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Nanomaterials In Soil

Our Future Food Chain?

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Institute for Agriculture and Trade Policy

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Overview

To feed a growing population under increasing natural resource constraints, the World Bank, the United Nations Food and Agriculture Organization (FAO) and other international organizations are promoting “sustainable intensification” as the future of agricultural production.¹ The application of nanotechnology techniques to agricultural crop inputs is one of the proposed tools for “sustainable intensification.”² These applications include reducing the volume of pesticide use through adding nano-silver particles to pesticides to make them more effective in targeting pests with a smaller pesticide volume; adding nano-metal oxides to target soil pathogens, e.g., those resulting from fertilizing with non-composted manure; adding nano-silicon to increase water uptake efficiency in plants; developing a DNA-based nanobio-sensor in a polymer to coat fertilizers, which would release only as much fertilizer as “demanded” by plant root ionic signals.

Engineered Nanoscale Materials (ENMs):

A nano-meter (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 micro-meters in length.³ 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 1-100 nm that can be engineered, visualized and manipulated.

Each of these applications presents its own opportunities, risks and knowledge gaps. Thus far, governments are allowing the commercialization of ENMs and nano-enabled products while they deliberate whether and how much to regulate nanotechnologies. One European Commission summary of a decade of tentative steps towards a mixture of regulation and industry “self-regulation” states, “Nanotechnologies-related products/activities are presently regulated essentially by using existing provisions, but given the unique features of nanotechnologies doubts exist about the effectiveness of this approach. The use of specific hard regulation is advocated by some parties, but so far, the strategies from authorities worldwide have been essentially on probing the extendibility of existing regulatory schemes to nanotechnologies and/or to ensure compliance with them. In the last few years, voluntary measures have been endorsed by public bodies and industry to build confidence and trust, promote safety or gather data.”⁴

As a result of the intragovernmental debate over whether to develop nanotechnology-specific regulation, governments have not yet conducted thorough assessments of

nano-specific risks, nor have they required pre-market and post-market safety assessments of nano-enabled products. Notwithstanding the lack of such assessments, a FAO/World Health Organization convened expert group report stated, “It is expected that nanotechnology-derived food products will be increasingly available to consumers world-wide in the coming years.”⁵

More than two decades ago, two eminent toxicologists advised that “it would be prudent to examine and address environmental and human health concerns before the widespread adoption of nanotechnology.”⁶ With the exception of some medical applications of nanotechnology, governments, corporations and even university-based start-up companies have ignored this advice. As a result, governments have allowed hundreds of—perhaps more than a thousand—consumer products marketed as incorporating ENMs⁷ to be commercialized without any pre-market safety assessment.

According to Internet advertisements, ENMs are already being used in “nano-fertilizers.”⁸ Because governments do not regulate ENMs in fertilizers, they do not test these products, nor, of course, their product claims. Due to manufacturer confidentiality claims, determining the volume of ENMs in consumer and industrial products is very difficult, but for the five most widely used of more than 250 ENMs, one academic study estimated up to 40,000 tons a year are produced in the United States alone.⁹

Nano-sizing, in theory, should make fertilizer nutrients more available to nanoscale plant pores, and therefore result in greater nutrient use efficiency. However, the dosing of fertilizers and “biosolids”—water treatment residues used as fertilizer—with ENMs also chronically exposes soil microbes and microfauna, as well as the plants themselves, to levels of chemical reactivity that may be toxic. Among the factors that are believed to increase toxicity of ENMs over their macro-scale counterparts are “particle size, shape, crystal structure, surface area, surface chemistry and surface charge.”¹⁰ Nano-sizing, because of its exponentially greater surface-to-mass ratio, makes toxins more bioavailable and bioaccumulative in tissues that macro-scale materials cannot penetrate.

Here we review a small part of the rapidly growing scientific literature that raises questions about how ENMs might affect soil health and soil biodiversity in field trials and subsequently the commercial and chronic application of ENMs in agricultural soil. The questions concern not only the intentional use of ENMs in fertilizers, but the incidental presence of ENMs in “biosolids,” defined by the U.S. Environmental Protection Agency (EPA) as “treated residuals from wastewater treatment that can be used beneficially.”¹¹ Biosolids are often used to fertilize agricultural fields. As a Purdue University

researcher recently noted, “Land application of biosolids is standard procedure now [at least in the United States] . . . If any of that [biosolid] contains nanotubes, that could be a problem.”¹²

That problem has many dimensions. U.S. regulators are only beginning to propose nano-specific occupational safety rules to protect workers, such as a new draft rule that will cover carbon nanotubes,¹³ but it is not clear if this rule would protect farmers and farmworkers applying nanotubes in biosolids. The farm workers who apply the biosolids with carbon nanotubes (CNTs), for example, might be, over time, at risk of the afflictions of laboratory rats’ lungs exposed to CNTs: “inflammation, fibrosis, and toxicological changes in the lung. When the [CNTs] are applied to skin cells, biochemicals that indicate cellular damage increase.”¹⁴

There is no informed, broad-based constituency to support regulating ENMs in fertilizers and biosolids to protect soil health and soil biodiversity. A first step toward the eventual regulation of ENMs in soil could be a series of participatory technology assessments that would bring together farmers, soil micro-biologists, fertilizer manufacturers, ENM manufacturers, biological engineers and interested civil society representatives. Such technology assessments would allow the layperson, informed by science, to raise questions about ENMs and nano-enabled products that should be asked prior to commercialization, and indeed, prior to technology investment, particularly with public funds. A hybrid of expert and layperson technology assessment could draw on some of the methodology of the Expert and Citizen Assessment of Science and Technology that fed into the Convention on Biological Diversity proceedings.¹⁵ However, the relatively smaller topical focus of nano-fertilizers would be conducive to mixing and matching different knowledge bases among participants. This process would also consider the broader natural resource and social context of the use of a technology.

