2015 Research report to the Agricultural Research Foundation

Management of Clubroot in Cabbage Family Crops

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Executive summary

This research has demonstrated that liming clubroot infected soils to a pH ≥7.1 is an effective practice for reducing both the incidence and severity of clubroot. Liming does not kill the pathogen but rather prevents spores of the pathogen from infecting the plant. This research demonstrated that highly reactive calcitic lime products could be substituted for hydrated lime as they effectively raise the pH of the soil to the target pH of ≥7.1 within a week after application. The project also demonstrated that boron and Serenade drenches did not suppress clubroot under field conditions.

In the greenhouse, liming two heavily infested soils to a pH >7.1 almost completely eliminated clubroot symptoms on cauliflower (cv 'Artica'). Under field conditions, liming a soil to a pH ≥7.1 reduced clubroot incidence by 44-77% and severity by 74-90% in 3 trials conducted in the same field in the spring and fall of 2014. Liming to pH ≥7.1 was not as effective in the field as in the greenhouse. Incomplete soil mixing in the field means that the pH of some soil particles is not raised to≥7.1, so in those areas, infection can occur. Nonetheless, clubroot disease incidence and severity are much lower and yields are higher in limed fields.

The profitability of liming Willamette Valley soils to a target pH of ≥7.1 as a clubroot control strategy will depend on several factors: the degree to which clubroot will reduce yield if no lime were applied, the cost of the lime product used and the lime rate (which depends on the pH buffering capacity of the soil as influenced by clay content, organic matter, and initial pH), and the value of the crop. Liming should always be used as one tool in an integrated clubroot management tool box that also includes rotation (4 or 5+ years), soil and irrigation management (to minimize waterlogging), and sanitation (use of clubroot-free transplants and prevention of clubroot movement from field to field).

Cooperators

Pearmine Farms, Dickman Farms**,** Sauvie Island Organics, and Gathering Together Farms

Educational and outreach efforts

Results from this project were disseminated in the following ways:

1. Presentation at the OSU Processed Vegetable Field Day (August 12, 2013, OSU Veg Research Farm) and creation of a clubroot handout available at OregonVegetables.com (http://horticulture.oregonstate.edu/content/liming-and-clubroot-control-brassicas-handout-2013-veg-field-day).
2. Presentation at the Oregon Processed Vegetable commission annual meeting (January 22, 2014, Linn County Fair & Expo Center, Albany, Oregon)
3. Two presentation at the North Willamette Horticultural Society: 1) Clubroot management strategies for brassica production and 2) Vegetable rotation for soil-borne disease management (January 13, 2015, Clackamas County Event Center, Canby, Oregon)

Leveraging data for additional funding

We used the results from this project to successfully secure the following grant:
2015 Western SARE Professional and Producers grant ($50,000): Integrated clubroot control strategies for PNW Brassica producers. WSARE Project OW15-005.

Background

Clubroot (causal organism, *Plasmodiophora brassicae*) is a major disease of brassica crops in the Willamette Valley. Some processed vegetables growers have told us that once clubroot has shown up in a field, they abandon that field to future Brassica production. By doing so, they have less flexibility in their ability to implement long, diversified crop rotations and may have to search for clubroot-free ground off-farm.

Dealing with clubroot is a challenge. Thick-walled resting spores have been shown to remain viable in soil for 10 - 20 years, making it difficult if not impossible to eliminate the pathogen from an infested field. Therefore, once pathogen populations have developed to levels that cause economically damaging clubbing, the goal of the farmer is to manage rather than eradicate clubroot. Control measures include liming to raise the soil pH to >6.8; rotation with non-host crops on a 5-6 yr cycle, which will not eliminate the pathogen from the soil but prevents build-up of very high pathogen populations; and irrigation and soil management to reduce the likelihood of soil waterlogging, which promotes infection. Growing resistant varieties is not typically a viable strategy as pathogen strains (races) vary from location to location and the pathogen readily evolves to overcome varietal resistance (Zitter, 1985). New cultivars from Europe may have potential for fresh market production as they are purported to have longer-lasting multi-gene resistance to clubroot; however, none of these are suitable for Willamette Valley processed broccoli and cauliflower production.

Soil pH management is considered to be the most practical control measure (in combination with rotation, soil moisture management, and sanitation) and has been shown to be effective (Dobson et al. 1983). Liming the soil to a pH of >6.8 has been so effective at controlling clubroot in areas such as the Salinas Valley of California, which is a major producer of brassicas, that the plant pathologist for the region does not work on the disease (Steve Koike, UC Cooperative Extension plant pathologist, personal communication). Liming does not kill the pathogen but reduces spore germination, thus reducing infection and clubbing (Dixon, 2009). By reducing clubbing, fewer spores are released back into the soil, helping to reduce future infection rates and severity. In a 2013 greenhouse trial, we showed that liming a heavily infested clubroot soil to a pH >7.0 reduced infection by 89% compared to an un-limed control with a pH of 6.8.

Why is clubroot a problem if liming is effective and California farmers have successfully implemented pH management? To answer this question, in 2012 we surveyed a group of 37 conventional and organic fresh market and processing vegetable farmers (who grow significant quantities of cabbage family crops) in western Oregon about the importance of clubroot and their experiences with pH manipulation. Eighty three percent had used lime in an attempt to control clubroot, yet only 21% of those that had used lime aimed for a pH of at least 6.8 (the minimum pH shown to control the disease). And of those that had used lime, 38% never followed up to determine if the target pH was reached. These survey results suggest that there is a general acknowledgement that pH manipulation can control clubroot, but that there is a need for step-by-step recommendations on how to successfully increase pH to >7.0 or 7.1 during the period the crop is most susceptible to clubroot infection.

While raising the pH of a soil is a common practice, raising the pH to >6.8 for a specific time period can be a challenge for the following reasons: 1) most extension publication recommendations provide information on how to with raise the soil pH to values <6.8, but not to a higher pH, so there isn't good information available on how to increase pH to 7.1; in addition, more lime is required to raise the pH at pH values over 6.8 in most soils (see Fig. 1) (Peterson, 1972); 2) in western Oregon, the soil may not stay at a high pH due to leaching (i.e. Oregon soils at pH >6.8 may equilibrate to a lower pH over the winter); 3) many "traditional" liming products may not be reactive enough to achieve a target pH >6.8, and no commercial ag companies currently apply the highly reactive lime product, hydrated lime, due to safety and handling concerns; and 4) reactive liming materials are expensive.

