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AGRONOMICS

Thatch control in bentgrass greens

The influence of cultural & chemical controls on rootzone nutrients

By Lloyd M. Callahan, University of Tennessee

Thatch accumulation naturally occurs at many managed turfgrass sites, however if it accumulates excessively it can seriously impede the health and long-term survival of densely grown turfgrasses such as on putting greens, so controlling thatch buildup is important. Thatch is defined as a tightly intermingled layer of dead and living stems, leaves, and roots that accumulates between the green vegetation and the soil surface.

Accumulation of thatch is a direct result of intensive management which causes the rate of plant organic matter (OM) accumulation to exceed the natural degradation process. Thatch accumulation has been reported to be favored by acid soils except where calcium (Ca) was applied. Thatch accumulation rate was found to be approximately twice as great below pH 4.0 as above 5.0. The presence of Ca, applied as calcium hydroxide, and the suppressive effect it has been shown to have, suggests that Ca might be a major factor involved in thatch decomposition under acidic conditions.

There are considerable differences of opinion as to what cultural practices, chemical treatments, or treatment combinations are most effective in controlling thatch when highly maintained at sites like a golf course. These differences are broad-based and cover the spectrum of management strategies.

Some researchers have observed that mechanical practices like core aerification are effective in reducing thatch alone or in combination with either vertical mowing or limestone applications. Others have reported little or no benefit of coring on thatch levels. Vertical mowing has also been shown to effectively reduce thatch in some studies, but has been ineffective in others. Likewise, frequent topdressing with sand or a high sand content soil mixture reduced thatch when performed alone or in combination with coring and vertical mowing, while others have reported no effect of topdressing on thatch.

Limestone has been used in some studies to maintain a favorable thatch pH to enhance microbial activity to speed thatch decomposition, but in still other studies, limestone application had no effect on thatch. Even extra potassium (K) and wetting agent treatments have been tested, but were also reported to be ineffective in reducing thatch.

This variance in results was less surprising when you consider that all of these previous tests were conducted on a variety of grasses grown on soil rootzones under an assortment of management strategies - from six tests on bermudagrass greens and one lawn to three on bentgrass greens, one on a bentgrass fairway, and two on Kentucky bluegrass lawns.

To bring some semblance of order to this diversity of hosts, management practices, and

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results we conducted a six-year study at the University of Tennessee. We compared the effectiveness of the most commonly used mechanical practices and certain chemical/nutrient treatments in controlling thatch on a creeping bentgrass green constructed to USGA specifications. Determinations were also included to assess the influence of these mechanical and chemical/nutrient treatments on the content of selected nutrients and the pH level of the USGA green rootzone.

Treatments Used

Cultural practices and chemical/nutrient control treatments were conducted on a Penncross bentgrass research green constructed at Knoxville, TN, expressly for the purpose of conducting these thatch control studies. The green was constructed to 1973 USGA specifications (9), except that the 1.5 inch thick intermediate coarse sand layer was omitted. An initial laboratory analyses of the 12-inch rootzone showed a composition of 95.3 percent sand (63 percent fractions between 0.25- and 0.5-mm diameters), 3 percent silt, 1percent clay, and 0.7 percent OM by weight. Analysis of the rootzone mixture also showed 36 percent capillary and 16 percent noncapillary pores, a bulk density of 1.41 g cm3, and infiltration and percolation rates of 9 inches per hour.

Dolomitic limestone and a 6-12-12 analysis fertilizer were thoroughly mixed into the rootzone giving an initial soil test of the top 6 inches of a pH 6.6, 60 lb/A phosphorus (P), 190 lb/A K, and 3563 lb/A Ca. Nitrogen (N) was ammonium nitrate, P was superphosphate, and the K was muriate of potash. Limestone treatments were not made after the initial application.

The green was fumigated with methyl bromide to eradicate nematodes, fungi, insects and weed seed, and seeded with Koban treated Penncross bentgrass in September. The first research treatments were made the following March.

Maintenance fertilization and height of mowing was uniform across the green. Nitrogen rates and mowing height were not used as treatment variables. Bentgrass annual maintenance fertilization (excluding extra K that was used as one of the main experimental treatments) totaled 263 lb/A N, 38 lb/A P, and 146 lb/A K.

Nitrogen applications were divided equally among March, April, May, September, October and November of each year. Annual phosphate and potash applications were divided equally among March, April, September, and October.

The green was mowed daily, Monday through Friday, with a greensmower at 6-mm-cutting height with clippings caught and removed. The green was irrigated with 1-inch of water Monday, Wednesday, and Friday, unless it rained, between June and September.

Fungicides and insecticides were applied as needed to control diseases and insects. No additional chemical or mechanical thatch control maintenance treatments were applied to the green throughout the entire period of these investigations except those applied as treatments.

Annual repeat test treatments, and their respective abbreviations in brackets, were:
(1) vertical mowing, 4 times (VM 4x)
(2) vertical mowing, eight times (VM 8x)
(3) core (or coring) aerification, four times
(4) vertical mowing plus coring, both four times (VM + core)
(5) a wetting agent, seven times (Wet Ag)
(6) extra K, four times (K)
(7) hydrated lime, four times (L)
(8) K plus lime, both four times (K+L)
(9) vertical mowing plus extra K, both four times (VM+K)
(10) vertical mowing plus lime, both four times (VM+L) and
(11) vertical mowing plus extra K and lime, all applied four times per year (VM+K+L).