Public engagement vs. technology assessment

A technology assessment is one form of public engagement in the governance of science and technology, a tool for democratic participation in science and technology policymaking. The nongovernmental Loka Institute has sought, for the past decade, to make public participation in nanotechnology policymaking a budgeted part of the (U.S.) National Nanotechnology Initiative (NNI), which in 2012 had a publicly funded budget of about \$2 billion.¹⁶ However, NNI “public engagement” remains a government outreach exercise to communicate the benefits of nanotechnology and to manage public perception about nanotechnology risks.¹⁷ The British government’s nanotechnology communication strategy is likewise a

one-way exercise: “We will engage with the public to make sure they are informed and confident about nanotechnologies and the products which contain nanomaterials.”¹⁸

The purpose of technology assessment is not for governments to provide information to sell the public on the benefits of nanotechnology. It is to evaluate the risks and benefits of nanotechnology applications without prejudging the questions asked or conclusions drawn from answers because of a government’s investment in nanotechnology or because particular applications already have been commercialized without government oversight. For a technology assessment of ENMs in fertilizers and other soil additives, the inclusion of farmer and consumer representatives would enhance democratic participation in scientific policymaking and investment. A broad array of assessments could aid the development of nanotechnology rules to protect natural resources in the environment as well as public health and the safety of workers that manufacture or use ENMs. The assessments could also advise the banning of certain applications even after commercialization.

Enhancing soil health and biodiversity: ENMs in soil

Even the very optimistic Lux Research forecast of \$2.5 trillion by 2015 in global value of ENMs and nanotechnology-enabled product sales,¹⁹ is dwarfed by the estimated economic value of the ecosystem services that depend on soil biodiversity. According to a speech by the executive secretary of the U.N. Convention to Combat Desertification, a 2009 European Union Joint Research Centre report estimated the monetary value of ecosystem services provided by soil to have been \$13 trillion USD in 1997.²⁰ Such estimates are subject to the scenario assumptions of econometrics. However, allowing for even a broad degree of methodological error, even the partial the loss of the economic value of soil due to the misapplication of ENMs in fertilizers and soil micro-nutrients, such as zinc, provides for more than sufficient justification for the precautionary approach taken by testing the effects of ENM on soil-like media in the laboratory.

During the past decade, soil science research has reacquired policy and budgetary prominence, insisting that “soils are back on the global agenda.”²¹ With the launch of the first conference of the Global Soil Partnership at a November 2012 conference in Berlin, the relatively low international profile of soil health and biodiversity research will become ever more relevant to the technology assessments of agri-nanotechnologies.²²

However,

To date, no legislation or regulation exists that is specifically targeted at soil biodiversity, whether at international, EU, national or regional level. This reflects the lack of awareness for soil biodiversity and its value, as well as the complexity of the subject. Several areas of policy directly affect and could address soil biodiversity, including soil, water, climate, agricultural and nature policies.”

Soil biodiversity: functions, threats and tools for policy makers, European Commission Directorate General for the Environment, February 2010.

Due to the absence of binding law to be implemented and resourced to protect soil biodiversity, European Commission researchers and soil scientists have prepared dossiers for legislators and other policymakers to consider in drafting such binding law. The researchers have depicted in great detail how soil works to provide ecosystem services, not the least among them crop production. In order to raise questions for a technology assessment on the interaction of micron-sized (1000 nanometers) fertilizer particles and ENMs with

soil, it is necessary to give a brief sketch of the real soil environment that is greatly simplified when scientists test the effects of ENMs in laboratory experiments.

While it is difficult to visualize the complexity of the trophic (feeding) relationships that produce soil, the schema below gives an overview of these relationships, i.e., the food chain in agricultural soils. The decomposition of plant matter by bacteria and fungi, and the trophic cycle of megafauna and microfauna that combines with the mineral pool, climate and fertilizers, both natural and chemical, represent the complexity of soil health. According to an International Food Policy Research Institute (IFPRI) briefing paper, abuse of the soil has a global economic loss value of about \$66 billion USD annually.²³

Not all ENMs used in soil additives will affect all of these points in the soil/plant food chain, but for our purposes, the crucial trophic relationships appear to be how the soil mineral pool, augmented by fertilizer particles of nitrogen (N), phosphorus (P) and potash (K), and ENM soil additives, interacts with the soil biological community. This community includes the micron-sized fungi and bacteria that are the beginning of the feeding chain for the earthworms and other fauna that would consume the ENMs.