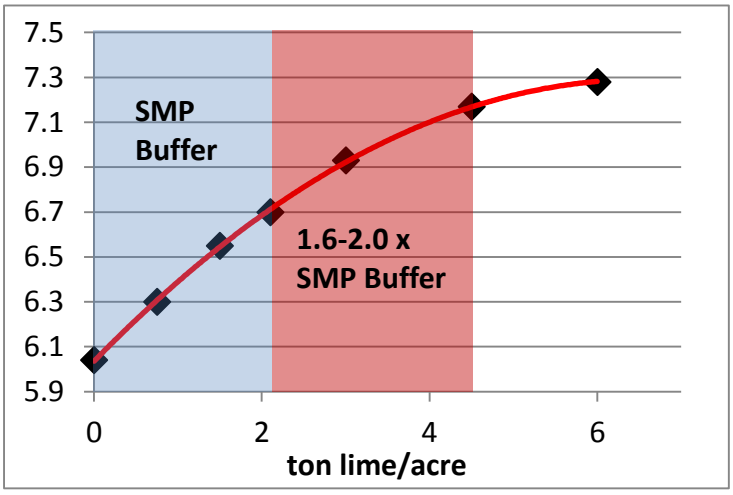

Figure 1. Generic soil pH response curve to lime. The response to lime is linear in the blue shaded area. In this range the SMP buffer value should be used to estimate lime additions. But, above a pH of ~6.7, the response curve becomes non-linear and the lime rate needed to increase the pH may be 1.6 to 2.0 times greater than the SMP buffer recommended value (based on small data set using 3 soils from incubations conducted in 2013).

Project objectives

1. **Evaluate the rate at which various liming products increase the soil pH from an agronomic target (~6.4) to a pH >7.0 (the minimum pH shown to control the disease).**
2. **Evaluate the effect of liming, boron and Serenade (biological, organic fungicide) on disease severity, yield, and quality of brassica crops in the greenhouse and field.**
3. **Evaluate the profitability and technical feasibility of liming.** Some of the highly reactive lime products are 2-3x more expensive than traditional "ag lime" and must be applied at high rates to rapidly achieve the target pH. These reactive products may also require special application methods or equipment.

Significant findings

Lab incubations

- The powdered lime products tested (Microna Ag H2O, Microna Ag lime sold as Access lime by Wilco, and Ashgrove Ag lime) are sufficiently reactive that they can raise the pH of a typical field soil to pH ≥7.0 within 1 or 2 weeks (thereby replacing hydrated lime, which has health and safety issues).
- Although the Microna powdered limes are more reactive, the Ashgrove Ag Lime is the most economical choice for raising the soil pH. Prilled products are prohibitively expensive at the rates required to raise the pH to ≥7.0.

Greenhouse study

- In soils heavily infested with clubroot, clubroot incidence was 100% in unlimed controls and >41% of plants were dead or dying. When these soils were limed to raise the pH to ≥7.1, clubroot incidence was almost zero and the plants grew vigorously.
- Soil drenches of Serenade Soil (biological fungicide) had no effect on clubroot incidence or severity.
- There was some benefit from applying boron at 10 lb B/acre, but the effect was not great enough to warrant its application without the addition of lime.

Field trials

- Under field conditions, liming a soil to a pH ≥7.1 reduced clubroot incidence by 44-77% and severity by 74-90% in 3 trials conducted in the same field in the spring and fall of 2014.
- Liming to pH ≥7.1 almost completely eliminated clubroot in the greenhouse, but liming did not completely eliminate clubroot under field conditions. Zones of lower pH occur in some areas of the soil volume due to the incomplete mixing of the lime into the soil volume, and where that occurs (in combination with clubroot spores), clubroot symptoms develop.
- Due to the reduction in disease incidence and severity in the limed plots, plant growth and yield were greater after liming than in the un-limed control.
- Soil drenching with Serenade Soil or boron (4 and 8 lb/acre) did not reduce clubroot incidence or severity.

Methods

Liming materials and soils

The liming materials used in the following lab, greenhouse, and field experiments and their characteristics are given in Table 1. The calcium carbonate equivalence (CCE) was determined by Brookside Laboratories Inc (New Bremen, OH). Microna Ag-H20 is an ultrafine lime with 99% and 50% passing a 325 and 2200 mesh screen, respectively. Because this lime is so fine, the company recommends applying it as a suspended solution. CCE is defined as the acid-neutralizing capacity of a liming material expressed as a weight percentage (%) of pure CaCO3 (100 g/mol). The Ashgrove lime contains CaO and $Ca(OH)_2$, which is why its CCE is >100.

Soil characteristics from field sites also used in lab and greenhouse experiments are given in Table 2. For use in the lab and greenhouse, the soils were sieved through a 4.75 mm mesh screen. These soils were stored at room temperature for 1-3 months prior to use.

Table 1. Product information of lime used in the clubroot studies.

Product	Manufacturer	Form	CCE[1]	$CaCO_3$	MgCO3	OR lime score
			%	%	%	
Ash Grove Ag lime	Ashgrove Cement Company	Powder	102	95	2.1	95
Microna Ag lime[2]	Columbia River Carbonates	Powder	99	96	0.5	97
Microna Ag-H_20	Columbia River Carbonates	Powder	98	96	0.5	97
CalPril	Pacific Calcium Inc.	Prilled	90	86	1.5	90
Microna Pearls	Columbia River Carbonates	Prilled	83	86	1	84
Hydrated lime[3]	J.T Baker, reagent grade	Powder	130	1.2	<0.3	130

1- Calcium carbonate equivalence method AOAC 955.01; 2- Carried by Wilco under the name Access Lime, 3- reagent grade $Ca(OH)_2$

Table 2. Properties of soils used in lab, greenhouse, and field experiments

Site	Soil mapping/ texture	pH	SMP buffer pH	OM[1]	CEC	Bray 1P	K
				%	meq/100g	----- ppm -----	
1- SAV	Burlington fsl	6.0	6.4	NA	15	133	238
2- GTF	Chehalem sicl	6.6	6.6	NA	30[2]	71	358
3- PEAR	Wapato sicl	5.9	6.1	4.5	29	96	329

1- 1.7*total C (by combustion); 2- estimated

Table 3. Lime treatments and rates used in the aerobic soil incubation. See Table 1 for lime properties.

Farm	Material	Applied	Rate 100% CCE equivalence
		ton/A	
SAV	Control	NA	NA
SAV	Microna Ag lime 1x	2.0	2.0
SAV	Microna Ag lime 2x	4.0	4.0
SAV	Microna Ag lime 3x	6.1	6.0
SAV	Microna Ag lime 4x	8.1	8.0
SAV	HL 0.5x	1.0	1.3
SAV	HL 1x	2.0	2.6
SAV	HL 1.5x	3.1	3.9
SAV	HL 2x	4.1	5.2
GTF	Control	NA	NA
GTF	Microna Ag lime 1x	1.2	1.2
GTF	Microna Ag lime 2x	2.4	2.4
GTF	Microna Ag lime 3x	3.6	3.6
GTF	Microna Ag lime 4x	4.9	4.8
GTF	HL 0.5x	0.6	0.8
GTF	HL 1x	1.2	1.6
GTF	HL 1.5x	1.8	2.3
GTF	HL 2x	2.5	3.1
PEAR	HL 0.5x	1.2	1.5
PEAR	HL 1x	2.3	3
PEAR	HL 1.5x	3.5	4.5
PEAR	HL 2x	4.6	6

Lab Incubations

Incubation 1:

Lime was added to the field moist soil (equivalent of 300 g oven dry soil) described above and thoroughly mixed. Using a spray bottle and DI water, soil moisture was adjusted to field capacity (estimated based on soil texture) and the soil was placed in a re-sealable plastic bag with a straw placed in the bag to provide for air exchange. Bags were incubated in the dark at 21.2 ± 0.8 degrees C. DI water was periodically added to the bags based on weight loss to maintain a constant moisture content. The treatments and liming rates are given in Table 3. To convert the application rate from tons lime/A to g lime/g soil, the weight of soil in an acre-6" was estimated to be 2 million lbs (equal to a BD=1.47 g/cm3). Treatments were not replicated. At wk 1, 2, 4, and 6, a 35 g subsample was collected from each bag, air dried, and ground in a mortar and pestle. The pH (1:2, soil:DI water) was determined on a 15 g sample.

