendix A, page 17.

Fall lime application can be just as effective as spring application a month before planting. Research in western Oregon with mid-August lime application has shown that the pH remained greater than 7.0 throughout the winter and into the spring (see story box, "Fall liming").

Fall liming has several advantages over spring liming. Wet spring conditions may prevent access to fields, and intense spring planting activities may make it difficult to apply lime far enough in advance of planting. With fall application, fields will be ready for spring planting as soon as conditions are suitable. Also, if a soil sample taken before planting shows that pH is still below 7.0, additional lime can be applied and incorporated prior to planting.

Step 6. Choose lime incorporation method

The success of a clubroot liming program hinges on thoroughly and uniformly mixing the lime with the soil (see story box, "Lime incorporation and disease control," page 15). Lime is not soluble in soil and moves very little with irrigation water or rain. It reacts only with the soil with which it is in direct contact. As a result, surface-applied lime typically increases the pH in just the top inch or less of soil.

Thorough mixing causes lime to react more quickly, produces a higher final pH, and reduces the potential for low-pH microsites where infection can occur (see Figure 5 and story box, "Lime incorporation and disease control," page 15). Use of equipment that creates a fine seedbed (such as a rototiller) or multiple tillage passes with a disk or power harrow may be necessary to achieve thorough mixing and a uniform increase in pH throughout the zone of incorporation.

If using prilled lime, additional tillage may be required to achieve a uniform pH (see sidebar, "Using prilled lime," page 11).

Fall liming

STORY

In fall 2014, a diversified organic vegetable farm in western Oregon began an aggressive liming program to control clubroot. In mid- to late August, 4 t/a agricultural lime was applied to five fields. Soil texture ranged from silty clay loam to silt loam. The farmer applied lime using a drop spreader and incorporated the lime with a disk and power harrow. Three months after application, soil pH was greater than 7.0 at four of the five sites. By spring (6 months after application), pH was high enough in all fields to control the disease (Figure 12). Even 1 year after application, soil pH in four of the five sites remained above 7.0.

These data show that fall lime application can be an effective clubroot control strategy for spring plantings.

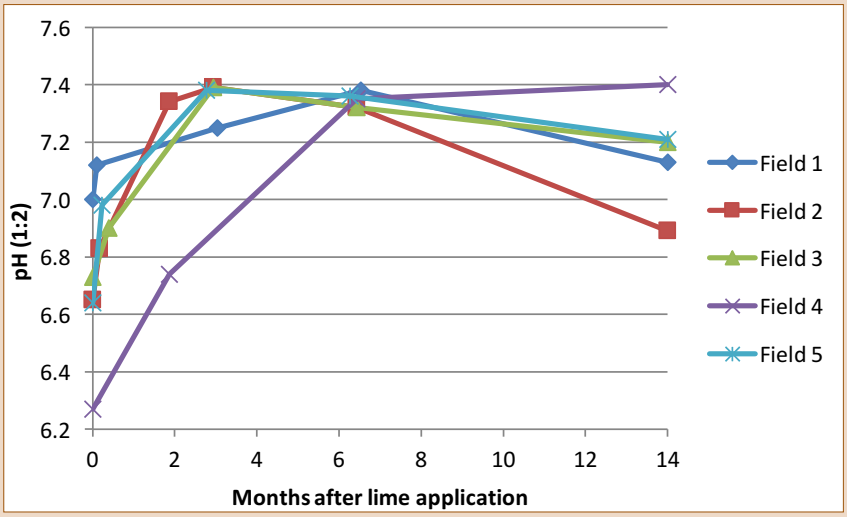

Figure 12. Soil pH following lime application and incorporation in fields in mid- to late August, 2014.

Lime incorporation and disease control

Thorough incorporation of lime is critical to suppressing clubroot. In greenhouse trials, clubroot was almost completely suppressed when lime was thoroughly mixed with sieved soil and pH of 7.1 or greater was achieved (Figure 13).

This level of control is unlikely in the field. For example, in western Oregon field trials (2014), pH was raised to 7.1 or greater. However, the infection rate was reduced by only 44 to 71 percent, and disease severity was reduced by 74 to 90 percent (Heinrich and Stone, 2014). The greater control achieved in the greenhouse likely can be attributed to more thorough mixing and elimination of low-pH microsites.