Three sub-plots crossed the main treatments and consisted of sand topdressing three (Tpd 3x) and six (Tpd 6x) times per year, and a no topdressing strip. Thus, each replication comprised a total of 36 individual plots.

Bentgrass stand density determinations were by monthly visual assessments in each sub-plot based on 0 to 100 percent. Main plot treatments of vertical mowing were performed with solid blades spaced one inch apart, slicing just above the soil surface, and with the raised plant debris removed immediately with a power vacuum. VM treatments were done in March, May, September, and October. Treatments applied eight times per year were done in March, April, May, June, August, September, October, and November.

Coring was performed with a power core aerifier with 0.25 inch diameter tines, two inches apart, and cutting to a depth of approximately three inches. Cores were allowed to air-dry for several minutes and then removed with a power vacuum. Coring treatments were applied in April, May, September, and October.

A non-ionic Wet Ag (Aqua-Gro) was applied annually in March, April, May, June, September, October, and November in a water dilution. Extra K, as muriate of potash, was applied at 36 lb/A in March, April, September, and October to provide 144 lb/A K annually.

Hydrated lime was applied in March, April, September and October at 218 lb/A in a water suspension.

A soil test was conducted at the end of the six-year test period at the 0 to 3-inch and 3- to 6-inch rootzone depths for determinations of Ca, K, P, and pH. Topdressing treatments applied three times per year were done in April, May, and September. Topdressing applied six times per year were done in April, May, June, August, September, and October.

Thatch depth was measured with a thatchmeter in June, August, and November for all six years of the study. The thatchmeter was selected over the ruler and total OM by loss-on-ignition methods because it proved to be the most sensitive, consistent, reliable, and fastest of the three methods investigated in a previous comparative study (4). The thatchmeter used was the "Thatchmeter II" developed by Volk.

Earthworm counts, pesticide treatments, other than maintenance treatments, and variable N rates were not used. Furthermore, the potential for confounding influences from surface and soil feeding insects was removed from these studies with the use of three different insecticides.

Thatch development at the test site - All 13 individual and combination treatments for thatch control began approximately seven months (in March) after construction was completed and the green was seeded to Penncross bentgrass (the previous September). Depth of thatch was approximately 3.5 mm when treatments began.

Thatch accumulation was variable between replications as measured by both the ruler and thatchmeter during the first three years of the newly constructed green as thatch began its initial buildup. By year four, all ruler and thatchmeter readings appeared consistent among samples within plots and between replications. Thus, discussion of results will only be presented for the last three years of the six-year study. Ruler measurements are only shown for consistency from the start of the study. Thatch depth by ruler measurements in non-treatment control (check) plots in March was 10.2, 12.7, and 14.8 mm for years 4, 5, and 6 respectively.

The University of Tennessee conducted a six-year study to compare the effectiveness of commonly used mechanical practices and selected chemical/nutrient treatments in controlling thatch on a creeping bentgrass green constructed to USGA specifications.

Thatch depth measurement values were consistently higher in June for every main plot treatment than corresponding values taken in November. Moisture content of grass leaves and the thatch was low in August and resulted in erratic results, probably due to higher temperatures and drier conditions, hence August was judged a poor time to make accurate measurements (see Table 1).

Thatch Control

The results listed in Table 1 of measurements conducted in June show the most effective main treatment methods of reducing thatch level (5.68-6.21 mm) were:

- VM alone at both 4 and 8x/yr
- VM + core, both conducted 4x/yr.

Thatch reduction increased as frequency of Tpd increased, except under the three K treatments regimen (see Table 2). AT the higher amount of Tpd (6x), treatments receiving extra K (VM+ K + L, K + L, K) appeared by visual observations to result in an increase in size, and possibly numbers, of stolons which may have resulted in an increase in thatch depth readings.

Least squares analysis showed no difference between VM 4x and 8x and VM + Core treatments under no Tpd. However, all main plot treatment effects exhibited lower values than untreated plots, except WetAg under 3x and 6x Tpd.

When lower amounts (3x) of Tpd was applied (April, May, and September) results were confounded and there were no differences among most main plot treatments, except for the individual treatments of Core, L, and Wet Ag (Table 2). Again there was no difference between VM 4x and 8x and VM + Core, but the confounding effect of K was removed and the non-significant main plot treatments included VM + L, instead of VM + K + L. Hydrated lime treatments did not influence thatch depth. The greatest decrease in thatch depth were observed on turf receiving large amounts of Tpd treatment (6x) plus VM (4x and 8x) and VM + Core (Table 2).

When comparing least squares analysis for Tpd frequency, both small (3x) and large (6x) amounts of Tpd significantly reduced thatch, as compared with no Tpd (Table 3). The largest amount of Tpd (6x) decreased thatch the most.

Lowest non-significant levels of thatch, or the highest level of thatch control, from cultural treatments resulted following VM 4x or 8x/yr and VM + coring. Tpd 3x or 6x/yr also effectively prevented thatch buildup.

Effects of Chemical/Nutritional Treatments on Thatch and rootzone nutrient levels The following discussions regarding levels of Ca, K, and P refer only to nutrient amounts in the rootzone reflected in the soil samples. No distinction is made as to what portion were removed by the plant nor what portion was lost through leaching. No leaf tissue analyses were conducted.

