AN INDEPENDENT NEWSLETTER FOR COOL SEASON TURF MANAGERS

# Turf Grass TRENDS

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# More than meets the eye:

## The microbiology of turfgrass soils

*by Dr. Eric B. Nelson*

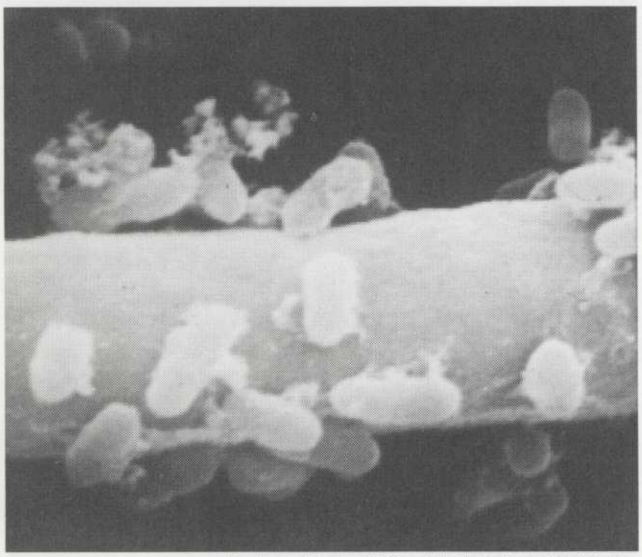

Photo provided by Dr. Eric B. Nelson, Cornell University

Bacteria adhere to the mycelium of a fungus. Note the size of the bacterial cells relative to the mycelium. See page 4.

FOR SOME TURFGRASS MANAGERS, soil is simply the "dirt" that holds plants in the earth and keeps them from falling over.

For the more advanced turfgrass manager, soil is held in higher esteem than dirt. Soil is considered by these turfgrass managers as the life-supporting matrix of the higher plant, since everyone knows that dirt is simply the stuff that accumulates under one's fingernails after a hard days work.

Turfgrass managers who know that plants are anchored in soil instead of in dirt might admit that, for the most part, their understanding of soil is poor at best. Everyone knows what soil looks like, but they are not quite sure where it actually comes from or how it can sometimes be black, brown, or red. Even though most people would admit that soil has a pleasant, somewhat fragrant odor, most are really not sure why soil smells as it does. They know that soil is a nutrient-holding material important in the health of the plant, although the exact manner in which this can be is sometimes obscure. Certainly most know that living things, such as worms and insects can reside in soil, but they're not sure where in the soil they live or what they live on.

In fact, it might be safe to assume that most turfgrass managers consider soil to be a mysterious world below the turfgrass canopy. Rarely do turfgrass managers consider soil as something that should be managed as prudently as the turf itself. It is becoming clear, however, that the management of the soil, in particular its biological components, is as important as the management of the plant for the long-term productivity and health of a turfgrass stand.

### What is soil, anyway?

Before we begin our microbial journey through soil, it is important to ask the question: What is soil anyway? Soil is simply the outer

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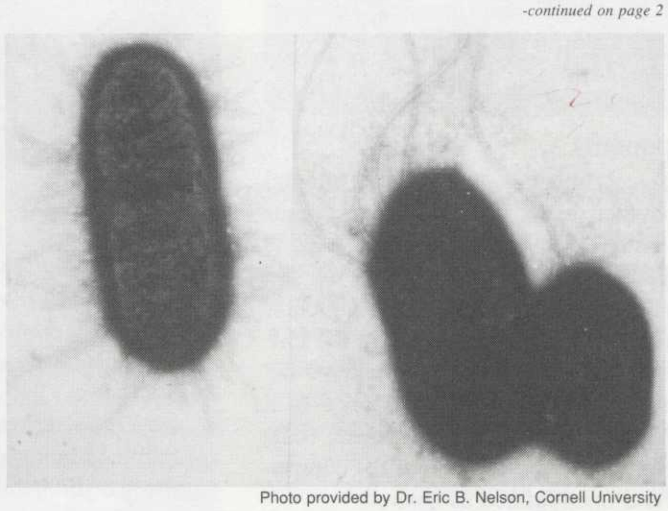


Photo provided by Dr. Eric B. Nelson, Cornell University

Bacteria have structures on their surface that facilitate reproduction and allow cells to swim in water films around soil particles. See page 4.

## IN THIS ISSUE

loose material of the Earth's crust that accumulates from the weathering of rocks, the decay of organic materials, and the activities of man and other living organisms.

