How do soils breathe?

Like the air in the atmosphere, soil air is vital to turfgrass health.

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Approximately 78 percent of the Earth's atmosphere is nitrogen and the rest is primarily oxygen (O_2), argon (Ar) and carbon dioxide (CO_2) (2-5). Together, these four gases make up more than 99.99 percent of the atmospheric air. These gases are also present in soil, but their proportions are very different. In particular, as a consequence of respiration and microbial activity, the concentration of carbon dioxide is much higher in soil air than in the atmosphere.

Managing putting greens to prevent high carbon dioxide levels in the root zone has always been a dilemma for golf course superintendents and turf researchers (4,5). Understanding air movement in the soil profile is important because soil air content in the root zone depends on air exchange between the soil and the atmosphere, the respiration rate of microorganisms and plant roots, and the solubility of gases in water.

CO_2 and O_2 in the root zone

Both carbon dioxide and oxygen play important roles in plant biological processes, especially photosynthesis and respiration. In photosynthesis, chlorophyll combines carbon dioxide and water to form sugars and release oxygen into the atmosphere. To prevent oxygen deficiencies and excessive carbon dioxide levels in most plants, oxygen levels in soil air must be maintained at levels 50 percent or greater than oxygen levels in the atmosphere (2). In respiration, plant cells consume oxygen and produce carbon dioxide. The rate of oxygen consumption can be as high as 60 to 75 percent of the carbon dioxide production rate. Carbon dioxide in the soil air is produced not only by plant root respiration but also from microbial breakdown of carbon-based organic compounds in the soil. However, carbon dioxide levels are highest when microbial and plant root activity are at a maximum. This is the main reason why carbon dioxide content in the putting green soil is low in the fall and winter, but high during the growing season (5).

CO_2 vs. O_2 in soil

Soil condition	CO_2 content	O_2 content
Soil texture		
Fine	high	low
Coarse	low	high
Soil structure		
Well aggregated	low	high
Poorly aggregated	high	low
Vegetated soil	high	low
Bare soil	low	high
Soil amended with organic matter	high	low
Fertilized soil	high	low
Soil water content		
Wet	high	low
Dry	low	high

KEY points

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Oxygen in soil air needs to be maintained at appropriate levels to promote plant health.

The proper root-zone mix contributes to air permeability and the proper mix of gases in the soil.

Mechanical aeration and high-pressure water-injection can improve anaerobic root zones.

Soil air renewal and movement

Many factors can influence soil air renewal and movement in the field (6). Nitrogen levels in the soil remain stable, but carbon dioxide levels are inversely related to oxygen levels. Renewal and movement of soil air are governed by air permeability of the rooting medium, convection induced by external factors and diffusion of various gases in the profile.

Air permeability

Air permeability relates to the pore-size distribution and water-retention capacity of the root-zone mix and depends in particular on the air-filled porosity of the rooting medium. *Macroporosity* means that pore sizes are equal to or larger than 0.075 mm in diameter. Currently, the USGA Green Section (9) recommends that the root-zone mix for a putting green has 15 to 30 percent air-filled porosity (equivalent to 30 centimeters water tension). (From 1960 to 1993, the USGA recommendation was 40 centimeters water tension. The authors of this paper prefer this earlier recommendation.) Therefore, it is extremely important to pick the right sand and amendment in preparation for the root-zone mix.

The amount of amendment in the root-zone mix also plays an important role in air-filled porosity. At Southern Illinois University–Carbondale, a laboratory study was conducted to examine the influence of amendments on air permeability and hydraulic conductivity of the root-zone mix. Hydraulic conductivity indicates how well fluid will flow through a porous medium, for example, soil or gravel. Something with a high hydraulic conductivity will conduct fluid well. Results indicated that both air permeability and hydraulic conductivity varied, depending on the texture of the sand and the amendment used. This study also found that increasing peat moss content increases resistance to the flow of both air and water. The peat moss may be coating the air-filled pores, thereby hindering air and water flow in the rooting medium.

