Environmental Occurrences, Behavior, Fate, and Ecological Effects of Nanomaterials: An Introduction to the Special Series

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The release of engineered nanomaterials (ENMs) into the biosphere will increase as industries find new and useful ways to utilize these materials. Scientists and engineers are beginning to assess the material properties that determine the fate, transport, and effects of ENMs; however, the potential impacts of released ENMs on organisms, ecosystems, and human health remain largely unknown. This special collection of four review papers and four technical papers identifies many key and emerging knowledge gaps regarding the interactions between nanomaterials and ecosystems. These critical knowledge gaps include the form, route, and mass of nanomaterials entering the environment; the transformations and ultimate fate of nanomaterials in the environment; the transport, distribution, and bioavailability of nanomaterials in environmental media; and the organismal responses to nanomaterial exposure and effects of nanomaterial inputs on ecological communities and biogeochemical processes at relevant environmental concentrations and forms. This introductory section summarizes the state of knowledge and emerging areas of research needs identified within the special collection. Despite recent progress in understanding the transport, transformations, and fate of ENMs in model environments and organisms, there remains a large need for fundamental information regarding releases, distribution, transformations and persistence, and bioavailability of nanomaterials. Moreover, fate, transport, bioaccumulation, and ecological impacts research is needed using environmentally relevant concentrations and forms of ENMs in real field materials and with a broader range of organisms.

Nanotechnology is defined as the broad range of techniques and materials that allow manipulation of matter on the atomic scale to form structures having dimensions between 1 and 100 nm and possessing novel properties relative to larger “bulk” forms of the material (Auffan et al., 2009; National Nanotechnology Initiative, 2010). The potential for nanomaterials to improve quality of life is tremendous. For example, nanomedicine is helping to provide better “targeted” therapies (Sakamoto et al., 2010), and polymer nanocomposites are providing lighter, stronger materials and advanced membrane technologies (Jancar et al., 2010). Nanotechnologies also hold great promise for using resources more sparingly, providing potable water, and improving the efficiency of energy production and use (Wiesner et al., 2006). The more frequent use of these materials in consumer goods and industrial sectors also means their occurrence in the biosphere will continue to grow (Wiesner et al., 2009).

The nanotechnology vision of building objects from the atomic scale up and the subsequent introduction of novel engineered nanomaterials (ENMs) into the environment have produced both innovation and controversy. The magnitude of the challenges in predicting the environmental behaviors and potential effects of ENMs is daunting given the tremendous diversity of nanomaterials already in production (e.g., carbonaceous nanomaterials, metals and metal oxides, self-assembling mixtures of these materials). As nanotechnology progresses, ever-increasing variations in the chemical and...
physical composition of nanomaterials can be envisioned. Many applications of ENMs require surface functionalization to stabilize them against aggregation, provide specific functionality, and make them biocompatible (Phenrat et al., 2008). The vast array of possible organic and inorganic surface coatings further expands the diversity of ENMs and complicates risk assessment. Predicting the behavior and effects of ENMs in the environment will ultimately require developing a fundamental understanding of the effects of ENM properties such as size, shape, and chemical composition of the core and coating on their interaction with surfaces and organisms, chemical, photochemical, and biological transformations, uptake, and toxicity.

As with any new technology having potential for widespread adoption, the potential exists for unanticipated consequences due to the production, use, recycling, or disposal of ENMs. Given that some of these materials possess properties unlike larger-sized materials of similar chemical composition (Auffan et al., 2009), prudent environmental stewardship argues for striving for a better understanding of the potential for negative impacts arising from these “novel” materials. One, although controversial, assessment by the National Nanotechnology Coordination Office estimated that in fiscal year 2010, about 5.1% of the US$1.78 billion USD federal nanotechnology research funding was invested specifically in environmental health and safety (EHS) research related to nanomaterials. In fiscal year 2011, nano EHS investment is projected to increase to 6.6% of the total nanotechnology investment of US$1.76 billion (National Nanotechnology Coordination Office, 2010). The appropriate size of the investment in EHS research is a much-debated topic, but most agree that this is one of the first times that a new technology is being developed alongside research on the potential environmental and human health consequences arising from its use. Ideally, research on the potential environmental impacts of ENMs will allow nanotechnology to develop in the most sustainable manner possible.