Agriculturally, this is the zone from which plants obtain mechanical support and most of their nutrients. Biochemically, the soil is distinctly different than the underlying bedrock, since many unique organic chemicals can be found there.

Microbiologically, soil is unique in that it contains a diverse array of bacteria, actinomycetes, fungi, algae, protozoa, and microarthropods. It is undoubtedly, one of the most dynamic sites of biological activity in nature. Nearly all of the processes, transformations, and associations important for the maintenance of healthy turfgrass plants take place at the microscopic level. Things such as nutrient cycling, organic matter degradation, nitrogen fixation, biological control of insects and pathogens, plant-microbe symbioses necessary for increased plant growth and pest resistance, and many more. All of these important attributes of the plant-soil association are mediated by a plethora of microorganisms. Without these microbial activities managing turfgrasses would be much more perplexing task than it already is.

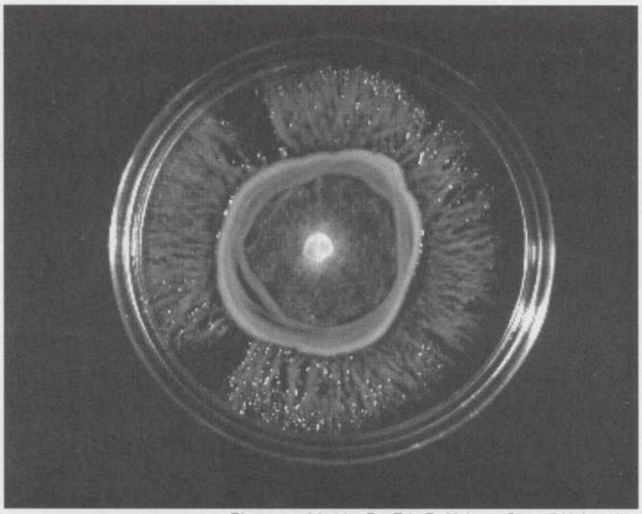


Photo provided by Dr. Eric B. Nelson, Cornell University

Bacteria compete efficiently with fungi. Here, bacteria on a petri plate ensheath the mycelium of a pathogenic species of Pythuim. See page 6.

## Soil has five components

Soil consists of five primary components: a mineral component, organic matter, water, air, and living organisms. For any given native soil, the mineral and organic matter content are relatively constant whereas the air and water (i.e. pore space) can fluctuate widely. These fluctuations can indirectly affect the living organisms in the soil. Modifying native soils with amendments can change the relative relationships of its components, but only to a limited extent. On the other hand, in custom-made rootzone mixes for golf course construction, all of the components may be varied and manipulated as desired.

Generally, for most mineral soils, half of the soil volume is composed of pore space, with the other half

Univ. of Georgia study

# Bad effects of soil compaction on turfgrass

Recent tests conducted at the University of Georgia have shown the detrimental effects of soil compaction on overall turfgrass growth and survival. Test plots were subjected to compaction that increased the soil bulk density by 6.1% at the 0-2 inch depth range and by 6.5% at the 2-4 inch depth. This increased the penetration resistance by an average of 23% at various depths down to 10 inches.

In the first year, this increased soil bulk density and penetration resistance reduced root density by 20% in the 0-4 inch range and by 77% in the 4-8 inch range. In these compacted soils, water extraction, a measure of the soil moisture holding capacity, decreased by 21% and 10% over the two depth ranges, whereas clipping growth was reduced by an average of 52%. Individual shoot size was reduced by an average of 23% whereas shoot density (number of shoots per area) increased by 9%.

The same research also examined five of the current soil aeration techniques for their abilities to correct the negative effects of compacted soils over three cultivations in a 15 month period. In the first year, only hollow and solid tine aeration eliminated the effects of soil compaction on soil bulk density at the 2-4 inch range and in the second year at the 0-2 inch range. However, all five aeration techniques eliminated root density losses in the first year at the 0-4 inch range by increasing root density by 23% over the non cultivated, compacted check. In the second year, all five techniques showed an average increase of 7% greater root density than the non-cultivated, non-compacted test plot at the 0-4 inch range. Additionally, all five restored water retention ability by 61% over the compacted, no cultivation check. Hollow tine aeration increased moisture retention by 16% over the no cultivation, no cultivation test plot.

