RESEARCH

Gases underground

Researchers seek answers to the roles of oxygen, carbon dioxide and other gases in root growth.

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Photos by B. Todd Bunnell

Poor soil aeration contributes to poor green performance.

The interaction of atmospheric and soil gases plays a major role in the performance of highly maintained turfgrass on golf greens.

Unfortunately, the relationship between soil gas composition and turfgrass physiology is not fully understood. Unanswered questions include:

- What are the broad-spectrum effects of differing gas concentrations, especially at varying temperatures?
- At what levels do oxygen, carbon dioxide and other gases influence turfgrass performance in a USGA or native soil (push-up) green?
- What parameters determine or influence the occurrence of these gases throughout the soil profile?

Soils have gas?

Gases make up approximately 25 percent of the soil. The soil atmosphere is defined as "the gaseous phase of the soil, being that volume not occupied by solid or liquid" (1). Generally, the composition of soil air is similar to the composition of the atmosphere with two major exceptions, oxygen and carbon

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KEY POINTS

- Oxygen and carbon dioxide seem to play important roles in root growth, but researchers haven't defined their optimal levels in turfgrass soils.
- In poorly oxygenated soils, toxic compounds form as plants remove oxygen components from existing compounds.
- Many factors — including compaction and soil water levels — influence soil gases.

continued from p. 65

dioxide. Oxygen and carbon dioxide usually fluctuate in the soil inversely, with an increase in carbon dioxide resulting in a decrease in oxygen.

What determines gas concentration?

Soil characteristics (compaction, moisture, root activity and microbial activity) determine the concentration of oxygen in a soil. When oxygen is in short supply, carbon dioxide, hydrogen sulfide and methane can become more prevalent.

Soil compaction

Soil compaction causes four main physical changes in soil structure (4):

- Reduced aeration porosity
- Increased bulk density
- Increased soil strength
- Altered pore size distribution

Increased compaction reduces overall aeration by limiting oxygen diffusion. Compaction decreases root and shoot growth, reduces carbohydrate reserves and decreases overall turfgrass quality.

Soil moisture

Over-watering is a common occurrence in turf maintenance. Excess soil moisture replaces air-filled pore space, reducing the ability for oxygen to diffuse readily through the soil. Oxygen diffuses through air 10,000 times faster than through water. Consumption of oxygen by respiration and lack of replenishment from the atmosphere potentially builds up toxic gases such as carbon dioxide, hydrogen sulfide and methane.

Root and microbial activity

Like mammals, roots and microbes respire using carbon and oxygen to produce carbon dioxide.

Because root cells are not photosynthetic, they require oxygen for respiration, growth, and water and nutrient uptake. An indicator of soil oxygen is the oxygen diffusion rate, which is the rate of oxygen exchange between the soil and atmosphere.

Turfgrass species have an unusually high tolerance of low levels of diffusion or oxygen availability — as low as 0.00000005 grams of oxygen per cubic centimeter of soil per minute (6). During summer months, turfgrass oxygen needs are greatest because high temperatures stimulate root and microbial respiration (5), which consumes available oxygen.

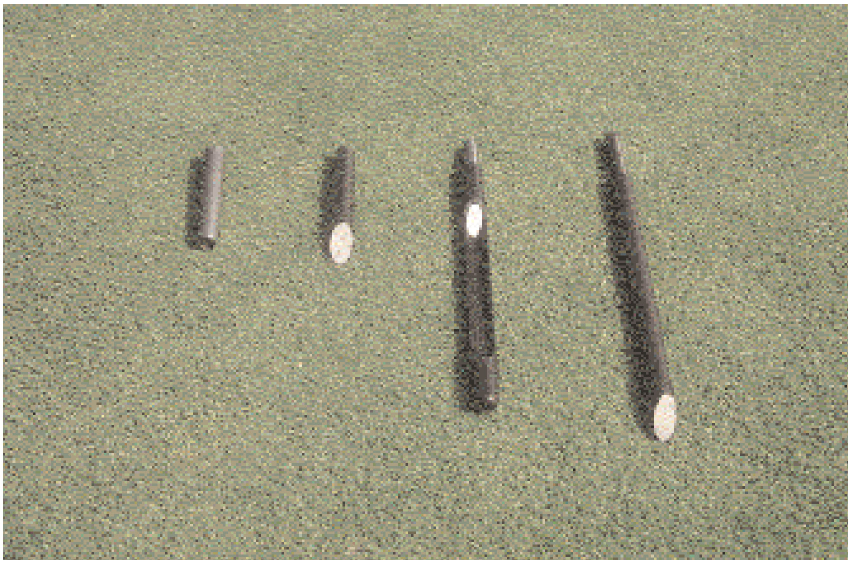
Little research has related soil oxygen levels to turfgrass growth. In one study, creeping bentgrass (*Agrostis palustris*) quality declined as temperatures increased and soil aeration decreased, but the research did not determine what percentage of oxygen is needed for healthy growth.

Oxygen composition in a putting green depends heavily on the interior architecture of the soil profile and drainage. In Clemson, S.C., in 1998, we

What's air made of?

Numerous gases make up the substance known as "air." Numbers are the percentages of each gas in clean, dry air near sea level (1).