Potassium Effects

Several researchers reported that K did not influence thatch accumulation. However, they conducted their studies for only 1 year and indicated that K might affect thatch accumulation over a period of years. Extra K treatments were included in this study not only to determine if K contributes to either an increase or decrease in thatch buildup, but also to determine if K has any influence on bentgrass recovery following mechanical treatment thinning for thatch control.

The initial soil test K level was 190 lb/A, plus six years of annual maintenance fertilizer providing 873 lb/A, combined with six years of extra K treatments totaling 857 lb/A, ending with a grand total of 1,920 lb/A in extra K treatment plots. The grand total of K applications in plots not receiving extra K was 1,063 lb/A.

A soil sampling at the end of the study from the 0 to 3-inch depth of the main treatment plots showed a K range of 133 to 83 lb/A for plots receiving extra K and a range for all other main treatment plots of 87 to 57 lb/A (see Table 4). On average K at the extra K plots after six years was 110 lb/A and showed a loss of 94 percent K from leaching and clipping removal in the 95.3 percent sand content USGA green. An average of all other main treatments not receiving extra K was 67 lb/A and also showed a 94 percent loss. Loss of K appeared to be proportionate to the amount present. A soil test of available K in the extra K plots would rank in the mid-medium range and available soil K in all of the other main treatment plots ranked in the upper low range.

Soil test from the 3 to 6-inch depth of the main treatment plots showed a K range of 83 to 50 lb/A for plots receiving extra K and a range of all other main treatment plots of 44 to 40 lb/A (Table 4). An average of the extra K plots was 63 lb/A or a 97 percent loss and the average for all the other main treatments was 43 lb/A or a 96 percent loss. Again, K loss appeared to be proportionate to the amount present. Available K in the extra K plots ranked in the upper low level soil test and for all the others, in the mid-low soil test range.

Previously it has been recommended that K levels in USGA specification greens be increased during the establishment period, and for the first few growth years, do to the high loss rate under the very low cation exchange capacity (CEC) sand-based conditions. Although the K loss was extremely high in this study, the bentgrass showed no deficiency symptoms. Apparently the grass was still able to satisfy its needs for K from the much higher measured K concentrations in the 0 to 3-inch rootzone depth (Table 4), which also is the depth containing the highest percentage of the grass's root system.

As mentioned under "Thatch Control", increasing Tpd (6x) generally resulted in decreased thatch, except with three of the four treatments involving extra K which exhibited increased thatch measurements (Table 2). Because of the longevity of this study, fungicides were used regularly throughout the six-year period to control all fungal activity to remove the confounding variability of disease incidence. Although K influence on disease resistance could not be determined, other physiological influences were observed. Bentgrass receiving extra K did not appear to maintain stand density, or influence rate of stand recovery following mechanical treatment thinning, any better than bentgrass mechanically thinned and not receiving extra K (Table 5). Thus, results of extra K treatments generally agreed with conclusions by other researchers.

Phosphorus Effects

The beginning soil test level of P was 60 lb/A, that plus six years of annual maintenance fertilizations which added 225 lb/A yielded total applications of 285 lb/A. The soil test at the end of the 6 years showed a P range of 83 to 38 lb/A in the 0 to 3-inch depth, an average of 55 lb/A, and 36 to 22 lb/A in the 3 to 6-inch depth, and average of 30 lb/A, for the main treatment plots (Table 4). Loss of P in the 0 to 3-inch depth was 81 percent and 90 percent in the 3 to 6-inch depth. Levels of P were significantly higher in the 0 to 3-inch depth in five of the six plots receiving extra K and L (K, K +L, K + L + VM, L, L + VM). Levels of P in the 3 to 6-inch depth was almost half that occurring in the 0 to 3-inch depth. Both soil test showed levels classified as high available P. Although the average P loss from the top 6 inches of this very high porosity green was 86 percent, the residual P level was still more than adequate for plant needs. As were recommendations for K, recommends for increasing P levels in USGA greens during establishment to assure sufficient levels for root development and off-set leaching losses and plant removal have been made. There were no indications that P level played a significant role in the increase or decrease of thatch. Although mechanical treatments of VM 4x and 8x, Core, and the chemical treatment of Wet Ag did reduce P levels significantly in the 0 to 3-inch depth (Table 4), there were no significant detrimental effects evident in bentgrass sod density (Table 5).

TABLE 1. THATCH MEASUREMENT WITH THE THATCHMETER

Thatch Measurement Means and Standard Errors for Main Thatch Control Treatments in June and November for thatch measurements with the thatchmeter for the last three years of a six-year study.

	Thatch measurement means	
Main Treatments	June	November
	mm	
V + Core	5.68	5.04
VM 4x	6.20	5.07
VM 8x	6.21	4.99
VM + K	6.66	5.80
VM + K + L	6.75	5.23
K	6.80	5.72
VM + L	6.80	5.30
K + L	6.95	6.07
Core	7.36	5.64
Check	7.73	6.40
L	7.96	5.60
Wet Ag	7.99	5.99

Standard errors for least square means, as determined by general linear mixed models analysis, for all means = 0.36.

Hydrated Lime, Calcium, and pH Effects

Researchers have conducted several studies to evaluate agricultural limestone ($CaCO_3$) for thatch control. In two studies, it was suggested that limestone may be effective in reducing thatch, but in other studies, limestone treatments were not effective. However, it was reported that the presence of Ca as hydrated lime ($Ca(OH)_2$) suggested that Ca may be a contributing factor in thatch decomposition.

