Nanomaterial Governance, Planetary Health, and the Sustainocene Transition

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15.1 Introduction

For good or bad, the immediate future of humanity is irreversibly entwined with technologies of the nanoscale. One of the great contemporary paradoxes is that solutions to global problems, such as pandemics, environmental degradation as well as lack of energy and food security, may reside in how we decide to govern materials operating at the scale of one billionth of a meter and involving probabilistic quantum effects. Increasingly scientists have begun to emphasize the importance of nanotechnology in systematically alleviating the critical problems facing humanity and its biosphere (Salamanca-Buentello et al., 2005). Here we argue one of the main ways nanotechnology can assist in this is via artificial photosynthesis and through its contribution to ensuring a global, equitable, domestic, or locally produced source of hydrogen or ammonia fuel as well as ammonia fertilizer and starch-based food. The hypothesis explored in this chapter is that nanotechnology (once appropriately regulated) will emerge in the future as a close "friend of the earth," indeed that this

is nanotechnology's "moral culmination." Further, we argue that embedded within the governance challenges related to such global deployment of nanotechnology are an array of exciting opportunities for transitioning toward a billion year period of human stewardship over planetary health known as the Sustainocene. The term "Sustainocene" was developed by Canberra-based eco-physician Dr. Bryan Furnass and has been promoted and expounded by the first author and others as a way of refocusing global policy discussion about the use of new technologies (such as nanotechnology) in assisting an indefinite number of future human generations to flourish as stewards over a sustainable and biodiverse environment.

15.2 Nanotechnology safety in global context

Earlier chapters in this book have highlighted how complex and challenging is the task of regulating nanotechnology so as to ensure environmental health and safety. On any reasonable criteria, we are absolutely right to ensure that poor regulation of widespread use of carbon nanotubes in building materials does not create a public health disaster akin to that with asbestos (see Chapter 3). An effective global governance system must ensure nanomaterials are safe in the laboratory (see Chapter 9), registered as safe for industry and the public (see Chapter 7), and create no hazards in the environment (see Chapter 6).

As the preceding chapters have emphasized, significant regulatory, public, and professional concerns have arisen about unforeseen and unique toxicities from nanoparticles within biological systems, fueled not only by consideration of factors such as their considerably larger surface area per unit mass (increasing their potential for reactivity, binding strength, and biopersistence), quantum effects below 10 nm involving altered conductivity, catalytic properties, and wavelength of emitted light (Royal Society, 2004), but their unusual shape, surface chemistry and charge, high mobility in the body and reactivities, as well as difficulties in determining reference materials and sizes (Nel et al., 2006; Oberdorster et al., 2005a,b; Borm, 2002). Blanket reassurances about human and ecosystem safety of nanoparticles continue to appear premature and unconvincing to a sceptical public (Borm et al., 2006).

Nonetheless, nanomaterial-based products are already making impacts in many areas related to human and environmental health. Nanotherapeutics [manufacturing medical products from ultra-small particles having at least one dimension <100 nm (0.00001 cm)] is a rapidly growing field, particularly in diagnostic imaging and devices and with many drugs involving nanotechnology as vectors and particle formulations already approved for human use (Grainger, 2007; US FDA, 2012). Similarly, large numbers of transnational food companies are involved in nanotechnology development (Lauterwasser, 2005), and it is anticipated that the convergence of nanotechnologies (as well as the convergence of that field with areas such as genomics, informatics, and even subatomic physics) could assist perpetuation of multinational corporate dominance over the global agri-food industry (Lauterwasser, 2005, p. 17; KPMG, 2013). In the fields of renewable energy and climate change mitigation,

however, nanotechnology offers extraordinary potential for environmental sustainability. This, as we shall see, is particularly through the development of artificial photosynthesis, that is the engineering into buildings, roads, and vehicles, the capacity for sunlight to split water as a source of hydrogen fuel (to be densely complexed in nanobuilding materials or stored with nitrogen in ammonia) as well as oxygen, while also absorbing atmospheric nitrogen and carbon dioxide to make ammonia fertilizer and starch (Faunce et al., 2013a,b; Faunce, 2013). As Nobel laureate, physicist Frank Wilczek put it when describing artificial photosynthesis as a technology that will change everything: "Evolution in its patient blindness managed to develop photosynthesis; with mindful insight, we will do better" (Wilczek, 2009).

Nanotechnology has arisen at an acute moment in the history of this planet and human occupation of it. The Holocene (recent whole) postglacial geological epoch (so named by the International Geological Congress in Bologna in 1885) began 10,000 years ago. From that time till about 1800 CE, humanity's activities were not enough to alter much the natural environmental systems of this world; for example, atmospheric carbon dioxide concentrations (as measured by ice core samples) did not rise above their natural variability, the amount of forest and biological species on the Earth's surface did not alter greatly. Yet, since the onset of the industrial revolution, the development of the energy-intensive capacity to fix atmospheric nitrogen as a fertilizer improved sanitation, healthcare, and transport; human population and its impact have dramatically increased to the point of absolute dominance (Steffen et al., 2011).

The overwhelming terrestrial impact of this collective human activity arguably has pushed this planet into what has been termed the Anthropocene period (Crutzen and Stoermer, 2000). The term "Anthropocene" was coined by Crutzen in 2002 (Crutzen, 2002). It refers to the present epoch where human interference with Earth systems (particularly in the form of influences on land use and land cover, coastal and maritime ecosystems, atmospheric composition, riverine flow, nitrogen, carbon and phosphorus cycles, physical climate, food chains, biological diversity and natural resources) have become so pervasive and profound that they are not only becoming the main drivers of natural processes on Earth but also threatening their capacity to sustain life (Steffen et al., 2007). Because these deleterious activities are mostly due to the decisions of artificial people called corporations, the 'Anthropocene' might more accurately (in the view of the first author) be termed the 'Corporatocene'.

Five characteristic features of the Anthropocene (or Corporatocene) epoch tend to dominate its policy debates (including areas such as research and deployment of nanotechnology). These may be summarized as follows:

1. National economies predicated on population expansion (to fuel growth in consumer demand)
2. Poverty (to create marginal efficiencies of labor in the developing world)
3. Preparation for war (as a major source of defense industry profits)
4. The subjugation of democratic and scientific public policy development to multinational corporate profits
5. The capacity of human systems to pollute and degrade their supporting ecosystems (Furnass, 2012).

Salutary facts that should drive academic and policy interest in how nanotechnology might assist in fashioning a transition from the Corporatocene to a more altruistic type of human-controlled epoch are not only the greenhouse gas driven increase in severe weather events but also the projected increase of global human population to around 10 billion by 2050 with associated energy consumption rising from ≈ 400 to over 500 EJ/year beyond the capacity of existing fossil fuel-based power generation (Rogner, 2004). The need to orient nanotechnology research and development toward global medicines, food, energy, and climate policy arguably should be recognized by policy makers as emerging strongly from influential commentaries such as the Intergovernmental Panel on Climate Change (IPCC, 2014) and the Stern Report (Stern, 2007), as well as the United Nations *Millennium Development Goals* (UN MDGs). Yet there seems to be a reluctance among the research, governance, and corporate communities for a connection to be firmly made between nanotechnology and the great public health and environmental challenges of our time. Part of this reluctance may be due to ongoing problems faced by researchers and corporate manufacturers with regard to regulatory certainty in the use of nanomaterials.

