Fern of the future?

Held in the palm of a human hand, a single specimen of *Azolla filiculoides* looks downright inconsequential. Even with the scaly leaves of this miniature aquatic fern spread flat, it barely spans the distance between the creases that cleave the flesh. Its fibrous root tendrils dangle like a lock of matted hair, adding to its overall impression of impotence and making it even harder to believe that *Azolla* might help address humanity's greatest challenges. That it could is the hope of a team of scientists investigating *Azolla*'s potential as a sustainable source of biofuel and protein. They presented their preliminary results last month at the EGU General Assembly.

Azolla filiculoides close up. (Credit: Robert Vidéki, Doronicum Kft., Bugwood.org)

More reminiscent of a moss than a fern, *Azolla* has a long history with humans. Rice farmers in ancient China used it for thousands of years as green manure to replenish their paddies, unknowingly harnessing the power of its symbiotic nitrogen-fixing cyanobacteria. *Azolla* then enjoyed a moment of global celebrity in the 1970's and 80's as Western agricultural researchers began to recognise its potential before it fell abruptly into disrepute. Invasive *Azolla* grows like a weed: in 1993, it made headlines in Europe when blooms choked the Guadiana River in Portugal following an influx of phosphate runoff from upstream farms and factories.

But this ignominious debut did not alert the scientific community to *Azolla*'s biofuel potential. In fact, the diminutive fern did not come to the attention of Henk Brinkhuis, a geologist at Utrecht University in the Netherlands, until eleven years later, when copious quantities of *Azolla* spores turned up in ancient sediments from the Arctic Ocean. Scientists collecting cores in the newly ice-free Arctic Ocean in 2004 discovered evidence that, during the balmy Eocene epoch about 50 million years ago, *Azolla* blanketed the pole. They hypothesised that, in collusion with other changing environmental factors, these humble plants might have altered the climate – kick-starting the global cooling that drove Earth into its present icehouse state – by consuming CO_2 and storing it in their biomass, where it has remained at the bottom of the Arctic Ocean.

Now, *Azolla* may be poised to help bring down CO_2 yet again, but in an entirely different way: awed by its irrepressible capacity for reproduction (it can double in mass every two days), Brinkhuis assembled an interdisciplinary group of scientists from Utrecht and Wageningen Universities in the Netherlands and Imperial College in the UK to investigate the suitability of several species of *Azolla* for commercial biofuel production. Peter Bijl, also a geologist at Utrecht, coordinates the project from the helm of the Laboratory of Palynology and Paleobotany (LPP) Foundation, a non-profit that specialises in bridging the gap between academia and industry.

"The *Azolla* lipids are very special in terms of composition and carbon chain length, diversity and functional groups," Bijl says, discussing the new results he presented at the EGU meeting. The long-chained lipids store energy, making them suitable for biofuel, while other types of *Azolla* compounds can be manipulated into specialised high-value chemicals like lubricants. From what remains of the fuzzy green-red ferns after extracting these molecules, Bijl and his colleagues demonstrated that they can concentrate protein of the desirably nondescript variety (think soy) used in processed foods and animal feed. This has tremendous benefits from an economic point of view, Bijl says: "Basically, you can sell the same product twice."

Azolla also stands out as a radical alternative to other biofuel crops like corn, oil palms, and sugar cane that have become the source of global controversy. The problems that plague these other biofuels – once a seemingly promising way forward – include their competition with food crops for arable land, their suitability to tropical regions that often face a trade-off between rainforest and crop land, and the fact that these crops require so much synthetic fertiliser that, in the long run, they are far from carbon neutral.

Azolla, however, might sidestep these issues. First, the fern can be grown on marginal land that lacks agricultural utility. For example, Bijl says: "In India, there are large coastal areas where the groundwater has become brackish, but there are certain species of *Azolla* that can tolerate this." Second, the fern, like its full-sized relatives, thrives in relatively low light conditions like the natural sunlight available at mid-latitudes, alleviating the burden on low-latitude countries to grow most of the world's biofuel or the need for expensive indoor growing facilities. Third, with an endless supply of nitrogen, it requires few inputs, especially if grown in a closed system.