In this study, dolomitic limestone ($CaCO_3$ $Mg CO_3$) was incorporated into the rootzone just before bentgrass seeding. No limestone was used thereafter, only selective applications of hydrated lime were made four times per year for six years in four main treatment plots.

The initial level of Ca in the top six inches of the rootzone, following a dolomitic limestone incorporation, was 3563 lb/A. With the addition of Ca as hydrated lime four times per year for six years in four main treatment plots, total background plus treatment Ca was 6,063 lb/A. The soil test at the end of six years showed an average level of Ca for main treatments in the 0 to 3-inch depth to be 2642 lb/A (Table 4), which was a 56 percent loss of Ca. Plots receiving L and extra K (L, K + L, L + VM, K + L + VM), with a pH 7.3, resulted in only a 53 percent Ca loss. The mean Ca level for main treatments in the 3 to 6-inch rootzone depth was 2980 lb/A, a 51 percent Ca loss.

However, plant needs for Ca is approximately 500 lb/A (12), thus more than adequate levels of Ca were available in the rootzone.

The starting pH of the top 6 inches of the rootzone was 6.6. The ending soil test pH after six years in the 0 to 3-inch depth showed a significant increase to 7.3 for the four main treatments involving lime (L, K + L, L + VM, K + L + VM) (Table 4). The pH for all other main treatments ranged from 6.8 to 6.4. Rootzone pH for all main treatments in the 3 to 6-inch depth ranged from 7.5 to 7.2, except for VM 4x which was significantly lower at 7.0 (Table 4).

TABLE 2. THATCH MEASUREMENT WITH THE THATCHMETER

Thatch measurement means and standard errors for main thatch control treatments by topdressing interactions for thatch measurement with the thatchmeter for the last 3 years of a 6-year study.

	Thatch depth for topdressing frequency		
Main Treatments	none	3x	6x
	mm		
VM + Core	6.06	5.32	4.70
VM 4x	6.43	5.56	4.90
VM 8x	6.62	5.44	4.75
VM + K + L	6.82	5.46	5.70
VM + L	6.95	5.87	5.33
VM + K	7.27	5.85	5.57
Core	7.45	6.40	5.66
K + L	7.47	5.97	6.09
K	7.58	5.20	6.01
L	7.80	6.63	5.91
Wet Ag	7.93	6.84	6.20
Check	8.29	6.76	6.14

Standard errors for least square means, as determined by general linear mixed models analysis, for all means = 0.40.

However, means of bentgrass stand density exhibited no visible effects which could be attributed significantly to these pH levels (see Table 5).

Bentgrass receiving L and no Tpd showed no evidence of reduced stand density that could be attributed to Ca deficiency after 5 and 6 years (Table 5) since Ca deficiency did not occur (Table 4). However, under both Tpd frequencies (3x and 6x), by year five, the lowest creeping bentgrass stand densities were recorded in the L plots (91 and 92 percent density), although by year six stand densities within Tpd frequencies were 99 and 100 percent. Results of L treatments indicate that L, at the rates used, had no significant benefits in controlling or reducing thatch, apparently because of the high soil pH levels which ranged from pH 6.4 to 7.3 in the 3 to 6-inch rootzone depth (Table 4).

Wetting Agent Effects

Two previous researchers used a Wet Ag and reported that it was ineffective in reducing thatch. The same non-ionic Wet Ag used in this study, but at a much higher rate than recommended by the manufacturer. Results indicated that Wet Ag increased thatch accumulation, regardless of whether Tpd was applied or not (Tables 1 and 2). It was previously suggested that Wet Ag treatments tend to promote quicker drying of the turf surface resulting in a interruption of the decay process thus enhancing thatch buildup. This may explain the deeper thatch layer observed where Wet Ag was applied in our year five.

What part, if any, the high porosity green rootzone influenced Wet Ag effects could not be ascertained. However, bentgrass stand densities were 99 and 100 percent for year five and all were 100 percent for year six in untreated plots and in Tpd 3x and 6x plots (Table 5).

When combining mechanical and chemical methods with Tpd, lowest levels of thatch resulted following VM 4x or 8x/yr, VM + coring, and VM + L, all combined with Tpd 6x/yr. Extra K (VM + K + L, K + L, K) and Wet Ag actually resulted in increased thatch. Lime did not influence thatch depth. Loss of rootzone K was 94 percent and increased with mechanical and chemical treatments. Loss of rootzone P was 86 percent but extra K and L treatments reduced P loss, especially under pH 7.3 following L treatments. Loss of rootzone Ca was 56 percent but L and extra K treatments under pH 7.3 reduced this loss.

If managers have adequate soil nutrient levels (as measured by a soil test) and they can be maintained through normal nutrient management practices, then the 4 and 8 times per year mechanical treatments combined with 3 to 6 topdressing applications per year appear to offer the best change to significantly reduce accumulated thatch on highly maintained bentgrass USGA putting greens.

If soil tests reveal consistently low soil K levels requiring supplemental applications or the use of high K fertility practices to reduce disease pressure are used, then

TABLE 3. THATCH MEASUREMENT WITH THE THATCHMETER

Thatch measurement means and standard errors for topdressing frequency for thatch control measurements with the thatchmeter for the last 3 years of a 6-year study.

Topdressing Treatment	Thatch depth June	Thatch depth November
	mm	
None	7.99	6.45
3x/yr	6.59	5.29
6x/yr	6.18	4.97

Standard errors for least square means, as determined by general linear mixed models analysis, for all means = 0.32.

higher thatch depths may result especially when measured in the usually more favorable fall months.