Research in western Washington in the early 1980s showed that even when bulk soil pH was high enough to suppress clubroot, control was greater when soil was sieved and lime was thoroughly mixed than when lime was incorporated with tillage equipment in the field (Table 8, "field mixed"). In the field-mixed soil, pH varied by 2.0 pH units among microsites. Clubroot spore germination was not suppressed in low-pH microsites, and root infection occurred even in the presence of bulk soil pH of 7.1 or greater. In contrast, the variability in pH in sieved soil was only 0.35 unit.

In 2015, a field trial was conducted with a fresh-market organic farmer in the Willamette Valley to explore the relationship between lime, tillage, and clubroot suppression. Following application of a powdered "superfine" lime (see Table 5, page 10, for definition of a superfine lime), the entire field received a pass with a power harrow. Selected plots were tilled again with a rototiller to more thoroughly incorporate the lime (Figure 14). Two weeks later, kale (cv. 'Lacinato') was transplanted. At that time, soil pH was greater in the rototilled plots (Table 9). Although overall pH in both treatments was high enough to suppress the pathogen, disease incidence, and severity were significantly lower in the more thoroughly mixed (rototilled) plots.

Although 100 percent control of clubroot with liming is unlikely in the field, greater disease suppression can be obtained when lime is incorporated thoroughly.

STORY

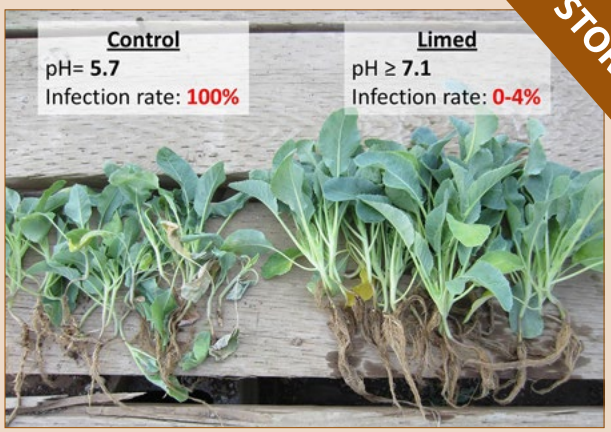

Figure 13. Disease suppression on cauliflower (cv. 'Artica') grown in a greenhouse when lime was mixed thoroughly with sieved soil. Photo by Aaron Heinrich.

Table 8. Microsite pH variability and clubroot control following mixing and liming in a greenhouse trial.

Treatment	Bulk soil pH	Infected plants (%)	pH variability (pH unit)
Control	5.9	100	0.70
Limed (field mixed)	7.3	48	2.00
Limed (sieved and thoroughly mixed)	6.9	18	0.35

Adapted from Dobson et al., 1983.

Table 9. Soil pH 2 weeks after lime incorporation, disease incidence, and severity at harvest.

Treatment	pH (1:1)	Disease incidence (%)	Disease severity[1]
No lime	6.8	59	39
Lime + power harrow	7.1	35	20
Lime + power harrow + rototill	7.4	8	5

[1]Disease severity was calculated using the method described by Dixon and Robinson (1986).

Figure 14. Lime incorporation following a single pass with a power harrow (left) and a pass with a power harrow followed by rototilling (right). Two weeks after incorporation, pH was greater in the rototilled plots (Table 9). Photo by Aaron Heinrich.

Step 7. Measure pH after liming

To verify that you reached your target pH following liming, measure soil pH before or at planting. This allows you to evaluate and fine tune your clubroot liming program. If you exceeded the target pH, you may be able to cut costs by reducing lime rates. If you did not reach your target, you may need to increase lime rates or modify the application timing or incorporation methods. Follow instructions in Step 1 (page 8) for determining soil pH.

Acknowledgments

We appreciate the support and collaboration of the following farms and companies: Gathering Together Farms (Philomath), Sauvie Island Organics (Portland), Sauvie Island Farms (Portland), Siri and Son Farms (Clackamas), Mustard Seed Farm (St. Paul), Wilco, Ashgrove Cement Company, and Columbia River Carbonates.