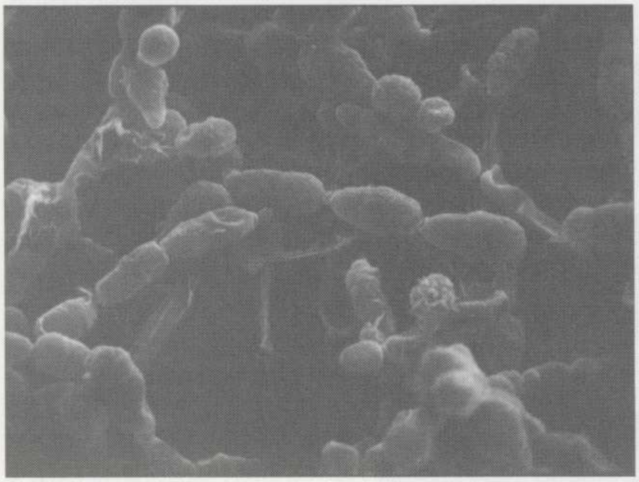
## Field tip

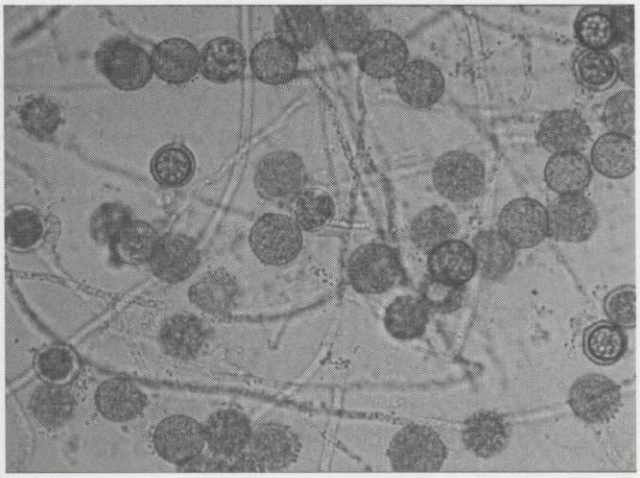
The results show that hollow tine and to a lesser extent solid tine aeration is an excellent aeration technique that will show positive results in most circumstances even when only used twice a year. It can be very beneficial in reducing soil bulk density and in increasing root mass and moisture holding ability when used on compacted soils. Slicing and deep drilling did not show the same consistency of results.

composed primarily of mineral matter. Organic matter may account for 2 - 10 % of the soil volume; the exception being organic soils where the organic matter content may range from 60 - 95%. Finally, small animals and microorganisms generally account for less than 1% of the total soil volume. Despite the small percentage of the soil matrix occupied by living organisms, this may be the most important soil component in terms of plant health.

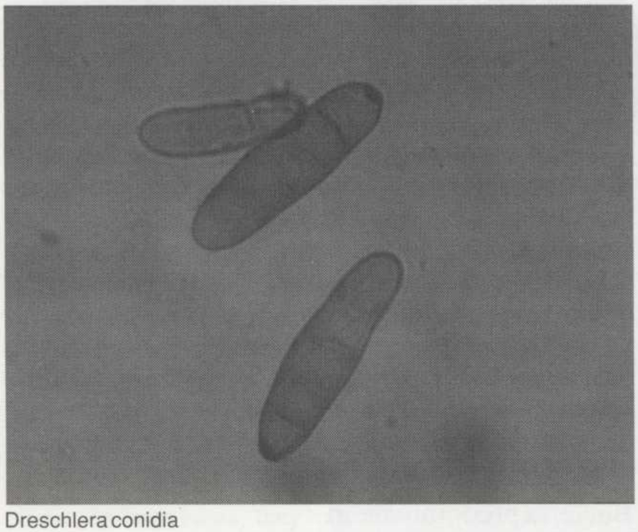
## Chemical properties of soil are important to plant health

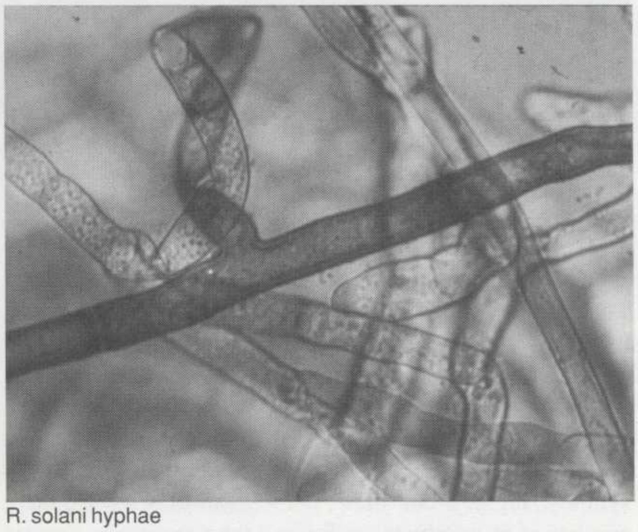
Chemically, soils are quite variable. However, with the exception of muck soils, they are comprised largely of silicon dioxide (generally 70-90% of the total mass). Aluminum and iron are usually quite prevalent, along with lesser quantities of calcium, magnesium, potassium, manganese, sodium, nitrogen, phosphorus, and sulfur. Carbon exists in soils in the form of decaying plant and animal material, living microbial cells, and humus which is a by-product of the metabolic activities of microorganisms. Although the exact chemical composition of humus is unknown, it can be characterized as a dark-brown to black organic complex of humic and fulvic acids together with other polymerized organic molecules.


