Soilborne pathogens

Reduction of potato scab and verticillium wilt with ammonium lignosulfonate soil amendment in four Ontario potato fields

N. Soltani, K.L. Conn, P.A. Abbasi, and G. Lazarovits

Abstract: Single applications of ammonium lignosulfonate (ALS, ca. 6 t solids/ha) were made at four commercial potato fields in Ontario (sites K, V, W, and G in 1998, 1999, 2000, and 2000, respectively). Potato tubers were planted 2–4 weeks after ALS incorporation. The effects on potato scab, verticillium wilt, tuber yield, soil chemistry, and soil microbiology were determined in the year of application, and for a second crop at sites K (1999), V (2000), and G (2001). Potato scab severity was significantly reduced (50–80%) by ALS treatment in the year of application at all sites. Significantly less scab was present for the second crop at sites K and G. The incidence of *Verticillium dahliae* infected plants was also significantly decreased (40–50%) by ALS treatment at all sites in the year of application and for the second crop at site K. Ammonium lignosulfonate significantly increased total tuber yield by 2.5 times at site G in 2000. There was no effect on tuber yield at the other sites. However, marketable yield (tubers with <5% surface scab) was significantly increased three- to seven-fold over the control plots at all sites in the year of application. Although marketable yield was consistently higher in subsequent crops at all sites, it was only statistically significant at site G. Soil pH was immediately reduced following application of ALS by 0.4–0.6 units at all sites except site W, where it had no effect. Soil pH returned to control levels by the second season at all sites except site G, which remained one log unit lower than the control treatment. Numbers of soil microorganisms increased two- to eight-fold at all sites within weeks of ALS application. Fungal numbers increased the most and remained elevated for two seasons at site K compared with control plots. The results of this study clearly demonstrate that use of ALS as a soil amendment can significantly reduce the severity of potato scab and verticillium wilt in potato crops.

Key words: ammonium lignosulfonate, potato scab, verticillium wilt, soil amendment.

Résumé : Des applications uniques de lignosulfonate d'ammonium (LSA, environ 6 t solides/ha) ont été effectuées dans quatre champs commerciaux de pomme de terre de l'Ontario (sites K, V, W et G en 1998, 1999, 2000 et 2000, respectivement). Les tubercules de pomme de terre ont été plantés de 2 à 4 semaines après l'incorporation du LSA. Les effets sur la gale, la verticilliose, le rendement en tubercules, la chimie du sol et la microbiologie du sol ont été déterminés pour l'année de l'application et pour une deuxième récolte aux sites K (1999), V (2000) et G (2001). Dans tous les sites, la gravité de la gale de la pomme de terre a été significativement réduite (50–80%) par le traitement au LSA lors de l'année d'application. Il y avait significativement moins de gale dans la deuxième récolte aux sites K et G. La fréquence d'infection des plantes par le *Verticillium dahliae* a aussi été significativement réduite (40–50%) par le traitement au LSA dans tous les sites lors de l'année d'application et pour la deuxième récolte au site K. Le LSA a significativement augmenté le rendement total en tubercules au site G en 2000, le multipliant par 2,5. Il n'y a pas eu d'effet sur le rendement en tubercules aux autres sites. Par contre, le rendement vendable (tubercules avec moins de 5% de la surface avec de la gale) a été significativement augmenté par rapport aux parcelles témoins, étant multiplié de 3 à 7 fois dans tous les sites lors de l'année d'application. Bien que les rendements vendables des cultures subséquentes aient été constamment supérieurs dans tous les sites, la différence n'a été statistiquement significative qu'au site G. Le pH du sol a été instantanément réduit de 0,4 à 0,6 unités après l'application du LSA dans tous les sites sauf au site W où il n'y a pas eu d'effet. Le pH du sol a retrouvé le niveau du témoin dès la deuxième saison dans tous les sites sauf au site G qui est demeuré une unité logarithmique plus basse que le traitement témoin. Après l'application du LSA, le nombre de microorganismes du sol s'est accru de 2 à 8 fois dans tous les sites en l'espace de

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quelques semaines. Ce sont les champignons dont le nombre a le plus augmenté et qui est resté élevé durant deux saisons au site K par rapport aux parcelles témoins. Les résultats de cette étude démontrent clairement que l'utilisation du LSA en tant qu'amendement du sol peut significativement réduire la gravité de la gale de la pomme de terre et de la verticilliose dans les cultures de pomme de terre.

