In elevated carbon dioxide, soybeans stumble but cheatgrass keeps on truckin'

June 22 2010

Cheatgrass photosynthesizes in an artificial atmosphere during a labeling experiment. The experimental "chamber" is essentially a CD jewel case fitted with an O-ring. Credit: Jacob Schaefer

In August of 2008 Jacob Schaefer, PhD, on vacation in San Diego, picked up a copy of the Los Angeles Times. As it happened, the newspaper was running a series on the wildfires in the western United States.

The wildfires, he read, are more frequent — they now occur every few years instead of every few decades — and they are burning larger areas.

The more intense fire cycle is fueled by cheatgrass (*Bromus tectorum*), an invasive plant that is rapidly displacing native sagebrush plant communities.

Schaefer, the Charles Allen Thomas Professor of Chemistry in Arts & Sciences, was intrigued. At home in St. Louis he was studying the response of soybeans to stressful growing conditions. Soybeans, frankly, were having trouble coping.

What about cheatgrass, he wondered? The way it was mopping up the West suggested it might be running its metabolism differently from other plants.

His hunch proved to be right. His results, published in the April 15 issue of the *Journal of the American Chemical Society*, show that cheatgrass biochemistry is better suited to elevated carbon dioxide concentrations than soybean biochemistry.

The research adds to a growing body of evidence challenging the idea that all plants will benefit from rising carbon dioxide levels. Some plants will be helped, but others will be harmed.

A grass' cheating ways

Like many successful invasive plants, cheatgrass has more strategies for outcompeting other plants than a Swiss army knife has blades.

It's called cheatgrass in the first place because it fools farmers into thinking their winter wheat is coming along well.

Cheatgrass sneaks ahead of other plants by growing early and fast, depleting soil moisture before other plants break dormancy. (It has a fibrous root system that draws down soil moisture to what is called "the permanent wilting point.")

Cheatgrass sets seed and dries completely in early summer, creating dense mats rich in lignin and aromatics, compounds that are easily ignited and burn well. "When lightning strikes a bed of dead cheatgrass, it's like dropping a match into a lake of kerosene," the L.A. Times reported.

Once cheatgrass invades, fires start earlier, when native plants are more susceptible to injury. Repeated burning eventually kills all the native plants, and cheatgrass competition prevents their re-establishment.

"A cheatgrass landscape is about as ecologically rich as a parking lot," said the L.A. Times.

The mystery of photorespiration

Schaefer wanted to know whether differences at the molecular level gave the plant its competitive edge.

All plants make a living by tapping the energy in sunlight to "fix" the carbon in carbon dioxide by incorporating it in carbon-based molecules such as sugar.

Soybeans and cheatgrass are both C3 plants that use an enzyme to bind carbon dioxide from the air and join it to a five-carbon molecule, producing a six-carbon molecule that quickly splits into two three-carbon molecules (hence the name C3).

But, as Schaefer was aware, C3 plants have a puzzling metabolic quirk. On a hot day, the plants close their stomata, the pores mainly on the undersides of leaves, to cut down on water loss. This in itself is adaptive.

But when the stomata close, the carbon dioxide concentration in the air spaces inside the leaf also falls.

Instead of binding carbon dioxide, the enzyme then binds oxygen and forms a five-carbon rather than a six-carbon molecule, which gets split into a three-carbon and a two-carbon molecule.

The math doesn't work.

The two-carbon molecule can't go through the carbon-fixing process directly. Instead it goes through a cascade of reactions and is then fed back into the carbon fixation cycle.

This process, called photorespiration because it occurs in the light and releases carbon dioxide, doesn't make a lot of sense. It uses energy instead of storing it, and releases carbon instead of fixing it.

The standard explanation, says Schaefer, is that the enzyme in question evolved when there was no oxygen in Earth's atmosphere. So it didn't matter that it could bind either carbon dioxide or molecular oxygen.

Now that oxygen levels are higher, however, the oxygen-based reactions get in the way of the carbon-based reactions.