In a separate incubation, using soil from site 3-PEAR, the liming materials listed in Table 1 were applied at a rate of 3 or 6 ton/acre on a 100% CCE basis. HL was applied at a rate of 1.5, 3, 4.5, and 6 ton/acre on a 100% CCE basis. The same procedures were used as described above.

Incubation 2:

Various liming products were applied to the soil from site 3-PEAR (see Table 4 for rates). The same methods were used as in Incubation 1 (above). A cost analysis was performed based on the lime rate required to raise the pH by 1 unit to a pH ≤7.0.

Greenhouse trial

Soil from each site was sieved through a 4.75 mm screen and stored for several months at room temperature before use. The treatments for each soil are given in Table 5. Three weeks before being placed in cone tubes, all soils were wetted up to field capacity using a squirt bottle and stirring continuously. Prior to being wetted, the Microna Ag lime treatments were mixed into the soil. Four days before potting-up, the hydrated lime treatments were applied. The soil was added to cone tubes and a minimum of 5 cauliflower (cv. 'Artica') seeds were sown in each tube, which was later thinned to 4 plants/tube. For each treatment 8 cone tubes were planted. Each boron treatment received a solution containing Solubor at a rate of 10 lb B/acre. Just enough solution was added to wet up the soil without causing drainage. Serenade Soil (5%v/v) was also applied at a rate that would wet the soil without causing drainage and was applied twice; immediately after seeding and 12 days later. At 52 days after seeding, the roots were washed, and evaluated for disease severity using the following scale: 0= no visible clubbing, 1= small clubs on lateral roots, 2= <25% of main root system clubbed, 3= 25-50% of main root system clubbed, 4= >50% of main root clubbed, 5= clubbing so severe that plant was dying and roots were rotting. Dry matter in aboveground biomass was also measured. When disease severity was compared amongst treatments, the numerical scale ratings were converted to mean severity: 0=0, 1=5%, 2=18%, 3=38%, 4=75%, and 5=100%. Analysis of variance was used to evaluate differences among treatments, and the Tukey HSD test was used to assess the significance of treatment differences.

Table 4. Materials and rates used in Incubation 2.

Treatment	Rate (100% pure CaCO3)	Rate (actual)
	---------- ton/acre ----------	
Control	0	NA
Ash Grove Ag lime 1x	3.0	3.0
Ash Grove Ag lime 2x	6.0	5.9
Microna Ag H_2O 1x	3.0	3.1
Microna Ag H_2O 2x	6.0	6.1
Microna Ag lime 1x	3.0	3.0
Microna Ag lime 2x	6.0	6.1
Cal Prill 1x	3.0	3.3
Cal Prill 2x	6.0	6.7
Garden Pearls 1x	3.0	3.6
Garden Pearls 2x	6.0	7.2
Hydrated lime 0.5x	1.5	1.2
Hydrated lime 1x	3.0	2.3
Hydrated lime 1.5x	4.5	3.5
Hydrated lime 2x	6.0	4.6

Table 5. At-plant soil treatments and pH in greenhouse study

Farm	Trt	Treatments	Target pH	Actual pH
SAV	C	Control	NA	5.7
SAV	L1	Lime	6.8-7.0	7.1
SAV	L2	Lime	>7.0	4.2
SAV	HL	HL	>6.8	6.3
SAV	L+HL	Lime + HL	>7.0	7.3
SAV	S	Serenade	NA	7.1
SAV	S+L	Serenade + Lime	6.8-7.0	7.1
SAV	B	Boron	NA	5.8
SAV	B+L	Boron+ Lime	6.8-7.0	7.1
SAV	S+B+L	Serenade + Boron+ lime	6.8-7.0	7.1
GTF	C	Control	NA	6.7
GTF	L1	Lime	6.8-7.0	7.4
GTF	L2	Lime	>7.0	7.3
GTF	HL	HL	>6.8	7.1
GTF	L+HL	Lime + HL	>7.0	7.6
GTF	S	Serenade	NA	6.8
GTF	S+L	Serenade + Lime	6.8-7.0	7.5
GTF	B	Boron	NA	6.7
GTF	B+L	Boron+ Lime	6.8-7.0	7.5
GTF	S+B+L	Serenade + Boron+ lime	6.8-7.0	7.6

Field trials

The following field sites were selected because they had a recent history of severe and uniformly distributed clubroot and their characteristics. We were unable to locate any processed vegetable fields that met these criteria. Roots were evaluated based on the rating scale given by Dixon and Robinson (1986): 0= no visible clubbing, 1= small clubs on lateral roots, 2= <50% of main root system clubbed, and 3=

>50% of main root system clubbed. When disease severity was compared amongst treatments, the numerical scale ratings were converted to mean severity: 0=0, 1=5%, 2=30%, and 4=75%. Analysis of variance was used to evaluate differences among treatments, and a Tukey test was used to assess the significance of treatment differences.

Sauvie Island Organics (Sauvie)

A trial was conducted at Sauvie Island Organics located on Sauvie Island outside of Portland. The soil is mapped as a Burlington fine sandy loam. Soil characteristics are given in Table 1. The experiment consisted of 2 treatments (Unlimed and Limed) replicated 4 times in a randomized complete block design. Microna Ag lime (sold as Access lime by Wilco) was applied by hand on April 2 at a rate of 6.8 ton/acre and incorporated with a spader to a depth of 8 inches. The following day broccoli (cv. Batavia) was transplanted. Soil was sampled 11, 55, and 80 days after lime application (DAA), air dried, and analyzed for pH (1:2 water). The soil was drip irrigated as needed over the growing season. A temperature probe (Hobo pendant datalogger) installed at 3.5" measured an average soil temperature of 60.7°F over the trial. On June 21 (80 DAA), plants were evaluated for aboveground biomass and head yield. Other than observational data, roots were not evaluated at this site. Due to a number of problems (i.e., did not reach target pH, gophers, poor weed control, and intermittent water), there were not enough plants to do a quantitative evaluation.

Gathering Together Farm (GTF)

Three trials were conducted at Gathering Together Farm (GTF) located outside of Philomath on a soil mapped as a Chehalem silty clay loam. Soil characteristics are given in Table 1.

Trial 1- The experiment consisted of 2 treatments (Unlimed and Limed) replicated 4 times in a randomized complete block design. Microna Ag lime (sold as Access lime by Wilco) was applied by hand on May 13 at a rate of 4.4 ton/acre and incorporated to a depth of 3" using a power harrow. On May 23 (10 DAA) the lime was further incorporated with a walk behind rototiller to a depth of 6". On May 26 (13 DAA), the broccoli variety 'Green Magic' was direct seeded. Soil was sampled 14 DAA, air dried, and analyzed for pH (1:2 water). Roots from every plant in the plots (average of 17, range 6 to 28; due to heavy flea beetle damage some plots had fewer plants to evaluate) were evaluated for clubroot infection rate and severity 84 DAA.