Alternaria


Pythium oospores

All photos provided by Dr. Eric B. Nelson, Cornell University


Dreschlera conidia


R. solani hyphae

Common soil fungi. Most spend their lives as quiescent spores. Only occasionally do fungi actively grow as a mycelium. See page 6.

The mineral components of soil, excluding stones, gravel, and foreign matter, are comprised of sand, silt, and clay. Sizes of these particles range from 0.05 - 2 mm for sand, 0.0002 - 0.05 mm for silt, and less than 0.0002 mm for clays. The relative proportions of these inorganic materials in soils is the basis for the different textural classes such as a clay loam, sandy loam, loam, etc. The different proportions of each of these mineral components, combined with organic matter, affect not only air and water movement and retention in soil but also affect nutrient-holding capacities and microbiological activities.

Another chemical feature of soils, is their ability to retain ions. Nutrient ions are compounds that have either a positive or negative charge. For example, ammonium nitrogen, calcium, magnesium, and potassium are all positively-charged ions called cations. Cations are readily removed from the soil solution by organic matter and clays; the soils ability to remove these cations is referred to as the cation exchange capacity. As might be expected, soils high in clay or organic matter content will have a higher cation exchange capacity than sandy soils low in organic matter or clay.

Nutrient ions such as nitrates, phosphates, sulfates, and bicarbonates are negatively-charged ions called anions. These are not readily retained in most soils and are easily leached from the root zone during irrigations or rainfalls.

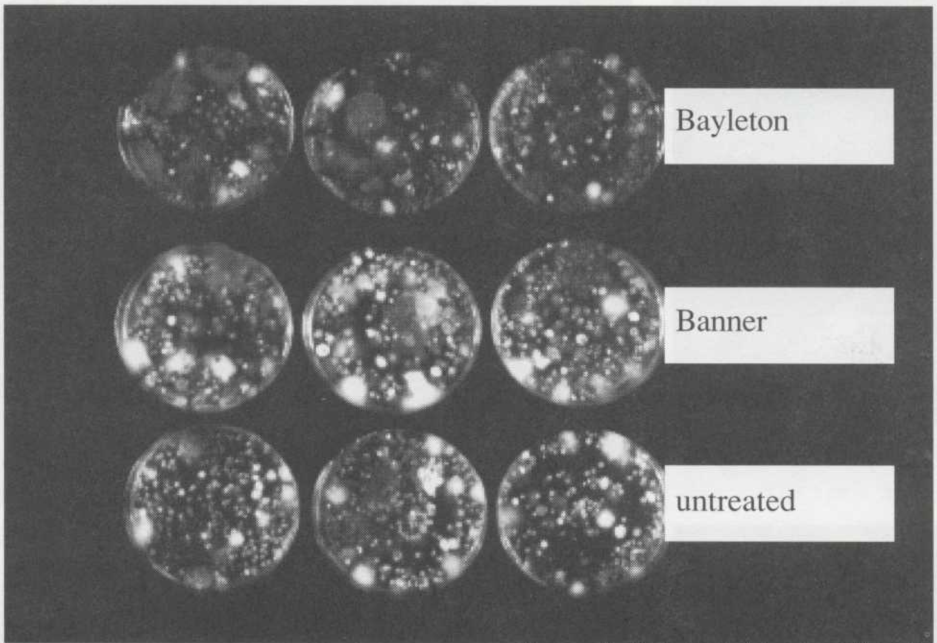



Photo provided by Dr. Eric B. Nelson, Cornell University

Broad spectrum fungicides may dramatically change the fungal species composition in turfgrass soils. Here are the fungal colonies from soils treated with Bayleton, Banner, or untreated. See page 6.