Mots clés : lignosulfonate d'ammonium, gale de la pomme de terre, verticilliose, amendement du sol.

Introduction

Lignosulfonate, a soluble derivative of lignin, is a by-product of the acid sulfite pulp-making process. Millions of tons of lignosulfonate are produced yearly, and most of it is incinerated. Like lignin, lignosulfonate has a very complex macromolecular structure that is not yet completely understood. The molecules are spherical in shape with negatively charged sulfonate, hydroxyl, phenolic, and carboxyl groups (39). These characteristics have given lignosulfonate the capability to chelate metals, adsorb to surfaces, and potentially be involved in a variety of reactions in soils (20). There are several types of lignosulfonates including ammonium, magnesium, calcium, and sodium lignosulfonates. Ammonium lignosulfonate (ALS) is produced when the sulfuric acid in the liquor is neutralized with ammonia. ALS is known to improve the physical, chemical, and biological properties of saline and eroded soils and reduce the evaporative soil water loss (2, 3). In addition, lignosulfonate is known to serve as a carrier of micro- and macro-nutrients and increase their availability to and uptake by plants (1, 4, 20, 30, 32, 37–40).

We have been using the potato crop as a model system to investigate the effect of organic soil amendments on soilborne plant diseases (16, 18). In particular, we have examined the effect on two economically important diseases, potato scab and verticillium wilt. Potato scab is caused by several *Streptomyces* spp. (9, 19) of which *S. scabies* is the predominant causal agent (15). Depending on the *Streptomyces* strain and the soil environment, bacterial invasion can lead to shallow, raised, or deep-pitted lesions (9, 19). Verticillium wilt is caused by *Verticillium dahliae* (Kleb.). This disease results in early dying of leaves and stems leading to severe yield reductions in a variety of important crops worldwide (28). *Verticillium dahliae* and *Streptomyces* spp. can survive in soil for more than a decade and pose a long-term threat to potato production in infested soils (14, 36). Currently, there is no effective disease-control strategy available for verticillium wilt or potato scab. Fumigation with chemical sterilants such as methyl bromide, vapam, and chloropicrin can reduce both diseases. However, these chemicals are not always available or when used can lower populations of nontarget beneficial soil microorganisms, which could lead to increased pathogen populations as antagonism and competition are eliminated (26). Various soil amendments have been shown to influence the severity of potato scab and verticillium wilt (5, 11, 12, 17, 26).

The objectives of this study were to investigate the effects of ammonium lignosulfonate soil amendment on potato scab, verticillium wilt, tuber yield, soil chemistry, and soil microbiology in four commercial potato fields in Ontario.

Materials and methods

Field experiments

Experimental plots were established in scab-infested commercial potato fields in Ontario near Delhi (site K), Alliston (site V), Guelph (site W), and Palmer Rapids (site G) during 1998–2000. Physical characteristics of the soils from these sites are shown in Table 1. Chemical analyses of ALS used at the sites is shown in Table 2. Liquid ALS batches containing 50% solids were diluted 50:50 with water to assist in application. ALS was applied to the surface of the plots, and the plots were immediately rototilled or cultivated to a depth of 15 cm. All treatments at each site received the usual fertilizer regime used by each grower unless stated otherwise below. The plots at each site were treated the same in all other ways by the growers. Soil samples from each plot were collected by taking about 20 soil cores to a depth of 15 cm with a soil corer and mixing these together for a composite sample. Soil microbiology and chemistry was determined as described below. The toxicity of ALS to *V. dahliae* microsclerotia was determined using microsclerotia buried in nylon mesh bags (10) at each site. Severity of verticillium wilt and potato scab was determined as described below. Tubers were harvested from the middle two rows of each plot and tuber yield determined. Yield data were converted to tonnes per hectare by assuming 30 300 plants/ha based on 30-cm spacing of plants and rows 110 cm apart. Tubers less than 5 cm in diameter were not included in the yield. Marketable yield of tubers was determined by multiplying tuber yield by the percentage of tubers with <5% surface scab.