The holy grail of a closed system – nothing added, nothing wasted, endless product – has proved elusive for traditional biofuels. However, *Azolla* cultivation might come close because free sunlight, nitrogen and CO_2 constitute the primary inputs, and the whole process

Azolla growth in Broken Creek near Cobram in Victoria, Australia. (Credit: Arthur Mostead)

takes place in isolated tanks where nutrients can be reclaimed from wastewater streams and fed back into the next batch. Heat speeds up the process, but that could come from unexpected sources. On an industrial scale, Bijl envisions coupling *Azolla* production facilities to industrial operations like concrete factories or steel plants where heat and CO_2 abound.

Other biofuel experts agree that *Azolla* truly does differ from previous crops in important ways. Keith Smith, a geologist at the University of Edinburgh who has studied the greenhouse gas emissions of growing traditional biofuels, says that *Azolla*'s natural nitrogen source would greatly reduce such emissions. Its ability to grow on marginal land helps too, he says, because what really matters is avoiding "land use change whereby forest land becomes converted to agricultural land. The CO_2 emissions associated with this process are huge compared with any environmental benefits from using biofuels instead of fossil fuels."

However, Tad Patzek, Professor of Petroleum and Geosystems Engineering at the University of Texas at Austin and a prominent biofuel critic, thinks *Azolla* is just another doomed biofuel darling. "It makes no difference what less or more exotic source of biofuels we find," he wrote in an email. "They all – without an exception – are unsustainable and/or harmful at the scales we want to deploy them." A truly closed system can't exist, he argues, because removing biomass and the micronutrients it contains violates "the thermodynamic definition of sustainability". In addition, there are other conceivable concerns regarding the threat posed by invasive *Azolla* if spores escape into the wild and cautionary tales of other non-food biofuel crops like switchgrass and jatropha that failed to fulfill perhaps overly-inflated hopes.

Bijl and the LPP Foundation harbor no delusions that *Azolla* will save the world. However, their research reveals that the fern could produce commercially viable quantities of chemicals and proteins without the human and environmental costs of other biofuels. With the results of the preliminary investigations now in hand, the LPP Foundation hopes to attract business partners like energy giants, specialty chemical companies, and food and animal feed manufacturers.

So far, Bijl says there have been hints of interest from potential collaborators, but nothing concrete. Will anyone bite? It's too soon to tell, but in the meantime, Bijl's vats of *Azolla* will just keep growing and growing, synthesising lipids and proteins without any regard for mankind, just as they have done for 50 million years.

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Flash, bang, jet: new observations of volcanic plumes

It erupts every day. Thousands of explosions occur every year. And, if you look closely, you might just catch sight of the lightning.

The Japanese volcano Sakurajima nestles in Kagoshima bay, spewing its jets of volcanic debris onto the 680,000 residents of the nearby city. Corrado Cimarelli, a volcanologist at the Ludwig Maximilian University in Munich, comes here to observe the lightning. He uses high-speed cameras to capture the moment and then recreates the spectacle in his lab.

"My colleague Miguel Alatorre-Ibargüengoitia was doing experiments looking at [volcanic] jets and we discovered the lightning in one of these experiments, completely by chance," says Cimarelli. "Miguel and I were looking at the videos and we thought: what was that white thing in the video? So we went back and we saw that there were actually many of these flashes."

To recreate volcanic lightning in his lab, Cimarelli uses about 100 grams of ash per experiment, but each one lasts for only a few milliseconds. "Without the high-speed camera you don't see anything, you just hear a big boom and everything is finished," he explains. The lightning is caused by the separation of charged particles within the plume: the ash carries electrical charges, the ash expands, and the electrical charges become separated. The flash of lightning occurs when the charge difference is so great that it can overcome the resistive air in between. Over time the lightning flashes get bigger but less frequent. "This is something we can actually observe in volcanic plumes," says Cimarelli, "you start with an acceleration of particles and you see a lot of crackling of lightning around the vent. Then, with time, you build up longer and more powerful lightning." Cimarelli and his team also found a relationship between the size of the particles and the number of flashes produced: more flashes are seen when there is a greater proportion of smaller particles.