Perhaps the most important soil component from the point of view of a microorganism, is the organic fraction. The organic fraction is often termed humus. Humus serves, in the absence of any plants, as the dominant food reservoir for soil microorganisms. When plant or animal remains land on, are grown in, or are incorporated into soil, microorganisms begin the process of decomposition, using parts of these remains for their cell energy as well as for synthesizing new cell mass. During this decomposition, a number of by-products are formed from the initial organic material as well as from the microbial cells themselves. These by-products become resistant to further decay and persist for extended periods of time in soil as humus.

## Biological components of soil are an important resource

Soils below turfgrass stands contain a vast array of living organisms, ranging from the larger macroscopic earthworms and insects, to the microscopic invertebrates, bacteria, fungi, actinomycetes, nematodes, algae, and protozoa. The physical and chemical characteristics of soil just described determine the nature of the environment in which these living organisms function. This environment further affects not only the types and numbers of organisms found but more specifically it affects their activities. These activities may be beneficial or harmful to turfgrass growth and development. The organisms most important to turfgrass health are the bacteria, fungi, actinomycetes, and algae.

Turfgrass managers are all too familiar with the harmful effects that some microorganisms have on turfgrass. These damaging microorganisms include fungal, bacterial, and nematode pathogens of turfgrass plants.

There are also cyanobacteria - a form of blue-green algae that causes black layer, and green algae that cause surface crusting and plant damage.

There are other groups of microorganisms that are indirectly harmful to turfgrass plants. These include pesticide-degrading non-pathogenic and pesticide-resistant pathogenic microorganisms. In nearly all cases, turfgrass managers have developed elaborate management techniques to avoid some of the detrimental effects caused by the activities of these organisms.

Not surprisingly, most soils contain large populations of beneficial microorganisms. These offer the most promise for enhancing turfgrass health and maintaining long-term productive turfgrass stands. (See Table 1 on page 5.) Yet, for the most part, we have not developed management strategies to promote the persistence and activities of these important microorganisms. In order to understand how to take advantage of these beneficial microorganisms, it is important that turfgrass managers develop a better understanding of the major groups of microorganisms in soil.

## Bacteria predominate in the soil microbial community

Of the microorganisms in soil, bacteria are found in the greatest abundance and are perhaps the most diverse in their morphology and activities. (See photo on page 1.) Many different populations of bacteria with a wide array of activities can be found in most turfgrass soils; many carry out processes important to plant health. (See Table 2 on page 7.) However, the bacterial composition of each soil may vary depending on the soil type, prevailing environmental conditions, and management practices.

Bacteria are small, rod-shaped organisms that reproduce prolifically by simple cell division, producing massive amounts of cells in a short period of time. (See photo page 1.) Under favorable conditions, bacteria may divide every

20 minutes, so that conceivably, one bacterium could give rise to one million bacteria in 10 hours! Although the total numbers of cells can be great, the size of each individual cell is quite small, usually not more than one or two microns (0.00004 inches) in length.

During the explosive growth of bacteria, a diverse array of food sources must be available to support such a high rate of metabolic and reproductive activity. During the utilization of food sources, a number of metabolic by-products are also produced. As a result, great chemical changes may occur in the soil as a result of the proliferation of bacteria in the environment. This makes bacteria such significant microorganisms in the turfgrass environment.

Bacteria require water to grow and reproduce. Their survival is limited if water availability diminishes. Although, many bacteria are excellent saprophytes (i.e. they prefer to live on decaying organic matter), some are endophytic (i.e. they live inside healthy plants, usually in roots), where a limited number can cause diseases in plants. Those found in turfgrass ecosystems are either saprophytic or endophytic. In both cases, they are usually good competitors with plant pathogens which results in reduced damage from diseases.

Of importance to turfgrass health are the bacteria that play a role in nutrient transformations in soil, particularly those involved in nitrogen cycling. Numerous bacteria within the genera *Azotobacter, Azospirillum, Enterobacter,*