Site K was established in May 1998. This was the first site where we tested ALS (10 and 20 hL/ha, 6000 and 12 000 kg solids/ha, respectively). Since the higher concentration did not provide better disease reduction than the lower rate and was phytotoxic, only the lower rate was used in subsequent studies. Data for the 2× rate of ALS is not shown, because this treatment was not repeated at any of the other sites. Three replicate plots per treatment were set up in a randomized block design. Each plot was 3.7 × 7.6 m with a 3.3-m buffer zone between each block. There was also a 0.6-m buffer zone between each plot within a block. Potato tubers cv. Yukon Gold were planted by the grower (four rows per plot) 4 weeks after amendment. Because of extremely dry conditions, the ALS treatments prevented the emergence of the potato plants in 1998, and these plots had to be replanted 4 weeks later. Soil samples were taken at 0, 1, 2, 8, and 14 weeks after amendment incorporation and at harvest. Potato tubers cv. Yukon Gold were again planted in these plots in 1999 and 2000 without further addition of ALS. Soil samples were taken in the spring and fall of each

Table 1. Physical characteristics of the soils at the commercial potato fields used in this study.

Location	Type	Clay (%)	Sand (%)	Silt (%)	Organic carbon (%)	Water-holding capacity (g/100 g dry soil)	pH
Site K	Sandy loam	8	67	25	1.2	13	6.1
Site V	Loam	9	56	35	1.3	19	6.7
Site G	Sandy loam	6	85	9	1.0	18	6.3
Site W	Sandy loam	11	64	25	1.9	19	5.4

Note: Sites K, V, G, and W, are near Delhi, Alliston, Palmer Rapids, and Guelph, Ont, respectively. Clay, sand, and silt were determined using the hydrometer method (31). Organic carbon was determined using the Walkley–Black wet oxidation–reduction method (35). Water-holding capacity of soils was determined by placing soils on filter papers in funnels, saturating the soils with water, transferring the soils to an oven 24 h later, and calculating water loss. pH was determined from soil (8 g) – water (40 mL) mixtures shaken for 1 h.

Table 2. Chemical analyses of ammonium lignosulfonate (ALS) used in this study.

Location	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Total carbon (%)	Dry mass (%)
Sites K, V, W	2.6	0	0	46	50
Site G	3.7	0	0	45	35

Note: Data are expressed on the basis of fresh mass. Density of ALS was 1.2.

year. Data for the third year is not shown, because third year data was not collected at any of the other sites.

Treatments at site V, established in May 1999, included a control, liquid ALS (10 hL/ha, 6000 kg solids/ha), and dried ALS (7000 kg/ha, 6600 kg solids/ha) replicated four times in a randomized block design. Since the dried ALS did not provide better disease reduction than the liquid ALS, only the liquid ALS was used in subsequent studies. Data for the dried ALS treatment is not shown, because this treatment was not repeated at any of the other sites. Each plot was 5.5 × 9.1 m with a 0.6-m buffer zone between each block. Potato tubers cv. Snowden were planted by the grower (six rows per plot) 1 week after amendment. The control plots received the usual fertilizer regime used by the grower, while the ALS plots received everything but nitrogen. Soil samples were taken at 0, 2, and 4 weeks after amendment incorporation and at harvest. Potato tubers cv. Snowden were planted again in 2000 without further application of ALS. Soil samples were taken in the spring and fall. Potato leaves were collected from each of 25 plants from the middle two rows of each plot in mid-August in both 1999 and 2000 and bulked for macro- and micronutrient analyses by A&L Canada Laboratories East, Inc., London, Ont.

Site G was established in May 2000. Treatments included a control and ALS (14.4 hL/ha, 6000 kg solids/ha) replicated three times in a randomized block design. Each plot was 5.5 × 9.1 m with a 1.5-m buffer zone between each block. Potato tubers cv. Shepody were planted by the grower (six rows per plot) 1 week after ALS application. Soil samples were taken after amendment incorporation and at harvest. Potato tubers cv. Shepody were planted again in these plots in 2001 without further application of ALS. Soil samples were taken in the spring and fall.