Trial 2- This experiment was conducted on the same experimental site as trial 1. Using the same plot layout as in trial 1, on August 5 we applied an additional 2.2 ton/acre of Microna Ag lime in the middle of the plots and 4.4 ton/acre along the edges so that the pH was uniform across the beds. The following day the lime was incorporated with a walk-behind BCS rototiller to a depth of 6". Kale (cv 'Lacinato') was transplanted by hand at 6" spacing. The plots were laid out in a split plot design with Lime/No lime being the main plot and the applied treatments as the subplot, and were replicated 3 times. The subplot treatments were: 1) Water, 2) Serenade, 3) 4 lb/acre boron, and 4) 8 lb/acre boron. All treatments were applied as a drench (5 liters per 25') in a 4" band using a watering can. Serenade Soil (AgriQuest) was applied as a 5% (v/v) solution. Serenade is a biofungicide that contains a strain of the bacteria *Bacillus subtilis*. The boron was supplied by Solubor (21% B) and the rate in the band was 4 or 8 lb B/acre. Total aboveground biomass was measured and roots evaluated 65 DAA from 12 plants (6 consecutive plants taken from each end of the plot 5' from plot edge).

Trial 3- Except for the following differences, this trial was the same as Trial 2 and occurred in the same field: 1) the layout was a strip plot design (same lime treatments but the subplot treatments were applied in a strip across a block, i.e. not randomized; this was done to be able to visually observe differences across lime treatments), 2) this field only received a single lime application (4.4 ton/acre of Microna Ag lime). All other conditions were the same as in trial 2.

Results & Discussion

Lab Incubations

Incubation 1:

Soil pH response to lime additions is given in Figure 2. Overall, maximum pH was reached 2 weeks after application. After 2 weeks the pH remained relatively stable (typically <0.2 unit change). The maximum pH obtainable with both hydrated lime (HL) and Microna Ag lime was ~7.4, but to achieve this pH, 2/3rds less HL was needed. The reaction rate of Microna Ag lime was comparable to HL over 1 to 2 weeks. Therefore, at a sufficiently high rate the ag lime is reactive enough to be used instead of HL and can be applied 1 to 2 wks before planting to achieve a target pH $\geq$7.0.

The main difference between HL and the ag lime is that the pH response to HL is linear, whereas the ag lime is relatively linear to pH 7.0 but then become non-linear (Fig. 3). For the 3 soils to which HL was added, the amount required to raise the pH by 0.5 units ranged between 1.7 to 2.2 ton/acre (Fig. 4). Previous data for 2 sicl and 1 sil soil (results not shown) showed that 1.2 to 1.8 ton/acre HL was needed to raise the pH by 0.5 units. Although this response rate will likely vary with soil type, a "rule of thumb" for soils that have a higher buffering capacity (such as heavier clay soils) may be to apply 2 ton HL/acre for each 0.5 unit increase desired.

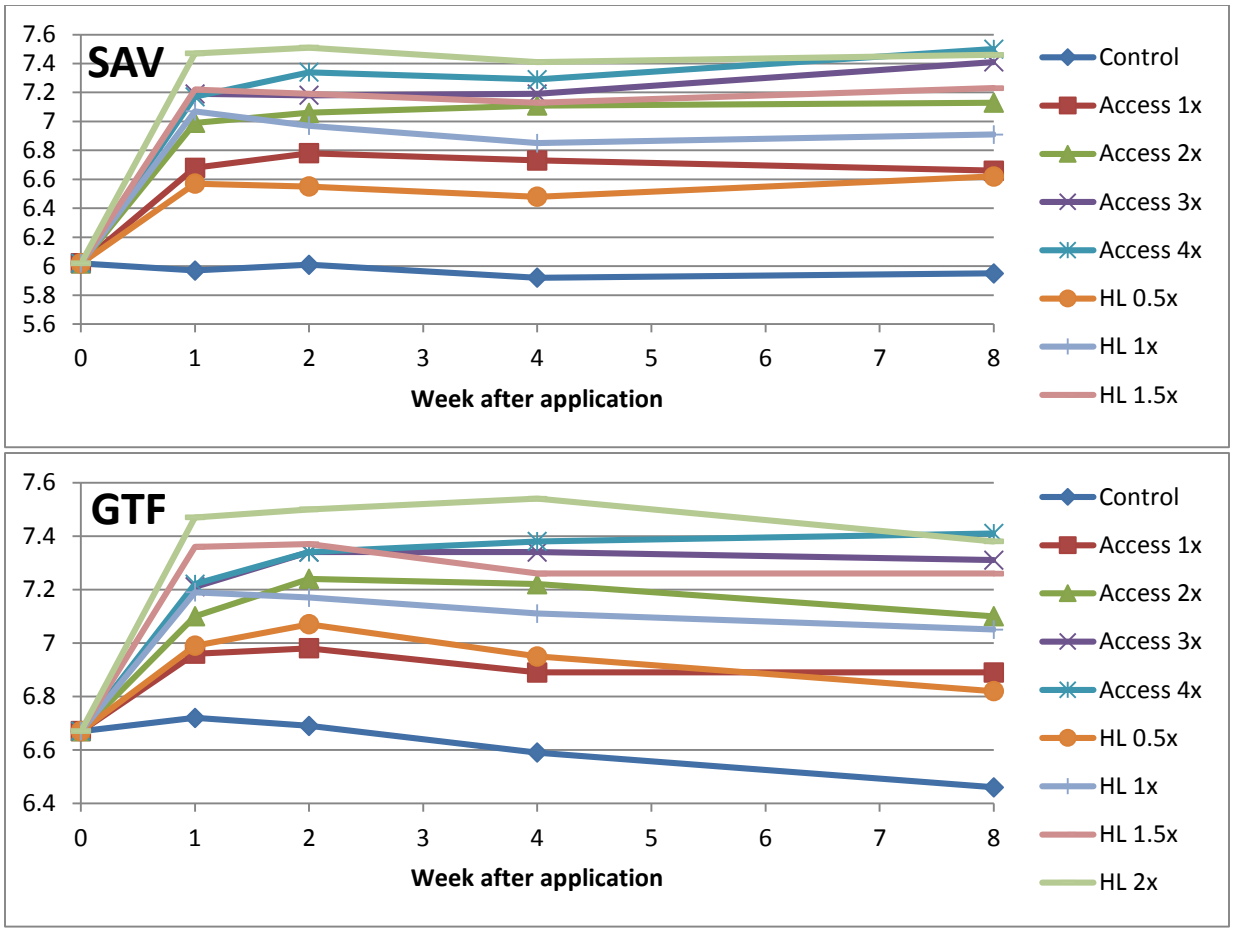

Figure 2. Soil pH response to lime additions for Microna Ag lime (Access) and hydrated lime (HL) in two field soils. See Table 3 for application rates.