15.3 Regulatory uncertainty and nano-sunscreens

The widespread use of titanium (TiO_2) and zinc oxide (ZnO) nanoparticles in marketed sunscreens (e.g., in Australia) is a good example of how publicity about regulatory uncertainty in one area can create a policy environment that may discourage more beneficial applications of nanotechnology. Concerns about the impacts of such nanoparticles on human health were never trivial. When TiO_2 particles, for example, are incorporated into cells, mobilization of electrons by absorption of ultraviolet (UVA) light causes the generation of reactive oxygen species (ROS) with induction of DNA in human cells (strand breakage and base modification) and cell membrane damage (NIOSH, 2005). The International Agency for Research on Cancer (IARC) and the US Toxicology Program rate TiO_2 as an improbable human carcinogen (NIOSH, 2005). Recent work, however, has shown that ultrafine TiO_2 (10–20 nm) induced oxidative DNA damage, lipid peroxidation, and micronuclei formation in a human bronchial epithelial cell line (Gurr et al., 2005). Inorganic zinc salts are known to be potent biocides, and zinc oxide nanoparticles (as well as manufacturing by-products containing zinc) manufactured for use in cosmetics and sunscreens are thus currently subject to disposal restrictions in most nations (Faunce et al., 2008).

Yet most studies indicating lack of engineered nanoparticles (ENP) dermal penetration below the dead cells of the stratum corneum have been done in nonhuman skin or on multiple sites in a single subject, taking little, if any, account of demonstrated wide interindividual variability (Flinders Consulting, 2006). Likewise, they appear not to have systematically considered cuts, abrasions, dermatological conditions, co-application of insect repellants, pre-existing UV damage, age or flexure

of skin, despite the impact that these factors are likely to have on ENP sunscreen absorption in daily life (Rouse et al., 2007). Rouse et al. (2007) found that flexing porcine skin for 90 min facilitated fullerene-substituted peptide ENP penetration of the dermis; ENP size is clearly of the utmost importance. Yet most researched preparations for which no dermal ENP penetration has been demonstrated have had effective particle sizes greater than those found in new “clear” or “microfine” sunscreens (Vogt et al., 2006). Vogt et al. (2006), examining ENPs to facilitate transcutaneous vaccination, have shown that, after cyanacrylate skin surface stripping (which removes 30% of the stratum corneum, including keratinized material, lipids, and cell debris from the follicular openings), ENPs of ≤ 40 nm do penetrate the stratum corneum, both via follicular ducts and in perifollicular tissue, to enter perifollicular Langerhans cells (potent antigen-presenting cells). A review of the literature concluded that very small (5–20 nm) TiO_2 ENPs penetrate into the dermis and can interact with the immune system (Gamer et al., 2006). Nonetheless, a paper involving two authors directly associated with the L’Oréal cosmetic company expresses the view that TiO_2 and ZnO nanoparticles in sunscreens pose no additional health risks (Nohynek et al., 2007). More recent research indicates the immune system may effectively remove nanoparticles (Fitzsimmons, 2014). Predictive toxicology strategies may be useful here (see Chapter 5).

The sense that the manufacturers and regulators of nanoparticles in sunscreens have “something to hide” was highlighted when a study showed that at least one Australian sunscreen contained nanoparticles in a formulation that caused photocatalytic roof degradation (Barker and Branch, 2008). Though it is suspected that product has been removed from the market, the identity of that sunscreen was never revealed to the Australian public (Faunce, 2010). In a regulatory system which currently does not require sunscreen manufacturers to label whether listed ingredients present in their product are in nano form, it becomes increasingly difficult for patients, pharmacists, and the general public to keep track of what is in the sunscreens they buy, and just how safe those sunscreens are. This has a broader negative impact on how policy makers and investors perceive nanotechnology should be utilized. The EU precautionary approach to nanoparticles could be a very useful case study in this context (see Chapter 12) (Faunce et al., 2008).

15.4 Regulatory uncertainty and nanosilver

Amongst the MDGs enunciated by the United Nations, there are two where silver nanoparticles, otherwise known as nanosilver, could make a direct positive contribution. These are Target 7c: reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation, and Target 7d: achieve significant improvement in the lives of at least 100 million slum dwellers by 2020 (UN, 2010).

Nanosilver has a wide range of potential applications in this context, including its role in spectrally selective coatings for solar energy absorption (Rand et al.,

2010) (see Chapters 2 and 6). Nanosilver's most significant potential immediate contribution to such global public health and environmental goals, however, may relate to its capacity to kill bacteria that cause disease (particularly in living conditions with low hygiene) through the contamination of food, water, and wounds. Interestingly, when 63 experts were asked to specify which aspects of nanotechnology could most assist the developing world, the role of nanosilver in water purification was not specifically mentioned. The nanotechnologies cited as likely to be important in this context were nanomembranes for water purification (admittedly this could involve embedded nanosilver), desalination and detoxification, nanosensors for the detection of contaminants and pathogens, nanoporous zeolites, polymers and attapulgite clays for water purification, magnetic nanoparticles for water treatment and remediation, and titanium dioxide nanoparticles for the catalytic degradation of water pollutants (Salamanca-Buentello et al., 2005). One reason for the diminished advocacy for nanosilver in this context is likely to relate to its potential environmental toxicity (Faunce and Watal, 2010).

Silver has long been known to keep water pure and keep external wounds clean, a capacity now known to be due to its oligodynamic lethality (only minute amounts are required) for bacteria. This is in part due to thiol group reactions that inactivate enzymes, a process enhanced by electric fields (Akhavan and Ghaderi, 2009), pure silver having the highest electrical and thermal conductivity of any metal (Chen and Schluesener, 2008).

A case can be made that nanosilver represents a new chemical entity with important physical and chemical characteristics distinct from silver on the macro-scale. Nanosilver preparations, for example, provide a greater surface area of silver exposed in solution and a potentially higher proportion of bioactive metallic silver (ionic silver becomes silver chloride in the stomach or bloodstream, being less bioactive, although some silver-chloro complexes, being uncharged, are therefore lipid soluble and potentially highly bioavailable) (Russell and Hugo, 1994). Conversely, it has also been argued that nanosilver acts similar to metallic silver in terms of toxicity (i.e., it dissolves to form ionic silver) (Wijnhoven et al., 2009).

Nanosilver is used extensively in medicine for prosthetics, in the treatment of skin disease wound management, particularly for the treatment of burns, various ulcers (e.g., rheumatoid arthritis-associated leg ulcers and diabetic ulcers) and toxic epidermal necrolysis, for healing of donor sites and in surgical mesh (Chen and Schluesener, 2008). Nanosilver particles in the 1–10 nm range have been shown to inhibit binding of HIV-1 to host cells (Elechiguerra et al., 2005). Nanosilver is also used to coat urethral and central line catheters and other implantable medical devices, such as infusion ports, orthopedic protruding fixateurs, endovascular stents, urological stents, endotracheal tubes, contact lens coatings, endoscopes, electrodes, peritoneal dialysis devices, subcutaneous cuffs, and surgical and dental instruments, to prevent the growth of slime-containing biofilms that promote bacterial infection and sepsis (Chen and Schluesener, 2008).

Nanosilver is also incorporated for its antibacterial, antiviral, and antifungal properties in a growing range of modern domestic or household items. It has the

highest degree of commercialization of nanoparticles in consumer products, with approximately 300 nanosilver products, including household appliances and cleaners, clothing (including socks and underwear), cutlery, children's toys, and personal care products (such as menstrual pads) currently on the market in the United States (Kimbrell, 2009; Woodrow Wilson Institute, 2009). Similar findings are likely to apply to the European Union, United Kingdom, and Australia (UK Gov, 2009). A typical example is Samsung's "Nano Silver Health System," which uses nanosilver in refrigerator trays, filters, air conditioners, and tubing to kill bacteria and the odors they produce (Silver Institute, 2009). Particularly widespread household uses of nanosilver include cosmetics, clothing deodorizers, paints, disinfectants, and cleaning products (Woodrow Wilson Institute, 2009).