This publication was made possible by grants from the USDA Western Sustainable Agriculture Research and Education program, the Agricultural Research Foundation, and the Oregon Processed Vegetable Commission.

Appendix A

Using hydrated lime

Hydrated lime is highly reactive and rapidly raises soil pH. Unlike "regular" lime (calcitic and dolomitic materials), which may require a month or more to reach the target pH, hydrated lime can be incorporated as little as 1 week before planting. Hydrated lime has the added benefit that the pH response to lime is linear, which minimizes the amount of lime that must be applied to reach the target pH (Figure A1).

The disadvantages of hydrated lime are that it costs more, requires additional safety precautions, and corrodes equipment. Because hydrated lime reacts completely when added to soil, there is no residual lime to buffer pH changes over time. However, the pH will remain high enough over the cropping cycle to suppress clubroot.

If regular lime cannot be applied far enough in advance of planting to achieve the target pH, hydrated lime can be used as an "emergency" treatment. If possible, however, plan ahead and use regular lime so as to avoid the disadvantages associated with hydrated lime.

To calculate the amount of hydrated lime to apply, use either *Method 1* (page 12) or Worksheet A1.

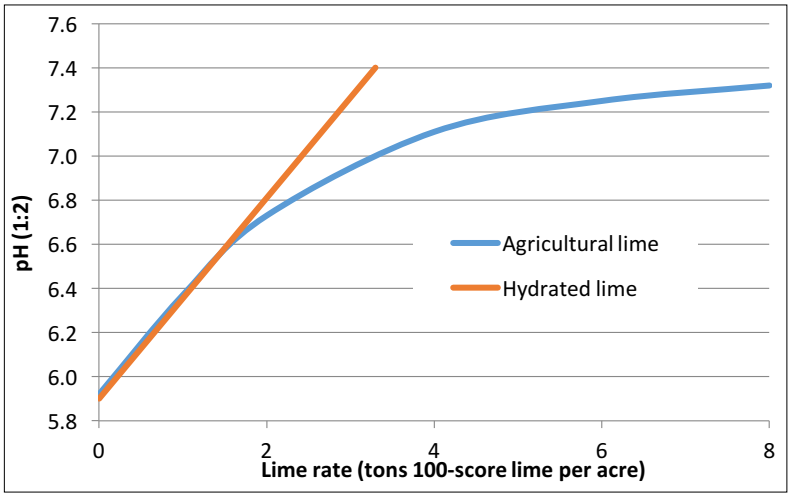

Figure A1. Lime response of a Sauvie fine sandy loam soil to agricultural lime and hydrated lime in a laboratory incubation 1 month after lime addition. In most soils, the response to agricultural lime is linear only to approximately pH 6.4. Source: Aaron Heinrich, unpublished research.

WORKSHEET A1. Estimating hydrated lime requirement, based on soil series

Line no.		Your value	Example	Unit
1	Soil series		Woodburn	—
2	Target pH (7.0 to 7.5)		7.1	—
3	Initial pH		6.0	—
4	Lime required (100-score) to increase pH by 1 unit (from Table 7, page 13)		2.7	t/a/unit pH change[1]
5	Lime required to reach target pH: (*line 2 – line 3*) x *line 4*		3.0	t/a[1]
6	Product lime score		130	—
7	Depth of lime incorporation		6	inches
8	Amount of lime product to apply, adjusted for depth of incorporation and lime score: *(100* x *line 5* ÷ *line 6)* x *(line 7* ÷ *6)*		2.3	t/a lime product

[1]100-score lime incorporated to a depth of 6 inches.

For more information

Extension publications

Applying Lime to Raise Soil pH for Crop Production: Western Oregon (EM 9057), Oregon State University. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/em9057.pdf

Clubroot of Crucifers (Bulletin HYG-3118-96), Ohio State University. http://www.oardc.ohio-state.edu/sallymiller/Extension/factsheets/CRcrucifers.pdf

Soil Sampling (Bulletin 704), University of Idaho. http://www.cals.uidaho.edu/edComm/pdf/EXT/EXT0704.pdf

Other publications

Baggett, J.R. 1976. 'Oregon CR-1' broccoli. *HortScience* 11:622–623.