Soil health in agricultural systems

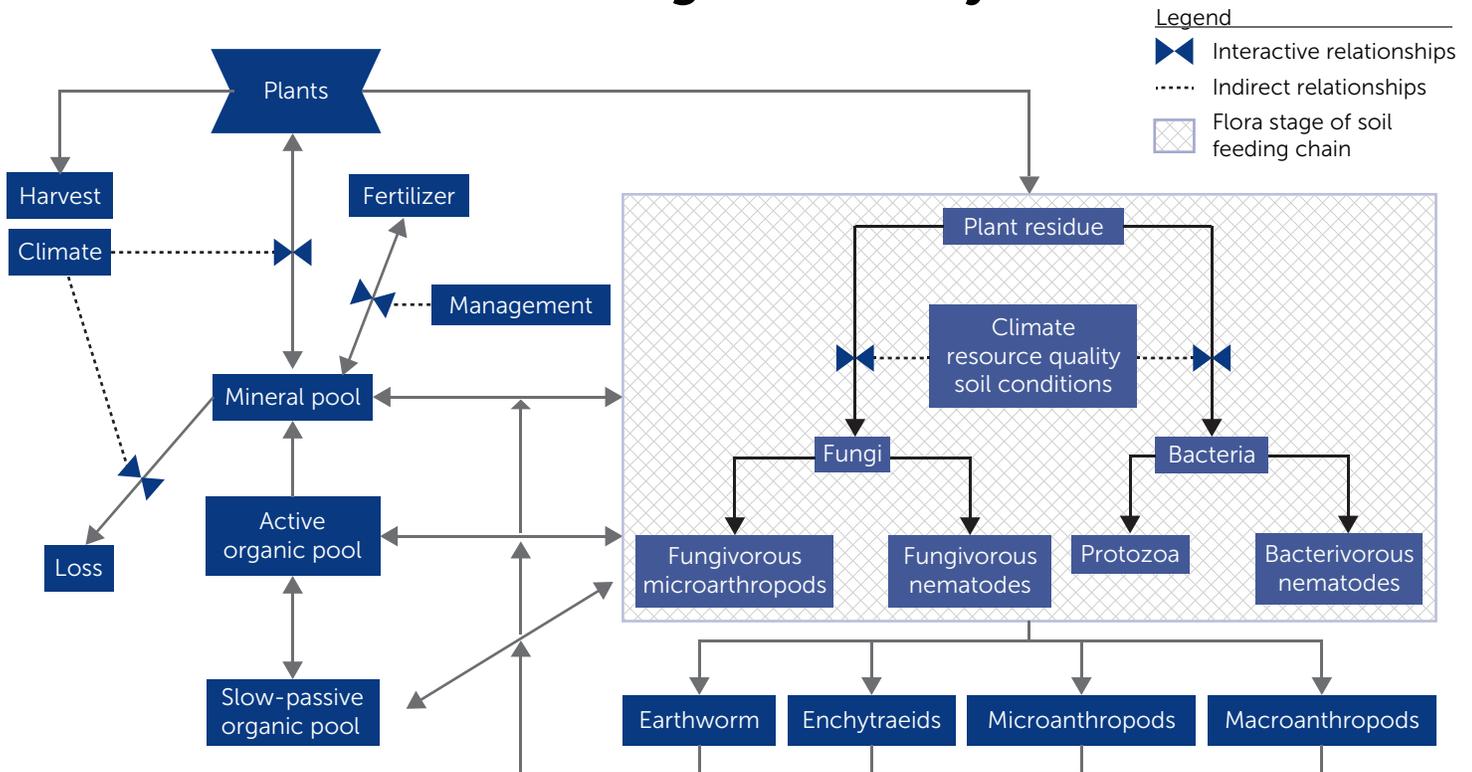


Chart 1: Kibbelwhite 688, "Soil health in systems" Permission granted by the Royal Society Publishing Major trophic relationships in the soil biological community of an agricultural soil under zero tillage (adapted with permission from Hendrix et al. (1986))

As described in the following chart from a European Commission study for policymakers, the main organisms in the soil biological community perform functions in soil building. This chart is from a European Commission Directorate General of Environment report that classifies the main organisms in the soil biological community and their soil-building functions. The protection of the biological regulators, ecosystem and chemical engineers would be a priority for any contribution of the rebuilding of global soil health to sustainable development. If ENMs are to be added to agricultural soil, whether intentionally or not, a technology assessment of agri-nanotechnologies will have to take into account research on soil degradation and soil health.

The consumption of the bacteria and fungi by the mites and nematodes and their consumption in turn by the termites, ants and earthworms is not simply a nutritional relationship that ENMs could disrupt. The soil-regulating and building functions of each of these main organisms would also be affected. As discussed below, scientists are currently testing for the effect of ENMs on earthworms and single soil microbes. As important as these experiments are, they do not claim to begin to test for the effect of ENMs on the trophic and functional relationships among the organisms of the soil biological community. When, for example, carbon nanotubes are added to soil in laboratory experiments to determine whether the nanotubes will increase seed germination rates, a technology assessment about such experiments needs to investigate also how those carbon nanotubes will affect the diverse soil biological and chemical regulators. While it is understandable that scientists choose the earthworm for toxicity testing

in soil, since the earthworm is near the end of the soil feeding chain, policy and soil health building practices also need to protect such microfauna soil builders as these:



Figure 2.9 of soil micro-arthropods 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).

Testing for soil health

Commercial farmers are advised to get their soil health tested yearly, just as they are advised to visit the doctor for a yearly checkup.²⁴ Farmers may conduct the tests on the different soil types and yield zones of their fields using commercially available kits or sending soil samples to laboratories to check up on the biological, physical and chemical dimensions of soil health. The results of the chemical analysis help determine what rebalancing of phosphate (P), nitrogen (N) and potash (K) and other soil additives should be bought to plant next year's crop. The tests are as routine as listening to the heart with a stethoscope, likewise, the testing technology is usually routine and readily affordable. (However, the remedies for fixing the biological and physical problems of the soil are not so quick as that of applying a new fertilizer mix to make up for PNK shortages or imbalance.)

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)

Table 2.1 - Summary of the characteristics of the three soil functional groups

To judge by recent reports of experiments to detect the presence and analyze effects of commercially available ENMs in agricultural soil, soil testing techniques are about to get a lot more complicated and expensive, whether or not farmers have chosen to add ENMs to their soil. Just detecting nano-scale additives to soil however, requires elaborate and expensive technologies, as well as trained technicians.

Question box 1

This article presents questions for a technology assessment of nano-enabled fertilizers or ENMs in biosolids used as fertilizers. Some of the questions are embedded in the main text of the article, while others are highlighted in this and subsequent “question boxes.” The order and content of the questions only indicate how technology assessment workshop organizers might use framework questions to promote discussion. Additionally some questions might represent issues that participants would raise in response to workshop presentations, written materials or in summarizing their analysis of the workshop.

1. If the future of commercial farming is to include the application of ENMs in soil, will the labs that currently test for soil health be also equipped to do testing for ENM detection and even to prescribe dosing the soil with nano-scaled chemical fertilizers and soil additives?
2. Will the recommended ENM dosing be defined and administered by those who own the technology?

The future of fertilizer

The future of fertilizer is forecast to lie in nanotechnology applications. One researcher attempted to forecast this future in terms of products or processes announced in patents granted: “While it may be hard to predict what future role nanotechnology will play in the development of fertilizers, there is a clear indication that the industry is heading in this direction.”²⁵ This clear direction is documented by the dozens of patents filed for nano-sizing and sometimes incorporating into fertilizers additional additives, such as nano-metal oxides that would target pathogenic soil microbes, e.g., *E. coli*.²⁶ Still, companies seem very reluctant to advertise those plans. A search with the word “nanotechnology” on the website of two of the largest fertilizer companies, Yara and Mosaic, yielded no search results.

It is likely that part of the future is already here. The patents for micron-sizing (1000 nanometers) of fertilizers are nearly thirty years old.²⁷ A manufacturer of machinery to micron-size fertilizer describes their product as “safe to handle and easy to apply.”²⁸ It is likely that current fertilizer products, such as Mosaic’s “Micro-essentials,” micron-size fertilizer nutrients rather than nano-size them.²⁹ The micro-sizing of fertilizers is a global commercial practice,³⁰ but some companies have begun to advertise their fertilizers as nano-sized.³¹

“Intelligent nano-fertilizer” has been proposed with nano-sized biosensors suspended in a biopolymer that coats micron-sized fertilizer particles. The nano-biosensors release the underlying fertilizer nutrients in response to plant needs, as communicated by root system ion signals.³² According to one review of agri-nanotechnology literature, “the use of NPs [nanoparticles] in agriculture is in its infancy, with relatively few publications, compared to the medical field.”³³ However, the infant, supported by both private and government

funding, is growing fast: “Scientific patents and publications on nanomaterials in fertilizers or plant protection have increased exponentially since the millennium shift.”³⁴

