Novel Entities and the GEF

Background Paper

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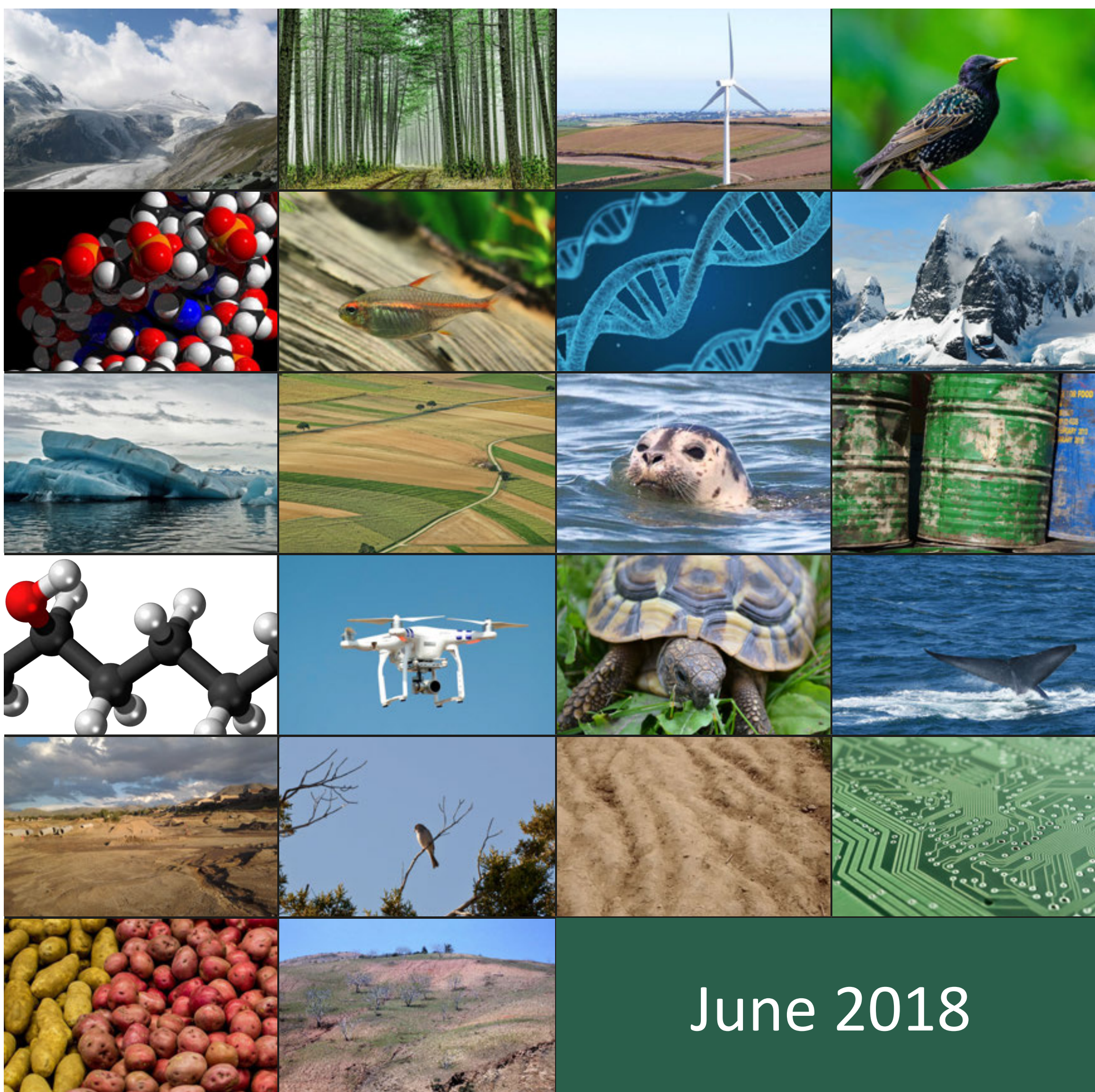

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CONTENTS

1. Background

The Scientific and Technical Advisory Panel (STAP) of the Global Environment Facility (GEF) is the advisory body to the GEF on science and technology. It is mandated to provide strategic scientific and technical advice on GEF policies, thematic areas of work, projects, and programs and to bring issues that affect global environmental change and sustainability to the attention of the GEF. In accordance with this mandate, STAP provides advice to the GEF on how best to address existing and emerging pressures and drivers of environmental degradation. The advice in this report is focused on "novel entities," which are broadly defined as *"things created and introduced into the environment by human beings that could have disruptive effects on the earth system"*. They may include synthetic organic pollutants, radioactive materials, genetically modified organisms, nanomaterials, and/or micro-plastics[1].

The report presents the results of a process developed to systematically identify novel entities that are relevant to the GEF and then advise the GEF on how it might respond to the challenges and opportunities that they present. The process involved the identification of a broad range of novel entities and then narrowing that list down to a group of those most pertinent to the work of the GEF based on the following criteria:

- Novelty – newness of the entity or new knowledge about the entity.
- Impact – this could be related to scale, timing, scope, and complexity of their impact.
- Relevance to the GEF:
  - The interaction between the identified entity and the GEF's work areas[2].
  - The extent to which the entity could negatively or positively affect the ability of the GEF to achieve its objectives, both in the near- and long-term.