Despite myriad reports available on research strategies and position papers on the promises and perils of nanomaterials, basic information regarding the health and environmental benefits or risks of ENMs is largely lacking (Wiesner et al., 2009). As is the case with all new technologies, it is unclear at the outset if the potential for significant harm even exists. And if it does exist, what will be harmed and does the harm caused outweigh the benefits from its use? This will probably depend on the type of material developed and its intended use. For example, despite health risks associated with nanotechnology-based drugs for treating cancer or other deadly diseases, the benefits (i.e., prolonging life) are likely to be judged to outweigh the risks where no alternatives exist. Furthermore, these materials are expected to be administered in small quantities. However, for nanomaterials for which the mass used is high and the benefits perhaps low (e.g., silver nanoparticles [NPs] to keep socks smelling fresh), the risks and associated costs may outweigh the benefits. But what are the costs? What are the potential adverse organism- and ecosystem-level impacts that may arise from the introduction of nanomaterials to the environment? These questions remain unanswered at present.

### Risks of Engineered Nanomaterials

Both exposure and a harmful effect are required for nanomaterials to pose a risk to human health or the environment (Robichaud et al., 2005). Therefore, to assess the potential for risk from nanomaterials, scientists need to better understand the potential for exposure to nanomaterials to occur, the likely range of exposure concentrations, and the form of the materials to which organisms will be exposed. This may be relatively straightforward for human exposures in the workplace where exposure concentrations may be directly monitored (Yeganeh et al., 2008) and the likely form is the relatively pristine nanomaterial. Exposure science is a mature field that can readily address the question of exposure dose in the workplace. Furthermore, a significant amount of work has been conducted on the inhalable fraction and the resulting health effects of fine particles (National Research Council, 2004). This knowledge may be directly applicable to nanomaterials. In contrast, potential for exposure to nanomaterials released to the environment, the range of potential exposure concentrations, and the form of nanomaterials that organisms are exposed to cannot be determined at present. A significant amount of fundamental information regarding releases, distribution, transformations and persistence, and bioavailability of nanomaterials is needed to assess the potential for exposure and the form of material to which organisms could be exposed. The toxicological effects of nanomaterials that have transformed in the environment also require assessment. In a number of cases, exposure of organisms to pristine nanomaterials in laboratory settings has resulted in toxicity, but the effects are not seen in the same or similar organisms when exposure occurs in environmental media (e.g., Kang et al., 2009; Tong et al., 2007). This special collection of papers focuses primarily on the first issue, exposure potential, as this is the more tractable of the two problems at present.

### Release of Engineered Nanomaterials

While scientists, government regulators, and public stakeholders continue to debate the degree to which ENMs pose a threat to human health and the environment (and the debate will undoubtedly continue for some time), all groups agree that ENMs will be released to the biosphere at one or more points along the lifecycle of consumer products containing nanomaterials. This includes releases of engineered nanomaterials and wastes from manufacturing, during use, recycling, and disposal (Fig. 1).

In some cases, exposure and releases during manufacture or use are expected to be quite limited but may become important when a product is disposed or recycled (e.g., carbon nanotubes [CNTs] in flat screen televisions). Although the amounts and forms (i.e., pristine NPs vs. those with attached matrix components) of materials released are unclear, evidence is accumulating that the transport properties, reactivity, and toxicity of released ENMs will be modified due to the presence of engineered surface coatings (King Heiden et al., 2009; Nel et al., 2009; Saleh et al., 2008), acquisition of organic coatings in the environment (e.g., natural organic matter) (Chen and Elmlech, 2007; Domingos et al., 2009; Hyung et al., 2007; Keller et al., 2010; Li et al., 2010), aggregation (Phenrat et al., 2009a), weathering (including redox reactions) (Li et al.,
After some 40 years of research on chemical bioavailability and transformations in the environment, knowledge about transformations of organic contaminants (e.g., polychlorinated biphenyls [PCBs], polycyclic aromatic hydrocarbons [PAHs], pesticides) and heavy metals in the environment allows reliable prediction of their behavior and ultimate fate after release (Mackay, 2001; Schwarzenbach et al., 2003; Stumm and Morgan, 1996). No such knowledge base currently exists for the transformations and bioavailability of nanoparticles. Therefore, prediction of their distribution in the environment, their persistence, their potential to transform into toxic byproducts, and their bioavailability is not currently possible. The principles of colloid science can help explain observations about transport and distribution, but the very small size, the unusual shape of some nanomaterials, and the unique engineered coatings present challenges to applying colloid science.