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TABLE 4. SOIL TEST LEVELS OF CALCIUM, PHOSPHORUS, POTASSIUM, PH

Means of main plot treatment soil test levels of calcium, phosphorus, potassium, and pH in the 0 to 3-inch and 3 to 6-inch rootzone depths after 6 years of thatch control treatments in a bentgrass green.

	Nutrient means in two rootzone depths (in inches)							
	K		P		Ca		pH	
Main treatments	0-3	3-6	0-3	3-6	0-3	3-6	0-3	3-6
	lb/A							
K	133	57	60	34	2672	2716	6.7	7.2
K + VM	130	83	38	28	2524	2530	6.6	7.2
K + L	94	60	83	29	2879	3850	7.3	7.5
Core	87	40	46	30	2445	2443	6.6	7.2
K + L + VM	83	50	73	36	2852	3827	7.3	7.5
Wet Ag	77	44	43	30	2645	2704	6.5	7.2
VM 4x	67	44	49	33	2484	2534	6.5	7.0
L	63	44	68	32	2838	3720	7.3	7.5
Core + VM	60	40	38	28	2435	2421	6.8	7.3
VM 8x	57	44	46	22	2471	2477	6.4	7.2
L + VM	57	44	54	25	2818	3555	7.3	7.5
Check	57	40	40	28	2550	2586	6.6	7.3
LSD (0.05)	52	12	23	12	208	300	0.41	0.33

Columns (down) are means of three replications, combining all Tpd treatments as one plot, and partitioned using LSD with alpha-risk set at 0.05.

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TABLE 5. PENNCROSS BENTGRASS STAND DENSITIES

Means of Penncross bentgrass stand densities in late June after 5 and 6 years of main plot treatments combined with sand topdressing treatments.

Topdressing (Tpd) frequencies

Main treatments	Year 5 Tpd None	3x	6x	Year 6 Tpd None	3x	6x
			-%-			
Core	100	100	100	100	100	100
VM + Core	100	100	100	99	98	97
Wet Ag	100	100	99	100	100	100
VM + L	100	96	94	98	99	97
K + L	100	92	99	100	100	99
L	100	92	91	100	100	99
VM + K + L	99	97	97	98	100	98
K	98	92	100	100	100	100
VM 8x	98	96	93	100	100	100
VM 4x	98	91	97	100	100	100
VM + K	98	92	93	99	99	98
Check	90	91	93	97	99	100
LSD (0.05)	3.9	2.7	2.7	1.3	1.2	1.2

Columns (down) are means of three replications and were partitioned using LSD with alpha-risk set at 0.05 for densities measured during the last 2 years of a 6-year study.

Nematodes as Allies

by *Jennifer A. Grant, Cornell University*

Nematodes are colorless, unsegmented roundworms that live in aquatic and soil environments. Their name is derived from a Greek word meaning "threadlike", which aptly describes their appearance. They commonly range in size from .3 to 2 mm in length. However, one species that parasites sperm whales is over 8 m long! The larger species found in soil are visible with the naked eye, whereas the majority of species require magnification for viewing. You have likely seen nematodes when examining a handful of soil or if you have ever dissected a fish or bird.

Nematodes inhabit a wide variety of environmental niches. Turf managers commonly think of plant parasites, but most nematodes are harmless or helpful free-living animals that feed on bacteria, fungi, algae or other nematodes. Approximately 50 percent are marine, 25 percent are free-living species found in soil or freshwater, 15 percent are parasites of animals, and 10 percent parasitize plants. The animal parasites are notorious for causing diseases such as heartworm in dogs and cats; and elephantiasis, trichinosis and river blindness in humans. However, animal parasites can be beneficial to us when insects are the host organisms. Nematodes that parasitize and cause disease in insects are referred to as "entomogenous", "entomopathogenic" or simply "beneficial". They occur naturally in soils and are also sold as pest control products.

Nematodes are the most numerous multicellular animals on earth, and their densities have been estimated from 3.5 to 9 million per m^2 of land (Sohlenius, 1980). In soil, nematodes play a major role in decomposing organic matter and recycling nutrients. Recently attention has been focused on using them as indicators of soil quality and health. Nematodes are also making a significant contribution to science in general by serving as models for studies in genetics, molecular and developmental biology.

Plant parasites

Plant parasitic nematodes are certainly not considered allies by turf managers. They have a spear-like mouthpart called a stylet that they use to penetrate plant tissue. In turfgrass, they attack root systems and feed externally or internally on root cells. Root lesions, swellings or knots often result. These nematodes directly damage plants by reducing root function, and indirectly by introducing other pathogens such as bacteria and fungi. Damage is most severe under hot conditions. The awl and sting nematodes commonly attack warm season turfgrass; whereas the dagger, spiral, stylet, ring, and lesion nematodes are problems on cool season grasses. The spiral, stubby-root, lance and root-knot nematodes affect both cool and warm season grasses. Diagnosis of plant parasitic nematode infections can be difficult, and should be verified by a plant disease diagnostic lab.