A broad definition of "novel entities" was adopted to include products (the entities), as well as the processes or applications that create the products. It is important to think of processes not necessarily as hardware, but as a body of knowledge about the design of certain technologies. These bodies of knowledge, which could include, for instance, fields as wide as chemical or biological engineering, provide the underpinnings for the design and production of a wide variety of novel entities that could be of relevance to the GEF.[3] In the case of potentially beneficial technologies, a focus on the process space offers greater opportunity for transformative change by facilitating scaling and multi-sectoral impacts (Figure 1), which are part of the objectives highlighted in the most recent GEF Strategic Plan[4]. A process focus also provides the GEF opportunities to impact technological development before the "lock-in effect" occurs —the tendency to resist change because upgrading or adopting new technologies or processes appears prohibitively burdensome. The lock-in effect may limit or preclude technological access in the developing world,[5] so it will be important to explore strategies (such as the support of open source approaches) to minimize the impact of lock-in and support wider access to technologies relevant to the needs of the developing world... Process innovation is also critical to one of the key priorities of the GEF: to "change the production of goods and services in a manner that reduces or eliminates impacts to the environment[6]." Focusing on processes provides an opportunity for the GEF to shift its focus from end-of-the-pipe solutions for environmental problems to actions that proactively prevent or mitigate environmental problems before they ocurr.

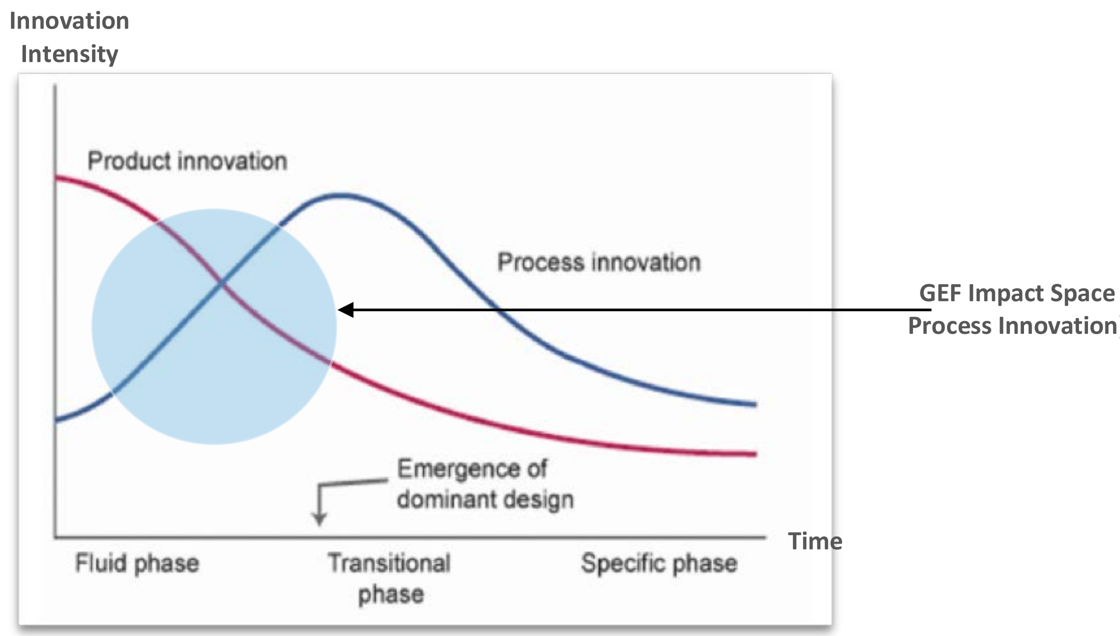

Figure 1. GEF impact space and process innovation.

2. Novel Entity Identification Process

The novel entities presented in this report were identified through a four-step process that involved horizon scanning, timing and impact analysis, an assessment of relevance to GEF programmatic areas, and translation of findings into strategic posture and possible actions (Figure 2).

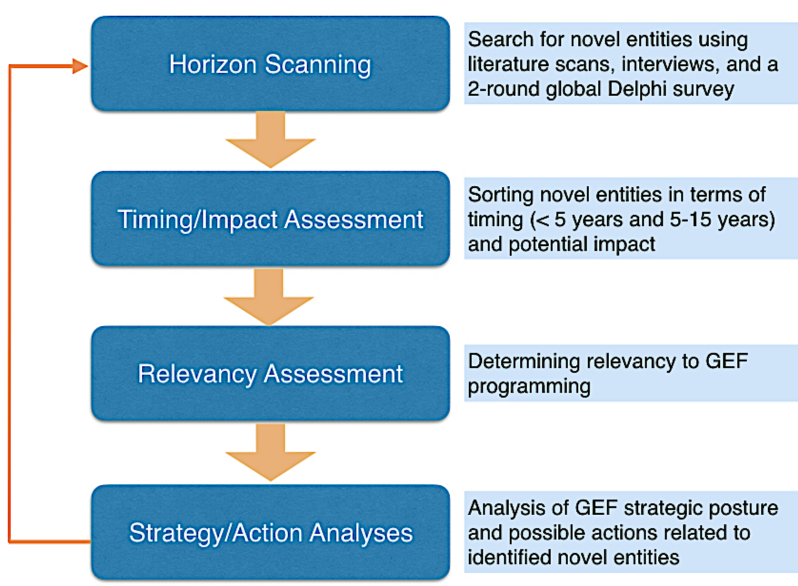

Figure 2. Novel entity identification and prioritization process.

