Nanotechnology Risk to Soil Health

Overview: Nanotechnology and its application to agriculture and food

The application of nanotechnology techniques and engineered nanoscale materials (ENMs) to agricultural inputs is one of the means proposed for the "sustainable intensification" of agricultural crop production.[1] The United Nations Food and Agriculture Organization (FAO) uses this term to describe techniques to increase yield in internationally traded crops to feed the project nine billion global population of 2050.

Despite the current lack of nanotechnology specific risk assessment metrics, and nano-specific mandatory regulation, a FAO/World Health Organization expert report stated, "It is expected that nanotechnology–derived food products will be increasingly available to consumers world-wide in the coming years."[2] According to a soon to-be-published 2013 Center for Food Safety (CFS) inventory, there are about 300 food or food-related products whose manufacturers claim to incorporate ENMs. Furthermore, "scientific patents and publications on nanomaterials in fertilizers and plant protection have increased exponentially since the millennium shift."[3]

Engineered Nanoscale Materials (ENMs):

A nanometer (nm) is one billionth of a meter, and an ENM, conventionally defined, has at least one dimension measured at less than 100 nm. A sheet of newspaper is 100,000 nm thick. A bacterium is about 25,000 nm or 2.5 micrometers in length. Conventional fertilizers can be refined down to about ten microns, with a micron being one millionth of a meter. Given the heterogeneity of ENMs and the novel properties associated with their size, shape and other aspects, a formal and comprehensive regulatory definition of "nanomaterial," which is adaptable to new scientific findings, is difficult to determine. However, the conventional definition is of a material measuring 1 to 100 nm that can be engineered, visualized and manipulated. A soil bacterium measures about 2,500 nanometers in length; a strand of DNA is about 2.5 nm in diameter.[4]

The arguments for ENMs in fertilizers seem compelling. The atomic to molecular size of ENMs, in theory, would enable nano-encapsulated fertilizers to more effectively deliver plant nutrients to nano-sized plant pores. Less fertilizer would be leached into the soil and/or volatilized to become a greenhouse gas.[5]

Most applications of ENMs and nanotechnology techniques to agricultural inputs are in the research and development stage. However, scientists believe that ENMs already in use for consumer and industrial products will reach ecosystems. Probably the greatest current nanotechnology-related risk to soil health comes from two sources of incidental contamination.

The first source is acknowledged in the National Nanotechnology Initiative's (NNI) 2014 draft strategic plan: migration to the soil via water of ENMs from nano-coated consumer and industrial goods put in landfills, especially electrical parts. The second source is the treated sewage waste ("biosolids" in Environmental Protection Agency terminology)

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applied at least annually to at least 70 million acres of U.S. agricultural land.[6] IATP commented on the failure of the draft strategic plan to recognize the risk posed by fertilizing agricultural fields with ENM-laced biosolids.[7]

As a Purdue University researcher recently noted, "Land application of biosolids is standard procedure now [...]. If any of that [biosolid] contains nanotubes, that could be a problem."[8] Carbon nanotubes, configured by chemical and irradiation processes from one-atom-thick sheets of graphene, are the hardest and strongest materials known. Presently they are used in bulk to reinforce industrial parts, but there are a broad array of potential uses under investigation.[9]