Nano-fertilizers, crop yields and greenhouse gas emissions

Among the technologies whose promoters claim to raise agricultural crop yields while reducing the environmental damage of agricultural enterprise, perhaps no claim is more appealing than transforming and reducing the use of chemical fertilizer inputs through nanotechnology. Greenhouse gas emissions³⁵ and hypoxia are just two of the negative environmental consequences of the massive use of chemical fertilizers for major cash crops.³⁶ For example, in the United States, fertilizer consumption for five crops has increased from about 7.5 million tons in 1960 to about 20.5 million tons in 2010, down from a peak of over 23 million tons in 2004.³⁷ Hypoxia is the scientific term for a “dead zone” area in a body of water, nearly deprived of oxygen as the result of agricultural water runoff carrying nitrates and phosphorus from fertilizer, e.g., the 6–7,000 square mile dead zone in the Gulf of Mexico.³⁸ Unduly optimistic estimates about the adaptability of agriculture to climate change, based on 1990s assumptions and data about agricultural mitigation potential, are fast giving way to a much tighter timeline for greater reductions in industrialized agriculture emissions.³⁹

Nevertheless, despite a Freight-on-Board price increase for nitrogen, potash and phosphate from an average index of 100 in 2002–2004 to 323 in the first half of 2011, the fertilizer industry projects that global fertilizer demand will increase two percent per annum from 2011 to 2015.⁴⁰ If the industry projections are correct, the negative environmental consequences of fertilizer use will likely increase. (To this increase should be added the huge methane releases from the hydraulic fracturing (fracking) methods used to produce the natural gas required for synthetic nitrogen fertilizer manufacture.⁴¹) Couldn’t the incorporation of ENMs into chemical fertilizers to increase nitrogen use efficiency enable crop yield increases of 70 percent to “feed the world” of 2050 without further damaging water quality and increasing greenhouse gasses? (This question references the econometrically projected productivity increase imperatives of so-called Climate Smart Agriculture advocated by transnational agribusiness and intergovernmental institutions, including the Food and Agriculture Organization and the World Bank.⁴²)

Furthermore, wouldn’t the nano-scaling or micron-scaling of fertilizer compounds and micro-nutrients enable a more sustainable use of available fertilizer and other supplement ingredients, since a much smaller volume of fertilizer would produce larger yields? (Researchers report other potential

soil applications of ENMs, mostly in laboratory experiments but with a few field trials, for reducing plant pathogens, for bio-fortification of plants and for phytoremediation of contaminated soil. Analysis of these uses is beyond the scope of this report.⁴³⁾

Indeed, among the international organization promoters of rapid increases in fertilizer use, nano-enabled fertilizers and the nano-scaling of inputs might be regarded as a proverbial “win-win-win” solution for increasing fertilizers sales and crop yields while protecting or even enhancing agricultural natural resources. Among the yield-related attributes of nano-fertilizer claimed in patents are controlled nutrient release and increased water retention in soil.⁴⁴

A 2005 product survey estimated that nano-enabled fertilizers would be commercialized in developing countries by 2015.⁴⁵ According to a 2012 report by the International Fertilizer Development Center (supported by the U.S. Agency for International Development), “Ghana, Kenya and Tanzania must nearly double their importation and use of fertilizer over the next three years” to achieve government-stipulated yield targets.⁴⁶ In the framework of the IFDC’s “Competitive Agricultural Systems and Enterprises [CASE] method of agricultural intensification” nano-fertilizers might be “one more tool in the toolkit” for increasing soil fertility in nutrient poor soil, such as many soils of Africa.⁴⁷

The grinding, etching and milling processes to manufacture ENMs from bulk materials are documented in dozens of patents filed on novel compounds or processes to produce nano-fertilizers, according to a comprehensive 2009 survey by Professor Maria DeRosa.⁴⁸ The utility claims in these patents, which often aim to increase fertilizer use efficiency, have a scientific basis in the nanoscale morphology of pores in plant roots and leaf surfaces.

In theory, nano-scaled plant nutrients may be able to penetrate these pores where macro counterparts of these nutrients cannot and thus are wasted on crop production.⁴⁹ According to DeRosa, “studies have shown that 50 to 70 percent of fertilizer nitrogen applied to farmland is lost to water, air and other processes,”⁵⁰—losses that have severe environmental and economic consequences. Thus the economic and environmental motivations to invest in applying nanotechnology to fertilizers are clear. However, a prominent research group notes, “whether NPs (nanoparticles) provide an efficacy and cost that justifies their development for use in agriculture is yet unproven.”⁵¹

Similarly unproven is whether ENM inputs can be used safely by farmers and whether their use can be justified in light of environmental, public health and worker safety (EHS) risks of growing and consuming agricultural crops raised with

nano-fertilizers. As DeRosa notes, “many patents and patent applications make claims that their [nano-fertilizer] formulation has zero toxicity, but in most cases, little evidence is provided to corroborate these statements.”⁵² Developing this missing evidence is no small task, in part because of the great variety of chemical-physical structures presumed to be used in proprietary nano-fertilizer compounds.

Question box 2

1. If fertilizers such as Mosaic’s “micro-essentials” include micron-sized (1000 nm) P, K or N, should they be risk assessed for their possible toxicity as ultra-fine particles under the U.S. Clean Air Act, even though macro-sized P, K and N are currently regulated under the authority of the Clean Water Act?
2. Should micron-sized P, K or N in fertilizers or nano-sized soil nutrients undergo a pre-market safety assessment for commercialization approval or denial on the basis of laboratory risk assessment only or should field trials, including occupational safety testing, also be required?
3. If laboratory experiments with nano-fertilizer component chemicals indicate significant potential for harm to environmental health and safety, what technology assessment process can be used to judge whether laboratory-indicated harm outweighs that caused by current fertilizer use practices?
4. What policy or technology alternatives are there to nanotechnology for the sustainable use of fertilizers and micronutrient supplements in soil?