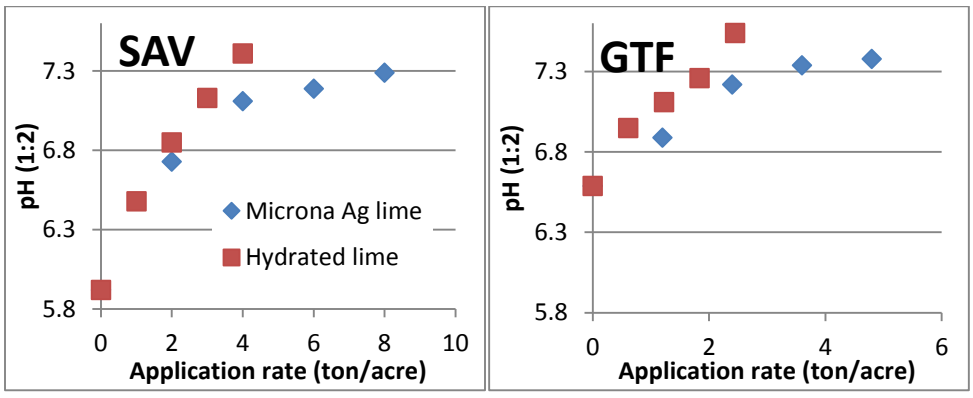

Figure 3. Soil pH response to lime additions for Microna Ag lime (Access) and hydrated lime (HL) in 2 field soils at week 4.

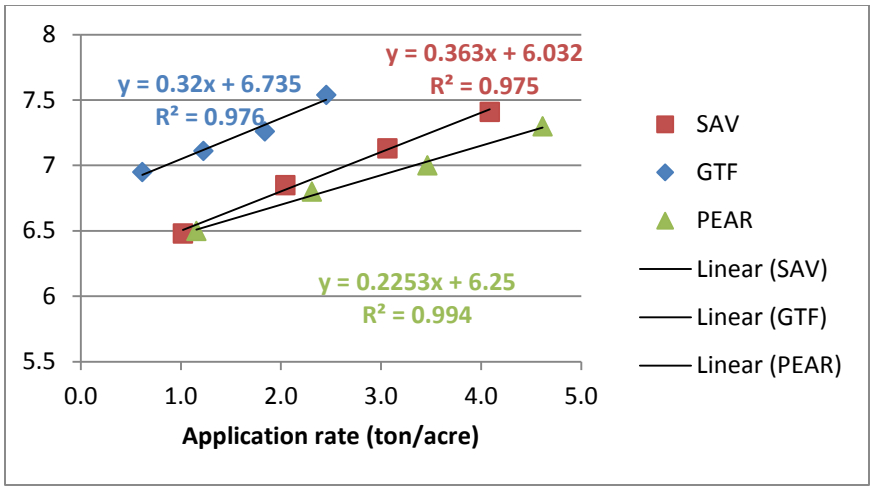

Figure 4. Soil pH response to hydrated lime additions at week 4. Divide 1 by the slope to calculate HL requirement to raise the soil pH by 1 unit.

Incubation 2:

The lime response of the different liming products tested applied at a 3 t/acre CCE equivalent is given in Figure 5. These results show that the ultrafine products, Microna Ag H2O and Microna Access (Ag Lime), were as reactive as HL at 1 wk after application. The lime response of the different liming products tested applied at a 6 t/acre CCE equivalent is given in Fig. 6. At the higher rate, the HL was more reactive than the other materials. What may be partly responsible for the difference in reactivity is the difference in response to HL and lime at higher pH (see Fig. 3). Despite the difference in reactivity, the powdered limes were able to achieve a pH of ≥7.2. The powdered lime products could be used as a substitute for HL, which is beneficial due to the health and safety issues associated with applying HL. The prilled products were less reactive. Although both CalPril and Garden Pearls are made from the same lime source, their composition (Table 1) and reactivity (Fig. 5) are different, suggesting that perhaps they were made from a different batch of lime.

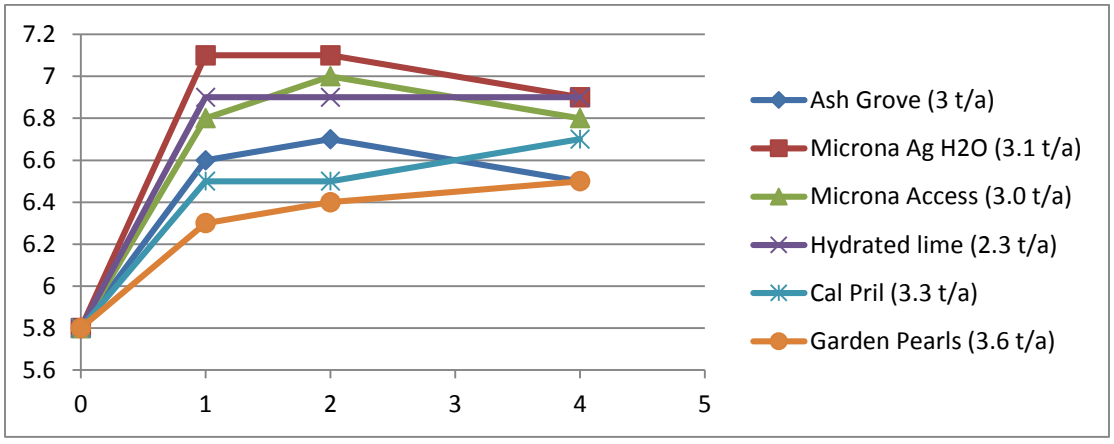

Figure 5. Lime response for 3 ton/acre CCE equivalence application rate (i.e., despite the difference in the rate applied, they all can neutralize the same amount of acidity. But how fast they react is based on the particle size and chemical composition).

Although the Microna powdered lime products were more reactive than Ashgrove lime, the Ashgrove lime is more economical due to the lower price (Table 6). The prilled products were prohibitively expensive, but their advantage is in the ease of handling and minimal lime dust. Liming to a pH ≥7.0 is relatively expensive regardless of what material is used due to the high rates required. One possible way to overcome this is to apply and till the lime only in the row (such as in a 12" band), however this may require a significant investment in equipment.

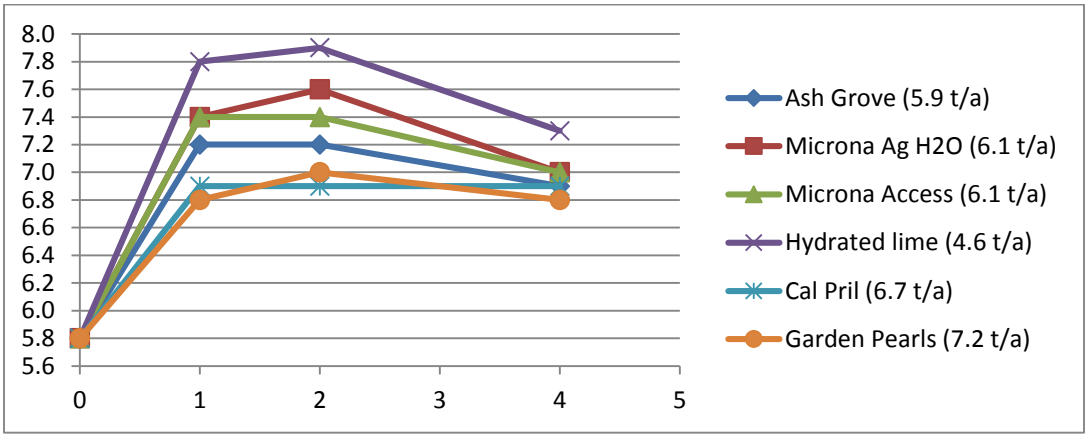

Figure 6. Lime response for 6 ton/acre CCE equivalence application rate.