Yet, there is little doubt that like silver itself, nanosilver can be highly toxic to cells. *In vitro* studies demonstrate that nanosilver is toxic to mammalian liver cells, stem cells, and even brain cells (Hussain et al., 2005). Silver ions and nanoparticles released from medical devices (such as catheters) form protein-silver complexes deposited in the liver, kidney, spleen, lung, brain, and skin (Landsdown, 2007). In 2006, a case report described a 17-year-old boy with burns on 30% of his body, whose nanosilver-coated wound dressings caused liver toxicity as well as argyria (Trop et al., 2006).

One issue that has promoted regulatory uncertainty here is whether nanosilver's cellular toxicity is a new phenomenon, given that colloidal silver preparations (which have always contained a certain proportion of silver in nanoparticle form) have been around for so long (Faunce and Watal, 2010). It is unclear whether nanosilver has an unusual capacity for attachment to cell membranes, thereby altering membrane permeability and the redox cycle in the cytosol, or for intracellular free radical accumulation or dissipation of the proton motive force for ATP synthesis (Choi and Hu, 2008). Nanosilver raises a vast swathe of potential health risks that are addressed elsewhere (Faunce and Watal, 2010). It also raises significant risks for the environment that have not been adequately addressed by regulators (see Chapter 6).

Indeed, in 2010, nanosilver in wastewater was listed by a team of public health experts as one of 15 nascent issues that could deleteriously affect the conservation of biological diversity (Sutherland et al., 2010). The two MDGs most relevant in this context are Target 7a (integrate the principles of sustainable development into country policies and programs; reverse loss of environmental resources) and Target 7b (reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss) (UN, 2010). The experts' concerns about widespread use of nanosilver relate not so much to direct poisoning of humans or the production of bacterial resistance in hospital settings, as to its high *in vitro* toxicity for aquatic organisms and capacity to environmentally persist (Luoma, 2008). No doubt they were aware that bulk form silver released into waste streams, particularly from photographic development, had previously been a major source of ecological toxicity (Brown et al., 2003). Toxicity of this nature can have far-reaching effects upon food supply and distribution, both via the poisoning of fish stocks and other food sources, and via contamination of water supplies.

The volume of waste containing residue nanosilver is increasing proportionally with its utilization in domestic products and medicinal applications (Morones et al., 2005; Benn and Westerhoff, 2008; Richardson, 2009). Nanosilver released in domestic wastewater may have a variety of fates, including being converted into ionic silver, complexing with other ions, molecules or molecular groups, agglomerating or remaining in nanoparticle form. Its potential for significant environmental toxicity revolves around its biocidal and catalytic effects on a wide range of organisms in the soil, including bacteria, fungi, and earthworms, along with reaction with other toxic substances, a toxic effect on groundwater and accumulation along the food chain (Blaser et al., 2008). Wastewater treatment relies on heterotrophic microorganisms for organic and nutrient removal, while autotrophic microorganisms play an important role in nitrification. Nitrifying bacteria in sewerage systems are especially susceptible to inhibition by silver nanoparticles (Choi et al., 2009).

Most recently, Bradford et al. determined that the "current and future predicted environmental concentrations of silver nanoparticles appear to be well below any impact threshold to the microbial health of the environment." However, their study on the impact of nanosilver contamination on natural bacterial assemblages in estuarine sediments was conducted over a short exposure time of 1 month and involved samples collected from a single estuary (Bradford et al., 2009). Further research needs to be undertaken with longer exposure times, covering different estuarine environments as well as investigating the effects of nanosilver in fresh water systems. Information about mass loading in the environment is currently unavailable for the purposes of nanosilver risk assessments, instead a major deficiency here being the inadequacy of government reporting requirements or manufacturer product information to construct reliable estimates of mass discharges (Luoma, 2008).

That this type of regulatory uncertainty should characterize the most widely used consumer application of nanotechnology throughout its life cycle, may be seen as a salutary warning by investors and policy makers who consider investing in nanotechnological applications that could be of global benefit.

15.5 Paths to greater nanoregulatory certainty

Apart from the need for coordination of metrological issues and accumulation of relevant fundamental data, there are many other areas of regulation including public safety legislation that create uncertainty about steering the global nanotechnological enterprise toward humanity's great contemporary public health and environmental challenges. A scoping study by the UK Central Science Laboratory, for example, found major areas of existing product regulation that are inadequate to handle the various scales of risk from nanomaterials that blur physicochemical rules (DEFRA, 2006). A report of the influential Project on Emerging Nanotechnologies at the US Woodrow Wilson International Center for Scholars went further and advocated regulatory technology that can tackle environmental and energy challenges, for example with new solar energy and water treatment technologies and to reduce the

amount of energy, water, and chemicals used in a whole range of nanotechnology manufacturing processes (Schmidt, 2007).

Safety and efficacy regulatory approval for nanotechnology-related medical products may create additional concerns for regulators. Nanodrugs, for example, will not fit into abbreviated generic (biosimilar type) safety and efficacy approval pathways if they involve increased bioavailability, faster onset of action, dose uniformity, and smaller and more stable dosage forms. Nanotechnology, additionally, will blur the different regulatory pathways that exist for drugs, devices, biologics, and combination products. There are also likely to be conflict of interest problems in industry-funded regulatory agencies, who will be under corporate pressure to achieve "fast track" approval of innovative nanotherapeutic products, rather than full implementation of the "precautionary principle" (Faunce, 2007b).

It is unacceptable from a public health point of view that no health technology international regulator currently specifies distinct safety regulations/requirements that must be met by manufacturers in health products. Similarly, few if any international regulatory agencies currently possess effective methods to monitor nanoparticle exposure risks (OECD, 2007). The aim eventually should be to improve manufacturing methods so that nanoparticles of a standardized size with known low toxicity can be incorporated into medically related products.

Nanotechnology drug development may not be well served by existing models where start-up and small biotech companies select profitable targets and carry out little preclinical safety assessment before acquisition or licensing by larger pharmaceutical multinationals (Nijhara and Balakrishnan, 2006; Kramer et al., 2007). Regulatory models promoting academic global cooperation, and developing world capacity building in nanotechnology for infectious disease diagnosis and treatment, should become a funding priority for governments and major charities (Smy, 2006; Tackling Global Poverty, 2007).

One often-overlooked regulatory consideration for nanomaterial-containing products relates to evidence-based assessment (at either national or international levels) of their comparative cost effectiveness (or "health innovation"). Those mandatory reporting schemes or voluntary industry codes of conduct that are currently being debated for nanotechnology regulation should not become a *de facto* substitute for rigorously enforced public health and environmental protection standards. Similarly, industry involvement in standard-setting committees should not be allowed to become a vehicle for shaping the regulatory architecture so that it freezes out smaller players, inhibits public interest disclosures by employees, or is used to avoid legal responsibilities and penalties. In the interim, before toxicity testing protocols, data and standards are in place, regulatory authorities should consider packaging disclosures of the average size or size range of ENPs involved.

Developing models for data collection about exposure in air and water, evaluating toxicity, and predicting life cycle impact have been presented as the major challenges for nanoregulation internationally in the next decade (Maynard et al., 2006). In terms of internationally harmonized regulation, related goals are being worked toward by the Organization for Economic Co-operation and Development (OECD)

Working Party on Manufactured Nanomaterials (WPMN) particularly under Project 3 in which various nations have agreed to take roles in providing regulators with consistent toxicity data on common nanomaterials (e.g., Australia is contributing on zinc oxide (used in sunscreens), cerium oxide (a fuel additive), and nanosilver (relevant to a wide range of medical and sanitary applications)) (OECD Environment Directorate, 2010). Another significant effort to harmonize international nanoregulation involves the International Standards Organization (ISO) Technical Committee which has published work on nanotechnology terminology and definitions (ISO, 2008a) and international standards on environmental, health, and safety issues concerning nanotechnology (ISO, 2008b). The ISO has proposed a definition of nanoparticle as one with all three external dimensions in the size range 1–100 nm (ISO, 2008a). Amongst self-regulation initiatives, the Responsible Nanocode has been developed to establish consensus of good practice in the research, production, retail, and disposal of products using nanotechnologies (Responsible Nano Code, 2008).