Treatments at site W, established in May 2000, included a control and ALS (10 hL/ha, 6000 kg solids/ha) replicated four times in a randomized block design. Each plot was 3.7 × 9.1 m with a 3-m buffer zone between each block. Potato tubers cv. Yukon Gold were planted by the grower (four rows per plot) 1 week after ALS application. Soil samples were taken at 0, 1, 2, 3, 4, and 8 weeks after amendment incorporation and at harvest. Potato leaves were analyzed for macro- and micro-nutrients by A&L Canada Laboratories East, Inc., London, Ont., as described above. Tubers (15–20 from each plot) were also analyzed for nutrient content at harvest.

Soil microbial enumeration

The soil microbial population was determined by adding 10 g of soil to 90 mL of sterile water agar (0.1% mass/v) in a plastic pouch (17 × 30 cm). The pouches were heat sealed and shaken on an orbital shaker (200 r/min) for 2 h. The soil mixtures were then homogenized by placing the pouches in a Stomacher blender set on normal speed for 30 s. Serial 10-fold dilutions were prepared in saline solution (0.85% NaCl) and placed onto two media, which were incubated at room temperature (22°C). The number of bacteria that grew on potato dextrose agar medium were counted after 7 days. Fungal numbers were determined on rose Bengal medium after 4 days. Numbers of microorganisms were adjusted to represent colony forming units (CFU)/g dry soil.

Soil pH and ion analysis

Soil (8 g) and water (40 mL) were shaken on an orbital shaker (200 r/min) for 1 h and pH determined. The mixture was then centrifuged for 5 min in a microcentrifuge, and the supernatant analyzed for anions and cations using a DIONEX DX-100 ion chromatograph. Anions were separated using an IonPac AS12A column (4 × 200 mm) with 2.7 mM Na_2CO_3/0.3 mM $NaHCO_3$ buffer (1.5 mL/min). Cations were separated using an IonPac CS12A column (4 × 250 mm) with 22 mM methane sulphonic acid (1.0 mL/min). Samples and standards (12.5 µL) were injected with concentrations in the 1–150 ppm range. Peaks were measured with an ion conductivity detector and quantified using Millenium TM software. All data were expressed as mg/kg dry soil.

Verticillium dahliae germination assay

Microsclerotia were produced as described by Hawke and Lazarovits (10). The microsclerotial germination assay was then carried out using a mesh bag technique as described by Tenuta (33). Microslcerotia (75–106 µm diameter, about 15 mg) were dispersed in crushed silica sand powder (5 g)

Table 3. Effect of ammonium lignosulfonate (ALS) soil amendment on potato scab in four commercial potato fields in Ontario.

Treatment*	Scab index†	Distribution of tubers (%) with surface area lesion coverage of		
		0–5%	6–35%	36–100%
Site K, first year				
Control	3.7±0.5 a	3	69	28
ALS	0.7±0.4 b	85	15	0
Site K, second year				
Control	2.3±0.6 a	40	49	11
ALS	0.1±0.0 b	97	3	0
Site V, first year				
Control	2.3±0.5 a	33	62	5
ALS	1.2±0.4 b	69	31	0
Site V, second year				
Control	0.4±0.2 a	94	6	0
ALS	0.2±0.1 a	99	1	0
Site G, first year				
Control	3.0±0.9 a	26	53	21
ALS	1.0±0.3 b	88	12	0
Site G, second year				
Control	3.8±0.6 a	7	54	39
ALS	1.1±0.3 b	72	26	2
Site W, first year				
Control	2.0±0.2 a	35	64	1
ALS	0.6±0.1 b	89	11	0

Note: Means (±SE) followed by different letters within each site and year are significantly different ($P < 0.05$, Student–Newman–Keuls method).

*A single application of ALS (about 6 t solids/ha) was applied in the spring of the first year at each site. One additional potato crop was planted at sites K, V, and G.

