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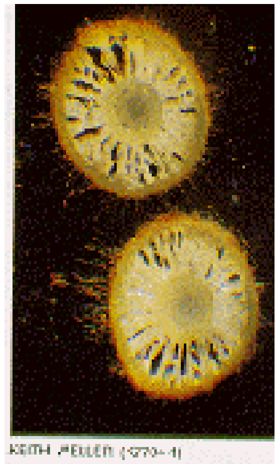
Aerenchyma — Lifelines for Living Underwater



By **Don Comis.**

Dark openings in this cross section of eastern gamagrass root are air passages that form in aerenchyma tissue and enable plants to grow in flooded conditions.

It all started with the "Great Dig of 1995" on the Spaulding farm in Missouri. In September of that year, a group of scientists from around the country had gathered near a soybean field. A backhoe had dug a trench 7 feet deep by 3 feet wide at the edge of a 50-year-old patch of eastern gamagrass that extended into the soybean field. The scientists sought the secret of a grass that farmers reported had thrived during droughts — as well as during prolonged flooding in 1993.

The first clue they got was that the roots reached down to at least 7 feet, easily passing through a clay layer that is impenetrable to most crop roots. And the roots of nearby soybeans seemed to go down deeper than the usual 2 feet, possibly because they were able to use the channels formed by previous eastern gamagrass roots.

The ability to penetrate the clay layer and explore deeper regions for soil water was one reason the grass could stay "green and nice when everything else was brown," says Richard W. Zobel. He is a plant geneticist with the Agricultural Research Service’s U.S. Plant, Soil, and Nutrition Laboratory at Ithaca, New York.

USDA NRCS scientists at the Big Flats New York Plant Materials Center excavate eastern gamagrass roots for study

Zobel squeezed some of the thick roots and found them squishy, something he had never seen in roots as healthy as these. But then Zobel had never felt the roots of eastern gamagrass. One of this country’s original prairie grasses that helped feed roving herds of bison, its population has declined under continuous grazing to where it isn’t even known to many experts—let alone the general public. But what Zobel would find when he put those roots under his microscope in his motel room later that evening would put eastern gamagrass on the road to becoming a household word—along with "aerenchyma."

That evening, Zobel excited his colleagues in the motel restaurant with his announcement that he had found aerenchyma in all the roots. Aerenchyma [pronounced air-ENK-a-ma], even less familiar to many than eastern gamagrass, is tissue with air passages that enable roots of plants

—rice, for example — to grow under water. In aquatic plants, the corky tissue aids gas exchange and buoyancy.

Instead of a root tightly packed with an organized array of cells, roots with aerenchyma are spongy, with large holes formed by cells either pulling apart or disintegrating. These holes run longitudinally through the roots. They enable flooded roots to snorkel air from the above-water parts of the plant.

W. Doral Kempe — former ARS national program leader for soil management, who is now retired — participated in the digging expedition organized by colleague E. Eugene Alberts at Columbia, Missouri. He explains that aerenchyma tissue enables roots to survive and punch through the clay pan layer when it's sopping wet, the only time it's soft enough to be penetrated.

"These roots live less than 2 years," Kemper says. "But when they die, they decompose slowly and help hold channels open for new generations of roots, providing the gamagrass with continued access to water in and below the clay pan."

This additional water reservoir enables the plants to continue growing during prolonged droughts. That's one of the reasons the aerenchyma study excites Kemper as no other field of research has in his extensive career. "It promises to relieve negative effects of both drought and flooding, which are the primary restraints to sustained production in soils with restrictive layers," Kemper says.

Plants as Rototillers

Alberts, who leads the ARS Cropping Systems and Water Quality Research Unit, says that part of the promise of aerenchyma-gifted plants like eastern gamagrass is using plant roots instead of machines or chemicals to improve a field. "Tillage machines can help break up the clay layer," says Alberts, "but the clay pan quickly returns. The only tools likely to permanently improve these dense soil layers in the long run are plant roots. They can literally be biological tillers, improving water movement and providing channels for other roots."

Not Just in Gamagrass

Agronomist Chet Dewald checks a corn-eastern gamagrass hybrid that is being grown in a project to map the genes that control aerenchyma formation and apomixis, or asexual reproduction by seed.

Zobel has also discovered aerenchyma in **vetiver grass**, a plant that farmers in India use in grass hedges to collect soil and build terraces similar to those built here with bulldozers. He has also found some short, upright types of eastern gamagrass that would be good candidates for grass hedges.