Such regulatory efforts, whilst appropriate for related safety issues, don't adequately emphasize the role that regulation should play in encouraging beneficial uses of nanotechnology. In 2005, for example, a survey of nanotechnology scientists and policy makers identified the top ways in which nanotechnology could benefit developing countries in the areas of water, agriculture, nutrition, health, and energy on criteria related to impact, burden, appropriateness, feasibility, reducing knowledge gap, capacity building, and income generation (Salamanca-Buentello et al., 2005). UN MDG 7 on environmental sustainability targets sustainable access to safe drinking water and basic sanitation and improving the lives of slum dwellers (UN, 2010).

Regulation related to nanotechnology in energy storage, production, and conversion could promote: (i) novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials, (ii) photovoltaic (PV) cells and organic light-emitting devices based on quantum dots, (iii) carbon nanotubes in composite film coatings for solar cells, (iv) nanocatalysts for hydrogen generation, and (v) hybrid protein-polymer biomimetic membranes (Faunce, 2012a).

Regulation related to nanotechnology in agricultural productivity enhancement could promote: (i) nanoporous zeolites for slow release and efficient dosage of water and fertilizers for plants, and of nutrients and drugs for livestock; (ii) nanocapsules for herbicide delivery; (iii) nanosensors for soil quality and for plant health monitoring; and (iv) nanomagnets for removal of soil contaminants (Faunce, 2012a).

Regulation related to nanotechnology in water treatment and remediation could promote: (i) nanomembranes for water purification, desalination, and detoxification; (ii) nanosensors for the detection of contaminants and pathogens; (iii) nanoporous zeolites and polymers, and attapulgite clays for water purification; (iv) magnetic nanoparticles for water treatment and remediation; and (v) TiO_2 nanoparticles for the catalytic degradation of water pollutants (Faunce, 2012a).

Regulation related to nanotechnology in air pollution and remediation could promote: (i) TiO_2 nanoparticle-based photocatalytic degradation of air pollutants in self-cleaning systems; (ii) nanocatalysts for more efficient, cheaper, and better

controlled catalytic converters; (iii) nanosensors for detection of toxic materials and leaks; and (iv) gas separation nanodevices (Faunce, 2012a).

Yet, many commentators remain skeptical that nanotechnology according to current patterns of research and development will assist economic development, improve global public health, and reduce poverty (Invernizzi et al., 2008; Missoni and Foffani, 2009). The hypothesis being explored here is that regulatory complexity and uncertainty is a factor in inhibiting this reorientation of nanotechnology research and development priorities.

Nanotechnology regulation in Australia is a valuable case study in this respect. Australia has four national chemicals assessment and registration schemes directly relevant to regulation of nanoparticles: (i) Food Standards Australia New Zealand (FSANZ) covering the food industry [Food Standards Australia New Zealand Act 1991 (Cth)]; (ii) the National Industrial Chemicals and Assessment Scheme (NICNAS) that covers industrial chemicals [Industrial Chemicals (Notification and Assessment) Act 1989 (Cth)]; (iii) the Therapeutic Goods Administration (TGA) that deals with pharmaceuticals [Therapeutic Goods Act 1989 (Cth)]; and (iv) the Australian Pesticides and Veterinary Medicines Authority (APVMA) that deals with agricultural and veterinary chemicals [Agricultural and Veterinary Chemicals (Code) Act 1994 (Cth); Agricultural and Veterinary Chemicals Administration Act 1992 (Cth)].

Both the APVMA and the TGA regulate products rather than chemical substances. NICNAS administers the Australian Inventory of Chemical Substances (AICS) just as the TGA administers the Australian Register of Therapeutic Goods (ARTG). These, in their respective fields, require applicant manufacturers of nanoparticles to submit comprehensive characterization data sets, which include, where appropriate, particle size and unusual characteristics. All food products (including those potentially containing nanoparticles such as nanosilver) supplied in Australia must comply with the Australia New Zealand Food Standards Code (ANZFSC) and be safe for human consumption. The use of industrial chemicals is also regulated at the state and territory level by a range of agencies. Additionally, the Australian Competition and Consumer Commission (ACCC) is responsible for product labeling in accordance with federal Trade Practices legislation (Faunce, 2008).

Safe Work Australia (SWA) revised the Code of Practice for Safety Data Sheets (SDS) and proposed the addition of a number of nonmandatory specific to nanoparticle safety guidelines, in addition to implementing a nanotechnology occupational health and safety program (see Chapter 3). There have been only two engineered nanomaterials for which Australian National Exposure Standards were promptly established: fumed silica and carbon black. SWA has established the Nanotechnology OHS Measurement Reference Group to progress the development of nanomaterials emissions and exposure measurement capability in Australian workplaces (Safe Work Australia, 2009). FSANZ has been seeking to amend the ANZFSC so that new applications contain information on particle size, size distribution, and morphology (FSANZ, 2009).

The TGA, after a review of nanoparticles in sunscreens, approved them for marketing in Australia on the basis that they do not penetrate below the stratum corneum, but the many researchers and the public remained concerned about patients with damaged or diseased skin (Faunce, 2009). In February 2010, the federal government announced a National Enabling Technologies Strategy which allocated around \$38 million over four years "to guide the safe development of new technologies such as nanotechnology and biotechnology." The strategy allocated \$18.2 million to the National Measurement Institute (Australian Government, 2010), but this funding program is not continuing. Concerns were raised as to whether these strategies adequately applied the precautionary principle; this permits regulation (even in the absence of scientific certainty about risk) if the consequences for public health and the environment are significant enough (Faunce et al., 2008).

In February 2006, NICNAS issued a voluntary Call for Information to Australian industry to provide information on the uses and quantities of nanomaterials being manufactured or imported for industrial purposes, or for use in cosmetics and personal care products. Only about 20 companies responded. Approximately one-third of those surveyed indicated that the nanomaterial(s) were only being used for research purposes. A second Voluntary Call for Information was initiated by NICNAS in October 2008, targeted at all manufacturers or importers of nanomaterials or products (mixtures) containing nanomaterials for commercial or research and development purposes in 2008 (the first call excluded the use of nanomaterials for R&D purposes). This had a similarly poor response (Trop et al., 2006). NICNAS, like its counterparts the European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) program and the United States Environment Protection Agency's Toxic Substances Control Act (TSCA), faces the challenge of how to define nanoparticles. The standard of <100nm probably needs to be supplemented by components acknowledging the importance of novel chemical and physical properties. There is also the issue of whether to deem nanoformulations of existing chemicals to be "new chemicals" for regulatory and safety purposes. To date, Australian regulators have been reluctant to recognize that nanoparticles present new and often greater toxicity risks than larger particles of the same chemical composition. In this they may have been hoping to protect and nurture investment in a young industry but may actually have been promoting the uncertainty that restricts the public embracing it. This conclusion may have been evident to the National Nanotechnology Strategy Taskforce which in its report recognized the need for a "whole of government approach" to dealing with the problems posed by nanotechnology and suggested that "existing regulations may need some adjustments" (Choi and Hu, 2008).