†One hundred tubers from each of three (sites K and G) or four (sites V and W) replicate plots per treatment were rated for scab on a scale of 0–6 based on the percentage of tuber surface covered with scab lesions: (0) 0%, (1) trace to 5%, (2) 6–15%, (3) 16–25%, (4) 26–35%, (5) 36–60%, and (6) 61–100%.

of similar diameter and about 25 mg of the mixture placed in polyester mesh (Saatilene High Tech Fabric, 48 µm pore size; SAATI S.p.a., Como, Italy) bags (about 15 × 20 mm diameter). The bags were attached to wooden stakes and placed in the plots immediately after incorporation of ALS, burying the bags to a depth of about 7 cm. The bags were removed 4 weeks later, air dried, and dispensed with an Anderson air sampler onto a Petri dish containing soil pectate tergitol agar. The dishes were incubated for 2 weeks in the dark at 24°C. Germination of microsclerotia was determined as the number of microsclerotia of 100 examined that formed colonies.

Disease assessment

Incidence of *V. dahliae* was determined by collecting a leaf petiole from the lower portion of each of 25 consecutive potato plants in the middle two rows of each plot in mid-August. The petioles were surface sterilized by placing them in 1.5% sodium hypochlorite for 2 min. Three sections from each petiole were placed onto a semi-selective medium (10), the plates were incubated at 24°C in the dark for 2 weeks, and the presence or absence of *V. dahliae* was determined microscopically. A plant was scored as infected if *V. dahliae* was present in just one petiole section.

The severity of potato scab was evaluated using a rating scale of 0 to 6 based on the percentage of tuber surface covered with scab lesions: (0) 0%, (1) trace to 5%, (2) 6–15%, (3) 16–25%, (4) 26–35%, (5) 36–60%, and (6) 61–100%. One hundred tubers were randomly selected from each of the replicate plots per treatment. Individual tubers were examined and placed in one of the seven categories with the aid of a disease assessment key showing percent surface areas covered with lesions.

Statistical analysis

Data were analyzed using Jandel SigmaStat statistical software. Percentage data were tested for normality and were arcsine transformed before analysis, if required. The ALS treatments reported in this paper were part of larger experiments at sites K and G. Analysis of variance and multiple comparison methods were performed using all treatments at these sites.

Results

Effect on potato scab

Potato scab severity was significantly reduced (50–80%) by ALS treatment in the year of application at all sites as compared with the control treatments (Table 3). There was significantly less scab disease present for the second potato crop at sites K and G. Scab severity for the second year at site V was still lower in the ALS treatment compared with the control, but the differences were not statistically significant. There was low disease pressure at site V in the second year, and none of the treatments, including the control, had any significant scab incidences (Table 3).

Effect on verticillium wilt and *V. dahliae*

The number of *V. dahliae* infected plants was significantly decreased (40–50%) by ALS treatment at all sites in the year of application and for one additional crop at site K as compared with the control treatments (Table 4).

The viability of *V. dahliae* microsclerotia buried in ALS-treated soils was found to be the same as the controls for all sites (data not shown). The colonies derived from the microsclerotia recovered from ALS plots, however, were often much smaller than from untreated plots, because the growth of the microsclerotia was inhibited by other fungi that were coisolated with the microsclerotia. Some of these fungi have been identified as *Trichoderma* spp.

Effect on total and marketable yield

Addition of ALS significantly increased total tuber yield at site G only and only in the year of application (Table 5). Yield at this site was increased 2.5 times over that of the control treatment. At site V, a yield increase for ALS treatment of about 30% over the control was found in the year of application (Table 5). While this increase was not statistically significant, it was noteworthy, because no nitrogen fertilizer was applied to the ALS treatment at this site. A decrease in yield following ALS treatment was found only at site K (Table 5). This reduction in yield was partly due to a combination of ALS phytotoxicity and extremely dry con-

Table 4. Effect of ammonium lignosulfonate (ALS) soil amendment on verticillium wilt in four commercial potato fields in Ontario.