ENMs in “biosolids” used to fertilize crop growing fields

Some scientific research into the ENM presence in agricultural soil and plants assumes that such presence is unavoidable. So, for example, the abstract of a recent study begins, “a large fraction of engineered nanomaterials in consumer and commercial products will reach natural ecosystems.”⁵³ The part of that large fraction which comes in the form of silver (Ag) nano-particles in biosolids will have undergone a process of sulfidation that “dramatically alters the properties of Ag NPs, including their surface charge, the ability to release Ags and toxicity.”⁵⁴ (Nano-silver is probably the most commonly used ENM, appearing as a biocide in socks, dishwashers and an array of medical products.)

In an article on the complex process required to detect nano-zinc oxide and nano-cerium dioxide (nano-cerium) particles in the edible part of the soybean, the researchers found that “With the increased use of engineered nanomaterials such as ZnO and CeO₂ nanoparticles (NPs), these nanomaterials will inevitably be released into the environment with unknown consequences.” The most likely form of release would be zinc and cerium ENMs in biosolids legally approved to fertilize fields.⁵⁵ (Chemicals in pre-nano biosolids have been identified as known or suspected

carcinogens and hormonal endocrine disruptors, leading to myriad human health problems.⁵⁶) The researchers note, such release of ENMs “can cause them to enter into the food chain and the next plant generation.”⁵⁷ Their tests determined that only nano-cerium, used in internal combustion processes, sunscreens, gas sensors and cosmetic creams, was detected in the edible part of the soybean.

Dr. Todd Kuiken, of the Wilson Center Project on Emerging Technologies, remarked of a similar study by many of the same researchers, “They dosed the hell out of a bunch of soil [with ENMs]. A soybean crop would never get dosed with that much.”⁵⁸ The dose is high because laboratory tests are short-term, usually 14–28 days, so a high dose is applied to see if the ENMs would be excreted through the leaves or remain in the edible part of the soybean. Yet, as Kuiken notes, the environmental and public health concern is not with the consequences of one crop’s single event exposure to ENMs, whether intentional or not, but the bioaccumulative effects of ENM exposure over several cropping years. Indeed, under current cropping and fertilizing patterns in major soybean growing countries, the inclusion of ENM soil additives, whether intentional or in the application of bio-solids, would be at least annual. Detection of the ENMs is a necessary first step towards making knowable the “unknown consequences” of releasing ENMs into the environment, as currently happens without pre-market safety assessment.

Several million dry tons of sewage sludge, also known as biosolids, are used as fertilizer on agricultural lands and given away or sold for use by homeowners and landscape contractors annually in the United States. Sewage sludge is the semi-solid to solid matter left over following municipal wastewater treatment. It commonly contains nutrient-rich fecal matter along with bacteria, viruses, parasites, heavy metals, pharmaceuticals and other chemical contaminants—many known to cause health effects.

For farmers, sludge is a less expensive alternative to synthetic fertilizers, but use of sewage sludge as fertilizer for food production increases our risk of exposure to sludge contaminants and their associated health effects. Due to the persistent nature of some of these contaminants, repeated applications to the same piece of land can increase soil contaminant levels and possibly food contaminant levels for centuries to come.

Marie Kulick, “Smart Guide on Sludge Use and Food Production,” Institute for Agriculture and Trade Policy.⁵⁹

The problem alluded to above by the Purdue University researcher, i.e., that carbon nanotubes could be in biosolids, has many dimensions, including the regulatory practice that allows the application of biosolids to agricultural soil as “safe.” Current risk analysis practice would require compelling and disaggregated evidence to show that the toxicity and exposure of soil microbes and microfauna to ENMs—and nothing

else in the biosolids—was hazardous to soil health and perhaps to human health. A recent news article on a Dutch doctoral student’s dissertation on the effect of nanoparticles on earthworms illustrates in a microcosm some of difficulties of moving from scientific studies to the regulation of ENMs to protect soil health.⁶⁰

The researcher showed that carbon and silver ENMs in the laboratory, mixed in prepared soil, increased earthworm mortality and reduced population growth by degrading the earthworms’ skin and intestinal wall. However, because there is not yet a reliable way to determine nanoparticle distribution in field conditions, the researcher said neither his laboratory results nor experimental design could be extrapolated to field trials. Given the economic interests in the ubiquitous commercial practice of applying biosolids to fields, it is not likely that laboratory proof of ENM harm to earthworms would suffice to ban the application of biosolids incorporating ENMs to fields. Rather, following the orthodox regulatory practice of determining a maximum tolerance of toxicity (Maximum Residue Levels, or MRLs) that still enables commercial use of macro-scale pesticides, it is possible, even likely, that regulators would seek to determine MRLs for ENMs in biosolids and other soil additives.⁶¹ The aforementioned FAO/WHO expert report stated that it believes current risk analysis and risk assessment practices are an adequate framework for setting standards to protect human health and to facilitate trade in nano-enabled food and agriculture products.⁶²

However, the results of a recent experiment that simulates field conditions for applying biosolids (called Slurry in the experiment’s report) gives reason to doubt that toxicity to earthworms or even reduced microbial mass in soil would be the most important criterion for deciding to prevent the fertilization of agricultural fields with Slurry containing nano-silver particles (AgNPs). Rather, one surprising consequence of the interaction between the AgNP mixed with Slurry and the soil microbial community is a dramatic increase in nitrous oxide (N₂O): “The N₂O flux was 350 percent higher in the Slurry plus AgNPs treatment than in the Slurry only treatment on Day 8 [of the 50 Day experiment], a dramatic increase given that N₂O is both an important greenhouse gas with 296 times the warming potential of CO₂ and N₂O is the dominant ozone depleting substance.”⁶³ However, this degree of N₂O flux was not observed on Day 50 of the experiment, even though differences in microbial activity and mass between the Slurry and Slurry plus AgNP treated soils persisted.

Because of the dramatic increase in N₂O emissions observed on Day 8 of the experiment, and because a comparable increase was not observed at the conclusion of the experiment, other research groups will very likely attempt to

replicate the results of this experiment. Apart from ensuring that the results on Day 8 were not a data misinterpretation error, these research teams also will be motivated to investigate further the effect of AgNPs mixed with Slurry on soil microbial communities because of the widespread use of Slurry as a soil additive: “An estimated 60% of the 5.6 million tons of U.S. biosolids produced each year in the United States is applied to land, and represents an important and understudied route of exposure of natural ecosystems to engineered nanoparticles.”⁶⁴

Due to transportation costs, these 3.36 million tons of biosolids are most likely to be applied on the agricultural land closest to the urban water treatment centers that produce the majority of the biosolids. According to the U.S. Environmental Protection Agency (EPA), “about two-thirds of the total value of U.S. agricultural production takes place in, or adjacent to, metropolitan counties (NRCS). About 1/3 of all U.S. farms are actually within metropolitan areas, representing 18% of the total farmland in this country.”⁶⁵ In sum, more than 70 million acres of the total 382 million U.S. cropland acres⁶⁶ will receive, on average, the majority of the 3.36 million tons of biosolids. That is a very large area to study for exposure of natural ecosystems to ENMs.