Table 1

## Predominant bacteria and their known activities in turfgrass soils

| Bacterial Genus | Principal Activities |
|---|---|
| *Arthrobacter* | Degradation of pesticides<br>Decomposition of organic matter<br>Pesticide degradation |
| *Azospirillum* | Nitrogen-fixation |
| *Azotobacter* | Nitrogen-fixation |
| *Bacillus* | Biological control of diseases and insects<br>Decomposition of organic matter<br>Degradation of pesticides<br>Denitrification<br>Phosphate solubilization<br>Conversion of ferric to ferrous iron<br>Release of native soil potassium<br>Manganese oxidation |
| *Desulfovibrio* | Conversion of sulfates to sulfides |
| *Enterobacter* | Nitrogen-fixation<br>Biological control of diseases |
| *Flavobacterium* | Decomposition of organic matter<br>Phosphate solubilization<br>Pesticide degradation<br>Biological control of diseases |
| *Klebsiella* | Nitrogen-fixation<br>Conversion of ferric to ferrous<br>Manganese oxidation<br>Pesticide degradation |
| *Nitrosomonas* | Oxidation of ammonia to nitrite (nitrification) |
| *Nitrobacter* | Oxidation of nitrite to nitrate (nitrification) |
| *Pseudomonas* | Decomposition of organic matter<br>Biological control of diseases<br>Plant growth promotion<br>Some species can be pathogenic to turfgrasses<br>Denitrification<br>Phosphate solubilization<br>Conversion of ferric to ferrous iron<br>Release of native soil potassium<br>Manganese oxidation<br>Pesticide degradation |
| *Thiobacillus* | Conversion of inorganic sulfur and iron compounds to sulfates and ferric forms of iron<br>Denitrification |
| *Xanthomonas* | Biological control of weeds<br>Some species are pathogenic to desired turfgrasses<br>Decomposition of organic matter |

and *Klebsiella* are efficient free-living nitrogen-fixing bacteria. They take nitrogen from the atmosphere and convert it to a form that the plant can use. Although they contribute significantly to the nitrogen nutrition of such grass species as *Poa pratensis* (Kentucky bluegrass), the magnitude of their contribution to the nitrogen nutrition of turfgrass plants in the field is unknown. Undoubtedly these nitrogen-fixing organisms could contribute substantially to the nitrogen economy of a turfgrass planting if they were managed in an effective way.

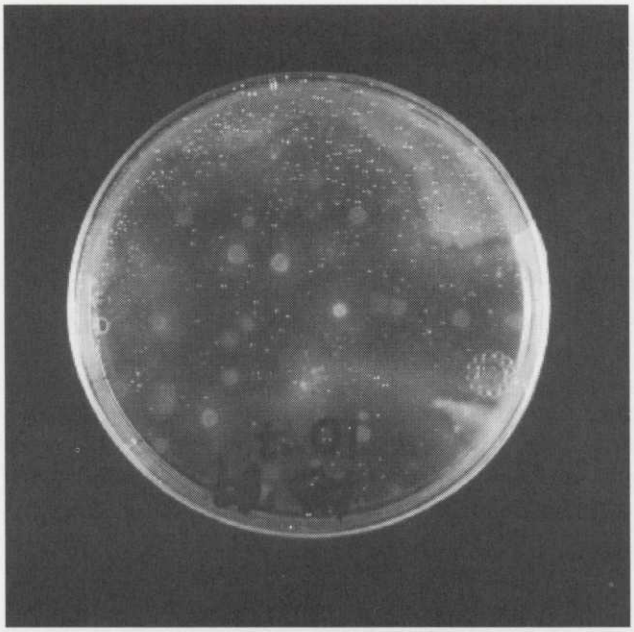


Photo provided by Dr. Eric B. Nelson, Cornell University

Soil actinomycete on a laboratory culture medium. These are antibiotic-producers, synthesizing by-products that inhibit fungi, bacteria, and other microorganisms. See page 7.

As important as the nitrogen-fixing bacteria are, there are more important microorganisms involved in organic matter degradation. These organisms play a key role in maintaining the delicate balance between thatch accumulation and thatch degradation. These organisms can be managed to some degree. In fact, there are a number of commercial preparations of thatch-degrading microorganisms as well as preparations of the enzymes that they produce. Some of these have been used successfully in a thatch maintenance program whereas other fail miserably.

One of the more pivotal groups of bacteria are those involved in the biological control of turfgrass pathogens. These bacteria can be found in all types of turfgrass soils, from low-maintenance to high-maintenance areas. Their effects often go largely unnoticed. However, they can have huge impacts on disease development. (See photo page 2.) In some cases, high populations of these bacteria are responsible for the development of what we call suppressive soils. These are soils where conditions are ideal for disease symptom development and the pathogens are present, but no disease develops because of the activities of these bacteria. Since all of these bacteria prefer to live on dead and decaying plant tissue, large amounts of organic matter, either in the form of top dressings or direct soil amendments, are usually very beneficial in promoting the activities of these bacteria.

Many of these biological control bacteria can be found in particular types of organic matter such as composted materials. In fact, the application of composted materials has been used as effective alternatives to fungicides in a number of instances. Similarly, a number of companies are now marketing preparations of bacteria as microbial fungicides. Although none of these materials are currently registered for use on turfgrasses, a number of materials are likely to be available in the near future.