	Verticillium wilt (%)[†]	
Treatment*	First year	Second year
Site K		
Control	28±1 a	22±3 a
ALS	16±7 b	8±5 b
Site V		
Control	87±1 a	64±5 a
ALS	51±11 b	73±11 a
Site G		
Control	89±1 a	nd
ALS	43±13 b	nd
Site W		
Control	59±7 a	—
ALS	34±7 b	—

Note: Means (±SE) followed by different letters within each site and year are significantly different ($P < 0.05$, Dunnett's method). nd, not determined.

*A single application of ALS (about 6 t solids/ha) was applied in the spring of the first year at each site. One additional potato crop was planted at sites K, V, and G.

[†]Percentage of plants infected with *V. dahliae*. Petioles were sampled in mid-August from 25 plants in the middle two rows of each of three (sites K and G) or four (sites V and W) replicate plots per treatment.

Table 5. Effect of ammonium lignosulfonate (ALS) soil amendment on tuber yield in four commercial potato fields in Ontario.

Treatment*	Total tuber yield (t/ha)	Marketable yield (<5% scab; t/ha)
Site K, first year		
Control	16±0.5 a	1±0.2 a
ALS	13±1.3 a	12±2.4 b
Site K, second year		
Control	9±0.7 a	3±0.9 a
ALS	7±0.7 a	7±0.6 a
Site V, first year		
Control	21±1.5 a	7±3.1 a
ALS	26±1.3 a	18±5.5 b
Site V, second year		
Control	14±1.7 a	14±1.7 a
ALS	17±2.6 a	17±2.5 a
Site G, first year		
Control	8±2.5 a	3±1.3 a
ALS	21±2.1 b	18±2.5 b
Site G, second year		
Control	14±1.0 a	1±0.6 a
ALS	11±1.3 a	8±3.9 b
Site W, first year		
Control	14±1.8 a	5±1.0 a
ALS	14±2.1 a	12±2.0 b

Note: Values are means ± SEs. Values followed by different letters within each site and year are significantly different ($P < 0.05$, Dunnett's method). Means were calculated from three (sites K and G) or four (sites V and W) replicate plots.

*A single application of ALS (about 6 t solids/ha) was applied in the spring of the first year at each site. One additional potato crop was planted at sites K, V, and G.

ditions. The potato plants and weeds in the ALS-treated plots were killed as a result of a crust that formed on the surface of the soil. This crust acted as a barrier to moisture penetrating into the soil and plants emerging through it. At least part of the lost yield was the result of the fact that the ALS plots were replanted 4 weeks after the initial planting. No ALS phytotoxicity was observed at any of the other three sites tested.

Marketable yield (tubers with <5% surface scab) was significantly increased three- to seven-fold by all ALS treatments at all sites in the year of application as compared with the control treatments (Table 5). Marketable yield was still consistently higher in subsequent crops at all sites but only statistically higher at site G. The potential increase in gross income resulting from the increased marketable yields is shown in Table 6.

Effect on soil pH and ion concentrations

Most of the ALS treatments caused an immediate reduction in soil pH of 0.4–0.6 units except at site W, where ALS had no effect (data not shown). At site W, there was essentially no difference in soil pH between the ALS and control treatments for the whole season. Soil pH of the ALS treatments at sites V and K remained 0.2–0.5 units lower than the control treatments for a second season at both sites. The difference in pH between the ALS and control treatments at site G increased to 1 pH unit by the first fall and remained so for the second season as well.

Addition of ALS generally caused an immediate increase in the amount of ammonium and sulfate ions in soil at all sites (data not shown). For example, at site K, the ALS treatment increased the amount of ammonium to 50 mg/kg soil compared with zero in the control. It raised the amount of sulfate to 75 mg/kg soil compared with the control at 25 mg/kg soil. No elevated levels of nitrite were detected in the weeks following application (data not shown). The amount of nitrate in the ALS treatment was double that of the control after a few weeks. Amounts of these ions returned to control levels by the end of the season.