15.6 Reorienting global regulation so nanotechnology assists the Sustainocene

So what is at stake in pushing for greater regulatory certainty concerning nanomaterials? Chiefly that the field will become more embraced by the public and investors

who see opportunities to marry profit and global benefit. Simply put, emerging technologies on the nanoscale have far-reaching potential for rectifying global problems such as anthropogenic climate change, the gap between global population and energy and food demand, biodiversity loss, and ecosystem pollution. These issues form intersections between international human rights, healthcare, and environmental ethics on the one hand, and international trade law on the other, and therein create one of the great normative challenges for global health policy. If humanity is to transition from the present era of corporate globalization built upon nonrenewable resource extraction [a period deprecatingly referred to as the Anthropocene (Steffan et al., 2011)], but possibly more accurately termed the 'Corporatocene' then we must attempt to use such norms to ensure the wonderful potential of nanotechnology to achieve what has been termed its moral culmination (Faunce, 2012a) in assisting humanity to create not only just and equitable, but sustainable habitats.

The term "Sustainocene" was coined by the Canberra-based Australian ecophysician Bryan Furnass in 2012 (Furnass, 2012). It has been more deeply characterized (Faunce, 2012d) as referring to a long-term period (millions of years) where governance structures and scientific endeavor coordinate to achieve the social virtues of ecological sustainability and environmental integrity as influentially propounded by eco-economists such as the EF Schumacher [with his concept of "small (and local) is beautiful"] and Kenneth Boulding (with his idea of "Spaceship Earth" as a closed economy requiring recycling of resources) as well as Herman Daly with his notion of "steady state" economies drawing upon the laws of thermodynamics and the tendency of the universe to greater entropy (dispersal of energy) (Faunce, 2012a).

One area of academic research and policy development that fits well with "Sustainocene" thinking is that centered on the idea that this planet should be treated not just as a distinct living entity (James Lovelock's Gaia hypothesis), but as a patient (Lovelock, 1991). "Planetary Medicine," as this field has become known, has become a symbolic rubric focusing not just public and governmental attention on the interaction between human health, technological development, and sustainability of the biosphere (Faunce, 2012b). In this emerging discipline, characteristic features of the corporate-dominated Anthropocene epoch, such as anthropogenic climate change and environmental degradation, as well as gross societal imbalances in poverty as well as lack of necessary fuel, food, medicines, security, and access to nature (Steffan et al., 2011), are targeted as intrinsically global pathologies the resolution of which requires concerted efforts to implement a wide range of not just renewable energy technologies (such as those using nanotechnology) but bioethical principles including those related to protecting the interests of future generations and preservation of biodiversity (Steffan et al., 2007; Vines et al., 2013) (Table 15.1).

15.7 Reorienting the scientific quest toward nanotechnology's role with the Sustainocene

At a very fundamental level, it must be part of any modern formulation of the foundational governance ideal known as the social contract (putatively the foundation

Table 15.1 Comparison of Corporatocene and Sustainocene

	Corporatocene	Sustainocene
Powered by "old" photosynthesis fuels	Yes	No
Powered by "new" photosynthesis fuels	No	Yes
Corporate-led governance and economy	Yes	No
Community-led governance	No	Yes
Governance protecting future generations	No	Yes
Governance protecting ecosystems	No	Yes
Governance protecting biodiversity	No	Yes
Enforceable rights of nature	No	Yes

of all regulatory systems) that all citizens be accorded just and equitable access to scientific knowledge (such as that related to nanotechnology), which reveals the basic order of things and facilitates technologies that relieve human suffering and the degradation of the biosphere. That social contract should also accord a place to artificial people (such as corporations) commensurate with their emerging legal responsibilities to more than just shareholder profit. It is a false idea dangerous to sustainability and human flourishing that the capacity of purely profit-driven corporations to develop marketable products is critical to the financial support of scientific knowledge. It should also now begin to place the interests and rights of other species and ecosystems alongside those of human beings.

This emerges both from traditional epistemology, and from an epistemology that is akin to an economic theory of knowledge, or a "street-level epistemology." Classic epistemology concerns general theories of knowledge—how things are known and justified to be true, particularly from the perspective of knowledge distributed throughout society. Street-level epistemology concerns what is known by the ordinary person on the street, it is a subjective rather than objective concern. At the street level, a great many scientific principles (such as those involved with nanotechnology) simply cannot be understood by individuals without many years of advanced education. Or from a classical epistemological perspective, broadly speaking such scientific knowledge is cumulative, and is usually embodied as institutional knowledge, which can create an abnegation of citizens' regulatory responsibilities to government or corporate-appointed "experts" who may not regard broader social and environmental interests as of paramount importance.

Questions of how our knowledge should be acquired cuts deep into the issue of how our new technologies (such as nanotechnology) best should be understood, and how that knowledge is or should be distributed throughout a culture. In the seventeenth century, the philosopher Benedict de Spinoza wrote in his *Ethics* (Bk II, Prop. XLIV) that it is the nature of reason properly applied to perceive things truly, that is, as they are in themselves, not as contingently existing as revealed by sensory experience. This pronouncement and its implications have often been ignored or dismissed

as a peculiar type of idealist rhetoric, subsequently characteristic of utopian rhetoric or human rights pronouncements. Yet Spinoza's realization paved the way for major breakthroughs in thinking not only about science but also in ethics—the realization that there could be true statements about reality that did not appear to correlate with common sense. One example was the vast speed of the Earth around the Sun, another the constancy of the speed of light regardless of speed of source. Later there was the particle wave duality of photons and atoms, then, of course, came the "big bang," "dark matter," and the mathematical likelihood of 13 or more dimensions if the mathematical equations of general relativity and quantum mechanics are to be reconciled as they must have been at the time of the "big bang" (Greene, 2004). In the eighteenth century, Immanuel Kant influentially contended that the capacity to form ethical concepts in the form of goals or end points for future actions, arises (like our understanding of time and space) *a priori*. That is, as a necessary precondition for accurate experience, rather than by being determined by experience. We now readily accept that reality is underpinned by physical laws that may act in ways that share little or nothing with our common experience of the world (such as the myriad curiosities of quantum mechanics that are such intriguing features of many applications of nanotechnology).

Science has provided the basis for the emerging social virtue of environmental sustainability as influentially propounded by eco-economists such as the E.F. Schumacher [with his concept of "small (and local) is beautiful"] (Schumacher, 1974) and Kenneth Boulding (with his idea of "Spaceship Earth" as a closed economy requiring recycling of resources) (Boulding, 1992). Science, particularly through the laws of thermodynamics, has also provided the basis for the economist Herman Daly emphasizing entropy (dispersal of energy) to champion the idea of "steady state" economics that financially values the maintenance of ecosystems equally with production and profits (Daly, 1999).

Science is now emphasizing the importance of global regulation to create safe boundaries for long-term human occupation of this planet (Steffen et al., 2011). This approach, we argue, shows the direction in which regulation of nanotechnology, in general, should head.

15.8 Rethinking the ethics of corporate globalization

The process of corporate globalization (with its subversion of core social contract principles such as democratic accountability and the rule of law) has been facilitated in large part by international trade law, a system with few formal connections to international human rights or environmental law and policy concerned with sustainability. Corporate-driven World Trade Organisation (WTO) agreements, such as those on Trade Related Intellectual Property Scam (TRIPS) and General Agreement on Trade in Services (GATS), did contain provisions that allowed exemption for government policies necessary to protect public order and morality [articles 27(2) and XIV(a), respectively].

International investment law is not supposed according to its constitutive documents, to create a jurisprudence, a body of decisions that can be referred to as

creating precedents, a common law of international trade. Yet the arbitrators are called into action only by corporations in their actions against the policies and legislation of democratic governments that are alleged to undercut their profits. The decisions of those arbitrators about damages paid by governments (the system never awards damages against corporations) privileges those corporate profits over aspects of every other component of the social contract. Public order or morals, which sometimes appear as exceptions in trade and investment agreements, are not explicitly linked in such agreements to established normative systems such as that of international or constitutional human rights, such as the right to health, or emerging environmental rights like biodiversity and ecosystem sustainability (Chapman, 2002). Trade or investment dispute panels instead, by their terms of reference, are permitted to consider vague enunciations of public morals such as "standards of rights and wrong conduct maintained by or on behalf of a community or nation" (WTO, 2005).