Volcanic lightning has been proposed as the 'spark of life', electrical discharges that aided the first formation of organic molecules. Cimarelli is excited by the possibility: "Volcanoes not only produce the spark but they actually contributed to the formation of the early atmosphere on the Earth. All the gases are actually escaping from the volcanoes. I'm not saying life was produced by volcanoes, but it's a sexy idea. We don't need to look for strange explanations if everything is there." Cimarelli hopes to pursue this idea in future experiments.

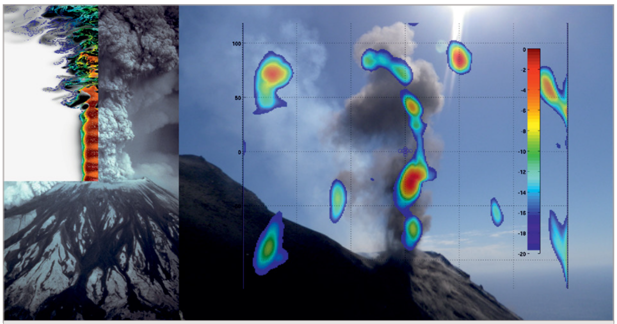
There's also a very practical application in the form of hazard management. "We cannot predict the eruption, but we can tell something about the structure of the plume and the fate of the ash from the plume. But we need to couple this technique with other monitoring," says Cimarelli. This is where the sounds come in. "During monitoring at night our camera can't see the very beginning of the eruption, but we can spot it because of the sound. So we can synchronise our camera with the microphone and then use the microphone signal to look in the video to find the beginning of the eruption." These techniques are being used in collaboration with researchers at the Universities of Kyoto and Kyushu in Japan.

Left: Volcanic lightning at Sakurajima volcano in Japan. Right: Volcanic lightning recorded by a high-speed camera in the lab. Images courtesy of Corrado Cimarelli.

Jörn Sesterhenn, from the Technical University of Berlin, is also very interested in the sounds produced by volcanic jets. When a volcano erupts the key parameters to determine are the diameter of the vent, the speed of the jet and the volume of ash in the flow. These variables can be very hard to measure directly, but, explains Sesterhenn, we can listen instead.

"We go to the volcano and take pictures and also place microphones. At home we compute the whole thing using a supercomputer. From this computation we find out how the acoustic waves radiate. From these characteristics we do what we call beam forming and identify the sources of the sound [in space]." In other words, Sesterhenn and his colleagues can make a map of where in the jet the noises are coming from.

Many volcanic jets are supersonic. "Every jet which has a pressure inside the volcano that is twice the ambient pressure will be supersonic," explains Sesterhenn. These supersonic jets have certain characteristics, which Sesterhenn has reproduced in his numerical models. When the jet first starts it produces a vortex ring. "It's a bit like a smoke ring," says Sesterhenn, "if you have a fluid coming out of a tube you have friction between the fluid and the wall and this causes the fluid to start turning." Then there are shock cells, patches in the jet that correspond to supersonic booms. Some jets are like



Left: The eruption column at Mount St. Helens and a numerical model of a volcanic jet. Shock cells are visible as dark red patches within the jet. Right: The location of acoustic sources within a volcanic jet. Images courtesy of the US Geological Survey and Jörn Sesterhenn.

single puffs of smoke – just one vortex ring is produced; others are more continuous and include lines of shock cells.

Sesterhenn is also able to learn about the ash content of the jet purely from acoustic observations. "If you have ash, the ash changes the structure of the jet. For example, with no ash you have a certain mode of behaviour for a certain Mach number (the ratio of the speed of the jet to the speed of sound) – for example a spiral motion. If you keep everything the same but alter the ash content then this motion changes. If we knew everything else about the jet we could infer the ash content from the type of motion – whether it's spiraling or flapping, for example. If we know other things, like the vent diameter, we can calculate the volume fraction of ash in the air."

"Ultimately this will be helpful for hazard management," he explains. "Microphones are very cheap devices – they cost a couple of hundred Euros – but it's not a short term goal."

Flashes and bangs in volcanic jets make for exciting research topics, but they also reveal vital information about volcanic eruptions as they progress. Hopefully, real-time observations of these sights and sounds will soon feed into disaster management initiatives.

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Notes

A video of Cimarelli's volcanic lightning in the lab is available online.

Sesterhenn's work has been accepted for publication in Geophysical Research Letters.

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Scrublands and carbon fluxes: an unexpected result?