Excited by the potential of aerenchyma to enable crops to thrive in wet soils and soils with restrictive layers, John W. Radin, ARS national program leader for plant physiology, helped Alberts, Zobel, and Kemper organize a workshop in Atlanta last year. They invited all ARS scientists known to be working on aerenchyma.

One of the workshop participants, plant physiologist Tara T. Van Toai, has soybean plants growing partly underwater in plots in Columbus, Ohio. Another, soil scientist James E. Box, Jr., is developing similarly flood-tolerant wheat varieties in Watkinsville, Georgia, while others in Florida are searching for ways to make sugarcane flood tolerant.

The Great Dig at the Spaulding farm led to the realization that the common thread was aerenchyma, a trait normally associated with aquatic plants. And, it was suggested, since eastern gamagrass is a relative of corn, the trait might be transferred to that crop.

Visiting scientist Victor Sokolov from the Institute of Genetics in Novosibirsk, Russia, analyzes chromosomal variations in the root tip cells of corn-eastern gamagrass hybrids

"Apparently it is possible," says Bryan K. Kindiger, who is a plant geneticist at the ARS Southern Plains Research Station at Woodward, Oklahoma. "We've done it, unintentionally," he says. "We've already crossed corn and gamagrass and generated hybrids that reproduce by apomixis, which is asexually, through seed." (See "Apomixis; It Could Revolutionize Plant Breeding," *Agricultural Research*, April 1993, pp. 18-20.)

"Apomixis allows corn to reproduce seed clonally, causing seed to breed true from year to year and enabling farmers to maintain high-yielding varieties indefinitely," says Kindiger. "By luck, we found the aerenchyma trait to be strongly associated with the same chromosome that carries the gene for apomixis."

Farmers have long dreamed of breeding apomixis into all major crops, says Kindiger. The location of the genes now promises to give them not only this goal, but drought and flood tolerance as a bonus.

"Science has caught up with the dream," says Kindiger. He and colleagues have introduced aerenchyma into corn by crossing it with teosinte, a large fodder grass that is a close relative of corn. "Our research emphasis is on improving gamagrass as a grazing crop for cattle," says

Kindiger, "especially in making gamagrass reproduce asexually. "I hadn't heard of aerenchyma until last year, but the aerenchyma angle represents a good spin-off to our apomixis research."

Kindiger says eastern gamagrass is a wild grass with a gene pool that has a lot to offer corn, including resistance to cold and insects—as well as tolerance to drought and flood.

"Although it's not even close to extinct, there's less than there used to be in this country," Kindiger says. "Domestic cattle have destroyed it in many places, eating it to the ground. They like it as much as buffalo did, but the roaming herds of buffalo used to move on before they finished the plants off. "And much of the prairie grass has been plowed under to grow corn and soybeans. But you can see gamagrass all over ditches on Interstate 70 between Kansas and Missouri. It is a very, very unique plant."

The successful cross-breeding of gamagrass and corn by Kindiger and Chet Dewald, an agronomist and plant breeder — along with a 15-species collection of gamagrass and several strains of teosinte — led ARS plant physiologist Jeffrey D. Ray to spend a week at Woodward last year.

Ray says his lab was inspired by the Spaulding farm dig. His colleague, plant physiologist Thomas R. Sinclair, was on that expedition. Sinclair and Ray and colleagues are looking for aerenchyma in various types of sugarcane and corn plants.

"Aerenchyma is already very common in sugarcane, but breeding improvements are needed," says Ray. "There's a special importance to this work because if sugarcane can produce in higher water tables, we can slow down the degradation of muck organic soils.

"We are losing about an inch of organic soil a year to rapid decomposition caused by exposure to air from drainage," Ray says. "The Everglades Restoration Project is very much interested in creating sugarcane that can grow in the Everglades with minimal drainage.

"We went to Woodward to see how prevalent aerenchyma was under well-aerated conditions, because many plant species such as corn have varieties that will produce aerenchyma tissue when flooded," says Ray. "We're interested in the kind of aerenchyma plants develop soon after sprouting. Also, we wanted to see if aerenchyma occurred in the offspring of the teosinte-corn crosses."

Ray and his colleagues pulled up plants, sliced them with razor blades, and viewed the cross sections under a microscope. They found aerenchyma in the teosinte-corn offspring, as well as in all of the eastern gamagrass growing on well-aerated soils.

Guarded Optimism

Ray cautions that while he and Sinclair are excited by the possibilities, "at this early stage there is no proof that aerenchyma is always beneficial to plants. In fact," he says, "we have found that aerenchyma may be a negative trait for sugarcane grown on sandy soils in south Florida. Our experiments demonstrate that aerenchyma tissue makes sugarcane more sensitive to drought.