Horizon Scanning: Historical studies have found that delays in policy or regulatory action in the face of rapid technological change are often due to a lack of effective "early warning" and an inability to search out and identify blind spots--e.g., a lack of situational awareness.[7] Horizon scanning systems, in theory, address both of these deficiencies. Research has also shown that decision-makers are more likely to use information generated from horizon scanning if they are involved in the design and implementation of the overall scanning system, which requires the integration of GEF staff and their viewpoints in the process.[8] The horizon scanning phase of this project used a number of approaches, including a review of relevant literature[9], interviews with experts within and outside the GEF[10], and a two-round Delphi survey[11]. Appendix A provides a summary of the Delphi survey demographics and results, and Appendix B provides a list of interviewed experts.

Timing and Impact Analysis: The horizon scanning process was structured to provide information on both potential impact of novel entities and timing of said impact, producing a cluster of entities that would be relevant to the GEF's upcoming four-year planning cycle and another set of entities that could inform future planning efforts. Novel entities identified during the process were sorted into two temporal categories—the next 0-5 years and the next 5-15 years--depending on the anticipation of shorter or longer-term impacts and the consideration of development trajectories.

In the context of emerging, potentially beneficial technologies, the process of sorting into temporal categories reflects largely technological feasibility, rather than implementation feasibility, which may be context- and country-specific and dependent on the existence of appropriate policy frameworks. Looking out more than five years is an uncertain exercise, but it still has value given that research illustrates that "one of the most frequently made mistakes [in strategic planning] is shortening the time horizon below five years."[12] A longer time horizon is not unusual in science and technology planning, given long innovation cycles, challenges inherent in scaling up new technologies, and time required for market penetration and diffusion. It is important to remember that many future technology trends are likely to be driven by idea- and capital-intensive industries like software and biotechnology, which tend to adhere to long-range corporate strategies. One reflection of these strategies is the tendency of these industries to invest in research and development even during times of economic unrest and uncertainty.[13]

The GEF will require time to integrate strategies related to novel entities into global, multilateral policy processes and frameworks. Timing matters from a policy standpoint since the rate of change in many technological sectors far exceeds that of the regulatory and budgeting processes affecting them.[14] It is important, therefore, that the GEF focus on those technology trends which might come to fruition the earliest and have the most impact on its programs and mission. These trends are probably making themselves felt already and may be moving into the marketplace[15].

As an initial sorting strategy, we identified 3-4 novel technologies in each of two timeframes--0-5 years and 5-15 years--based on an assessment of timing and impact from the Delphi survey and other inputs from experts (Figure 3). In some cases, there were overlaps between entities, such as gene editing and gene drives, which allowed us to cluster choices.

Assessment of Relevance to the GEF: The previous GEF strategy (GEF 2020) reflected the desire for more cross-programmatic impact than currently exists. This exercise sought to identify novel entities that cut across multiple areas of interest and that would be relevant to the GEF's integrated goals in work areas including food security, sustainable cities, and fisheries. There is a need to also look at relevance to broader frameworks relevant to the GEF, such as the Sustainable Development Goals. An assessment of this relevance was used to further narrow down the long list of identified entities. Figure 4 shows an assessment of the relevance of identified entities to a selection of GEF work areas.