The normative evolution toward justiciable and enforceable international human rights as a functional part of a global social contract implies a combination of both self-assurance about the universal regulatory and symbolic importance of assisting humans to interact with each other and their environment in ways that promote mutual flourishing, and mistrust of governments to pursue that agenda (Hart, 1979; Raz, 1984; Brugger, 1996).

Largely missing from such jurisprudential discussions has been consideration of how human beings should make basic rules governing their relationship with the environment including how regulatory systems should assist new technologies like nanotechnology to be responsive to normative principles and rules focused on sustainability. One exception in practice has been the precautionary principle. This emerged in German regulatory policy during the 1970s and rapidly spread through the international policy arena (including into European nanotechnology policy) as a philosophical challenge against free-market policies that demanded an often unrealistic level of scientific certainty about risks before recommending or implementing public health and environmental protection measures in relation to the use of new technologies. A well-known international enunciation of the precautionary principle is found in Principle 15 of the *Rio Declaration on Environment and Development* (1992): "Where there are threats of serious or irreversible damage lack of full scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation" (Faunce et al., 2008).

Another important and illustrative part of this process may involve the development of a system of ethics for Planetary Medicine (as a foundation for nanoregulatory systems) that parallels the earlier development of universalist medical ethics. Historically, the development of medical ethics (as a professional subset of general ethics) and human rights are intriguingly parallel systems bearing upon equitable access to new health-related technologies and services (Beauchamp, 1995; Pellegrino, 1995; Jonsen, 2000). John Locke, a founding father of human rights jurisprudence, was a physician pupil of Sydenham, a great clinical empiricist inheritor of the Hippocratic tradition (Borden, 1967; Dewhurst, 1995; Davey, 2001). Indeed, it

is interesting to speculate that a major factor promoting both the corpus of human rights norms, as well as the norms of medical ethics deriving from the Hippocratic Oath, may have been the influence of clinical practice on the humanistic conceptions of Locke, including the inspirational example of Sydenham's loyalty to the coordinating professional virtue of relief of individual human suffering (Faunce, 2007a). Science likewise is now awakening the conscience of humanity toward the suffering experience by other species and the ecosystems of this planet. Medical ethics needs to embrace the idea that there is no human health on a dead planet. It can do this practically by introducing more formally and explicitly into its normative structure responsibilities to the environment, even indirectly as a means of assuring human health. These then will become powerful underlying drivers to reshape regulatory systems for new technologies (such as nanotechnology).

The standard national and corporate policies advocating unlimited economic growth that currently drive the global macroeconomy are increasingly recognized to impinge detrimentally on the finite resources of the global ecosystem and on global public health (Daly, 1990; Ayres, 2008). The argument here is that the hypothetical rules to govern how this and future generations should put to use the new technologies their collective scientific effort have produced surely have taken into account species survival and the integrity of ecosystems. Global ethics and law must address how nanotechnology, in other words, should be regulated in order to provide a nonpolluting source of fuel and food, or assist to create a sustainable biosphere. These questions are at least equivocally as important as similar issues arising with the use of nanotechnology to develop equitable access to medicines, medical devices, and medical services.

As has been mentioned, nanotechnology can be seen to develop in this broader context as not merely an enabling technology, but as a moral culmination—an enablement of great twenty-first century ecocentric foundational social virtues and ideals like environmental sustainability. Our regulatory systems globally should be trying to help nanotechnology break the paradigm of corporate globalization driving economic and survival dependence upon the depletion of nonrenewable resources to create disposable consumer products with marginal utility in terms of contentment and wisdom.

15.9 Reorienting international law to nanotechnology's role with the Sustainocene

The urgent moral need to focus nanotechnology on issues of environmental sustainability inevitably will bring pressure to bear to reform the application of normative instruments such as the United Nations Scientific, Education Cultural Organisation (UNESCO), Universal Declaration on Bioethics and Human Rights (UDBHR), the International Covenant on Economic, Social and Cultural Rights (ICESCR), the policies and programs of the World Health Organization (WHO), the UN MDG, the recommendations of the Intergovernmental Panel on Climate Change (IPCC),

and the Copenhagen Accord on Climate Change, in addition to the implementation of international treaty and national constitutional provisions on the right to health, sustainable development, and environmental protection. These intersections then will shape not only the principles and rules governing equitable access to essential nanomedicines, nanotechnology-based hospital and healthcare services, but will also shape nanotechnology research, development, and transfer toward sustainable energy generation, food production, and environment protection.

The UNMDGs represented an important rationale for scientific research to focus on issues of energy storage, production and conversion, agricultural productivity enhancement, and water treatment and remediation, and to do so with respect for the basic virtues and principles of bioethics and international human rights, including environmental sustainability, justice, equity, and respect for human dignity (UN, 2010).

Likewise, article 15(1) of the United Nations ICESCR provides: "The States Parties to the present Covenant recognize the right of everyone: (b) To enjoy the benefits of scientific progress and its applications (REBSPA) are found in article 27 of the United Nations Universal Declaration of Human Rights. Article 12(2) on freedom from hunger refers to making full use of scientific knowledge, articles 2(1) and 23 of the ICESCR refer to scientific assistance in achieving the specified rights and there are implicit scientific aspects to the right to health in article 12 of the ICESCR.

Several significant and largely unresolved issues are immediately presented by any attempt to apply REBSPA to facilitate equitable global access to scientific advances in nanotechnology. The first concerns the jurisprudential and philosophical basis of a right to enjoy the benefit of scientific progress and its applications. Other work on economic, social, and cultural rights confirms that they are subject to a margin of appreciation given the limited nature of State resources and competing demands, as well as varying cultural sensitivities (Chapman, 2009).

A second problem with applying REBSPA to assist policy support for nanotechnology-oriented human development is that its constitutive documents do not provide a definition of "science" or "scientific." A core definition of science is likely to include the empirical sciences, wherein knowledge is obtained from experiments about observable phenomena, and is subsequently capable of being tested for validity (including being falsified) by other researchers working under the same conditions. Clearly, applied nanotechnology falls within this definition. Yet a workable definition of science should include not only formal fields such as mathematics, statistics, or logic but also encapsulate an ethical dimension necessarily linking science to foundational social virtues—justice, equity, respect for human dignity and environmental sustainability.

A major challenge then to interpreting this REBSPA as it applies to nanotechnology, and therein to health and food supply, involves defining its core components. On one approach the core component of the REBSPA seeks to protect, fulfill, and respect the scientific enterprise insofar as it contributes to achieving

human rights obligations. It aims to protect the capacity of the scientific enterprise to bring benefits to everyone. This is done through encouraging measures that permit the critical analysis, honesty, and objectivity of scientific researchers and their employers, through facilitating government regulatory systems based on a scientific evaluation of the risks, and by assessing the benefits and cost effectiveness of new technologies. The right may be viewed as seeking to support mechanisms that incorporate traditional knowledge (e.g., of indigenous peoples) into the scientific enterprise according to standards supported by international human rights. For the purposes of this right, states have an obligation to ensure that science conducted within their boundaries is coherent with international human rights.

Third, article 15(2) of the ICESCR refers to "conservation, development, and diffusion" of science as one of the steps to be taken by States Parties to achieve full realization of the REBSPA. Challenges to interpretation of the right in this context include the extent to which "conservation" refers to measures to prevent loss of expertise and infrastructure relevant to nanotechnology, particularly in developing nations. Measures for consideration here include how the policies of developing nations to retain scientific expertise relate to WTO General Agreement of Trade in Services (GATS) obligations.