Baggett, J.R. 1983. Clubroot-resistant cabbage breeding lines Oregon 100, 123, 140, and 142. *HortScience* 18:112–114.

Baggett, J.R and D. Kean. 1985. Clubroot-resistant broccoli breeding lines OSU CR-2 to OSU CR-8. *HortScience* 20:784–785.

Chupp, C. 1917. Studies on clubroot of cruciferous plants. *Bulletin of the Cornell University Agricultural Experiment Station* 387:419–452.

Diederichsen, E., M. Frauen, E.G.A. Linders, K. Hatakeyama, and M. Hirai. 2009. Status and perspectives of clubroot resistance breeding in crucifer crops. J*ournal of Plant Growth Regulators* 28:265–281.

Dixon, G.R. and D.L. Robinson. 1986. The susceptibility of *Brassica oleracea* cultivars to *Plasmodiophora brassicae* (clubroot). *Plant Pathology* 35:101–107.

Dixon, G.R. and E.L. Tilston. 2010. Soil-borne pathogens and their interactions with the soil environment. In *Soil Microbiology and Sustainable Crop Production.* G.R. Dixon and E.L. Tilston (eds.). Springer, Dordrecht, Netherlands.

Dobson, R., R. Gabrielson, A. Baker, and L. Bennett. 1983. Effects of lime particle size and distribution and fertilizer formulation on clubroot disease caused by *Plasmodiophora brassicae*. *Plant Disease* 67:50–52.

Heinrich, A.H. and A. Stone. 2014. Clubroot (*Plasmodiophora brassicae*) control strategies on brassicas. Research report to the Oregon Processed Vegetable Commission. http://horticulture.oregonstate.edu/content/clubroot-plasmodiophora-brassicae-control-strategies-brassicas-2014

Heinrich, A.H. and A. Stone. 2015. Clubroot (*Plasmodiophora brassicae*) control strategies on brassicas (2015). Research report to the Oregon Processed Vegetable Commission. http://horticulture.oregonstate.edu/content/clubroot-plasmodiophora-brassicae-control-strategies-brassicas-2015

Hwang, S.F., H.U. Ahmed, S.E. Strelkov, B.D. Gossen, G.D. Turnbull, G. Peng, and R.J. Howard. 2011. Seedling age and inoculum density affect clubroot severity and seed yield in canola. *Canadian Journal of Plant Science* 91:183–190.

Hwang, S.F., R.J. Howard, S.E. Strelkov, B.D. Gossen, and G. Peng. 2014. Management of clubroot (*Plasmodiophora brassicae*) on canola (*Brassica napus*) in western Canada. *Canadian Journal of Plant Pathology* 36(S1):49–65.

McLean, E.O. 1982. Soil pH and lime requirement. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties,* 2nd ed. A.L. Page, R.H. Miller, and D.R. Keeney (eds.). American Society of Agronomy, Inc., Madison, WI.

Peterson, P. 1971. Liming requirement of selected Willamette Valley soils. M.S. thesis, Oregon State University. http://hdl.handle.net/1957/35805

Sharma, K., B.D. Gossen, and M.R. McDonald. 2011a. Effect of temperature on primary infection by *Plasmodiophora brassicae* and initiation of clubroot symptoms. *Plant Pathology* 60:830–838.

Sharma, K., B.D. Gossen, and M.R. McDonald. 2011b. Effect of temperature on cortical infection by *Plasmodiophora brassicae* and clubroot severity. *Phytopathology* 101:1424–1432.

Strelkov, S.E. and S.F. Hwang. 2014. Clubroot in the Canadian canola crop: 10 years into the outbreak. *Canadian Journal of Plant Pathology* 36(S1):27–36.

Thuma, B.A., R.C. Rowe, and L.V. Madden. 1983. Relationships of soil temperature and moisture to clubroot (*Plasmodiophora brassicae*) severity on radish in organic soil. *Plant Disease* 67:758–762.

Wallenhammar, A.C. 1996. Prevalence of *Plasmodiophora brassicae* in a spring oilseed rape growing area in central Sweden and factors influencing soil infestation levels. *Plant Pathology* 45:710–719.

Published August 2016.