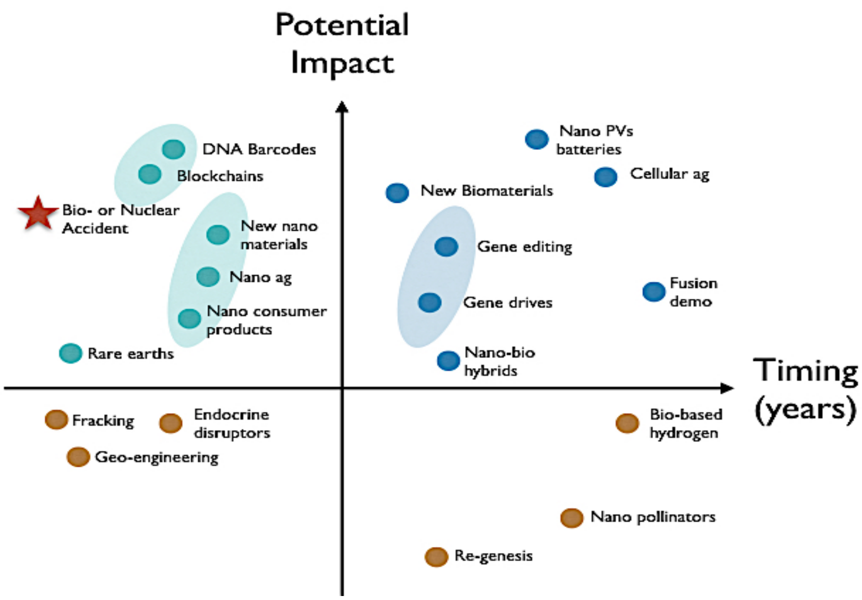

Figure 3. Assessment of novel entities by potential impact and timing

	Biodiversity	Climate Change	Chemicals and Waste	International Waters	Land	Forests	Food Security	Sustainable Cities	Fisheries
Technology-critical elements	●	●	●	●	●	●			
Next-generation nanotechnology		●	●	●			●		
Blockchains	●	●	●					●	●
New engineered bio-based materials	●		●	●		●	●	●	
CRISPR/Gene editing	●	●	●			●	●		
Cellular agriculture	●	●		●	●	●	●		
Nanotechnology-enabled energy		●	●					●	

Figure 4. Relevance of identified entities to GEF focal areas

Strategic Posture: The manner in which the GEF thinks about novel entities and technological systems will be crucial to its ability to shape outcomes in the science and technology space. This is one of the most important questions the GEF must answer over the next five years and beyond: adapt to technological change or shape it? The GEF will have to consider uncertainties associated with the novel entities as these could impact planning processes and organisational strategies. As some researchers have noted, "underestimating uncertainty can lead to strategies that neither defend against the threats nor take advantage of the opportunities."[16]

For this project, we drew upon the three-horizon approach[17] developed by the consultancy McKinsey to help organizations prioritize strategic actions in the future. We modified the approach by collapsing the taxonomy into two time horizons that map into the GEF planning cycle and used the framework as a way to aid the GEF in translating insights on novel entities into strategies and potential actions. This exercise strove to identify which emerging trends could have a major impact in the short term (0 – 5 years) and the longer-term time (5 - 15 years), while also considering the sequencing of impacts[18] and linking trends to strategies and actions. We employed the three-horizon approach as a framework for analyzing the results of the horizon scanning exercise. We wove this framework into our workshop, attended by experts from within and outside the GEF. The impact/strategy matrix (Figure 5) is designed to help decision-makers at the GEF translate trends with differing levels of impact into three possible organisational postures and strategies:[19]

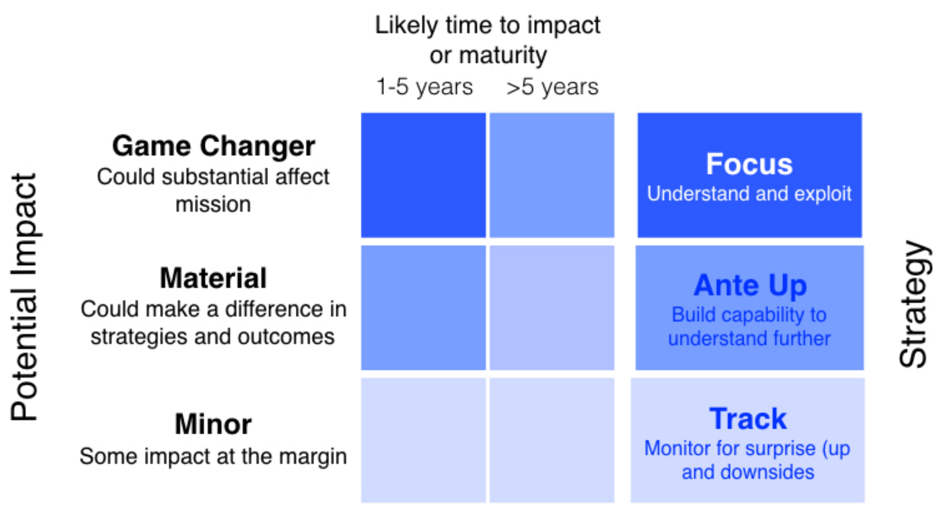

Figure 5. Potential impact and response strategy

"Focus": The emergence of a game-changing novel entity requires the GEF to focus resources--human and financial--on opportunities to exploit technological changes while mitigating risks. In this area, a possible role for the GEF could be to help direct the course of the technology to ensure that it does not result in negative environmental impacts. Alternatively, the GEF could help scale up or improve the accessibility and affordability of a novel application, therefore accelerating benefits for the environment and communities affected by the technologies.

"Ante up" represents a strategic posture that allows the GEF to "reserve the right to play" or hedge against uncertainties and potentially constraining changes. This posture may include taking certain actions now so that the GEF remains able to either exploit a beneficial opportunity or prevent negative impacts as they appear, as well as to quickly recover if an assumption fails. Implementing an "ante up" strategy requires maintaining flexibility and building a portfolio of actions. Strategies could include making a number of small-scale investments, launching pilot projects, or running other experiments, as well as exploring strategies that can take the pilots to scale under a variety of external constraints. Key to this approach are options that allow the GEF to change course quickly, if needed.