Question box 3

1. Some companies, e.g., General Mills⁶⁷, already ban their suppliers from using biosolids to grow crops that are the raw materials for their products. Given the expense and difficulty of detecting ENMs in soil and determining whether their bio-accumulation poses a hazard to human and/or environmental health, should governments ban ENMs in biosolids or should they try to determine Maximum Residue Levels (MRLs) of ENMs in biosolids that would still protect consumer health? Or should consumers try to protect their health by relying on company assurances that their supply chains are free of crops grown with biosolids?
2. According to the ETC Group, reliable nano-toxicity tests are decades away for some ENMs.⁶⁸ If MRLs cannot be reliably estimated for those ENMs, should governments allow the commercialization of agricultural products that are enabled with those ENMs, such as crops grown with ENM infused biosolids?
3. If a government agency determines that there is a “safe” amount of particle distribution of ENMs that can be present in soil in which crops are grown, and another agency determines that unacceptable amounts of greenhouse gases are released from ENM treated soil, how should these differing determinations be adjudicated or reconciled?

It is by no means certain that establishing MRLs for fertilizer ENMs to protect soil microbes and microfauna is technically feasible. However, prior to investing in the research that would provide risk analysis evidence for establishing such MRLs, it would be prudent to research whether there are less

expensive and risky means than nano-enabled fertilizers to achieve the technical objectives of yield enhancement and reduced environment harms from agricultural production.

Testing the ability of earthworms to digest Multi-walled Carbon Nanotubes in prepared soil samples

Scientists at the (U.S.) National Institute for Standards and Technology (NIST) reported on a 28-day experiment designed to measure the absorption rates of Multi-Walled Carbon Nanotubes (MWCNTs) in three uniformly prepared soil samples from plots in Michigan.⁶⁹ These plots were chosen to allow for comparisons to previous experiments using Single Walled Carbon Nanotubes and soil from the same plots. The NIST researchers wanted to understand the environmental effects of the bioaccumulation of the MWCNTs in soil. They anticipate that the estimated 350 tons of carbon nanotubes produced in 2007–2008 for myriad industrial uses would increase in coming years. Earthworms are commonly used to test for toxicity in soil because they are constantly processing soil and are consumed by larger vertebrates.

The nanotubes were coated with a polyethyleneimine (PEI) solution, a polymer measured to ensure uniform soil moisture and a half milligram of MWCNTs distributed in each soil sample that the worms ingest and excrete. The methods used to coat the MWCNTs and to prepare the soil give the researchers a 95-percent confidence interval that the elimination rates of the MWCNTs by the earthworms was not influenced by how they prepared the MWCNTs and the soil. Conclusion: “worms can readily eliminate any accumulated MWCNTs.” However, the results of the experiment “suggest that such surface coatings (e.g., PEI) are unlikely to influence organism accumulation of MWCNTs. The lack of accumulation suggests that one mechanism for MWCNT toxicity may be through impacting organism digestive processes and tissues.”⁷⁰

For scientists who are interested in using carbon nanotubes to increase seed germination rates, e.g., Aline da Costas Lima and her colleagues at the University of Campinas,⁷¹ this result must be encouraging. If the earthworms can eliminate the nanotubes while they are processing soil, nano-enabled increases in seed germination might be environmentally sustainable. However, the NIST experiment cannot serve as a declaration of carbon nanotube-infused soil health, nor do the scientists make that claim. But a nanotech entrepreneur, who is seeking funding to develop a patent into a commercial product, might make such a broad claim.

Earth worms isolated in experiments do not represent the microfauna communities that the earthworms ingest to survive. The short-term capacity of earthworms to excrete

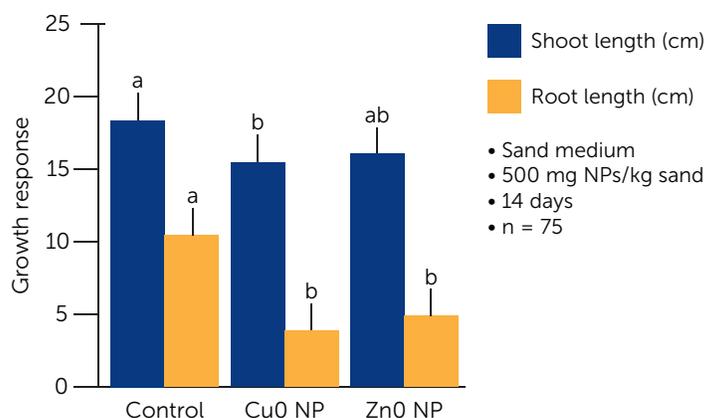
MCWNTs, despite the damage to the earthworm digestive tract reported in the aforementioned Dutch research, bodes well for the earthworms' short-term work as builders of soil. However, to demonstrate that MWCNTs did not harm the microfauna food chain that the earthworms fed on, the NIST experiment would need to measure the ability of each element in the above illustrated microfauna food chain to ingest and excrete the MWCNTs. How will these micro-fauna communities, to be discussed shortly, be affected by even short-term exposure to MWCNTs, to say nothing of chronic exposure? In order to be sustainable for agriculture, ENMs must not harm the complex feeding chain of fungi, nematodes, bacteria, protozoa, micro-arthropods, macro-arthropods, etc., that are stewards of soil health.

Testing the effects of commercially available ENMs on a soil microbe in terms of wheat plant growth

A presentation to a National Institute of Food and Agriculture (NIFA) conference, "Engineered nanoparticles in agricultural settings,"⁷² reviewed a study that measures the effect of three nano-metal oxides known for their antimicrobial properties on a specific soil microbe and on wheat plant growth. The authors begin by outlining the broad and growing range of anti-microbial NPs in consumer products and note pointedly that none of these products are regulated. The researchers mixed 500 milligrams of commercially available nano-silver (Ag NP), nano-copper oxide (CuO NP) and nano-zinc oxide (ZnO NP) in a kilogram of sand containing a soil microbe, PcO6, which enables drought tolerance in wheat. The sand is a neutral medium for evaluating the effect of the ENMs on the PcO6 microbe and hence on wheat shoot and root growth.