Component	Percent
Nitrogen (N_2)	78.09
Oxygen (O_2)	20.94
Argon (Ar)	0.93
Carbon Dioxide (CO_2)	0.0332
Neon (Ne)	0.0018
Helium (He)	0.00052
Methane (CH_4)	0.00015
Krypton (Kr)	0.0001
Hydrogen (H)	0.00005
Nitrous oxide (N_2O)	0.000033
Carbon Monoxide (CO)	0.00001
Xenon (Xe)	0.000008
Ozone (O_3)	0.000002
Ammonia (NH_3)	0.000001
Nitrogen dioxide (NO_2)	0.0000001
Sulfur dioxide (SO_2)	0.00000002



Different aerification tines and depths should be used on golf greens to help maintain adequate soil oxygen and reduce compaction and layering.

saw oxygen levels fluctuate from 15 to 21 percent in a USGA green and from 9 to 21 percent in a native soil green, with the lower range attributable to increased bulk density and greater water-holding capacity in the native soil green. Of course, oxygen diffusion rates are usually lower deeper in the soil. Therefore, if oxygen is limiting, rooting may be limited throughout the soil profile.

Carbon dioxide: a toxin?

Carbon dioxide comprises a very small portion of the atmosphere, approximately 0.03 percent. Much higher levels are found in soils, where oxygen is produced by microbial and root respiration. Soil carbon dioxide can accumulate to levels toxic to root growth (7). Well-aerated soils generally have less carbon dioxide because it is replaced by oxygen and readily diffuses out of the soil.

Soil moisture influences carbon dioxide levels. When a soil becomes highly saturated, the oxygen diffusion rate is reduced, allowing the buildup of carbon dioxide. Generally, native soil greens have higher carbon dioxide concentrations than sand-based greens (3). However, when highly saturated, all green types can have high carbon dioxide levels.

Several theories attempt to explain how carbon dioxide damages roots. The most widely accepted asserts that high carbon dioxide levels decrease the cytoplasmic pH of root cells, interfering with water and nutrient uptake (2). Distilled water saturated with carbon dioxide has a pH around 4.0 because of the production of carbonic acid (2). As carbon dioxide enters the plant cell, the pH can drop to lethal levels.

As with oxygen, little research has investigated the effects of carbon dioxide on turfgrass root growth. One study found high soil carbon dioxide injured root systems and stunted growth (7). In another study, increased carbon dioxide levels reduced water and nutrient uptake by roots (2). However, the threshold at which carbon dioxide becomes toxic to turfgrasses remains unknown.

Plants are thought to tolerate levels of carbon dioxide as high as 10 percent (2). However, turfgrass species on a golf green under constant stress may not maintain healthy roots at such levels. Current research at Clemson University is measuring Crenshaw creeping bent-

continued

continued from p. 67

grass root growth at differing levels of carbon dioxide in a USGA green.

Methane and hydrogen sulfide

In highly saturated soils, toxic gases may form. As soil oxygen becomes more limited, soil organisms extract the oxygen component from other gases to survive. The resulting gases, with less oxygen attached, generally are toxic to root growth.

For example, the reduction of carbon dioxide by soil organisms produces methane, and the reduction of sulfate (SO_4^{2-}) produces hydrogen sulfide (H_2S). Methane and hydrogen sulfide can exceed atmospheric levels in overwatered, poorly drained soils.

A soil's moisture content determines the redox potential, which is the tendency of a system to reduce or oxidize chemicals. High redox potentials relate to aerobic or oxidizing conditions, whereas low (or negative) potentials indicate reducing or anaerobic conditions. Redox is not only important in the production of methane and H_2S, but black layer formation as well. When iron is introduced to reducing (anaerobic) conditions, it forms ferrous oxides. A anaerobic black layer occurs when ferric oxide (FeO) is reduced to ferrous sulfate ($FeSO_4$).

Improving soil gas

Improved soil gas exchange occurs when agronomic practices maintain the 25 percent soil pore-space component. There are several methods of improving soil aeration:

Aerification. Frequent aerification of golf greens opens the soil to the atmosphere, allowing rapid exchange of soil air, with ambient air replenishing oxygen and purging carbon dioxide, H_2S and methane. Aerification depths (shallow vs. deep) and core types (hollow vs. solid) should be rotated to prevent compaction and layering.

Watering practices. Maintain greens as dry as possible. The drier the soil, the more oxygen present. Highly saturated greens — especially in the summer —

Oxidized and reduced compounds in soils

Element	Oxidized form in aerobic soils	Reduced form in anaerobic soils	Bacteria type and conditions present
Oxygen	O_2	H_2O	aerobic and bacteria conditions
Nitrogen	NO_3^- (nitrate)	NH_4^+(ammonium) N_2O (nitrous oxide) N_2 (nitrogen gas)	facultative anaerobic bacteria and conditions
Iron	Fe_3+ or Fe_2O_3 (ferric oxides)	Fe^{2+} (ferrous oxides)	
Sulfur	SO_4^{2-} (sulfate)	S^{2-} (sulfide) H_2S (hydrogen sulfide)	obligate anaerobic bacteria
Carbon	CO_2 (carbon dioxide)	CH_4 (methane)	

Photo by Bert McCarty

Black layer often occurs in highly saturated golf greens with the formation of ferrous sulfate ($FeSO_4$).

are at risk for toxic gas buildup.

Subsurface air movement. The ability to pull and push air through the root zone via drain lines allows for immediate air exchange and oxygenation of the root zone. Pulling air increases drainage and air-filled pore space, while pushing air adds oxygen into the lower areas of the soil profile.

Monitoring soil gas levels. Soil gas probes can be purchased and easily operated, allowing a superintendent to monitor gas levels daily. Although toxic levels are not yet defined, gas levels can be useful information.

The future

Superintendents face increased expectations to produce the highest-quality putting surfaces possible. Planting creeping bentgrass in the South is one manifestation of these demands. But maintaining bentgrass in hot, humid climates requires water, which in excess can be detrimental to soil oxygenation. This, coupled with increasing compaction caused by high traffic, may create poor soil gas exchange. ■

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