"Tracking" strategies are designed to identify "signposts" — indicators of changing opportunity or vulnerability. Maintaining this posture requires monitoring early signals of change that could include environmental indicators of decline or degradation, numbers of new scientific publications, media convergence around an issue, or public and private sector investment flow. This activity could be done internally within the GEF (for example, by the STAP), by external contractors, or it could be done by exploiting other open source intelligence sources. Tracking serves the critical function of making sense of novel events, reducing uncertainties, and clarifying areas where the GEF should ramp up investment and engage or continue to monitor for further possible changes. It is always worth going back to check whether outcomes align with expectations, predictions, or scenarios.[20]

3. Novel Entities with Strategic Implications for the GEF

This section provides brief descriptions of the resulting novel entities from the process described in Section 2. It includes background information on the novel entities, enumerating their potential impacts and relevance to the GEF, as well as some suggestions for how the GEF could respond to them. Figure 6 shows the novel entities and highlights their importance, relevant time horizon, and suggested strategic posture. The novel entities presented do not represent all those that appeared in the background exercise (see Appendix A for the full list), but reflect those that fit the defined criteria in Section 1. They do not necessarily represent a definitive list of novel entities that should interest the GEF.

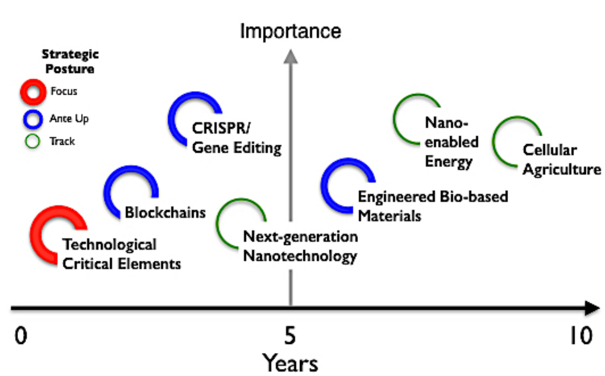

Figure 6. Novelty entities with strategic importance to the GEF

3.1. Uptake of technology-critical elements into the environment – FOCUS

Impacts : Biodiversity, Climate Change, Chemicals & Waste, International Waters, Land, Forests

Overview:
Many emerging technologies—particularly sustainable technologies and those that help mitigate climate change—rely on a group of elements that we term "technology-critical elements" (TCEs).This group includes most rare-earth elements (REEs), a group of 17 elements including the lanthanides, scandium, and yttrium. It also includes the Platinum group metals and Ga, Ge, In, Te, Nb, Ta, Tl. The use of TCEs in emerging and green technologies is resulting in their release into the environment . TCEs are important for many high-tech consumer products and emerging technologies, including those related to renewable energy and energy efficiency. They are required for production in the quickly-growing market of green technologies, including hybrid vehicles, solar cells, and wind turbines. TCEs are also critical to technologies relevant to defence, the aerospace industry, and medicine, as well as personal electronics, like cell phones, computer hard drives, and television monitors, and phosphate fertilisers used in agriculture.

The extraction and processing of TCEs, especially rare earth elements, has increased significantly in the past four decades (Figure 7), with China dominating[21]. Demand is growing at a rate of 15% annually driven largely by production of wind turbines and electric vehicles.[22]

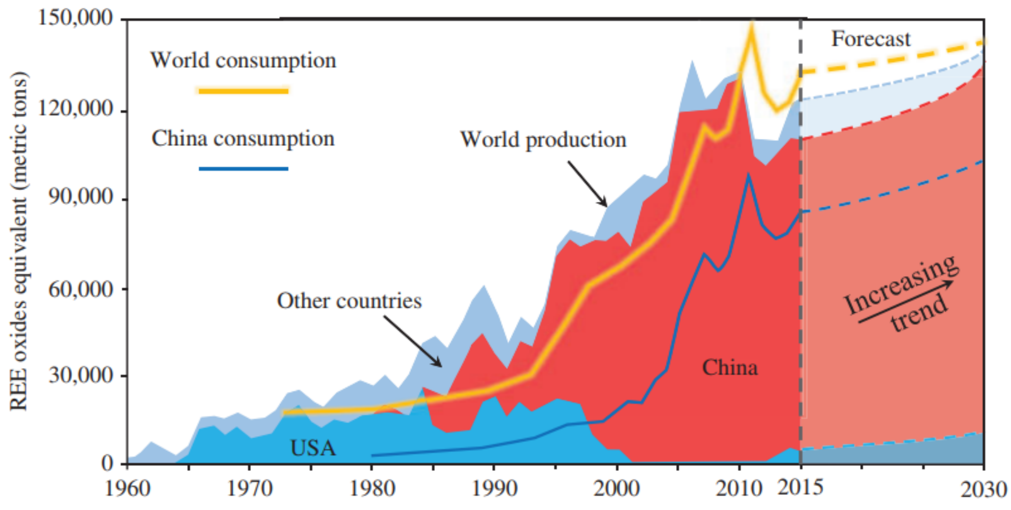

Figure 7: Global production (filled area) and consumption (lines) of rare-earth oxides and future projection *Source: Huang et al., 2016*[23]