Driving forces in gas transport

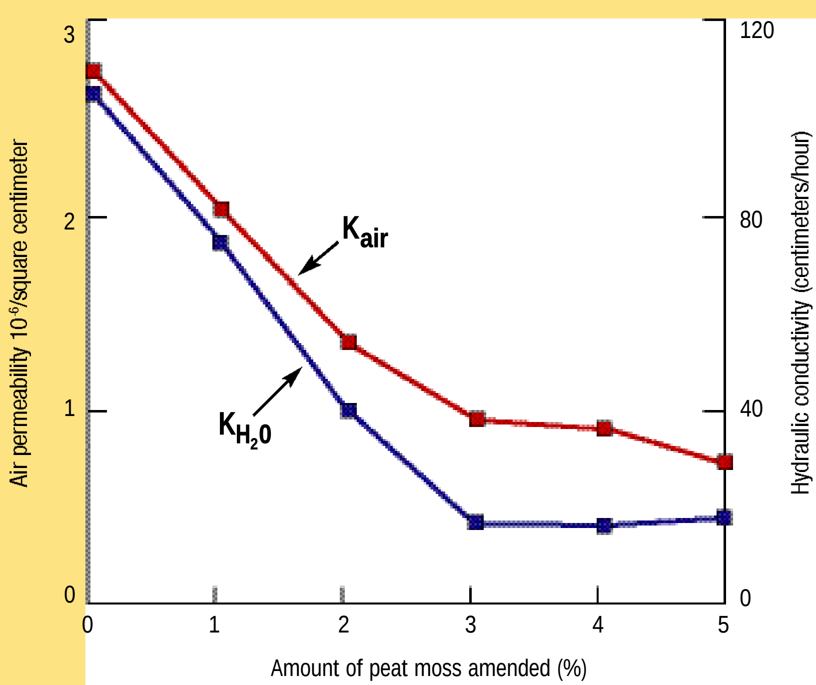
Two major mechanisms are involved in air transport in soil: mass flow and diffusive flow. Mass flow is induced mainly by temperature changes, barometric pressure fluctuations, wind velocity over the turf surface and infiltration of water (2,6,7). Diffusion is generally caused by concentration differences among gases, but it also can be influenced by differences in air pressure or temperature.

Practically, it is difficult to separate the effect of each mechanism on gas transport. Temperature differences between various parts of the soil (for example, the surface soil has a higher temperature than the subsoil) could result in density and pressure gradients that cause gas to flow, especially in the surface layer of greens. An increase in barometric pressure in the atmosphere would reduce soil air volume, which would cause movement of the same volume of air from the atmosphere into the root zone to fill the void. In contrast, a decrease in barometric pressure in the soil profile would allow soil air to expand and enter the atmosphere.

Research on the effect of wind velocity on soil air movement in putting greens is lacking. However, barometric pressure fluctuation, soil and air temperature changes, and wind blowing over the turf surface seem to have little effect on gas renewal and composition.

Infiltration and drainage of water may flush or displace air and consequently trigger airflow in the profile. In addition, irrigation and rainfall may carry dissolved oxygen to the root zone. Similarly, when excess water is removed by drainage, air will replace the water.

Hydraulic conductivity, air permeability



Variations in hydraulic conductivity (K_{H_2O}) and air permeability (K_{air}) in sand mixes amended with different amounts of peat moss.

Carbon dioxide at soil profile bottom

Carbon dioxide levels are often higher at the bottom of the soil profile because aeration rates are poorer at the bottom of the soil profile or root zone than in surface soil. Higher carbon dioxide concentration at greater soil depths may also be attributed to molecular weight differences among gases. Gases with higher molecular weights often stay at the bottom of the soil profile, whereas gases with lighter molecular mass are found closer to the surface.

Soil air in general has higher moisture content than air in the atmosphere. Intuitively, moist air would seem to be heavier than dry air because it contains moisture, but moist air is actually lighter. Otherwise, clouds would not hang high in the sky.

Dry air is dominated by nitrogen, carbon dioxide and oxygen. Moist air contains these three gases plus water vapor. Air changes to moist air when a water molecule replaces a carbon molecule. The molecular masses of nitrogen, carbon dioxide, oxygen and water are 28, 44, 32 and 16 grams, respectively. Therefore, when a water molecule with a molecular weight of 16 replaces a carbon molecule with a weight of 44 grams, the resulting moist air is lighter than the dry air.