Schaefer was aware of the photorespiration problem because he had worked in the 1960s and 1970s at Monsanto, the St. Louis-based agricultural business.

"The consensus at the time was that photorespiration was wasteful, and if you could inhibit it, the plant would be more productive," Schaefer says.

"Monsanto had a big research effort to find a chemical that would do that. They had hundreds of guys working on it. I started using nuclear magnetic resonance to characterize photorespiration, but I didn't have the right techniques to resolve the chemical interactions I wanted to study."

Invasive cheatgrass is displacing the native sagebrush communities that, together with wild mustangs, are icons of the American West. Credit: Stock photo

The rooftop experiment

By the time he read about cheatgrass in the L.A. Times, however, Schaefer had the technique he needed (see sidebar "The Right Tool for the Job.") So when he returned to St. Louis, he started growing pots of cheatgrass on the roof of WUSTL's McMillan Hall.

In a special labeling experiment, one pot was exposed to an atmosphere with a carbon dioxide concentration of 200 parts per million, substantially below the current atmospheric level. The other pot was exposed to 600 parts per million, a concentration likely to be reached by 2050.

Both the nitrogen in the fertilized soil and the carbon in the carbon dioxide were unusual isotopes. The isotopes acted as tracers, allowing the scientists to see how the plant used the nitrogen and carbon. (They also explain the small scale of the experiment, because one bottle of artificial air with labeled carbon dioxide costs $4,000.)

The cheatgrass labeling experiment was then compared to a labeling experiment performed on soybeans in 2006.

A video of the scientists running the soybean labeling experiment can be found on Schaefer's lab page.

Dried cheatgrass is tinder waiting to be set alight. Credit: USGS

The surprising results

Neither plant behaved as it was supposed to in the low carbon dioxide atmosphere.

Both plants made glycine, an amino acid that is an intermediate product in the photorespiration cascade, but the glycine, instead of being fed back into the carbon fixation process, was combined with other amino acids to form glycine-rich proteins.

Glycine-rich proteins are structural proteins that the plants use to strengthen cell walls, particularly those in xylem, the specialized water-transporting tissue, and to counter the effects of dehydration.

So instead of spinning their wheels, the plants were responding adaptively to the low carbon dioxide condition, strengthening tissues that would help them survive the water stress for which low carbon dioxide is usually a proxy.

Their response to the high carbon dioxide atmosphere was another matter entirely.

The soybeans stopped making the glycine-rich protein and instead starting routing most of the glycine back to carbon fixation in classic photorespiration wheel-spinning fashion. In other words, they stopped responding adaptively and started wasting energy.

The cheatgrass, on the other hand, kept right on trucking, churning out more glycine-rich protein.

What it all means

Soybeans probably have a switch, or control system, Schaefer says, that responds to carbon dioxide concentrations inside the leaf. If the carbon dioxide level falls, this switch turns on protein synthesis. If the carbon dioxide level rises, the switch turns off protein synthesis.

Cheatgrass, on the other hand, runs the protein biosynthetic pathway full out under all conditions. It seems to lack a switch or control system.

Soybeans, in other words, are optimized for the low carbon dioxide concentrations and abundant water that were common over the last half million years.

Cheatgrass, however, evolved in arid conditions where it made sense to strengthen water transport tissues.

Unfortunately, the climate of the future is likely to be more like the one to which cheatgrass is adapted.

"We believe," says Schaefer, "that as carbon dioxide rises and we try to farm more marginal land to feed a burgeoning population, plants like cheatgrass will have a large advantage over plants like soybeans."

In 2006, the University of Illinois at Urbana-Champaign, published the results of an experiment where soybeans were exposed for four months to carbon dioxide released under computer control on the upwind side of a field plot.

The experiment showed that soybeans benefited much less from elevated carbon dioxide levels than earlier experiments in greenhouses and laboratories had suggested they would.

Schaefer believes his work shows why.

Provided by Washington University in St. Louis