TCEs can escape into the environment in a variety of ways. The mining of TCEs may disperse dust into the air, while leaving overburden and waste rock piles to sit may allow them to leach into surrounding waters. Furthermore, once ores are extracted, they require refining so that individual elements may be isolated, further providing opportunity for TCEs to enter the air, water, or land. The refining process also requires the use of blends of chemicals. This results in the generation of solid waste, including radioactive materials[24]. More insidious than the processes of extracting and refining these elements, however, may be the eventual disposal of products containing TCEs. Because these elements are closely embedded with other product components, their separation for recycling is difficult. Hence, they tend to flow linearly through the global economy, ending up in landfills, with less than 1 percent being recycled or reclaimed[25].

Potential Impacts: As communities around the globe increase their consumption of and reliance upon a wide variety of technologies containing TCEs, a greater proportion of these elements is expected to find its way into the environment. Increased use of TCEs in an expanding range of end products is resulting in a change in how they cycle through the environment[26], and environmental concentrations of some of these elements have already increased.[27]. The precise impacts of a higher concentration of TCEs in the environment remain to be seen, though there is evidence to suggest that this heightened concentration could have a mix of both adverse and beneficial effects on human and ecological health.[28]

Some studies[29] of the impacts of rare earth elements (REEs)—a subset of TCEs--on plants indicate that these elements might augment plants' resilience to water stress by increasing production of an amino acid that facilitates hydration. The presence of REEs in the environment may also aid photosynthesis, seed germination, and plant growth. Other studies, however, indicate that REEs could be antagonistic to plant mineral nutrition and may increase de-structuring of plant cell organelles.

Studies have also highlighted the bioaccumulation of REEs in marine organisms, animals and humans[30]. Decreased function of the renal system, heart, liver, blood, and central nervous system are among other health defects due to exposure to REEs[31]. Despite these indications, insufficient evidence exists to determine safe levels of REE exposure for humans and other animals.

Relevance to the GEF: Many TCE products, such as electric cars, wind turbines, and solar cells, contribute to climate change mitigation. However, the mining and processing of TCEs are sources of greenhouse gas emissions[32], and this mix of benefits and drawbacks needs to be considered.

The mining and processing of TCEs, as well as the disposal of TCE products, could negatively impact the GEF's work in the work areas of biodiversity, land, forest, international water, and food security. Significant land, surface and groundwater contamination from mining and processing TCEs, including chemical and radioactive contamination, have been reported[33]. Most REEs are extracted using open-pit mining, which results in the disruption of thriving ecosystems and biodiversity. An estimated 300 square meters of vegetation and topsoil are removed for every ton of rare earth oxide extracted, with 1,000 tons of contaminated wastewater generated and 2,000 tons of tailings discarded[34]. Mining and processing TCEs also result in the generation of various harmful and potentially toxic chemicals, which could affect the GEF's goal of helping to eliminate or reduce harmful chemicals and waste globally[35]. Furthermore, the limited cases in which REEs have been recycled have been linked to the emission of pollutants including dioxins – a Stockholm Convention Persistent Organic Pollutant[36].

There are indications that African countries offer significant potential for future TCE production[37] making this an important subject for the GEF. For example, experts have indicated that going forward with a planned rare-earth mine in Madagascar would result in loss of surrounding rainforest, including a protected area that serves as habitat for endangered lemurs and other unique wildlife[38].

How can the GEF respond? Given that supporting the sound management of chemicals and waste is one of the primary objectives of the GEF's work, staying abreast of changes in the environmental concentration of TCEs fits squarely into its goals. Despite the importance of these materials in the global economy, there are no studies providing a comprehensive material and energy analysis of the production of rare-earth metals[39]. The GEF could play some roles in the near term (1-5 years) by:

- Support policies and actions that promote the sustainable extraction of TCEs, including through developing alternative or substitute technologies that reduce the environmental damage from mining, refining and recycling TCEs, or that lessen overall dependency on TCEs. These technologies could include nanotechnology[40].
- Facilitate the improved design of TCE products so that they more effectively use the elements. There should also be emphasis placed on improving the process of recycling component TCEs. One piece of this would be promoting a circular economy and life-cycle assessment. Studies suggest that recycling REEs has less environmental impact than primary production[41].
- Support efforts to quantify the demand for, material and energy needs of, and environmental implications of emerging applications that could increase global dependence on and use of rare-earth, such as magnetic refrigerators or next-generation LED lighting.[42]
- Help to raise awareness of the possible environmental and health impacts of continued unsustainable production and consumption of TCEs.
- Collaborate with and support partnerships aimed at ensuring sustainable TCE production and consumption, including public-private cooperation.