Effect on soil microbial populations

All ALS treatments increased fungal and bacterial numbers in soil two- to eight-fold over control treatments at all sites in the year of application (data not shown). Numbers returned to control levels by the end of the first year except at sites K and G, where fungal numbers remained fivefold higher for a second year. In addition to increased microbial numbers, shifts in the populations of bacteria and fungi occurred (data not shown). For example, *Trichoderma* spp. often became one of the dominant fungal genera present after application of ALS. Another known biological control agent, *Talaromyces flavus*, was also isolated.

Effect on leaf and tuber nutrient content

Leaves collected in mid-August and tubers from site W were analyzed for nutrient content. Levels of macro- and micro-nutrients were similar in the control and ALS-treated plots except for manganese (data not shown). Manganese content of leaf tissue from the ALS-treated plots was 1200 mg/kg compared with 400 mg/kg for leaf tissue from

the control treatment. Manganese content of tubers was 12 mg/kg in the ALS treatment compared with 2 mg/kg in tubers from the control. Leaf tissue was also analysed for both the first and second season at site V (data not shown). At this site, there was not any difference in nutrient content between the control and ALS treatments, even for manganese.

Discussion

The results of this study clearly demonstrated that incorporation of ALS into soil significantly reduced the severity of potato scab by 50–80% and verticillium wilt by 40–50% as compared with control treatments in the year of application at all four commercial potato fields tested. The single application of ALS significantly reduced the severity of potato scab for an additional year at sites K and G. The number of *V. dahliae* infected plants was significantly less than the control for a second year at site K. A third crop of potatoes was planted at site K. The number of *V. dahliae* infected plants was still significantly less than the control, but the scab severity was not significantly different from the control (data not shown). We also tested a higher rate of liquid ALS (20 hL/ha) at site K, and a dry formulation of ALS at site V. Both these treatments were as effective in reducing the severity of potato scab and the number of *V. dahliae* infected plants as the regular ALS treatment (data not shown).

The soils at the four sites used in this study had different soil characteristics. For example, the organic carbon content ranged from 1 to 2%, and the pH ranged from 5.4 to 6.7. Thus, the efficacy of ALS to reduce potato scab and verticillium wilt in this study was not site or soil specific, unlike other amendments we have tested, which were greatly influenced by organic matter content and soil pH (5, 6, 33, 34).

Previous studies have shown that high nitrogen-containing amendments such as chicken manure, meat and bone meal, and soymeal can reduce these diseases to near-zero levels in the year of application (5, 17). However, these diseases returned to control levels or higher in subsequent years in these studies. In this study, disease reduction by ALS was not quite as dramatic in the year of application, but disease severity remained lower than control treatments in subsequent years. Since the disease incidences changed over the years of testing, the degree of protection conferred in the second year was not always obvious.

Three of the four sites used in this study received the grower's usual fertilizer regime along with the ALS. At site V, no additional nitrogen fertilizer was added along with the ALS. The yield for the ALS treatment at site V was the same as the control indicating that the ALS provided sufficient nitrogen for the potato crop. Thus, it is important to consider the nitrogen contribution of ALS at least during the year of application. Yield at site K, however, was reduced in the year of application because of phytotoxicity of the ALS at that site. Doubling the rate of ALS at this site reduced yield by 50% in the year of application, and yield was still reduced in the second year compared with the control treatment (data not shown). ALS used at rates above 6 t/ha of solids can be toxic to crops under certain environmental conditions. Any phytotoxicity observed at rates below 6 t/ha was transitory and short lived. Considerable work needs to be carried out as how to best exploit the benefits of such amendments in a cropping system.

Table 6. Effect of ammonium lignosulfonate (ALS) soil amendment on the gross income to growers.

	Income above control ($/ha)*		
Location	First year	Second year	Total
Site K	1810	660	2470
Site V	1810	490	2300
Site G	2470	1150	3620
Site W	1150	—	1150

Note: A single application of ALS (about 6 t solids/ha) was applied in the spring of the first year at each site. One additional potato crop was planted at sites K, V, and G.

*Values were determined by taking the difference in marketable tuber yield (t/ha) between the control and ALS treatments (Table 5) and multiplying by $165/t.