Additional challenges with respect to "development" of the science of nanotechnology in the context of sustainability include reporting obligations by States Parties on investment in related science education, grant funding, and infrastructure. Challenges with respect to "Sustainocene diffusion" include the responsibilities of States Parties to facilitate community access to scientific information, fostering of open scientific debate, and appropriate use of science in regulatory processes. Other challenges arise with respect to the creation of mechanisms, which ensure that publicly funded research recuperates a percentage of the profits that are ultimately produced by private sector involvement in the research development. Another Sustainocene challenge arises with the maintenance of the "research use" exemption for public funded universities, and measures to prevent any systematic inhibition, misrepresentation, or concealment of scientific data by private or public research organizations.

Fourth, article 15(3) requires States Parties to the Covenant to undertake to respect the freedom indispensable for scientific research and creative activity. One Sustainocene challenge here may involve the need (in order to achieve full realization of this right) for the equivalent of a "Hippocratic Oath" for nanotechnology researchers and senior management of research organizations utilizing substantial funding by States Parties. Another challenge to full realization of REBSPA may involve consideration of laws that financially reward informants revealing fraud on the public purse in scientific research. Consideration could also be given to the need for United Nations "Office of Research Integrity" to generate guidelines, procedures, and standards that protect vulnerable populations, and that encourage active and informed participation of lay individuals and communities in policy decisions and their impact. The funding rules for award of research grants in nanotechnology by States Parties may also be an important challenge under this head.

Fifth, article 15(4) of the ICESCR refers to an obligation of States Parties to fulfill, protect, and respect the benefits derived from the encouragement and development of international contacts, and cooperation in scientific fields such as nanotechnology. Challenges for full realization of this aspect of the right in the Sustainocene include the extent to which grant funding by States Parties facilitates this aim (i.e., by including awards fostering such contacts and cooperation).

Sixth, full realization by States Parties of the REBSPA concerning nanotechnology in the Sustainocene necessarily involves considering potential challenges to that right. A probable challenge is identified by the authors, as residing in potential disputes relating to the role of evidence in energy, health, and environmental policies before WTO Dispute Settlement mechanisms, and in investor-state dispute settlement mechanisms. As new scientific technologies become available for dealing with crucial issues for States Parties such as energy security, water security, food security, and climate change mitigation (such as artificial photosynthesis), questions will arise as to whether the right requires exceptions to WTO, bilateral, and regional trade agreements. Particularly where these agreements may, through increased monopoly privilege (patent) protections, inhibit enjoyment of the benefits of that science and its applications. Regulatory dilemmas also clash with the full realization of the REBSPA. These arise from the imprecise relationship between implementation of the precautionary principle, the activation of investor-state rights, and the use of regional and bilateral trade agreements to undermine science-based mechanisms to evaluate the "health innovation" of new technologies.

International humanitarian law (IHL) is another source of norms with relevance in the Sustainocene transition to both global healthcare ethics and to burgeoning new fields like nanotechnology. IHL has also grown to have complex intersections with environmental and trade law norms. This is particularly true in relation to not only restricting the research, development, and transfer of new military technologies (including those on the nanoscale), but facilitating reasonable access to new health-related technologies for prisoners and wounded in war. IHL is an aggregation of customary and treaty-based norms concerned with the treatment of the wounded combatants, civilians, and prisoners in war. It has many areas of overlap with both medical ethics and human rights law.

Medically related NGOs, such as the International Red Cross, Physicians for Human Rights and Médecins Sans Frontières, though often focused on applying medical ethics in the context of armed conflict, are increasingly involved in monitoring, preventing, alleviating, and even defining state violations of IHL including those related to restricting civilian, wounded, and prisoner access to necessary health technologies (Rubenstein, 2009). Along with nonphysician groups such as Amnesty International and Human Rights Watch, many of their members view themselves as being at the vanguard of a cosmopolitan world order normatively governed by both IHL and the UDHR of particular relevance to Sustainocene policy. Of particular relevance, the UDHR has provisions for the progressive realization of the human right to a standard of living adequate for health and medical care (article 25), and the human right to share advancement and its benefits (article 27) (UN, 1948).

Modern cosmopolitanism is not wedded to the notion that there is immutably little higher legitimate legal or even moral authority over states. It questions the capacity of nation states and the normative systems that create and support them, to effectively address transnational legal issues, such as technology transfer and the transnational benefits therefrom. Positing the universal interests of humanity—considered directly and not through the prism of state sovereignty—as the fundamental cosmopolitan normative ground of technology transfer obligations in the Sustainocene, would avoid the problem of needing to link such a norm (as is often required by international law) to the interests of the signatory nations or their dominant cultural, religious, or economic classes.

Positing that technology transfer and transnational benefit principles actually have their firmest normative foundation in emerging cosmopolitanism, also may encourage support from individually and socially applicable virtues and universal principles stemming from practice at the local level, including the global charitable funding networks and community structures in international civil society. The UDBHR's great contribution to evolution of technology transfer and transnational benefit norms in the Sustainocene may be related to the fact that it not only targets different actors to public international law (individual corporations and professionals as well as states) but also involves norms with a potentially more cosmopolitan theoretical background and with a substantially more inclusive conceptual foundation for international governance and regulation.

Applying a medically derived ethical framework grounded in cosmopolitanism provides a useful foundation of principles from which a new approach to nanotechnological development, distribution, and application could evolve in the Sustainocene. Nanotechnology can not only have implications for health technology but also for health ethics, norms, and laws.

Perhaps the apotheosis of such efforts to use regulation to promote uses of nanotechnology relevant to global health and sustainability of the environment will be a macroscale global scientific project, similar in scope to the Human Genome Project, but aimed at utilizing nanotechnology to develop revolutionary advances in energy production, energy storage, and a host of other game changing innovations, could emerge from the legal milieu of rights to science and technology. Such a project would require the support of governance structures emphasizing international law, and which might seek to protect nanotechnology used this way from excessive patents that promote inequitable or unsustainable use within the class of United Nations treaties involved with protecting the common heritage of humanity [such provisions cover, for instance, outer space (UN, 1967), the moon (UN, 1979), deep sea bed (UN 1982), Antarctica (UN, 1959), and world natural heritage sites (UNESCO, 1972)].

Five core components are generally regarded as encompassing the Common Heritage of Humanity concept under public international law that might apply to nanotechnology in the Sustainocene transition. First, there can be no private or public appropriation, since no one legally owns common heritage spaces or materials. Second, representatives from all nations must manage such resources on behalf

of all (this often necessitates a special agency to coordinate shared management). Third, all nations must actively share with each other the benefits acquired from exploitation of the resources from the common heritage region, which requires restraint on the profit-making activities of private corporate entities, and linking the concept to that of global public good. Fourth, there can be no weaponry developed using common heritage materials. Fifth, the commons should be preserved for the benefit of future generations (Frakes, 2003; Pardo, 1968). The claim for nanotechnology to common heritage status is a radical one that cuts across and seeks to modify corporate dominion over nanotechnology in the interests of global public health and environmental sustainability.

15.10 The moral culmination of nanoregulation in globalized artificial photosynthesis

There has been much policy interest in developing what is termed the "hydrogen economy" in which hydrogen is used ubiquitously as a carbon-neutral energy vector (e.g., source of electricity via fuel cells or as a fuel itself and source of small amounts of fresh water, when combusted) (Sarbaeva et al., 2008). Major policy documents have outlined the case for such an economy (FCH JU, 2013; US DOE, 2013). Some of the challenges include the need to lower the cost of hydrogen fuel production to that of petrol, the difficulties in creating a sustainable and low carbon dioxide route for the mass production of hydrogen, the need to develop safe and more efficient storage (including the difficulties of compressing and cooling the hydrogen), the need to develop regulations and safety standards at national and international levels as well as the need to develop stable incentive systems for large-scale investment in this area that will not fluctuate with oil prices. Nanotechnology offers solutions in all these areas—not only in increasing the surface area of photon harvesting systems but also in enhancing the capacity of building materials to densely store hydrogen (Faunce, 2013).