"While it can help plant roots thwart drought by penetrating hard layers, it could be a detriment in times of drought in sandy soils that are well aerated and well drained and have no hard layers," says Ray.

Yet, this past summer, Van Toai grew soybeans with aerenchyma in an artificially flooded field in Columbus. The plants, offspring of plants that survived a "flood of the century" in China in 1991, thrived—despite being partially submerged the entire season, beginning 2 weeks after the seedlings sprouted.

In a project sponsored by the U.S. Soybean Board, Van Toai is working with 10 other scientists across the country to breed new varieties of these flood-and-drought-tolerant soybeans within 4 years. They have screened 230 soybean lines for DNA markers linked to flooding tolerance and have identified several.

Van Toai analyzed eastern gamagrass samples taken both from the Shepherd farm in Cliftonhill, Missouri, where it survived the flood of 1993, and from samples at another location that was not flooded. She found that the Shepherd farm samples had more aerenchyma.

Dan Shepherd is not surprised. He traces his 1,200 acres of eastern gamagrass back to a clump of unknown grass his father found in clay soil surviving a killer drought in 1980, a drought that baked all other grasses and plants to death with temperatures up to 112^{o}F.

After a state prairie biologist identified the grass, Shepherd went to Dewald at Woodward for help in growing eastern gamagrass. The USDA Plant Materials Center in Manhattan, Kansas, gave him Pete, or PMK-24, the eastern gamagrass variety that he started his prairie pasture with. Now he sells the seed and fattens up all 700 of his buffalo herd on gamagrass for 8 or 9 months out of the year.

Box, who retired in 1996 but is still doing collaborative research, says the discovery of aerenchyma in eastern gamagrass has a significance that goes well beyond the practical implications for growing gamagrass. "It convinced people that aerenchyma is an important mechanism that should be incorporated into major crops," he says.

Penetrating Hardpan, Acid Soils

When he started studying aerenchyma in wheat in the 1980s, Box found it hard to convince plant breeders or farmers of its practical use, because they didn’t recognize lack of oxygen in soil as a significant yield robber.

Box says his work at the ARS Southern Piedmont Conservation Research Center in Watkinsville, Georgia, convinced him that lack of oxygen in a wet, restrictive layer during the winter months was the reason winter wheat in the Southeast roots shallowly and yields only 30 to 35 bushels an acre—barely at the break-even level, when it should be yielding 100 to 200 bushels.

Farms that should have tremendous yields of wheat, corn, or soybeans have been planted with trees or overrun with weeds because of the combination of summer drought and a restrictive soil layer, says Box.

Acid soils and hardpan layers restrict root growth, not only in large portions of the Midwest and the Southeast, but also in most of the eastern United States, where there is enough rainfall to at least meet crop needs. This amounts to a total of more than 250 million acres.

"Worldwide, acid soils make up about 10 billion acres," says Dale A. Bucks, the ARS national program leader for water quality and water management. "This restriction limits the water available to crops, resulting in drought and lower yields in areas with otherwise enough rain for the best yields."

Charles D. Foy, one of the pioneers in finding crops that will tolerate acid soils, agrees that shallow rooting caused by acid soils and hard layers—as well as other associated factors, such as aluminum toxicity and low oxygen—is an important yield-limiting factor for crops worldwide. He has found that eastern gamagrass roots are very tolerant of soil acidity.

"Its roots grow well in soils with pH in the range of 4.2 to 5.0, which is common for clay pans and other restrictive layers and is toxic to roots of most crops," says Foy.

He suspects that oxygen brought into the soil by the gamagrass roots might be rendering toxic forms of minerals such as iron and manganese harmless by oxidizing them to less soluble forms.

Ralph B. Clark, an ARS plant physiologist at Beaver, West Virginia, who has devoted his career to finding ways to grow plants on acid soils, says eastern gamagrass may also rely on beneficial fungi, called mycorrhizae, on its roots to help ameliorate aluminum toxicity. He found high numbers of them on root samples from the Great Dig. Mycorrhizae also help plants acquire essential nutrients under very deficient conditions, such as those in subsoil.

Jean L. Steiner, who heads the Watkinsville lab, is continuing Box’s research, working with Box and Jerry Johnson, a plant breeder at the University of Georgia at Athens. They are field-testing wheat types with aerenchyma bred into them and expect to have commercial varieties in 2 years.

Steiner says the breeding techniques Johnson is using with soft red winter wheat would apply to all other types of wheat.

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