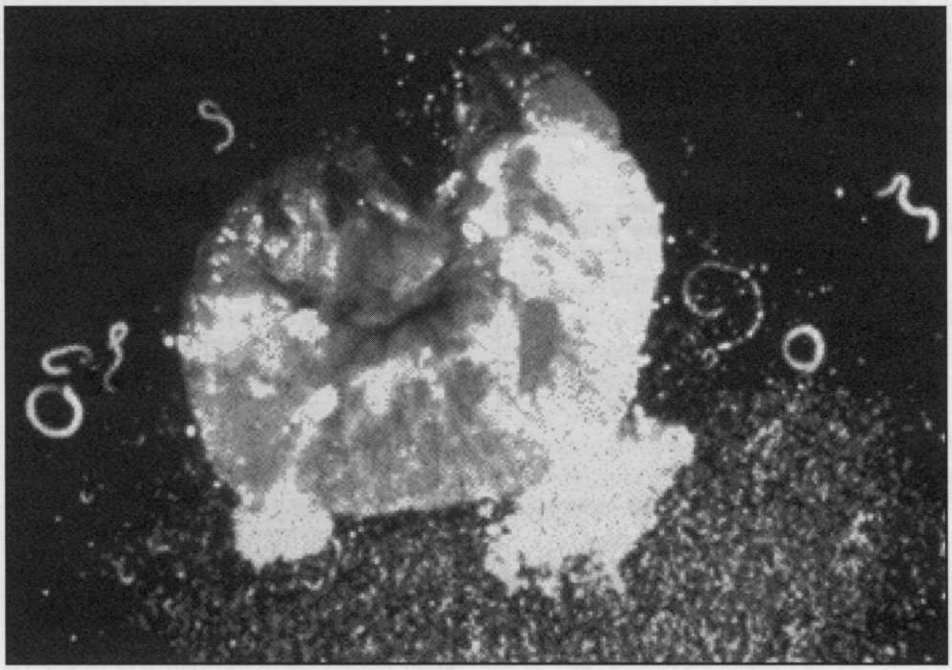
Insect parasites

Many nematodes are parasites of insects. Some large nematodes act as true parasites, which means that only one or two worms infect a host and the insect may remain healthy enough to live, feed and reproduce. However, the nematodes that have received the most attention as biological control agents act more like pathogens than parasites. This means that several nematodes invade a host, reproduce exponentially inside the insect and kill it relatively quickly. The term "**entomopathogenic**" used to describe these nematodes means "to cause disease in insects". Nematodes in the genera *Heterorhabditis* and *Steinernema* are the best studied examples and have been used commercially for several years. The story of how these worms infect and kill insects is complex and fascinating, and depends heavily on mutualistic bacteria to do the dirty work. Following is a general description of the life cycle of *Heterorhabditis* and *Steinernema* nematodes.

Nematodes exist in the soil as infective juveniles (IJs) and carry a mutualistic bacteria in their intestines. IJs come in contact with a suitable insect host and enter it through natural openings such as the mouth, anus or spiracles (breathing holes), or sometimes actively penetrate the insect's cuticle. When the nematode reaches the insect's haemocoel (body cavity), the bacteria are released and begin to rapidly multiply. The bacteria produce toxins that kill the insect host in 24-48 hours.

Nematodes and bacteria have evolved together to form a close and interdependent association. Each species of entomopathogenic nematode carries a unique species of bacteria. Heterorhabditids are associated with bacteria in the genus *Photorhabdus*, and Steinernematids are associated with *Xenorhabdus*. The bacteria perform several important functions in addition to causing rapid death of the host. They release antibiotic compounds that protect the insect cadaver from being invaded by secondary, opportunistic bacteria and fungi. The bacteria also break down and digest the host tissues to fuel their reproduction. The nematodes in turn survive by eating the bacteria as well as the broken-down insect body contents. This all seems wonderful for the nematodes, but what do the bacteria gain by the association? Nematodes provide two important services: they transport the bacteria safely through the soil from one host to the next, and they penetrate the insect and deliver the bacteria to the gut of the new host. These bacteria cannot survive on their own in soil, and have no form of locomotion. In the laboratory, nematodes can kill insects and survive without the bacteria present. However, it is unlikely that this situation is common in nature.

While bacteria are busy multiplying in the insect gut, the IJ nematodes who entered the host mature into adults, mate, and begin their own exponential reproductive process. One or two pioneering nematodes are sufficient to start a new colony, since some species are hermaphroditic. A mated female (or hermaphrodite) carries many of her eggs internally that eventually hatch inside her. These first stage juveniles molt into a second stage and then exit the mother into the body cavity of the insect cadaver. Here they normally feed, mature and produce one or two more generations, depending on food supply and crowding. The third stage juveniles from the final generation are the IJs that exit what

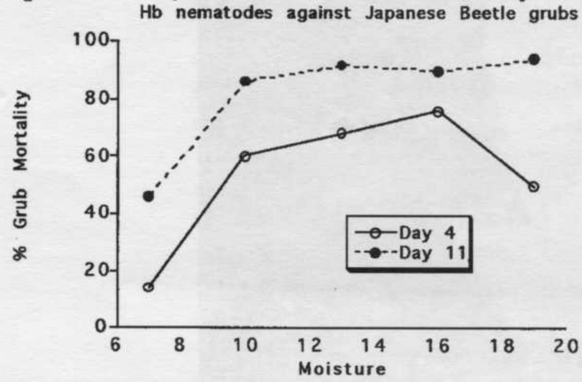


Japanese beetle grub infected with Heterorhabditis bacteriophora with reproductive nematodes visible through cuticle. Photo credits: J. Ogrodnick, NYSAES

remains of the cadaver and go out into the soil to start a new colony in another host. The IJs do not require food, and are physiologically and morphologically adapted to survive in the harsh soil environment while waiting or searching for a new host (Poinar, 1990). New IJs leave the cadaver one to two weeks after the infection is initiated.