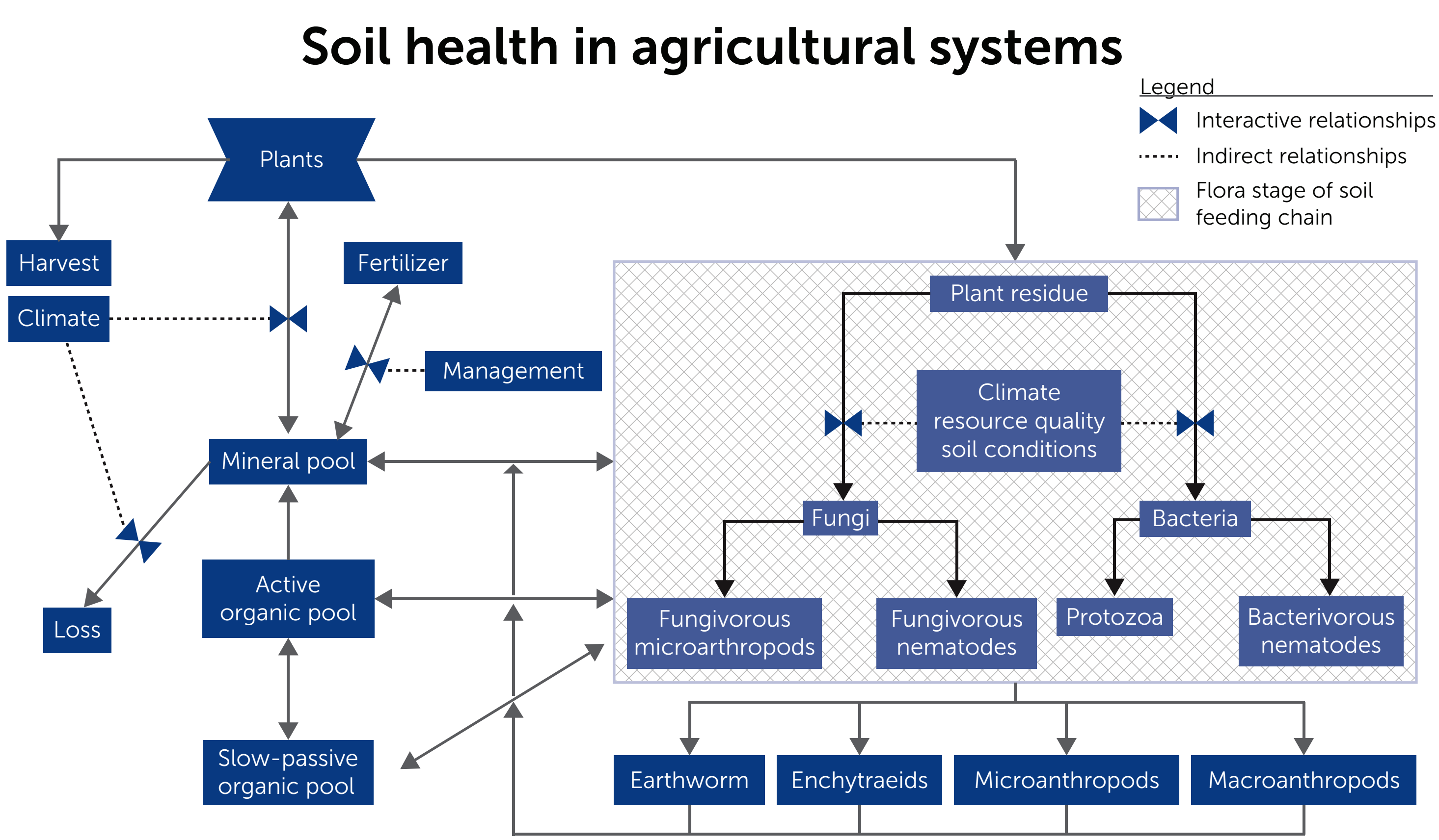
The crux of this problem for all bio-accumulating ENMs, particularly metal oxides and carbon nanotubes, is at least three-fold. First, ENM manufacture and incorporation into products is subject to 20th-century regulations. Second, ENMs entering wastewater streams, whether accidentally nor not, are processed by water treatment plants not designed to filter or treat ENMs. Third, the EPA regulation of biosolids is based on the pre-nano water treatment process, with no testing of the effect of ENMs on public health, farmworker health or soil health.

A laboratory experiment that computer simulated the wastewater treatment process in an anaerobic digester suggests that over a six-month period nano-silver particles would become a silver sulfide and less bio-reactive. However, these researchers acknowledge that further research on the effect of biosolids with silver nano-particles in field condition soil would be needed to show that the water treatment process had rendered the nano-silver particles less toxic.[10]

The interface of ENMs and soil health is a major concern. Farmers are told to check their soil health at least annually. There is cause for concern that even if a farmer does not fertilize with biosolids, their soil could be at risk from nearby fields so fertilized. Although testing for basic nutrients in soil is not expensive, testing to detect ENMs in soil is and likely will be. Since there is no law, much less a federal budget, dedicated to protecting soil health, until there is mandatory regulation of ENMs and their use, it is very well possible that a field near you is experiencing some of the effects described here.