Hydrogen (H_2) requires 3000 times more space for equivalent amount of energy, but on a weight basis H_2 has three times the energy content of gasoline. Liquifying H_2 requires complex and expensive process (precooled with liquid ammonia to -40°C then to -196°C with liquid nitrogen, then helium in compression-expansion to get liquid H_2 at -253°C). Thirty to forty percent of H_2 energy is lost in liquification and 1–5% must be lost to atmosphere each day to avoid pressure buildup and explosion. Compression similarly requires 10–15% energy and requires cylindrical shape (Olah et al., 2009). One of the main problems at present with moving to a global hydrogen economy is the carbon-intensive energy required to produce hydrogen in large quantities.

Yet a cheap and abundant source of H_2 is readily at hand as an output of nanotechnology (and other materials systems approaches) that enhances the splitting of water using sunlight. One of the reasons for focusing on this as the main energy supply of the Sustainocene is that more solar energy strikes the Earth's surface in

1 h of each day than the energy used by all human activities in 1 year. At present, the average daily power consumption required to allow a citizen to flourish with a reasonable standard of living is about 125 kWh/day. Much of this power is devoted to transport (~ 40 kWh/day), heating (~ 40 kWh/day), and domestic electrical appliances (~ 18 kWh/day), with the remainder lost in electricity conversion and distribution. Global energy consumption is approximately 450 EJ/year, much less than the solar energy potentially usable at $\sim 1.0 \text{ kW/m}^2$ of the Earth— 3.9×10^6 EJ/year even if we take into the Earth's tilt, diurnal and atmospheric influences on solar intensity (Pittock, 2009; MacKay, 2009).

Photosynthesis as a natural process is equally important with DNA in the progress of humanity. Photosynthesis provides the fundamental origin of our oxygen, food, and the majority of our fuels; it has been operating on Earth for 2.5 GYr. Photosynthesis can be considered as a process of planetary respiration: it creates a global annual CO_2 flux of 124 PgC/year and an annual O_2 flux of $\sim 10^{11}$ t/year. In its present nanotechnologically unenhanced form, photosynthesis globally already traps around 4000 EJ/year solar energy in the form of biomass. The global biomass energy potential for human use from photosynthesis as it currently operates globally is approximately equal to human energy requirements (450 EJ/year) (Faunce, 2012c).

It is quite remarkable that contemporary energy policy analysts have failed to appreciate the significance of the fact that natural photosynthesis is capable of substantial improvement with nanotechnology. When photosynthesis is considered in this context, it is usually as a source of biofuels, often with a deleterious cost to rainforests or agricultural lands. Further, even if 3000 m^2 per person is devoted to biomass production, this will provide only fuel to 36 kWh/day per person (well short of the 125 kWh/day required for people to live comfortably) (MacKay, 2009). PV energy systems are improving their efficiencies toward 25%, and the cost of the electricity they produce is nearing or has past grid parity in many nations. The development of "smart grid" (allowing energy carrying capacity to fluctuate coherently in accord with input and output) and "pumped hydro" (using diurnal PV electricity to pump water to high reservoirs so it can be run down through turbines at night) will assist the viability of electricity as a national energy source. But even large solar farms (e.g., taking up 200 m^2 per person with 10% efficient solar panels) could produce but ~ 50 kWh/day per person (MacKay, 2009).

Indeed, a natural extension of the hypothesis developed in this chapter is the claim that natural and/or artificial photosynthesis should be regarded as common heritage of humanity under international law. This normative claim has as its closest analogy claims that the genetic diversity of agricultural crops, plant genetic resources in general, biodiversity, or the atmosphere should be treated not just as areas of common concern, but should be subject to common heritage requirements under international law. A nonbinding UNESCO Universal Declaration on the Bioethics and Human Rights of Natural and Artificial Photosynthesis could support the REBSPA by declaring in Article 1 that "Natural and artificial photosynthesis underlies the fundamental unity of all life on Earth. In a symbolic sense, it is

Table 15.2 Energy Consumption and Solar Power

Parameter	Energy/Power
Annual solar energy intercepted by the Earth at -1.37 kW/m^2	$5.5 \times 10^6 \text{ EJ/year}$
2008 primary energy consumption	352.8 EJ
2050 primary energy consumption	590–1050 EJ
2100 primary energy consumption	880–1900 EJ
Ratio of potentially usable annual solar energy to current primary energy consumption per year	~9000 to 1

Source: Rogner (2004) and International Energy Agency (2010)

the heritage of humanity." Article 2 might state: "Photosynthesis in its natural state shall not give rise to financial gains" (UNESCO, 1997) (Table 15.2).

Artificial photosynthesis, however, could be not just a plentiful source of zero carbon hydrogen fuel; it can also be a source of fertilizer and food (through absorption and reduction of atmospheric nitrogen and carbon dioxide) (Faunce, 2013). In each case it can be seen how artificial photosynthesis is likely to be crucial to supporting a Sustainocene.

The first author has proposed a Sustainocene model emphasizing that artificial photosynthetic hydrogen fuel-producing products installed as a global policy priority on infrastructure including roads, dwellings, and vehicles have great potential to promote more ecocentric systems of governance involving individual and community economic autonomy and less need to deleteriously exploit the natural environment (Faunce, 2012d). Such a model proposes that in the Sustainocene every human-engineered structure on the planet will have a built in artificial photosynthetic capacity allowing it to be a positive contributor to the biosphere—improving the atmosphere, providing hydrogen fuel (which when burnt provides energy and water), and basic food and fertilizer (through conversion of atmospheric carbon dioxide and nitrogen) (Faunce, 2012d). There is a simple public policy message at the core of a vision such as that of the Sustainocene. It involves telling people that nanotechnology will be used to make buildings function like trees. A device that can do this and is available for cheap purchase and installation, like the mobile phone or internet, by providing decentralized power equitably could rapidly transform society to one that is less corporate driven and more genuinely community and values oriented. Presumptively, there are no economic disparities in the Sustainocene because local nanofactories and nanotechnology-based artificial photosynthesis allow each family and community to be self-sufficient in energy and food.

The vision of nanotechnology having a moral culmination in globalized artificial photosynthesis unashamedly has a physics-based natural law orientation. It arises from the hypothesis that the patterns of regulation humanity create to bring order to its interactions mirror the patterns of interaction that are deeply imbedded in nature—right down beyond the nanoscale to that of string theory. It incorporates the hypothesis that there is a field of what we term "consciousness" as a

further embedded part of reality and that the conjunction of global problems such as overpopulation, resource depletion, and anthropogenic climate change has not by mere coincidence arisen at the same time as nanotechnology. They present us with a choice, an opportunity for the exercise of free will in difficult circumstances. By applying universally applicable principles to resolve that choice in the face of many obstacles, our species has the opportunity to acquire virtue. One outcome of a virtuous choice following principles such as respect for human dignity and environmental sustainability may be humanity flourishing whilst acting as good steward of its environment through a billion year occupation of Earth. This vision of nanotechnology assisting our future of Earth is unashamedly idealistic. It is something that sound regulatory systems can assist and poor regulatory systems will hinder.

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Sustainable Nanotechnology: A Regional Perspective

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16.1 Introduction

Nanotechnology has been hailed as the next industrial revolution (Roco, 2003), and the current convergence of tools, materials, and know-how suggest a future of technological advances that merit such a superlative. Without question the last 100 years have shown marked increases in wealth and well-being around the world (Figure 16.1). Such dramatic improvement in the human condition can be largely attributed