"For starters, checking for rattlesnakes before collecting samples is a must!" laughs Andrew Cunliffe from the University of Exeter in the UK, a young scientist member of the EGU who has just presented in the session on dynamic soil landscapes at the 2014 General Assembly. His talk was on redistribution of soil organic carbon (SOC) in semi-arid rangelands (grazing land with shrubby vegetation). He used the Chihuahuan desert in New Mexico, USA as a case study for understanding SOC dynamics in this relatively understudied area of soil science.

Semi-arid rangelands tend not to get the bulk of attention from soil scientists studying SOC because there is little growth of plants in scrublands, and there is little SOC available to begin with. Coupled with this is the fact that human activities have less impact on how soil carbon is distributed in semi-arid lands compared to intensively managed agricultural landscapes, so dryland SOC dynamics tends to be rather static and uninteresting to soil scientists. And yet, this type of land makes up around 40% of the world's land surfaces, representing an important part of the global terrestrial carbon sink. Further, it helps sustain a sixth of the global population, often in marginal environments. Recognising this, Cunliffe and his colleagues set out to investigate particulate SOC distribution and redistribution over the constantly changing interface between grasslands and semi-arid scrublands.

The study of SOC is important because of its key link to climate change: how is carbon transported and stored within Earth's biogeochemical systems? Not only that, but understanding SOC dynamics helps us understand the impact that changes in land cover have on different soils and wider ecosystems. It is especially important when considering the long term soil quality and fertility for supporting crops and livestock. Understanding what land management practices can keep SOC in the soils for the longest can help us work with farmers to ensure they have the best land for growing crops. Combining an understanding of SOC dynamics with climate and land use change can also help us prepare farmers for climate change and the subsequent changes in soils and land management they will need to endure and practice.

In Cunliffe's study, he collected 50 samples from four plots with different types of vegetation and examined the concentrations of particulate SOC in various particle-size fractions obtained from these samples, leading to some interesting results.

Soil components can roughly be separated into three parts: coarse, medium and fine. Generally, it's thought that there's no organic carbon to be found in big soil particles (those greater than 2 mm), and little in medium-sized ones (0.25–2 mm). However, Cunliffe's findings have shed new light on the distribution of organic carbon across soil aggregates. While fine soil particles (those under 0.25 mm) have relatively high concentrations of organic carbon, a finding in line with soil other science research, the medium-sized particles were surprisingly rich. The biggest particles were the biggest surprise, containing a similar concentration of organic carbon as the smaller (sub 2 mm) aggregates. The amount of carbon stored in scrubland soils could be severely underestimated if these size fractions are ignored.

View across the Sevilleta National Wildlife Reserve, in the Chihuahuan desert in New Mexico, USA. Inset: rattlesnake beneath a creosote bush where Cunliffe had wanted to collect a soil sample. (Credit: Andrew Cunliffe)

Surface runoff is a major erosive process in semi-arid rangelands. Here, rainstorm intensities exceed the soil's infiltration capacity and excess water flows over the land surface, carrying with it some of the soil. This process leads to wide redistribution of soil particulates and, in addition, SOC.

Eroded sediments are commonly enriched in SOC relative to the eroding topsoil. This is widely attributed to the fact that water erosion tends to favour the smaller particle sizes, which usually have relatively high SOC concentrations. However, Cunliffe's work has shown that this size selectivity explains less than 15% of the SOC enrichment they've monitored and he is working to find out why. Furthermore, they've found large changes in SOC enrichment when vegetation changes from grasslands to shrublands, which are currently very poorly understood.

Cunliffe's study helps to show that common practices of understanding of SOC distribution (and redistribution) are not always directly applicable for semi-arid rangelands. As these landscapes hold one of the largest carbon sinks in the world, it may even be that we are underestimating the amount of SOC these environments contain by excluding coarse soil fractions in SOC studies. For Cunliffe, this was an exciting and unexpected result.

So where will Cunliffe go next with these exciting results? He's now deploying remote sensing technologies to survey these landscapes and examine fine-scale controls on the distribution of SOC. He hopes this will help understand catchment-scale SOC dynamics in semi-arid rangelands and help scientists better understand how carbon is collected, redistributed and locked up in Earth processes.

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