ENM effects on soil health indicators and agricultural plants: laboratory and field-like experiments

The complex geo-bio-chemistry of soil feeding chains is such that the design of experiments to isolate the effect of ENMs on soil is greatly simplified in the laboratory. For example, scientists at the National Institute for Standards and Technology (NIST) wanted to understand



Kibbelwhite 688, "Soil health in systems" Permission granted by the Royal Society Publishing
Major trophic relationships in the soil biological community of an agricultural soil under zero tillage (adapted with permission from Hendrix *et al.* (1986))

the effects on earthworms of dosing soil samples with a solution containing multi-walled carbon nanotubes (MWCNTs). A typical use of MWCNTs is to increase the strength of automobile parts while decreasing their weight and therefore, increasing fuel efficiency.

The researchers estimated that perhaps 350 tons of carbon nanotubes were produced in 2007-08, and that this volume would increase greatly in the coming decade. Manufacturers are not required to report the volume nor the kinds of nanomaterials they are producing, so ENM manufacture estimates are highly conjectural. However, one academic study estimated that for the five most widely used of 250 ENMs, about 40,000 tons a year are produced in the United States alone.[11] Without a more precise idea of what, where and how much of ENMs are produced, assessments of human and environmental exposure to ENMS are impossible to determine.

The NIST researchers uniformly prepared three soil samples from plots in Michigan. They put half a milligram of MWCNTs in a polymer solution to ensure their uniform distribution in the soil. Over 28 days they observed the effects of MWCNT dosed soil on earthworms, the most widely used indicator species in soil health experiments. They concluded, "worms can readily eliminate any accumulated MWCNTs."[12] For Brazilian scientists interested in using carbon nanotubes to increase seed germination rates,[13] this conclusion likely comes as happy news, since the earthworms appear to have survived the MWCNTs dosed soil and carried out their soil engineering functions, at least over the 28-day experiment. (Most experiments on the environmental impacts of ENMs are short, 7–28 days, perhaps because of the expense of renting nanotechnology visualization equipment.)

However, the NIST researchers noted, "The lack of accumulation [of the ENMs] suggests that one mechanism for MWCNT toxicity may be through impacting organism digestive processes and tissues."[14] This suggestion was confirmed in experiment reported in a Dutch doctoral student's dissertation. Carbon nanotubes and nano-silver, when mixed in prepared soil samples increased earthworm mortality compared to a control group, by degrading the earthworms' skin and intestinal wall. The Dutch researcher cautioned that the results from his laboratory experiment could not be extrapolated to a field conditions trial, since there was not a reliable way to determine ENM distribution in field conditions.

Another research group has attempted to determine how and why nano-silver, nano-copper oxide and nano-zinc oxide "modify important aspects of metabolism of microbes and plants at sub-lethal levels. These changes, some of which may be viewed as beneficial and others detrimental, add to the microbial interactions with plants in the soil." Indirectly addressing ENM manufacturers, they write, "These findings raise further questions about how manufacturers' [nano-]coatings and dopings of different particles will influence bioreactivity." They anticipate that the bioreactivity of the same ENMs will vary depending on the agricultural soil type. Finally, "there is likely to be extreme variability in the dose-response level between different NPs [nanoparticles] and the microbial populations that regulate plant performance."[15]

Our evaluation of these researcher conclusions is that it will be very difficult to achieve the predictive nanotoxicology and risk evaluation in agricultural fields required for agri-nanotechnology regulation. The "extreme variability" of ENM dosing and soil microbial response will make it very difficult, perhaps impossible, to establish Maximum Residue Levels of ENMs intentionally applied to soil that regulatory authorities deem to be "safe" for soil and agricultural plants. But as noted before, the most widespread current exposure of agricultural soil to ENMs is through the fertilization of field with biosolids. The following chart, from a European Commission study on soil health, outlines the functions and organisms that could be harmed by nano-metal oxides during the soil feeding process. For example, if the metabolism of bacteria or fungi is altered by the consumption of nano-titanium dioxide, will they still be able to carry out their chemical engineering function of organic matter decomposition effectively?