Insects, of course, have some defenses against nematodes and their allied bacteria. For example, insect immune systems react to foreign invaders by encapsulating them or walling them off in melanin (a liquid material that hardens around the invader). Nematodes are often too large for this strategy to work, and the bacteria are protected up to the time they are released and begin rapid multiplication. Another defense used by Japanese beetles and other insects is to groom themselves with their legs to remove irritants such as nematodes on their skin (Gaugler et al., 1994). Many scarabs also have fine mesh sieve plates covering their spiracles (Gaugler et al., 1994; Wang et al., 1995), forcing nematodes to use an alternate route of entry. There are also natural mortality agents such as fungi, insects and other nematodes that attack entomopathogenic nematodes. The insect defenses and natural mortality agents can usually be overcome by inundating an area with nematodes as part of a pest management program.

Fig. 5 Impact of soil moisture on the activity of Hb nematodes against Japanese Beetle grubs



Impact of soil moisture on the activity of Hb nematodes against Japanese beetle grubs.

Nematode behavior

The behavior of nematodes in soil differs between species and significantly affects which insects are commonly attacked. One way of life employed by nematodes is called an "ambush" or "sit and wait" strategy. Typically, the worm is attached by its tail to a soil particle at one end while the body is extended outward waving and waiting for a host to pass by. The nematode can spring and leap off the soil particle if it senses a suitable host or wants to move to a new location. *Steinernema carpocapsae* is a commercially available nematode that exemplifies this strategy. It prefers to live in the upper 15 cm of the soil (Ferguson et al., 1995) and works best against pests that are actively moving through the thatch and soil such as cutworms and webworms.

At the other end of the spectrum of behaviors are "hunting" or "searching" nematodes. *Heterorhabditis* bacteriophora and *Steinernema glaseri* typify this strategy. These nematodes actively swim through the soil in search of hosts, and travel as deep as 35 cm deep (Ferguson et al., 1995). They are ideal agents for combating sedentary pests such as scarab grubs.

Environmental factors, especially the availability of adequate soil moisture, are critical for entomopathogenic nematode performance in the field (Georgis and Gaugler, 1991).

Because entomopathogenic nematodes need both high relative humidity to survive and a film of free water for movement, moisture conditions have been recognized as one of the most important factors in the soil environment affecting survival, infectivity and persistence of nematodes (Curran 1993, Klein 1990).

Investigations in our laboratory have shown wide variations in entomopathogenic nematode performance at varied soil moistures. For example, Figure 5 shows mortality of Japanese beetle grubs exposed to *Heterorhabditis bacteriophora* (HB) nematodes. Mortality was significantly lower in dry soil (7 percent w/w) after both 4 and 11 days. The 4 day readings also suggest that very moist soil (19 percent w/w) may inhibit nematode activity.

Another test compared mortality of Galleria (waxmoth) larvae exposed to three species of nematodes in high moisture soils (15 percent w/w) and low moisture soils (6 percent w/w). (SC = *Steinernema carpocapsae*, SF = *Steinernema feltiae*). In the high moisture treatments, efficacy of SC dropped significantly by the fifth reading (15 days after nematode inoculation); whereas the other two species continued to cause near 100 percent mortality. In the dry soil, the Steinernematid species began with high activity that dropped steadily over the first five readings. HB appears to be more sensitive to the dry conditions, and caused minimal mortality during the same time period. After the fifth reading, soil moistures in all treatments were raised to the level of the wettest treatment (hydration). This resulted in 100 percent of the insects being killed in all dry treatments—suggesting that entomopathogenic nematodes can endure long periods of dry soil conditions in a quiescent (inactive) state.

Currently, we are conducting a full year investigation to determine how long quiescent nematodes can live in dry soil and then be reactivated by the addition of moisture. We are comparing three nematodes (HB Oswego strain, HB Tuscarora strain, and SG) at four initial soil moistures ranging from very dry to very moist (6-15 percent w/w). At the most recent reading (month 7), the HB strains stored in the driest soils were 100 percent infective after rehydration. This information can aid the selection of species and strains that would survive best in irrigated and non-irrigated turf. In the future it may also be possible to apply inactive nematodes at a convenient time during the growing season, and later activate them with irrigation.

Field Applications

Many factors make nematodes an ideal microbial control agent: they have a relatively broad host range, will not attack plants or vertebrates, are easy to mass produce, and can be applied with most standard insecticide application equipment. Additionally, nematodes can search for hosts and kill them rapidly, and can release thousands of mobile progeny able to locate and infect new insect hosts within weeks of the initial infection. Because they are considered predators, entomopathogenic nematodes are exempt from registration by the United States Environmental Protection Agency (US EPA). This exemption from long term safety and water quality studies has greatly reduced the costs and risks typically associated with registering a new insecticide.

It may be possible to apply inactive nematodes at a convenient time during the growing season, and later activate them with irrigation.

Although there have been many successful field applications of entomopathogenic nematodes for turf insect control, problems with product quality, persistence and host specificity have led to some unsatisfactory results. Entomopathogenic nematodes have a fairly broad host ranges in laboratory studies, but different strains and species of nematodes vary in activity against insect species in the field.