**Key Research Areas and Needs**

A pressing need exists to elucidate the fundamental nanomaterial properties and environmental processes that will govern their fate in the environment and their bioavailability. This understanding will continually evolve as new nanomaterials and applications appear and it becomes necessary to determine the exposure potential and impacts of each type of ENM on the environment. Important questions include: How much will be released? In which environmental compartments will they reside? What are the environmentally relevant forms of the material? How do environmental conditions determine the ENM form? A new risk paradigm is unlikely to be needed to assess the risks from nanomaterials (Shatkin and Davis, 2008); however, without answers to these questions and some understanding of the relevant ecological toxicity endpoints, we cannot reasonably predict the fate and effects of these materials. Research efforts need to focus on understanding (i) the form, route, and mass of nanomaterials entering the environment; (ii) the transformations and ultimate fate of nanomaterials in the environment; (iii) the transport, distribution, and bioavailability of nanomaterials in environmental media; and (iv) organismal responses to nanomaterial exposure and effects of nanomaterial inputs on ecological communities and biogeochemical processes at relevant environmental concentrations and forms. Assessing these processes and effects requires developing methods and perhaps new instrumentation capable of quantifying nanomaterials in environmental matrices and in organisms. A merely phenomenological understanding of these processes will prove inadequate. Rather, a mechanistic understanding of the fate, transport, and effects of nanomaterials will be required, linking nanomaterial properties to their environmental behavior and bioavailability. This will likely require developing a more thorough understanding of aspects of environmental and biological systems that are important for nanoparticle behavior in the environment and uptake by organisms.

**Sustainable Development of Engineered Nanomaterials**

Understanding the fundamental properties of nanomaterials that lead to unique routes of exposure and uptake of materials to organismal compartments or to effects that could not be predicted from the bulk materials alone will inform industry and society how to proceed with the development of nanotechnology in the most environmentally sustainable manner possible. This is not likely to eliminate all potential hazards posed by ENMs, as some hazards (e.g., ability to produce reactive oxygen species for disinfection) are required to reap the benefit of the material. However, prudent selection of materials and incorporation of those materials into matrices that prevent release will inevitably decrease the number and magnitude of adverse nanomaterial effects relative to the scenario in which potential impacts from these materials are not considered during the development of nanotechnology. Understanding nanomaterial properties that provide the desired benefits of nanotechnology without producing adverse ecological and human health consequences is one of the main goals of the National Science Foundation/USEPA–funded Center on Environmental Implications of Nanotechnology (CEINT) and University of California Center on Environmental Implications.
of Nanotechnology (UC CEIN), and EHS research integrated into the National Science Foundation Nanoscale Science and Engineering Center at the University of Wisconsin–Madison.

Contents of the Special Collection of Papers

This special collection of papers begins to address some of the issues surrounding the environmental impacts of nanomaterials. Three review papers in this collection provide background and context for assessing ENM fate, transport, and transformation in air, water, and soil, including the challenges facing researchers due to the unique properties of nanomaterials compared to more thoroughly studied chemical pollutants (Horze et al., 2010; Lin et al., 2010; Tiwari and Marr, 2010). One review paper provides an ecological perspective on the role of natural nanomaterials in biological processes and outlines important issues that need to be addressed in future research to determine the ecological responses to ENMs (Bernhardt et al., 2010). Four research papers focus on ENM sources, fate, and bioavailability including the magnitude of Ag NP releases from consumer products (Benn et al., 2010), transport and distribution of fullerene materials in soils (Wang et al., 2010), quantum dot partitioning to biofilms including novel methods to pinpoint their location (Morrow et al., 2010), and Cu NP bioavailability to the earthworm *Eisenia fetida* and the significance of this entry point for NPs into the food web (Unrine et al., 2010). This collection of papers also highlights several data gaps that must be filled to allow risk assessment using existing tools.