At the end of 14 days, wheat root and shoot growth in the CuO NP- and ZnO NP-treated roots are markedly stunted. (For reasons not explained in the slide presentation, the effect of Ag NP on plant root and shoot growth are not presented.) The authors show the toxicity mechanism and metal oxide accumulation that affects the soil microbe's ability to confer drought tolerance.

Nanoparticles' (NP) Influence on Wheat



Dimпка et al., submitted 2010

David Britt et al., "Engineered Nanoparticles in Agricultural Settings," presentation at the National Institute of Food and Agriculture Nanotechnology Conference, December 2010.

A review article by many of the same researchers in this NIFA presentation explains much more than the most evident reason for the wheat root and shoot stunting: the anti-microbial activity of these ENMs, which is beneficial for attacking pathogenic microbes, such as *E. coli*, damages beneficial microbes, such as the wheat root colonizing microbe PcO6. They note that Ag, CuO and ZnO NPs "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 complexity of the microbial interactions with plants in the soil."⁷³ From the viewpoint of these biological engineers, the crux of the ENM/microbe interaction is to understand "the factors in soil" that change the chemical activity of the ENMs. They have a wide array of instrumentation to visualize and interpret the ENM activity.⁷⁴

However, these environmentally precautionary and very well-equipped scientists do not yet understand how the ENMs affects their bioreactivity, for good or ill, with the soil microbe. Indirectly addressing ENM manufacturers, they write, "These findings raise further questions about how manufacturers' coatings and dopings of different particles will influence bioreactivity."⁷⁵ The researchers further anticipate that the bioreactivity of the same ENMs will vary depending on the agricultural soil type. Therefore, nanotoxicological predictability and risk evaluation in the agricultural field, even with the most sophisticated equipment, will be difficult to achieve. Furthermore, on the basis of their own experiments and a review of the work of other research teams, they believe "there is likely to be extreme variability in the dose-response level between different NPs and the microbial populations that regulate plant performance."⁷⁶ This extreme

variability in ENM dose-response will make it extremely difficult to regulate nano-fertilizer compounds on a case by case basis.

It appears that in soil humid conditions, as opposed to the sand medium of the laboratory experiment, ENMs agglomerate and as a result are not toxic: “in a comparison of Ag Nps in soil vs. sand, we find that soil negates the killing activity [of the AG NPs].”⁷⁷ Part of the cause of this negation is the covering of the Ag NPs with pore water from the root system, which aggregates the NPs and prevents them from entering the root pores. They conclude, “Clearly the fate of the NPs in the agricultural environment will vary with soil and water components.”⁷⁸ This conclusion adds the degree of soil and root humidity to the soil types and microbial communities accounting for the “extreme variability” of ENM–soil microbe interaction.

The conclusions that the scientists draw from their experiments suggest that applying ENMs intentionally or incidentally to soil microbe communities cannot be done with any precision, even if soil testing yields reliable and accurate information about the soil microbes that populate a soil type. For a technology assessment about the use of ENMs in soil, a few questions about the “extreme variability” of each ENM dose and each soil microbe response can be raised.

Question box 4

1. If scientists were able to identify a reliable dose-response level for specific ENMs that would kill specific pathogenic microbes while leaving beneficial microbes unharmed, would such a dose response rate also leave unharmed soil macro- and microfauna?
2. If a fertilizer could be manufactured that contained a precisely calculated dose rate for one or more ENM components, would farmers have to apply such a fertilizer with a like degree of precision for each soil type in their fields in order for the dose not to be lethal to the microbial communities in their fields?
3. If commercially available fertilizers that claim to incorporate ENMs were tested by scientists with the requisite equipment and training to do so in a field trial, and found to be harmful to microbial communities, is there any current law that would authorize government to ban such fertilizers or soil additives?
4. Since Ag NPs in the dose tested do not have an anti-microbial effect, in part because of the water in the pores of the wheat roots, does the killing effect of Ag NPs emerge during times of drought?

From technology transfer to technology assessment to regulation of nanotechnology: not a linear process

Despite the scientific uncertainties and the “extreme variability” of ENM dose-response in soils, efforts to push ENMs out of the laboratory and into the fields are underway, both in the U.S. and abroad. Some of the justification for accelerating the development of nanotechnology is the need for “pro-poor” applications of nanotechnology in developing countries, such as that suggested by a survey by the International Food Policy Research Institute (IFPRI).⁷⁹ A typical expression of hope for a technological solution to a broad array of problems is: “Nanotechnology holds the promise of new solutions to problems that hinder the development of poor countries, especially in relation to health and sanitation, food security, and the environment.”⁸⁰ However, for a technology to reach developing countries at an affordable price, a legal mechanism for transfer of technology that diminishes the high cost and royalty payments of these intensively patented technologies, will be needed. At the United Nations Rio+20 meetings, more than 200 papers were submitted towards the creation of a Technology Facilitation Mechanism for Sustainable Development.⁸¹ The discussion of such a mechanism has a long and frustrated history within the United Nations and elsewhere.

Technology transfer agreements were first proposed in the 1970s to enable developing countries to bypass old and polluting technologies to realize sustainable development, rather than buy rich country technological castoffs. Despite extensive international negotiations on technology transfer, “soft law” mechanisms for voluntary codes of conduct for technology transfer have not lead to any international agreement that would fund technology transfer.⁸² Technology transfer provisions, for example, in the U.N. Framework Convention on Climate Change, remain unfunded. Paying for climate change adaptation and mitigation technologies is more typically proposed in terms of private-public partnerships, in which governments supply policy guarantees to protect private investments plus government loan guarantees and/or co-financing for purchase of an imported technology.⁸³

Despite the diplomatic stagnation of technology transfer to developing countries, there is an urgent need for technology assessment prior to technology transfer. The ETC Group, the pioneer among NGOs researching nanotechnologies and other emerging technologies, has proposed a U.N. Office for Technology Assessment to enable evaluation of the social, legal, environmental, economic and safety consequences of investments in new technologies.⁸⁴ Given the history of products commercialized despite early warnings about harm to human and environmental health,⁸⁵ a strong case can be

made generally that technology assessment should become a well-established practice in science and technology policy before technology transfer occurs.

