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Can Root-Inhabiting Fungi Save the World?

Summary of a Cooper Fellow lecture by Professor David P. Janos of the University of Miami Department of Biology



At present, you are one of 7.1 billion people on Earth, a population that is predicted to increase to between 9.6 and 12.3 billion by the year 2100¹. Because of population growth and also because of loss attributable to salinization of irrigated lands and other soil degradation, the amount of arable land per person, 0.2 hectare in 2012 according to the World Bank, is less than half its 1961 value of 0.5 hectare. In other words, right now your share of land for food production is a bit less than half the size of an American football field (excluding the end zones). What will your share be in 35 years, in the year 2050?

Pressure on arable land is worsened by people shifting their diets to increased protein, and by diversion of crops such as corn in the United States and sugar cane in Brazil to biofuel production. If you eat beef, pork, or poultry, it takes 7, 4, and 2 kilograms of feed grain, respectively, to produce one kilogram of meat – a bit more than two pounds. At current rates of improvement, yields of maize, rice, wheat, and soybean, which together account for two-thirds of agricultural calories, are unlikely to achieve the doubling predicted to be needed by 2050².

Gains in agricultural production that compensate for the diminishing share of land per person come chiefly because of fertilization. Fertilizers not only enhance crop growth but also replace mineral nutrients removed in harvested materials. Those bananas you ate because your mother told you they would provide potassium, represented potassium export from wherever the bananas were grown.

When you buy any container of fertilizer, it will have three numbers listed prominently on it. Those are the concentrations of nitrogen, phosphorus, and potassium that it contains. Always listed in that order, plants must acquire these three elements from the soil in the largest amounts. So, in order to sustain – not to mention, increase – current crop yields, we need to ask how long the world's supplies of these elements will last.

The International Fertilizer Industry Association forecasts that for 2017/18 world agriculture will consume slightly more than 116, 45, and 33 million metric tons (Mt) per year of nitrogen, phosphorus, and potassium, respectively³. Fortunately for us, as long as we can afford the energy required for the conversion, we can produce nitrogenous fertilizer from the effectively unlimited supply of nitrogen in the air. But phosphorus and potassium must be mined, and readily-accessible world reserves are estimated to be 5079 Mt of phosphorus (as P₂O₅)⁴ and 8300 Mt of potassium (as K₂O)⁵. Simple long-division suggests that if our rate of fertilizer use remained constant at 2017/18 levels, readily-accessible potassium would last 250 years. Additionally, there is a similar amount of difficult and expensive to extract reserve that could double the time to potassium exhaustion.

In contrast, phosphorus is a major concern for future fertilizer needs because at current

rates of use we have only 112 years' worth of easily-accessible phosphorus. Typically, however, extraction of mineable natural resources such as phosphorus (and oil) reaches a peak, and then, as extraction becomes increasingly difficult and expensive, annual production diminishes until the reserve is exhausted. For phosphorus, peak production might come as early as 2033⁴, or sooner if rates of fertilizer use continue to increase.

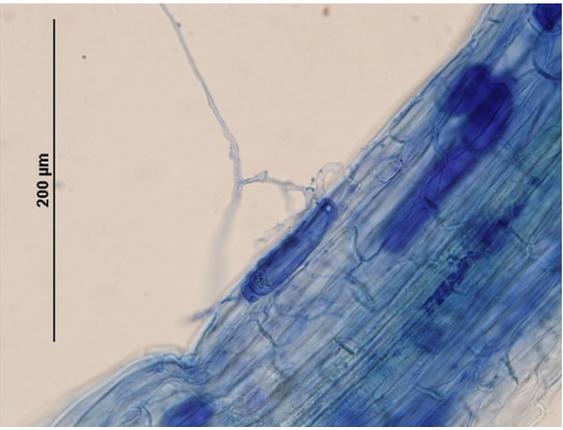


Figure 1. Magnified view (the scale bar is about one-fifth the thickness of a dime) of a blue-stained plant root and its accompanying root-inhabiting fungus which is visible as bumpy, threadlike filaments outside the root and darkly-stained fungus storage structures within the root. Photo by J. Weremijewicz

What can we do about this impending phosphorus crisis? Because the amount of phosphorus on Earth is finite, the only option for its sustainable utilization is to limit consumption to an amount that can be satisfied by recycling – a considerable challenge in the face of an expanding human population and diminishing arable land. Although technologies exist to minimize fertilizer over-application and consequent loss, most of the world's farms lack access to them. Moreover, even technological economies lack infrastructure for phosphorus recovery and recycling from waste streams. To presage such approaches which will be needed eventually, can we enhance the efficiency of phosphorus uptake and use by plants?