Table 6. Cost of liming products to raise soil pH by 1 unit (to a pH of ≤7.0). Above a pH of 7.0, the lime response is nonlinear and more lime is needed to increase the pH.

Product	Est. cost material only **$/ton**	Lime requirement to increase pH by 1 unit[1] **ton/A**	Cost to increase soil pH by 1 unit **$**
Ash Grove Ag lime 1x	61	3.3	200
Microna Ag H2O 1x	210	2.4	494
Microna Access 1x	105[2]	2.5	266
Cal Prill 1x	260	4.8	1,242
Garden Pearls 1x	392[3]	6.0	2,356
HL	260[4]	2.0	520

1- to a pH of ≤7.0, in this range lime response is relatively linear; 2- $105/ton for 250+ tons to $117/ton for 30 tons; 3- based on cost of 50 lb bags, bulk pricing likely cheaper; 4- estimated $0.13/lb

Greenhouse study

Results from the greenhouse trial are given in Figure 7. Damping off killed some of the plants, so 18 to 30 individual plants from at least 7 cone tubes were evaluated in each of the treatments. The plant weight was measured as a composite weight of all plants in each treatment (no replication).

In the greenhouse experiment using Sauvie Island soils, disease incidence in the control treatment was 100% and disease severity was 89%, with 56% of the plants dead or dying. The addition of Serenade Soil (S) did not reduce disease incidence (100%) or severity (90%). Although applying boron (B) did not decrease incidence, it reduced disease severity to 52% (with no dead or dying plants) and increased aboveground biomass (Fig. 7). The increase in soil pH from 5.7 to 6.3 due to the hydrated lime (HL) treatment slightly reduced disease incidence, reduced disease severity to 55%, and increased aboveground plant biomass. However, it was only in treatments that raised soil pH to 7.1 or above that disease incidence was reduced essentially to zero. At pH > 7.1, the application of Serenade and boron had no effect on disease incidence or severity.

In the Gathering Together control treatment, clubroot incidence was 100% and severity was 85%, with 41% of plants dead or dying. Drenching with Serenade Soil (S) did not reduce disease incidence or severity. Applying boron (B) reduced disease incidence by about 25% and increased plant growth, but did not significantly reduce overall disease severity. The HL treatment (pH 7.1) reduced clubroot incidence by 43% and severity by 49% and increased aboveground plant biomass. In the L1 and L2 treatments (pH≥7.3) clubroot severity was reduced to essentially zero. This is in contrast to the result at Sauvie Island, where the liming treatment that generated a pH of 7.1 almost completely suppressed the disease. Our target pH for L1 was between 6.8-7.1 and for L2 it was >7.1. When the soil was collected from a recently limed field, the pH was 7.1. But there was unreacted lime still visible in the soil and after adding water and incubating the soil for 3 wks, the pH increased to 7.4. This highlights the need to keep soils moist to promote the liming reaction.

Field trials

Sauvie: Insufficient lime was applied to achieve the target pH of ≥7.0 (Fig. 8). Based on the SMP buffer pH (Table 1) and Table 3 in OSU's lime guide (Anderson et al., 2013), we estimated that ~7.4 ton/acre-6" of lime was needed. Although we applied 6.8 ton/acre, it was incorporated to a depth of 8", resulting in a rate of 4.5 ton/acre-6". Based on the actual rate applied and the change in pH, we calculated that 7.5 ton/acre-6" of lime was required to raise the soil pH by one unit, which is very close to the estimated recommendation calculated using the SMP buffer pH and Table 3 in OSU's lime guide. The pH did not significantly change between 11 and 80 DAA (Fig. 8), suggesting that much of the lime had reacted in the first 11 DAA. This is consistent with the incubation results discussed above, which showed that the very finely ground Microna Ag Lime almost completely reacted by 14 DAA.

Due to insufficient irrigation as well as insect and weed problems, the plants in this field trial were small and the yield was poor. However, despite these problems and not achieving the target pH of ≥7.0 (limed soil was pH 6.7), average total plant weight was 2.7 times greater in the limed plots compared to the unlimed (Fig. 8) and no marketable heads (crown >4") were present in the unlimed plots. Although we did not quantify clubroot infection rate and severity, we qualitatively observed a functional difference in disease severity on the roots (Fig. 9). These results suggest that even if a pH of ≥7.0 is not reached, there is some suppression of clubroot that occurs with the addition of lime to a low pH soil.