Form, Route, and Mass of Nanomaterials Entering the Environment

Understanding the sources of nanomaterials to the environment is an essential first component of any risk assessment. In particular, the form, route, masses, and temporal nature of inputs of nanomaterials entering the environment must be known. Benn and Westerhoff (Benn et al., 2010) build on their previous work on Ag NPs in socks (Benn and Westerhoff, 2008) and report significant releases of Ag NPs from a range of commercial products representing several important matrices including woven fabrics, liquids and pastes, and polymeric and metallic matrices. They found silver concentrations in commercial products spanning five orders of magnitude and found that quantities released from these matrices ranged over three orders of magnitude and depended strongly on the matrix. Making reasonable assumptions about use scenarios and the products’ lifecycles, they estimate the most likely current sources of Ag NPs to the environment. Similar estimates for sources of other nanomaterials constitute basic inputs required for risk assessments.

Research needs on sources of ENMs to the environment include the following:

- **Determination of the magnitudes of nanomaterial releases from commercial products along their life cycles.** Standardized testing methods are needed to assess ENMs released from manufacturing processes, including the waste streams from those processes, and from various product matrices that will be used including polymer composites, fabrics, creams/cosmetics, and so on.
- **Development of methods to “categorize” ENMs with respect to similar biological or ecological effects** (or lack thereof). Although it is increasingly clear that categories based solely on chemical composition or class (e.g., metals, metal oxides, carbonaceous) will probably not be appropriate, categorizing ENMs into groups that lead to similar exposure routes, effects, or toxic pathways may lead to relevant groupings for assessing environmental risk.

Transformations and Ultimate Fate of Engineered Nanomaterials in the Environment

The production and use of nanomaterials will result in their entry into the atmosphere, soil, sediment, water, and biota. Physical alterations such as aggregation/agglomeration, and chemical transformations such as dissolution, ligand exchange, biotic and abiotic redox reactions, and photolysis are expected to affect the fate and persistence of nanomaterials in the environment (Fig. 1). Lin et al. (2010) review the literature and conclude that most ENMs are present in aqueous environments as aggregates rather than as individual particles. Thus, research on transport, transformations, and fate processes and bioavailability should focus perhaps on aggregates rather than on individual NPs. Hotze et al. (2010) also discuss the importance of aggregation on ENM fate and bioavailability in the environment. They discuss how novel features of nanomaterials, such as unusual shapes and the presence of engineered macromolecular coatings, complicate the application of traditional colloid science to predict aggregation. These same features also influence ENM deposition to environmental surfaces, a process with profound implications for transport, fate, distribution in the environment, and bioavailability. Furthermore, they postulate that heteroaggregation with naturally occurring colloids (e.g., clay particles, natural organic matter) is potentially more important than ENM homoaggregation due to typically much higher concentrations of natural colloids in natural aqueous media. While the physical and chemical properties affecting homoaggregation are similar to heteroaggregation, the wide array of naturally occurring particle types complicate prediction of the extent of heteroaggregation.

Nanomaterials entering the environment will not remain in the form in which they are released. This is perhaps most obvious for ENMs released to the atmosphere where oxidation and photolysis are expected based on previous research on aerosols. Tiwari and Marr (2010) review the limited literature in this area and argue that oxidation and photolysis in the atmosphere are indeed likely at time scales relevant for transport. Furthermore, they indicate that these transformations will impact ENM fate in the environment (e.g., air–water exchange), as well as the potential for these materials to exert toxicity. Tiwari and Marr (2010) indicate that acquisition of natural organic matter (NOM) coatings is also to be expected in the atmosphere. Low volatility organic compounds in the atmosphere (e.g., pinene and its lower volatility ozonation products) will condense on nanomaterials. Adsorbed NOM will alter their surface properties and therefore their fate in the environment, as discussed by Lin et al. (2010) and Hotze et al. (2010). The expected transformations of nanomaterials under representative environmental conditions (e.g., anaerobic, sulfidic conditions vs. aerobic; eutrophic vs. oligotrophic; low salinity vs. high salinity environments) need to be elucidated to
research needs on environmental transformations of ENMs include the following:

- Elucidation of biologically mediated transformations of ENMs in the environment. Understanding these transformations would enable development of standard “aging” procedures for specific environmental conditions (e.g., a sulfidic environment vs. an oxic environment) that can be used to generate transformed materials for further study.