Several of the questions suggested here for a technology assessment have pointed to legal authorities or risk assessment needs for the regulation of ENMs in soil additives, but technology assessment need not have as its purpose the regulation of nanotechnology products, if the result of assessments is that an ENM or a nano-enabled product is too hazardous or even technically difficult to regulate, particularly within the budget constraints of an anti-regulatory political environment. For example, in the United States, both federal and sub-federal law permit fertilizing agricultural fields with biosolids, with greater or fewer restrictions.⁸⁶ If the biosolids are shown to be laced with carbon nanotubes and nano-metal oxides, a technology assessment of ENMs in biosolids might show that the benefits of a less expensive fertilizer for farmers would be outweighed by the loss of fertility, due to a loss of beneficial soil microbes and microfauna.

If the market for biosolids diminished because of the loss of soil fertility, the case for regulation to prevent incorporation of ENMs in biosolids might be made more effectively and earlier in the ENM manufacturing and waste control process. (Of course, human health consequences of crops grown with ENM-laced biosolids would also make the case for regulation, and perhaps more rapidly.) Alternatively and additionally, a technology assessment can compare nano-enabled soil additives with organic soil building techniques, both in terms of risks and benefits, as well as costs.⁸⁷

Thus far, the nanotechnology industry has resisted not only mandatory regulation but even the voluntary submission of data on ENM use in their products.⁸⁸ Indeed, among some nanotechnology promoters there is a fear that regulation to protect the environment, public health and (farm) worker health will impede the development of nanotechnology as the prime driver of a “New Industrial Revolution,” the 21st century “green economy,” etc. For example, William Norwood, the president of NanoAgri Systems, speaking to the International Food Technologists’ International Nanoscience Conference in 2009, stated, “The benefits of nanotechnology across a wide range of industry could be more important than nuclear energy. But restrictive rules could kill it . . . Nano is now a fear word.”⁸⁹ The industry fear that regulation will kill innovation is counter-factual and based on a narrow understanding of what is innovative, but the well-documented demonstration of how some companies innovate in response to regulation has not sufficed to remove that fear.⁹⁰

Happily for Mr. Norwood and other nanotechnology product developers, commercialization of the manufacture of ENMs and their use in consumer products continues without regulation, notwithstanding the efforts of nongovernmental organizations, including IATP, to compel governmental regulation.⁹¹ Regulation begins with product data and scientific studies. Thus far, U.S. government agencies have not required ENM manufacturers and product developers to report such data and studies they have as a result of their research and development programs. (However, the U.S. Food and Drug Administration (FDA) has advised industry that the agency would be unlikely to consider nano-scale food ingredients to be Generally Recognized As Safe (GRAS) just because the macro-scale counterparts of those ingredients had been designated GRAS.)⁹² Attempts to elicit voluntary cooperation, e.g., through the EPA’s Nanoscale Materials Stewardship Program, have met with little success.

So for example, according to a U.S. General Accountability Office (GAO) report, “EPA estimated that companies provided information on only about 10 percent of the nanomaterials that are likely to be commercially available. In addition, EPA reported that its review of data submitted through the program revealed instances in which the details of the manufacturing, processing, and use of the nanomaterials, as well as exposure and toxicity data, were not provided.”⁹³ Nevertheless, as we have shown, some research scientists are concerned enough about the build-up of already commercialized ENMs in soil to conduct laboratory tests. The results of those tests should raise questions among the public and policymakers about whether soil health and everything that depends on it can be sustained without regulation.

Regulation requires not just political will but adequate budgets for research into the effects of ENMs on human health and the environment. In 2006, Andrew Maynard and his colleagues challenged the “global research community to ‘develop robust systems for evaluating the health and environmental impact of engineered nanomaterials over their entire life, within the next five years.’”⁹⁴ At least as far as ENMs in agricultural soil (and plants) are concerned, the research community is just beginning this vital task.

Conclusion

Scientists will seek to replicate and extend the path-breaking experiments reviewed in this report. Given the prevalence of biosolids used to fertilize U.S. agricultural fields, if there are no gross errors in experimental design or data interpretation of these and follow-up experiments, regulatory authorities will be faced with a difficult decision. Either they will continue to allow fertilization with biosolids, a cheap source of nutrients, and hope that nanomaterials do not accumulate

sufficiently to harm soil health and the health of those who process and apply biosolids. Or, they will conclude on the basis of peer-reviewed science, that there is sufficient evidence to warrant a moratorium on fertilizing with biosolids produced in sewage treatment plants near nanomaterial manufacturing and nano-fabrication facilities. A moratorium will allow time to determine whether there are ways to make nanomaterials safe in soil, and to research how to build soil health without dependence on biosolids.

A moratorium would also allow for the inclusion of the results of citizen technology assessments. Technology assessment is part of a broader due diligence that governments should carry out prior to investing public funds in private-public partnerships for nanotechnology product development. Currently, in the U.S. government, there is no public technology assessment that compares one technological application to another for achieving a public policy or technological objective.

Citizens cannot wait for governments that have invested so heavily in nanotechnologies to drive the “next Industrial Revolution” to evaluate dispassionately whether there are less risky and expensive ways than nano-enabled soil additives to enhance soil health and increase crop yields. We should not leave the biological and chemical engineers who produced the kind of technically scrupulous research reviewed above to speak only to other specialists or to their government or private industry funders. The sooner we can hold robust technology assessments about nano-enabled soil additives with the participation of biological engineers, soil scientists, farmers and concerned citizens, the sooner we will understand what nanotechnology can do well and safely, and what it cannot do well and safely for our soil. Such technology assessments likely will overlap with other environmental and public health issues, e.g., the pre-nano weak regulation of biosolids spread on agricultural fields, but such an overlap, though conceptually messy in terms of defining nano-specific risks and benefits, will reflect better the real-world context of agri-nanotechnology ambition.

There is an urgent public policy need to acquire the data necessary to determine the environmental fate of agri-nanotechnology applications from the field to the fork. Understandably, perhaps, there is greater awareness of about the risks of eating ENMs in foods than there is about any risks to soil health.⁹⁵ However, if we are what we eat, surely what we eat is only as healthy and sustainable as the soil it comes from. In the United States, where soil is taken for granted by non-specialists and non-farmers, the prospect of ENMs in millions of agricultural acres is a blessing in disguise, if it helps mobilize citizens, as well as scientists, to defend soil health in law and practice.

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