Marketable yield (tubers with <5% surface scab) was significantly increased three- to seven-fold at all sites by application of ALS. Marketable yield remained consistently higher in subsequent crops as well. We calculated that the gross income above the control treatments at these sites could translate into $1150–2470/ha during the first year and $490–1150/ha in the second year (Table 6). The cost of having ALS (50% solids) delivered to Ontario potato fields was about $100/hL when we started this study and is currently estimated to be $150–200. At $200/hL, the cost of applying 10 hL/ha would be about $2000/ha plus the farmer's application costs. Thus, at the current price, application of ALS to potato fields to reduce these diseases is probably not economically viable. The economic return of ALS treatment would be improved if increased marketable yields can be demonstrated to last longer than 2 years.

We do not know how ALS reduced the severity of potato scab and verticillium wilt in these four potato fields. We do know that reduction in verticillium wilt was not due to toxicity of ALS to *V. dahliae*. The viability of microsclerotia buried in the plots immediately after ALS application was not reduced compared with control treatments. We have not yet determined if ALS is toxic to *S. scabies* in soil. Nematode populations can affect verticillium wilt (28), but nematode numbers in the fields in this study were low (data not shown) making it impossible to assess the effect of ALS on nematodes or their role in verticillium wilt in this study. Davis et al. (7, 8) showed that the incidence of verticillium wilt decreased after 2 years of green manuring although inoculum levels of the pathogen stayed the same, or in some cases increased two- to four-fold. They attributed disease reduction to biological control. Increased soil biological activity and stimulation of biological control after application of organic amendments to soil is one mechanism that can reduce soilborne diseases. Both competition and antibiosis have been implicated in biological control of potato scab (25). In this study, incorporation of ALS into soil caused an increase in most microbial numbers and diversity, particularly that of fungi. Colonies of *V. dahliae* derived from microsclerotia recovered from the ALS plots were often much smaller and heavily infested with other competing fungi than from untreated plots. Among the fungi that increased in numbers, we have isolated known bi-

ological control agents such as *Trichoderma* spp. and *Talaromyces flavus*. This aspect is under investigation.

Reduction in soil pH has been shown to reduce potato scab severity (13). Addition of ALS to soil usually changed soil pH as well as the concentrations of various ions in the soil, which can also have an impact on the incidence of verticillium wilt and potato scab (13, 27). At site G, where ALS reduced the soil pH from 6.2 to 5.2, it may have been a disease moderating factor. However, ALS had no significant effect on soil pH at site W, and thus, pH could not explain the disease reduction at this site. The levels of sulfur and ammonium derived from ALS increased in all the soils, which have been shown to reduce scab (13). Nitrogen transformation products, such as ammonia and nitrous acid, can also play a role in reducing the population of plant pathogens, but neither soil pH nor concentrations of ammonia or nitrite were conducive to the formation of these toxicants. In fact, ammonia volatilization and nitrification have been found to be inhibited by ALS (20, 29, 39).

Manganese has also been shown to help control potato scab (13). Addition of ALS to site W increased the concentration of manganese in both leaf tissue and tubers in the year of application. Increased levels of exchangeable manganese may be directly toxic to pathogens or may increase the resistance of plants to pathogen attack by improving metabolism (21–24). If manganese was a factor involved in scab reduction at site W, it appeared not to be a factor at site V, however, where no elevated manganese levels in leaf tissue were found.

Davis et al. (8) examined 100 commercial potato fields for soil, disease, and yield variables and found that the factors most closely related to soil integrity (organic matter, organic nitrogen, and increased nutrient availability) were associated with reduced diseases and higher tuber yields. Factors related to loss of soil integrity (sodium and reduced nutrient availability) were related to increased disease and reduced yield. The authors concluded that organic matter is one factor that can be manipulated to improve potato crop health and productivity. ALS is a promising material for increasing organic matter and for changing the disease profile of a potato soil. Its use in a disease control strategy for potato scab and verticillium wilt needs to be further validated. In this study, we used four different batches of ALS applied in three different years to four potato fields. All combinations reduced disease severity in the year of application and reduced disease levels remained in subsequent years at some sites. Work is continuing toward determining the mode(s) of action of ALS, effect on other plant pathogens, and development of ALS into a formulated product for management of soilborne diseases and other agricultural uses.

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