- Study of ENM heteroaggregation with natural colloids such as clays and those of biogenic origin. Numerous papers have been published on the homoaggregation of ENMs. While such studies have highlighted the importance of ENM aggregation in aquatic systems, heteroaggregation is expected to influence ENM fate, perhaps to a larger extent than homoaggregation. Heteroaggregation between engineered nanoparticle (ENP) aggregates and other particles in the environment is anticipated to be an important fate process that has received scant study to date.

- Refinement of existing techniques and development of novel methods to detect and quantify ENMs to facilitate investigation of their fate and transport in natural complex media.

- Development of a mechanistic understanding of how engineered and environmentally acquired coatings affect ENM aggregation, transport, bioavailability, and impacts. As discussed by Hotze et al. (2010), naturally occurring and engineered surface coatings greatly affect these processes. These can be inorganic coatings such as metal sulfides on quantum dots, or organic coatings such as citrate, polymers and polyelectrolytes, and natural organic matter. Predicting the fate of intentional coatings on ENMs is also needed.

Transport, Distribution, and Bioavailability of Engineered Nanomaterials

The risks associated with chemicals such as chlorinated organics could be assessed only after sufficient understanding of their transport, partitioning, and bioavailability had been developed. Several decades of research have demonstrated that properties such as hydrophobicity (as expressed by the n-octanol-water partition coefficient, $K_{ow}$) and vapor pressure of apolar and weakly polar organic contaminant (e.g., PCBs, PAHs) can be used to predict their partitioning among environmental media (Table 1), as well as the potential for bioaccumulation. Further refinement of this approach has included the development of multiparameter linear free energy relationships to provide a more fundamental basis for the interactions between these chemicals and environmental media (Schwarzenbach et al., 2003).

Most nanomaterials are not molecules, and the properties of nanomaterials that can be used to predict their distribution among environmental media, transport, and bioavailability in the environment remain to be clarified. The $K_{oc}$ of fullerene (log $K_{oc}$ = 6.67) has been suggested as an indicator of its low aqueous solubility and high potential to bioaccumulate (Jafvert and Kulkarni, 2008), but this concept will probably not be applicable to a range of nanomaterials such as metals and metal oxides. Just as the soil–water partition coefficient, $K_{st}$, describes the association of chemicals with soil particles, the attachment efficiency ($\alpha$) provides a measure of the tendency for a particle to associate with a surface. Attachment efficiency depends on the properties of the ENM and the surface (e.g., clay, silica, iron oxide), as well as solution conditions (e.g., pH, ionic strength). The calculation and treatment of forces controlling ENM attachment to environmental surfaces (e.g., van der Waals attractions, electrostatic interactions, electrosteric repulsion) will differ from those controlling equilibrium partitioning of chemicals between two phases and thus the models appropriate for molecules do not apply to ENMs.

Hotze et al. (2010) detail the challenges that nanomaterials pose to predict accurately ENM attachment to surfaces. The novel shapes and surface chemistries of some ENMs make existing theory, such as the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory, difficult to apply to calculate the forces of interactions. Furthermore, DLVO theory has never been successfully used in a predictive manner in complex environmental systems; rather, it is typically used to explain trends in behavior of particles in the environment. While attachment to mineral surfaces in the environment has been studied for decades by colloid scientists, we know comparatively little about the distribution of ENMs into biofilms coating those surfaces. Furthermore, few tools are at our disposal that are capable of detecting or imaging the locations of those particles. Morrow et al. (2010) demonstrate that quantum dots partition to biofilms and use confocal fluorescent microscopy to determine their location within the biofilm. They also demonstrate the impact of surface chemistry (e.g., PEGylation vs. carboxylation) on their partitioning to biofilms.