The answer may lie in the Gifford Arboretum, just as it does in most native vegetation worldwide. If you microscopically examine the roots of more than 80 % of the world's plant species, you would find them associated intimately with fungi (Figure 1) belonging to a unique, ancient group, the Glomeromycota⁶. Within root cortical cells, Glomeromycotan fungi form tiny, bush-like, much-branched structures called 'arbuscules' that facilitate exchange of phosphorus from the fungi in return for energy-rich carbon compounds from host plants. Threadlike filaments of the fungi extend beyond roots to provide an extensive, better-distributed and less energy-expensive absorptive network than roots and root hairs. Root hairs are extensions of single epidermal cells and rarely exceed the diameter of a penny in length, but the external filaments of arbuscular, root-inhabiting fungi can extend 'tens of pennies' beyond roots. Thus, the fungi can gather and transport phosphorus to roots especially efficiently.

Of course, if phosphorus is abundant and readily available in the soil, the help of root-inhabiting fungi is irrelevant to plants which can do fine on their own. But, when phosphorus is limited, the fungi can substantially improve plant growth (Figure 2). Such growth improvement is known as the 'responsiveness' of a plant species or crop variety to root-inhabiting fungi^{7,8}.

As phosphorus availability in soil increases, plant responsiveness diminishes. That has led crop scientists to think that deliberately breeding crop varieties to take best advantage of fertilization inadvertently might reduce their capacity to benefit from root-inhabiting fungi. A new analysis⁹, however, suggests this need not happen. Nevertheless, crop breeders should try intentionally to produce varieties capable of maximizing the yield advantage to be gained from association with root-inhabiting fungi, which so far has not been attempted.

Having crop plants that efficiently use phosphorus proffered by root-inhabiting fungi brings with it a second challenge which is the need to make sure that the fungi are present and available to associate with roots. Unfortunately, so far no one knows how

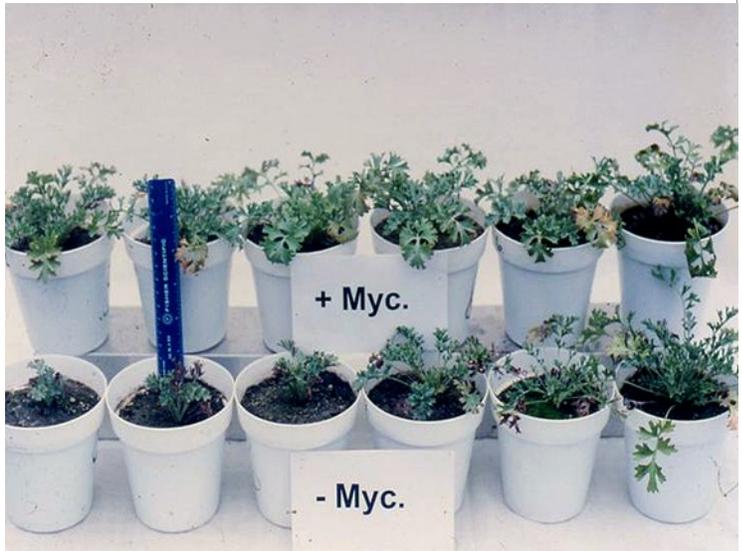


Figure 2. Pyrethrum chrysanthemum (*Tanacetum cinerariifolium*) plants grown with (+ Myc.) and without (- Myc.) beneficial, root-inhabiting fungi across a range of phosphorus fertilization from low (left) to high (right). 'Myc.' abbreviates 'mycorrhiza' which literally translates as 'fungus root,' the name given to the absorptive organ jointly formed by roots and ancient, Glomeromycotan fungi. Photo by D. Janos

to grow the fungi cheaply in pure cultures, although there are several commercial enterprises, for example in Colombia, India, France, and the United States, that produce inoculum somewhat laboriously and expensively by growing the fungi on living roots. An alternative is to learn how to manage the fungi in the field – as nature has done for millennia – to ensure their abundance.