In the mid 1980's, several species of entomopathogenic nematodes became commercially available for insect pest management. Initially, small-scale production and limited marketing resulted in these products being used mainly for home gardens, lawns and landscapes. More recently, a few large companies have attempted mainstream marketing aimed at the commercial turf, vegetable, and fruit industries, but acceptance has been hindered by variability in the success of the nematodes' ability to control target insects.

The preceding information on nematode biology and behavior provides a good base for discussing the practical aspects of using entomopathogenic nematodes for management of insect pests. Many previous unsuccessful field applications of entomopathogenic nematodes for scarab grub control can be traced to inappropriate conditions at the time of application and for several weeks post application (Villani et al. 1992). Turf managers can get more consistent results by following these suggestions. First and foremost, turf managers should follow the basic principles of good pest management. This means you need to know the identity, biology, location and density of your target pests, which will require scouting and monitoring. The next step is to determine if any commercially available beneficial nematodes are known to attack your pests.

Another consideration is the life stage of your pest species. Nematodes are usually most effective against the early stages of larval insects. Eggs, large larvae, pupae and adults are often difficult or impossible to infect. One exception is *S. scapterisci* that infects adult mole crickets as they tunnel in the soil. If you are in doubt about the timing of a nematode application, consult the supplier or your local Cooperative Extension agent.

Nematodes can be applied with most standard pesticide application equipment if the psi does not exceed 300, and the screen mesh is no less than 50 microns. Because the material is live, users must be very careful to store it in a cool place and not exceed the recommended shelf life. The nematodes must also be agitated while in the spray tank to ensure uniform distribution and to circulate oxygen to them. The suggested application rate is one billion nematodes per acre for most soil insects. Higher rates can be used when drenching ornamental plantings.

Your turf management practices before, during and after a nematode application impact its effectiveness. Turf should be irrigated before and after an application to prevent nematodes from drying, sticking and dying on the grass blades. The heaviest nematode mortality occurs in the first few minutes and hours after application (Smits, 1996), so this time period is critical. The post application irrigation will also help wash the nematodes down through the turf and thatch layers. Be sure the turf remains well irrigated during the subsequent weeks, since nematodes need a moist environment to be infective, as discussed previously. Chemical pesticides applied shortly before or after the nematode application may lessen effectiveness, since nematodes are often sensitive to them. The following turf products have been shown to negatively impact *H. bacteriophora* nematodes: bendiocarb, chlorpyrifos, and ethoprop, the fungicides anilazine, dimethyl benzyl ammonium chloride, fenarimol, and mercurous chloride, the herbicides 2,4-D and trichlopyr, and the nematicide fenamiphos (Rovesti et al., 1988).

Another basic pest management principle to follow is to monitor the pest population after the nematode application to evaluate its effectiveness. It may take a few days for nematodes to locate a host, but the insect will die in 24-48 hours after a successful infection. Infected insects have a characteristic, uniform color because of the bacteria present. *Heterorhabditis-Photorhabdus* infections produce red or purple cadavers and the bacteria actually glow in the dark! *Steinernema-Xenorhabdus* cadavers are tan or beige. The cadavers are flaccid, intact, and typically do not show signs of

TABLE 1. TURFGRASS INSECTS ATTACKED BY NEMATODES

Target Pest	Nematode Species
Scarab grubs, black vine weevils	*Heterohabditis bacteriophora*
Mole crickets	*Steinernema riobravis, S. scapterisci*
Billbugs	*H. bacteriophora, S. carpocapsae*
Armyworm, Cutworm, Webworm, Annual Bluegrass Weevil*	*S. carpocapsae*
Plant pathogenic nematodes (possibly)	*S. riobravis*

**some success reported*

TABLE 2. ENTOMOPATHOGENIC NEMATODE SUPPLIERS

Product name	Nematode Species	Supplier or Producer	Telephone
Heteromask	Hb (Oswego)	IPM Laboratories	(315)-497-2063
Grub Away	Hb	Gardens Alive	(812)-537-8650
Lawn Patrol	Hb	Hydro-Gardens	(800)-634-6362
Beneficial Nematode	Hb (Merilatus & HP88)	M & R Durango	(800)-526-4075
Grub Guard	Hb & Sf	North Country Organics	(802)-222-4277
Guardian	Sc	Hydro-Gardens	(800)-634-6362
Ecomask	Sc	IPM Laboratories	(315)-497-2063
Beneficial Nematodes	Sc (All & Kapow)	M & R Durango	(800)-526-4075
Combo (Lawn Patrol + Guardian)	Hb & Sc	Hydro-Gardens	(800)-634-6362
Scanmask	Sf	IPM Laboratories	(315)-497-2063
Beneficial Nematodes	Sf	Gardens Alive	(812)-537-8650

Nematode species
Hb = *Heterorhabditis bacteriophora*, Sc = *Steinernema carpocapsae*, Sf = *Steinernema feltiae*

other infections (e.g. fungus) or rotting. Live nematodes can be seen through the cuticle of some insects. When monitoring, keep track of the number of healthy and infected insects detected.

Entomopathogenic nematodes can be introduced or conserved from local natural populations in turfgrass plantings, to help keep insect populations in check. Remembering the ecological and management principles outlined here will help in accomplishing that goal. The next time you see a dead or dying insect on a lawn or golf course, take a moment to try and figure out if our small friend the nematode played a role.

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