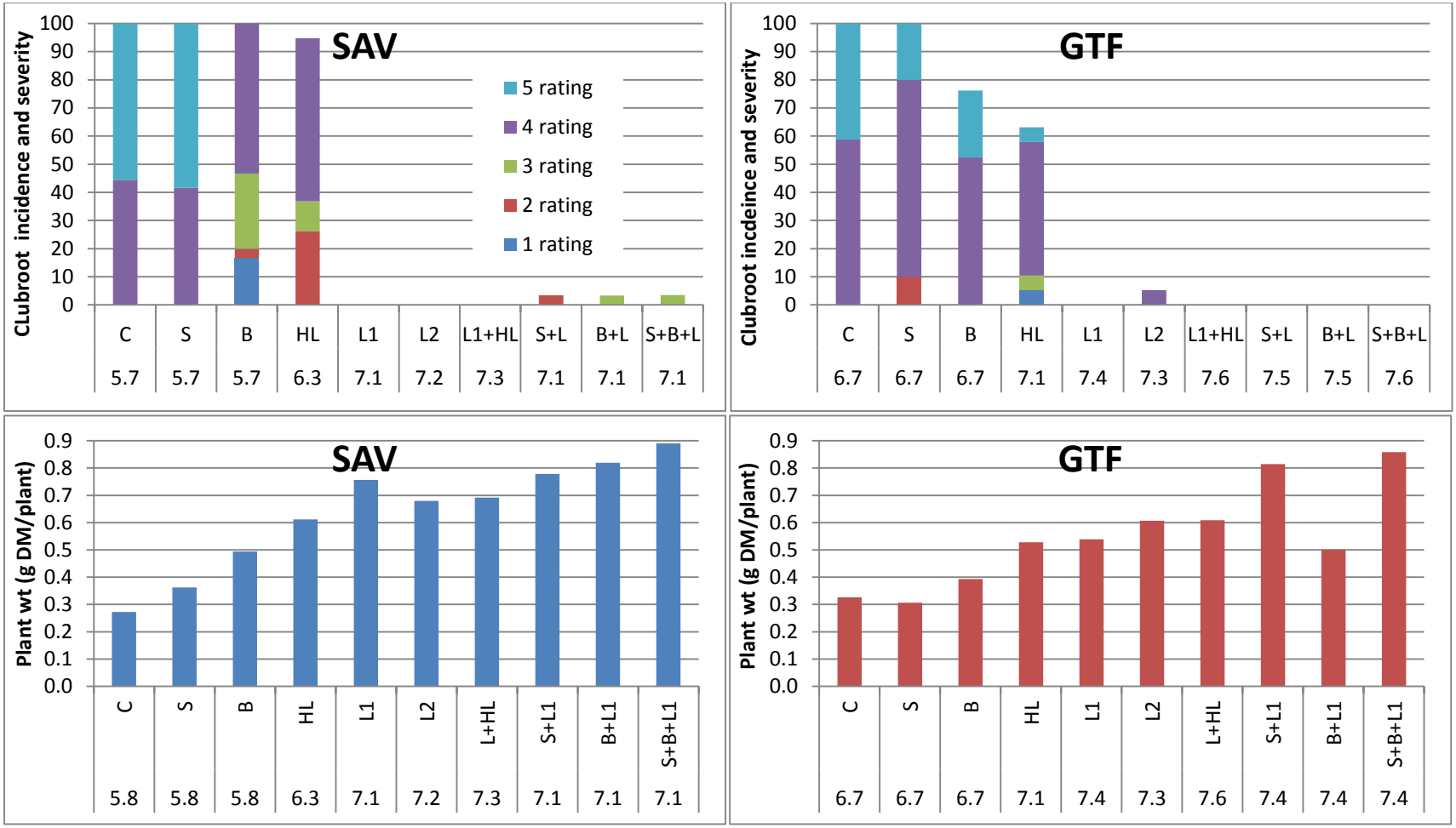

Figure 7. Clubroot incidence and severity and aboveground biomass in greenhouse experiments. Treatments: C=Control, S=Serenade, B= Boron, HL= hydrated lime, L1= lower rate lime addition, and L2= higher rate lime addition. Disease severity ratings: 0= no visible clubbing, 1= small clubs on lateral roots, 2= <25% of main root system clubbed, 3= 25-50% of main root system clubbed, 4= >50% of main root clubbed, 5= clubbing so severe that plant was dying and roots were rotting. Eighteen to 30 plants taken from 7 to 8 cone tubes were evaluated for each treatment (some plants damped off). The plant weight was a composite weight of all plants in the treatment (unreplicated). The bottom row of numbers represents soil pH for that treatment.

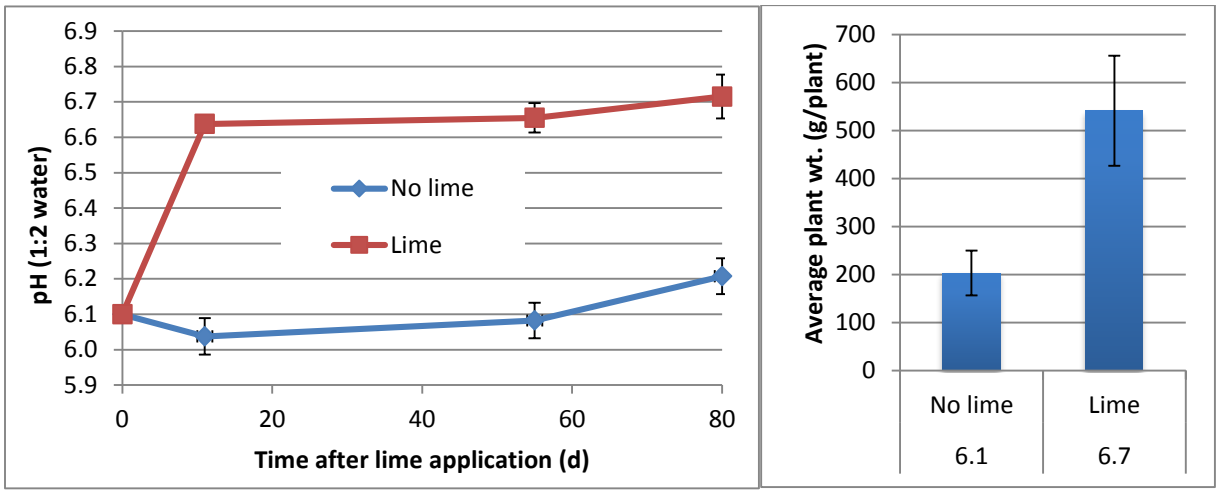

Figure 8. Soil pH and plant weight after application of 6.8 t/acre-8" (4.5 t/acre-6") of Microna Ag lime.

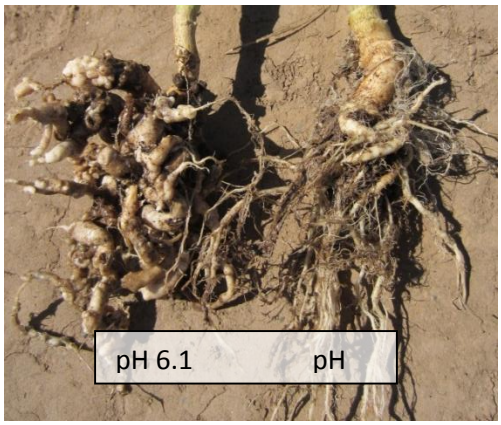

Figure 9. Clubroot severity on broccoli plants sampled from soil that received no lime (left) and lime (right) in the SAUVIE field experiment. Quantitative data could not be collected from this field experiment due to weediness, irrigation, and other factors. However, overall, disease incidence and severity appeared lower in the limed when compared to the unlimed plots.

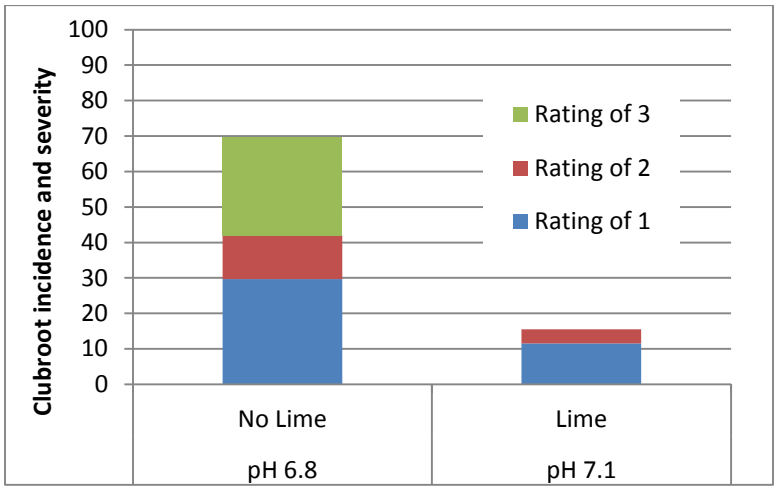

Figure 10. Clubroot incidence and severity, GTF field trial 1. Disease rating: 1= small clubs on lateral roots; 2= <50% of main root system clubbed; and 3= >50% of main root system clubbed.