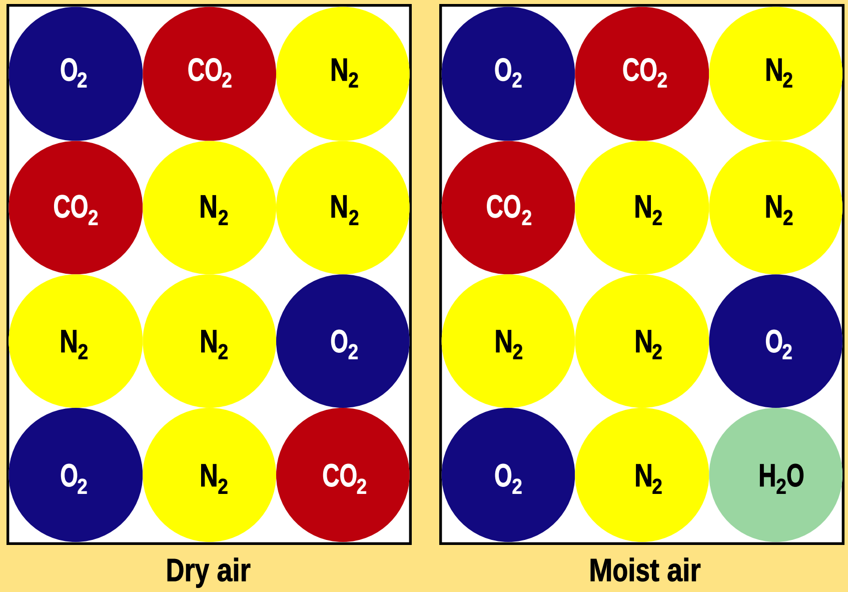
In most cases, water vapor will stay in the surface soil and will eventually evaporate and enter the atmosphere. In contrast, carbon dioxide, which has the heaviest molecular weight (44 grams), will stay at the bottom of the soil profile.

Anaerobic greens

In late summer, carbon dioxide levels as high as 20 percent have been detected in putting greens (4). High carbon dioxide content is found mostly in waterlogged areas because compaction and black layer formation are some of the most common environmental settings for anaerobic conditions in greens. Although improper green installation or management can cause compaction or layer formation, traffic from golfers and maintenance crews is the major cause of compaction, and thatch accumulation and transport of fine particles in the profile can cause black layer formation.

Using the wrong maintenance equipment and topdressing materials may speed up the anaerobic process. It is often suggested that the texture of topdressing sand should be the same as or coarser than what was already present in the green. As noted earlier, when peat moss, such as sphagnum or reed-sedge peat, is used as an amendment in the root-zone mix, fine particles can hinder air and water circulation. Poor aeration, high moisture content and low temperature and pH combined with the application of iron chelate (to promote a darker green turf color) create optimal conditions for black-layer in putting greens (1). Wise irrigation is critical in successful greens management.

Dry air vs. moist air



When a water molecule replaces a carbon dioxide molecule in an air pocket,that pocket changes from dry air to moist air and has a lighter molecular weight.

Soil aeration

Amelioration of an anaerobic root zone is not easy, and it can also be costly. Mechanical cultivation is the most common means of improving a green that is anaerobic because of compaction and/or black layer formation. Various methods commonly used in green cultivation include coring, slicing, spiking and forking. Mechanical aerification is usually performed in the early spring and/or in the fall for cool-season grasses. Aerification by high-pressure water injection (8) can be performed even in the summer with minimal disturbance to the green. Both mechanical cultivation and water injection only temporarily alleviate compaction and layer formation problems, but a regularly scheduled, aggressive aerification program can solve these problems in many cases (5).

Summary

Preventing high carbon dioxide levels in the root zone has always been a dilemma for golf course superintendents and turf researchers. The first step toward guaranteeing appropriate oxygen levels and a healthy root zone and putting green occurs during construction when the proper root-zone mix is selected and correct installation procedures are followed. Cultivation can enhance soil aeration and promote healthy levels of soil gases, but aerification must be continued on a regular basis or its benefits may decrease with time.

Acknowledgments

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