Lin et al. (2010) and Hotze et al. (2010) report that the transport of ENMs in environmental matrices (e.g., in porous media) determines the extent of movement of ENMs away from the source.
from their source, as well as their potential to be removed from water and wastewater by filtration. Wang et al. (2010) investigated the transport of C_{60} in soils experimentally and using mathematical models. As is the case for many types of bare and coated NPs, they found that transport of these materials in real heterogeneous soils with organic matter present is quite limited. These findings suggest that many ENMs will indeed be removed during filtration processes, thereby limiting the potential for exposure to these materials in drinking water. Of course, it also implies that these materials may build up in the backwash water from sand filters and membrane processes and potential require additional treatment.

Assessing ENM bioavailability to organisms is paramount to assessing their potential risks. Unrine et al. (2010) demonstrate that earthworms (Eisenia fetida) exposed to Cu NPs accumulate both oxidized Cu NPs and Cu dissolved from the NPs. They discuss the implications of their findings on the entry of Cu NPs into terrestrial food webs via earthworm uptake. While they focus on only one combination of ENM and organism, their study demonstrates the significant potential for ENMs to enter food webs and perhaps biomagnify. Such behavior must be considered in models designed to assess potential exposures to ENMs. Lin et al. (2010) reviews mechanisms of NP uptake and bio-processing by aquatic and terrestrial organisms; however, information correlating NP properties such as coating type with bioavailability to aquatic and terrestrial organisms is extremely scarce, especially under environmentally relevant concentrations.

Research needs in ENM transport, distribution, and bioavailability include the following:

- **Study of ENM transport in actual porous media.** Many studies have been published on the transport behavior of pristine ENMs in model systems; very few studies have been conducted in real soils. Valid assessment of transport in porous media requires more realistic test conditions. Furthermore, most models are largely empirical. Mechanistic models for ENM distribution and transport are necessary for more broadly assessing risk.
- **Determination of the bioavailability of ENMs in environmental media.** If nanomaterials are not bioavailable, they are not likely to have an impact. The extent and mechanisms of NPs uptake by plants in real soils and subsequent translocation remain to be clarified. Characterizing intracellular transformations (e.g., intracellular dissolution of Ag NPs) is also necessary to assess bioavailability.

### Effects of Engineered Nanomaterials on Organisms, Ecological Communities, and Ecosystem Function

Ecosystem functions could be affected by ENMs (largely driven by effects on plants and microbes), or ENMs could have no effect on these basal communities but may bioaccumulate into higher trophic levels. Bernhardt et al. (2010) point out that the body of literature on the potential toxicity of NPs to humans continues to increase; however, most studies have focused primarily on establishing dose–response relationships rather than on elucidating mechanisms of toxicity and correlating specific particle properties with toxicological effects. Furthermore, most previous studies have relied on acute, rather than chronic or subchronic, exposures to NPs. Unrine et al. (2010) report subchronic toxicity of Cu NPs spanning particle sizes from 20 to 100 nm but conclude that earthworm mortality is unlikely unless concentrations exceed 65 mg kg\(^{-1}\). This is a relatively high concentration and perhaps not expected to be observed in the field.

Bernhardt et al. (2010) and Unrine et al. (2010) identify several research needs in organismal effects:

- **Effects research at environmentally relevant concentrations and using environmentally relevant forms.** Most studies have been conducted at doses much higher than would be expected in natural systems.
- **Study of bioaccumulation, trophic transfer, and chronic effects rather than solely acute effects.** Many studies rely on gross measures of toxicity (e.g., mortality, malformations) rather than more subtle effects that may have population-level impacts.
- **A broader range of species needs to be investigated for ENM impacts.** The most well studied taxonomic group is bacteria; however, nearly 50% of the studies reporting NP impacts on bacteria have been conducted with a single enteric species (*Escherichia coli*). Such studies may have limited relevance for terrestrial and aquatic bacteria exposed to NPs in environmental media. Many classes of important organisms have received no study (e.g., fungi, aquatic macrophytes, predatory organisms, terrestrial herbivores). Future studies need to place more emphasis on environmentally relevant species and conditions.