3.2. Next-Generation Nanotechnology – TRACK

Impacts: Climate Change, Chemicals & Waste, International Waters, Food Security

Overview: Nanotechnology generally refers to materials and systems with dimensions of less than 100 nanometers (for comparison, a human hair is 80,000 to 100,000 nanometers wide and a strand of DNA is 2.5 nanometers in diameter). It is an enabling technology with a wide variety of applications, including healthcare, electronics, agriculture, aerospace, energy production and storage, water treatment, food processing and consumer products.[43] Although less institutionalized in developing countries, many nanotechnology applications may be relevant to their sustainable development, including for improving energy availability, enhancing agricultural productivity, and remediating air and water pollution[44].

There is a continuous transition in the development of nanostructures and nanosystems and their applications. Figure 8 shows approximately the present transition from passive to active nanostructures visible in existing research[45]. The next generation of nanotechnology, including molecular nanosystems and integrated nanosystems, will allow fundamentally new functions and emergence of advanced applications of nanotechnology[46]. It is, therefore, important to think beyond the implications of existing passive nano-scale particles and their applications and to understand more generally where societies are on a longer-term technological trajectory, how these positions differ from country to country, and how countries can harness the opportunities from nanotechnology for global good.

Though nanotechnology presents many positive opportunities, it also presents potential negative environmental impacts. Little is known of the long-term effects of these materials on the environment and human health, and there are calls to apply the precautionary principle to pursuing related technologies[47]. It will be important to close the knowledge gap on the unknown long-term effects of nanomaterials on human health and the environment and how to ensure proper governance regarding associated risks[48].

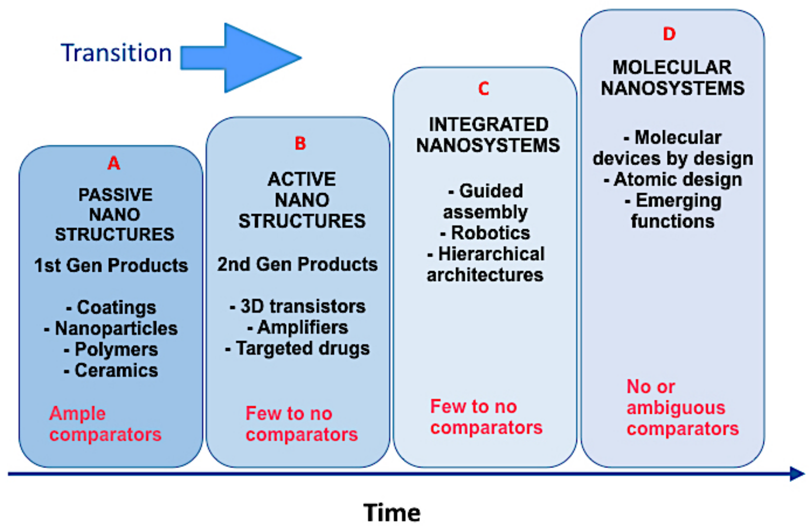

Figure 8. Development trajectory for nanotechnologies. The graphic provides some rough guideposts for tracking progress and shows approximately the present transition from passive to active nanostructures visible in existing research and some emerging commercial products. (Adapted from the US National Nanotechnology Initiative, see reference 55)

Potential Impacts: The market for nanotechnology is expected to grow by 18.1 percent globally to reach approximately 174 billion dollars by 2025[49]. This will produce positive impacts in diverse fields, including agriculture, electronics, energy, healthcare, water management, and mitigation of contaminated lands. The transition to next-generation nanotechnology is expected to further expand applications of nanotechnology. For example, researchers recently created three-dimensional nanostructures with 10,000 components that self-assembled with potential application in structural biology, biophysics, synthetic biology and photonics[50]. However, as more nanoproducts are made available, it is likely that they will leak into the environment during their lifecycle[51]. Studies have suggested that active nanoscale structures and nanosystems could negatively affect human health, the environment, as well as aspects of social lifestyle, human identity and cultural values[52]. Nanomaterials can also affect plant growth, gene expression and the structure of soil microbial communities[53]. They could also be a threat to aquatic organisms and other biodiversity[54].

An important question is whether risks associated with nanotechnology will decrease or increase as our ability to design and engineer specific functions into materials improves and these materials become "active" and can respond to their external environments. What risks and benefits are unleashed by materials that can self-assemble at nanoscales, enabling manufacturing systems capable of building, with molecular precision, complex systems with many components?[55] Parallel to these issues is the question of how to deal with legacy risks from older products incorporating first generation, so-called "dumb" passive nanoparticles, including fabrics, cosmetics, coatings, etc.