GTF

Trial 1: The pH of the unlimed and limed plots the day after seeding was 6.8 and 7.1, respectively. By increasing the pH by 0.3 units, disease incidence was reduced by 77% and severity by 90% (Fig.10).

Trial 2: Of all the subplot treatments, only the high rate of boron appeared to reduce clubroot infection rate and severity, but the effect was small. Therefore, the following discussion will focus just on the difference between the liming treatments. By increasing the pH from 6.7 to 7.3, disease incidence was reduced by 61% (from 92 to 26%), and disease severity was reduced by 86% (from 60 to 8%) (Fig. 11). As the result of reducing disease severity, aboveground biomass in the limed plots increased by 64% compared to the unlimed plots (Fig. 11).

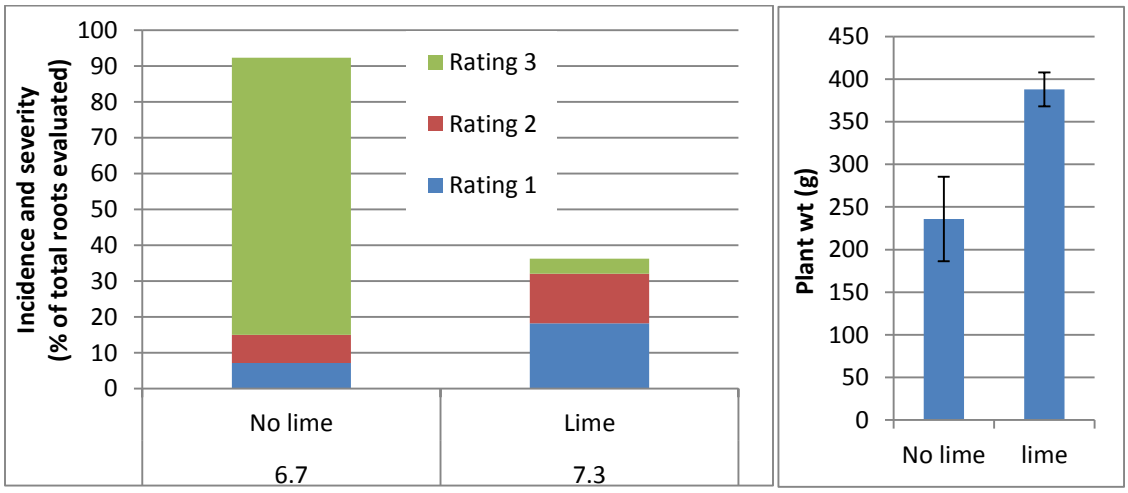

Figure 11. Clubroot incidence and severity, GTF field trial 2. Disease rating: 1= small clubs on lateral roots; 2= <50% of main root system clubbed; and 3= >50% of main root system clubbed. The pH is given below the lime treatment. Error bars represent the SE (n=3).

Trial 3: For the subplot treatments, there was no significant difference in plant growth, infection rate, or disease severity between treatments. Therefore the following discussion will focus only on the difference between the limed and unlimed plots. In this trial there was little or no clubroot in row 1 of the trial in both the limed and unlimed plots (Fig. 12). This may have been the result of straddling a previous non-brassica planting, resulting in a significantly lower level of inoculum in this row. This row was removed from the analysis and discussion.

	Row 4	Row 3	Row 2	Row 1
No lime	2.5	2.8	1.2	0.2
Lime	1.1	1.8	0.2	0
Lime	1	2	0.6	0.2
No lime	3	3	1.8	0.3
No lime	2.6	3	1.8	0.2
Lime	0.6	1.4	0.8	0.1
Lime	0.1	0.4	0	0.1
No lime	2.1	1.7	0.3	0.2

Figure 12. Average clubroot disease rating (n=12) from limed and unlimed plots in Trial 3 at GTF. The pH of the unlimed and limed plots was 6.8 and 7.2, respectively. Green and yellow colors indicate low disease severity while orange and red indicate moderate to high severity.

By increasing the pH from 6.8 to 7.2, disease incidence was reduced by 44% (from 71 to 40%) and severity by 74% (from 46% to 12%) (Fig. 13). Although there was a difference in root health, there was not a difference in aboveground biomass (results not shown). No boron phyotoxicity was observed even at the higher rate (8 lb B/acre).

For both trial 2 and 3, only when disease severity was >60% (moderate to severe clubbing) did plant growth begin to suffer (Fig. 14). This is consistent with what we have observed in farmer fields which was when disease severity is low, plants can tolerate the infection without any noticeable effect on plant growth. But, through the winter season we may see the severely infected plants dying. We will monitor their growth over the winter.

Figure 13. Clubroot incidence and severity, GTF field trial 3. Disease rating: 1= small clubs on lateral roots; 2= <50% of main root system clubbed; and 3= >50% of main root system clubbed. The pH is given below the lime treatment.

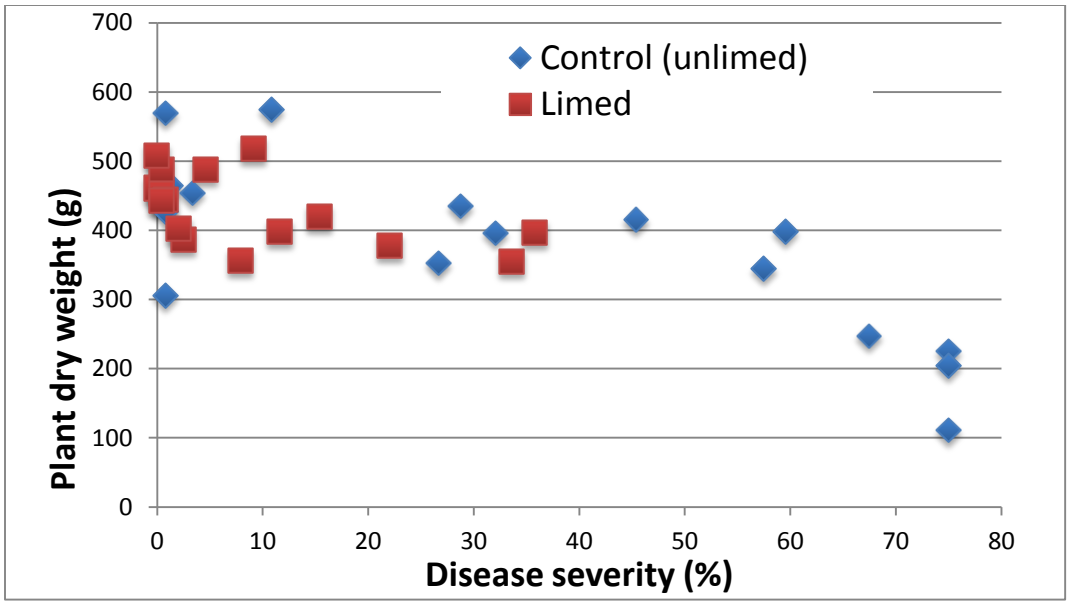

Figure 14. Relationship between disease severity and yield of lacinato kale from GTF field trials 2&3.

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