## Fungi - both friend and foe

Perhaps the next most abundant group of microorganisms in turfgrass soils are fungi. (See photos on page 3.) The fungi are best known for their disease-causing activities on turfgrasses since nearly all of the economically-important turfgrass diseases are caused by fungi. However, pathogenic fungi represent only a small proportion of the total communities of fungi in soil. The vast majority of fungi found in turfgrass soils are beneficial to plant health. Some of the major genera of fungi present in turfgrass soils include *Penicillium, Aspergillus, Trichoderma, Gliocladium, Fusarium, Mucor,* and *Mortierella.*

Fungi obtain their energy for growth through the decomposition of organic matter. It is not surprising, therefore, that organic matter decomposition is one of their predominant activities in turfgrass ecosystems. Generally fungi are more prevalent than bacteria in soils of pH lower than about 5.5 whereas bacteria tend to predominate in higher pH soils.

Since fungicides are the primary pest control chemical used on golf course turf, soils at these sites can vary dramatically in the composition of fungal communities, depending on the type, rate, and frequency of fungicides used. (See photo page 4.) Aside from the plant pathogenic and organic matter decomposition activities of soil fungi, some groups perform more specialized functions in direct association with the turfgrass plant.

Mycorrhizal fungi form unique symbiotic associations with plant roots called mycorrhizae. In mycorrhizal relationships, the fungus benefits from the carbon provided by the plant while the plant benefits from the increased phosphorus nutrition and water movement to the roots. Both bentgrasses and bluegrasses have been reported to be mycorrhizal, although little information is available on the beneficial or detrimental properties of mycorrhizae in these grasses. As with other fungi, mycorrhizal fungi are sensitive to a number of fungicides commonly used in turfgrass management.

Some of the better-known fungi used in turfgrass management are endophytes. Fungal endophytes are typically found in the seeds and leaf sheaths of nearly all of the turfgrass species. Most commonly, however, the endophytes of perennial ryegrass, tall fescue, hard fescue, chewings fescue, and creeping red fescue have been exploited. Useful endophytes have not been found in creeping bentgrass and Kentucky bluegrass.

The major fungus involved in these endophytic relationships is the genus *Acremonium*. This is a common soil fungus that infects the plant through unknown means. However, once inside the plant, the *Acremonium* fungus provides the host plant with increased insect and disease tolerance as well as improved stress tolerance. The nature of these effects are currently unknown but are being studied.

Many commercial varieties of turfgrass can be bred with known levels of endophyte infection. However, it should be noted that endophytic fungi remain viable in the seed for only about one year, unless the seed is refrigerated. Endophyte-infected seed should therefore be stored in a cool dry location to assure maximum benefits from the *Acremonium* infection.

## Actinomycetes produce antibiotics suppressive to plant pathogens

One of the least known and least understood groups of soil microorganisms are the actinomycetes. These microbes are classified more closely with the bacteria but they grow more like a fungus. Although their populations in some soils can be quite high, their growth rates are much slower than the other microorganisms in soil. Much of the smell unique to high organic matter soils comes from the volatile compounds produced by actinomycetes.

Actinomycetes are typically more abundant in drier soils high in organic matter or in high temperature soils. As a group, they are not tolerant of low soil pH (i.e. less than 5.0). They prefer to grow at temperatures ranging from 80 to 100 degrees Fahrenheit. Some of the major genera of soil actinomycetes include *Streptomyces, Nocardia, Micromonospora,* and *Actinoplanes*.

These organisms are best known for their abilities to produce a number of industrially- and medically-important compounds. Many of the clinically-important antibiotics used in human and animal medicine come from soil actinomycetes. Like the fungi, actinomycetes rely on organic matter for their nutrition. In particular, actinomycetes appear to be more adapted to the decomposition of the more resistant plant polymers such as cellulose, hemicellulose and lignin as well as the fungal and insect polymer, chitin. In doing so, actinomycetes play a major role in the formation of humus in soils.

Actinomycetes also play a role in the suppression of soil borne diseases of turfgrass plants. Many of the antibiotic compounds produced by actinomycetes also affect the growth and development of pathogenic fungi. (See photo page 6.) Composts are particularly rich sources of actinomycetes that suppress turfgrass pathogens. Part of the beneficial effect of amending soils with composts is the disease control provided by these compost-inhabiting actinomycetes.