Bernhardt et al. (2010) note that the effects of engineered nanomaterials on populations of organisms and on entire ecosystems is essentially unexplored at this time even though naturally occurring nanoscale minerals (e.g., nano clays, iron oxides, and volcanic ash) are present in all ecosystems and play a significant role in ecosystems. The negatively charged surfaces of nanoscale clay minerals, for example, contribute substantially to the cation exchange capacity of soils and influence soil fertility by preventing the loss of nutrients (NH\(_4\), Ca\(^{2+}\), K\(^{+}\), and Mg\(^{2+}\)) from soil. A consensus exists among researchers that natural NPs contribute importantly to the biogeochemical cycling of carbon, nitrogen, sulfur, and phosphorus in the environment. While these naturally occurring NPs are ubiquitous, the extent to which ENPs will exhibit unique physical and chemical attributes in the environment is virtually unknown.

At present, the potential ecological impacts of ENPs can only be guessed at based on fate and transport or toxicity studies conducted in highly simplified experimental settings. Bernhardt et al. (2010) argue that in addition to initiating new research efforts that examine the effects of ENPs on ecological interactions (e.g., interactions between organisms or between organisms and their natural environment), chemists and toxicologists must focus a larger portion of their laboratory research on experiments conducted in complex media using realistic exposure scenarios.

Research needs in ecological effects are summarized in Bernhardt et al. (2010). Highlights include the following:
• Studies explicitly focusing on ecological impacts of ENMs are needed. As of 2009, there were less than 10 published reports on nanomaterial effects that were ecological in design.

• Field measurements of ENM impacts and laboratory studies in real environmental media are needed to account for the effects of environmental transformations of ENPs as discussed by Hotze et al. (2010) and Lin et al. (2010) in this collection. Field studies need to be designed to include the influence of community adaptation, food web complexity, and trophic transfer, as well as multiple stressors that may affect the magnitude of the impact of NPs. Predicting the ecosystem-level effects of nanomaterials will require the development of ecosystem-level models that include mass and energy budgets.

• Synthesis of a wide variety of studies will be necessary. Ecosystems are complex. Massive amounts of data will ultimately be collected on NPs properties, media properties, and organism types and properties. All three are needed to interpret results and cross-compare to other materials, environments, and organisms. Data collection (including metadata), synthesis, and bioinformatics are needed to better understand the big picture of how complex systems in ecosystem are affected. These datasets, reporting all potentially relevant details of the experiments, should be made available in repositories. Furthermore, publishing “no effect” results at relevant concentrations rather than only materials and doses that have a dramatic effect will help guide synthesis toward sustainable nanomaterial properties more rapidly than simply reporting on materials that demonstrate harm.

Future of Nanotechnology and Associated Risks

The behavior of engineered nanomaterials in the environment and their effects on organisms remain largely unknown, even for first-generation nanoparticles such as metals (Ag, Au), metal oxides (CeO₂, Fe₃O₄), and carbonaceous materials (CNTs, C₆₀). As nanotechnology continues to advance to produce “active” nanostructures, or materials containing mixtures of the above materials, along with complex organic macromolecular coatings, the challenges to understanding their behavior and effects in the environment will continue to mount. Traditional risk assessment of ENMs is not feasible at this time due to the general lack of data on environmental occurrence and toxicity of ENMs and insufficient understanding of the releases, transformations, transport, and fate of ENMs in the environment. Such data are needed before a regulatory direction can be established. But it will require a concerted collaborative effort among disciplines to acquire this data in both laboratory and field conditions, and to understand at a mechanistic level the potential for ENMs to affect the environment and human health.

Acknowledgments

The authors GVL, MRW, and ESB recognize the National Science Foundation and the USEPA for funding for the Center for Environmental Implications of Nanotechnology (EF-0830093 and R833326). JAP recognizes the National Science Foundation for funding via the Nano Science and Engineering Center at UW–Madison (DMR-0832760). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the Environmental Protection Agency. This work has not been subjected to USEPA review, and no official endorsement should be inferred.

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