Ways of maintaining the fungi in the field include avoiding tillage which disrupts their filamentous networks, cover cropping, and using companion plants that ‘nurse’ the fungi. That is possible because the fungi have nearly unrestricted host ranges. The same fungus species that associate with corn also may associate with Tulip tree (*Liriodendron tulipifera*, Magnoliaceae), and those hosts are as distantly-related as can be. So, not only can one plant make the fungi available to another, but additionally, the fungi can persistently physiologically interconnect multiple plants belowground. The fungus is sort of like a cable TV network or the Internet, to which many plant ‘households’ hook-up. Just as with cable and the Internet, however, there might be ‘cable piracy’ (a plant getting more than its fair share of phosphorus for the amount of energy it pays) or even the equivalent of an Internet denial-of-service attack if one plant can preempt all the fungus’ phosphorus.

Plants interconnected by root-inhabiting fungi can compete more strongly with one another than if they were not connected¹⁰. That presents a dilemma for agronomists because while close-spacing and consequent networking may most effectively promote abundance of the fungi, generally crops are grown with sufficient spacing to minimize the negative effects of adjacent plants on one another. Fortunately, even though networked plants in dense monocultures can compete across root-inhabiting fungus networks, improvement of phosphorus or other limiting mineral nutrient uptake that enhances the growth of the largest plants at the expense of the smallest nevertheless can increase total yield¹¹.

When two or more crops (such as the traditional corn, beans and squash polycultures of meso-America) feasibly can be grown together in the same field as an ‘intercrop,’ different times to maturity and complementary root attributes especially might help to maintain root-inhabiting fungi. Even though maintaining the fungi, however, intercropping also might diminish their benefit because increasing overall plant density often diminishes the average per plant benefit gained from the fungi. Notwithstanding, several combinations of two plant species have been found that increase both species’ responsiveness at the plants’ highest joint density¹². What we don’t know is why they do so!

Satisfying the growing human population’s need for food without running out of phosphorus fertilizer is likely to become an increasingly expensive and acute problem by or before 2050. The problem can be mitigated by crop breeding, by improving commercial production of beneficial root-inhabiting fungus inocula, and by devising farming systems to manage the fungi. Pursuing those options, however, will take much additional investigation, and time – like phosphorus – is running-out.

Footnotes:

1. Bradshaw & Brook. 2014. Human population reduction is not a quick fix for environmental problems. PNAS 111:16610-16615.
2. Ray, et al. 2013. Yield trends are insufficient to double global crop production by 2050. PLOS One 8(6): e66428.
3. Heffer & Prud’homme. 2013. Fertilizer outlook 2013-2017. International Fertilizer Industry Association.
4. Cordell, Drangert, White. 2009. The story of phosphorus: global food security and food for thought. Global Environmental Change 19:292-305.
5. Roberts. 2008. Global potassium reserves and potassium fertilizer use. International Plant Nutrition Institute.
6. Exceptions would be pines and oaks, which have a different type of mycorrhiza – ectomycorrhizas – in association with “higher” fungi.
7. Janos. 2007. Plant responsiveness to mycorrhizas differs from dependence upon mycorrhizas. Mycorrhiza 17:75-91.
8. Nodulated legumes associated with effective strains of rhizobia tap atmospheric nitrogen directly. Interestingly, most legumes will not nodulate with the bacteria until and unless they first form arbuscular mycorrhizas. Both the processes of nodulation and especially nitrogen fixation by bacteroids in the nodules are energy-intensive, and because phosphorous (as ATP) mediates energy transformations, the legumes need for phosphorous takes precedence over the need for nitrogen.
9. Sawers, et al. 2010. Characterizing variation in mycorrhiza effect among diverse plant varieties. Theoretical and Applied Genetics 120:1029-1039.
10. Janos et al. 2013. Arbuscular-mycorrhizal networks inhibit *Eucalyptus tetrodonta* seedlings in rain forest soil microcosms. PLoS ONE 8(2): e57716.
11. Weremijewicz & Janos. 2013. Common mycorrhizal networks amplify size inequality in *Andropogon gerardii* monocultures. New Phytologist 198:203-213.
12. Schroeder-Moreno & Janos. 2008. Intra- and inter-specific density affects plant growth responses to arbuscular mycorrhizas. Botany 86:1180-1193.

Elegantly Stated:

Biodiversity is a simple way to describe the complex and beautiful web of life that has made our planet capable of supporting us and all other living beings.

- Jon Letman, from “Walking in Time” in The Bulletin of the National Tropical Botanical Garden, Fall, 2014