Table 2

### Important beneficial microorganisms found in turfgrass soils

| Microbial Group | Major Benefit to Turfgrasses |
|---|---|
| Nutrient-cycling microorganisms | Making nutrients available to plants<br>Decomposition of organic matter |
| Thatch-degrading microorganisms | Thatch maintenance |
| Nitrogen-fixing microorganisms | Improvement in turfgrass nutrition |
| Endophytes | Pest resistance<br>Stress tolerance |
| Mycorrhizal fungi | Improved phosphorus nutrition<br>Plant growth promoting rhizobacteria<br>Improved root development<br>Disease tolerance |
| Biological control organisms | Protection from pests |

## Algae can cause significant problems in turfgrasses

Algae can be found in essentially all soils worldwide. However in most turfgrass soils, the algae are a minor microbial component of the total microbial ecosystem. Nonetheless, under certain conditions their presence can create difficult management problems. Unlike the previously-mentioned groups of microorganisms, algae do not require organic matter for energy and growth. Most algae are capable of photosynthesis, allowing them to produce their own carbon compounds. Since algae require light, their presence in turfgrass plantings is often observed on the soil surface in sparsely seeded areas and in excessively close-cut turf such as on putting greens.

The types of problems caused by algae in turfgrasses include 1) the formation of surface crusts, 2) the production of copious slime, and 3) the formation of 'black layer'. The soil algae responsible for these problems can be classified into the green algae and the cyanobacteria (formerly referred to as blue-green algae). The genera of green algae recovered from turfgrasses

-continued on page 14

University of Rhode Island study

# Tall fescues are more efficient at leaf growth

A study at the University of Rhode Island tested six varieties each of three turfgrass species for their ability to take up nitrogen and their ability to turn that nitrogen into leaf growth. Six varieties of tall fescue, bluegrass and perennial ryegrass were rated for their ability to produce clippings, nitrogen leaf concentrations, and efficiency of nitrogen use. Over the growing season, the tall fescue varieties produced an average of 50% more leaf tissue while having the lowest leaf nitrogen content and the greatest nitrogen-use efficiency. Table 1. below lists the results of this study.

***TGT's view:*** *Tall fescue varieties would be excellent choices for turf areas that have limited fertility or that have limited budgets for control or preventative applications. Tall fescue's efficient use of available nitrogen combined with that species insect and disease resistance make it an excellent choice for low maintenance areas.* —CS

Table 1

| Species | Leaf Growth | Nitrogen Leaf Content | Nitrogen Use Efficiency |
|---|---|---|---|
| Ryegrass | 0% increase | 16% increase | 4% increase |
| Bluegrass | 28% " | 12% " | 0% " |
| T. fescue | 50% " | 0% " | 21% " |

***Meets the Eye*** *continued from page 7*

include *Cosmarium, Coccomyxa, Cylindrocystis, Dactylothece, Mesotaenium, Klebsormidium,* and *Ourococcus*. All but the latter two are capable of producing surface crusts and slime. The two most abundant genera of cyanobacteria in turfgrasses include Nostoc and Oscillatoria. The latter genus has been implicated as the primary cause of slime formation on golf greens. The cyanobacteria are also known for their abilities to fix atmospheric nitrogen, which, in some instances, may actually contribute to the nitrogen nutrition of the turfgrass plant.

Algae are strictly dependent on adequate soil moisture for activity. Algal problems occur whenever the soil remains wet for prolonged periods of time and where the soil surface is exposed or the turfgrass stand is thin and weak. Although fertility has no clear relationship to algal activity,the use of acidifying fertilizers such as ammonium sulfate can enhance algal colonization.

In addition to the more conspicuous colonies of algae on the surface of turfgrass soils, many algae colonize the surfaces of plants. Although in greenhouse ornamental production, many of these plant-colonizing algae can be detrimental to plant growth, their effects on turfgrass plants are largely unknown.

## Challenges for the Future

Soil contains an extremely rich wealth of biological resources in the form of microorganisms. These microbes influence all of the important processes related to plant nutrition and the general maintenance of plant health. Furthermore, soil microbial communities provide a genetic resource of potentially useful products and processes that can be exploited for the management of turfgrasses. The challenge to turfgrass managers is to become experts, not only in the management of what they can see above-ground, but to master the management of the beneficial soil microorganisms to achieve the maximum, sustainable means of plant nutrition and plant protection.

***Science Trends*** *continued from page 9*

enhancing fertility and horticultural properties. This emphasis will reflect sources of future funding for turfgrass research as well as a renewed sense of accountability among scientists and academic institutions in addressing and solving problems facing our society.

Because of the increased technical competence and knowledge base required of turfgrass professionals in coming years, we at *Turfgrass Trends* will do our best to keep you abreast of the latest developments in turfgrass science and technology as well as in management and regulatory issues affecting your profession. Information management will be central to your abilities to keep up with a rapidly changing societal, political, and scientific environment.