As far as we know, the largest field condition study of ENMs in soil and the one of longest duration was reported in February 2013.[16] The researchers mixed soil samples, biosolids and very low doses of nano-silver in large containers (mecocosms), and measured several environmental and plant growth parameters over a 63-day period in outdoor weather. Microbial mass declined by about a third compared to soil not dosed with biosolids and nano-silver (Figure 5, Colman et al.). The plants' growth was stunted by about 25 percent, compare to the control (Figure 4, Colman et al.). But the finding that most surprised the researchers was the large increase in nitrous oxide releases in the biosolids with nano-silver compared to the biosolids without nano-silver, a difference of 350 percent by day 8 of the experiment. Nitrous oxide is "the dominant ozone depleting substance" and has about 300 times the global warming potential of carbon dioxide.[17]

However by day 50 of the experiment, the difference in nitrous oxide production between the nano-silver doped biosolids and the undoped biosolids had diminished even though the difference in microbial mass and plant stunting between doped soil and the control planters remained. The findings of this study will certainly be subject to the scrutiny of other research groups that will attempt to replicate its findings. But absent experimental design flaws or major errors of measure or data interpretation, this experiment and others like it should start an overdue public policy debate. At stake in that debate is the ability of the soil feeding

Characteristics	Chemical engineers	Biological regulators	Ecosystem engineers
Main organisms	Bacteria, fungi	Protists, nematodes, mites, springtails (Collembola)	Ants, termites, earthworms, plant roots
Function	Organic matter decomposition, mineralisation + nutrients release, pest control toxic compounds degradation	Regulation of microbial community dynamics, faecal pellet structures, mineralisation, nutrient availability regulation (indirect), litter transformation and organic matter decomposition	Creation and maintenance of soil habitats; transformation of physical state of both biotic and abiotic material, accumulation of organic matter, compaction of soil, decompaction of soil, soil formation
Body size	0.5–5 μm (bacteria) 2–10 μm (fungal hyphae diameter)	2–200 μm (protists) 500 μm (nematodes) 0.5–2 mm (mites) 0.2–6 mm (springtails)	0.1–5 cm (ants) 0.3–7 cm (termites) 0.5–20 cm (earthworms)
Density in soil	10^9 cells/g of soil (bacteria) 10 metres/g of soil (fungal hyphae)	10^6 g/soil (protists) 10–50 g/soil (nematodes) 10^3–10^5 per m^2/soil (mites) 10^2–10^4 m^2/soil (springtails)	10^2–10^3 m^2/soil (ants) 10–10^2 m^2/soil (earthworms)

Summary of the characteristics of the three soil functional groups

Figure 2.9 of soil micro-arthopods from EEA report on soil health and soil biodiversity from *Soil biodiversity: functions, threats and tools for policy makers*, European Commission Directorate General of Environment (2010).

chain, including the micro-arthopods pictured in Figure 2.9 maintain and build soil health.

Conclusion

As suggested by the scientific literature reviewed, there is "extreme variability" of bio-reactivity between different ENMs and microbial communities in agricultural soils. Much, if not most, of this bio-reactivity is likely detrimental to soil microbes, earthworms and other elements of the soil feeding chain. While the intentional application of inputs with ENMs is largely in the research and development stage, the fertilization of fields with biosolids containing bio-accumulative nano-metal oxides poses present risks that have been defined, if only partially, by researchers.

In the absence of the mandatory regulation of ENM manufacture life-cycle monitoring of ENMs, it is very likely that more ENMs will bio-accumulate in natural ecosystems, including agricultural fields. Because nanotechnology promoters, including the NNI, view myriad nanotechnology applications as constituting the "next industrial revolution," there is a tendency to view regulation as an impediment to nanotechnology innovation.[18] But like the economic crash resulting from unregulated Wall Street financial "innovations," the continued failure to regulate nanotechnology to prevent environmental, public health and worker safety harm could likewise "crash" the soil health whose economic value alone dwarfs that of nanotechnology.

Endnotes

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