During interviews to support this effort Professor Matthew Hull, of Virginia Polytechnic Institute, spoke to the potential consequences of expanded use of nanotechnology in everyday life:[56] Nano-engineering will open avenues for the development of polymer nanocomposite materials that are lighter and stronger. He posited that we are likely to see these materials surface with increasing frequency in wearables and electronic devices—products humans are intimately connected with, like clothing items and cell phones. Hull noted that as nanotechnology is integrated into consumer goods, the interface between humans and nanomaterials becomes closer. As such, any negative impacts that emerge from nano-engineered products may have stronger impacts on human health and wellbeing. He, therefore, emphasised the importance of building the infrastructure to properly monitor potential impacts.[57]

Relevance to GEF: Several nanoproducts have direct applications and can contribute to achieving global environmental benefits in GEF focal areas. For example, nanomaterials could be used for pest control, for precision delivery of agrochemicals and genetic materials, and for detection of plant diseases.[58] These applications could help increase agricultural productivity and significantly reduce the use of harmful chemicals in agriculture, like pesticides that are regulated by chemical conventions. Another promising application relevant to the GEF is the design of a biodegradable nanomaterial from wood, which has better heat-insulating properties than existing insulators, with potential for use in the design of energy-efficient buildings with climate benefits[59]. Another possible application would be to use nanoscale technology for the desalination of water with little-required energy input; this could help alleviate water scarcity[60]. Nanotechnology could also yield climate benefits through, for example, lightweight nanocomposites that can reduce the weight, and consequently the fuel consumption, of cars; nanocatalysts to improve vehicle fuel-use efficiency; and nanoCO_2 harvesters that produce methanol from atmospheric CO_2[61]. These and other applications of nanoscale innovations offer myriad potential solutions to some of the world's most pressing environmental challenges, but they also require significant study and monitoring.

How can the GEF respond? While nanotechnology offers many potential environmental benefits, the unknown negative impacts cannot be ignored. It is suggested that the GEF stay abreast of ongoing developments in the field and watch for potential opportunities or threats to people and the environment. In doing this, the GEF could consider the following actions in the near term:

- Conduct a detailed assessment of trends in nanotechnology design, production, and use and study how ongoing developments in the field could affect the goals and objectives of the GEF.

- Monitor and support current efforts aimed at understanding the transport, fate, and behaviour of nanomaterials in the environment, including potential threats to environmental and human health.
- Monitor and support effort towards sustainable nanomanufacturing and green nanotechnology. These are emerging nanotechnology fields that aim to improve the sustainability of nanomanufacturing by minimising the use of toxic chemicals and lessening the amount of energy required to produce nanomaterials[62].

3.3. Blockchain – ANTE UP

Impacts : Biodiversity, Climate Change, Chemicals & Waste, Sustainable Cities, Fisheries

Overview: A blockchain is a digital ledger that decentralises data and eliminates intermediaries typically required to validate transactions. It uses a distributed database to store information securely, transparently, and efficiently and can, therefore, improve processes that require secure sending, storing, accessing, or verification of information[63]. In blockchains, information is parcelled into blocks and encrypted, with a new set of blocks added to form an expanding chain. It differs from traditional databases or ledgers because the chain of blocks is not stored centrally but copied and distributed in a computer network , making it incorruptible and ensuring that everyone has a copy when new blocks are added[64].

Blockchain was created in 2009 by an individual under the alias Satoshi Nakamoto. The source code was originally designed to support the virtual currency Bitcoin[65,66]. Nearly ten years later, the average investment per blockchain project in 2017 was $1 million, and the global market is expected to be $20 billion by 2024[67]. Companies like IBM have dedicated nearly $200 million in funding and over 1,000 employees to work involving blockchain, highlighting the market potential it has within the tech industry[68].

Emerging markets in blockchain exploration include digital contracting, management of healthcare records and personal identification information, supply chain management, and banking. Some funding organisations are exploring “blockchain for development” applications, which include applications for micro-financing, micro power grids, traceability of resources, land tenure, and tracking of genetic resources. Although the public reception has thus far been positive, there remain those who are sceptical of the technology’s resilience to hacking and those who are concerned about the energy consumption cryptocurrencies like Bitcoin require.

Potential Impacts: Recent reports and analyses have highlighted the energy impacts of blockchain as the underlying technology for Bitcoin, and the negative consequence with respect to climate change[69]. The Digiconomist[70] estimates the current annual electricity consumption of Bitcoin transactions at 65.63 (TWh) with electricity consumed per transaction estimated at 854 (KWh) as of May 2018. They estimate that current energy consumption of Bitcoin could power more than 6 million households in the United States. Another analysis indicated that the annual energy consumption of Bitcoin exceeds that of 159 countries combined. Though estimates of blockchain energy consumption vary, there is a consensus that the technology can take a toll on the environment. Additionally, cryptocurrency mining is rapidly expanding in countries, for example China, where energy-intensive server farms are being used, often connected to coal-fired electricity systems[71]. The boom in Bitcoin mining has been linked to the reopening of a coal-fired power plant in Australia[72]. Venezuela is exploring Bitcoin mining in response to its economic crisis[73] and activities are emerging in Puerto Rico, where 450,000 people remain without electricity[74]. However, there have been efforts to reduce the energy consumption of Bitcoin[75].

Blockchain technology can, however, help address environmental challenges and improve environmental practices. The technology could be used to provide consumers with better information on sources of materials and how products have moved through supply chains. This would allow for more consumer awareness of the environmental implications of product choices and improve industry transparency.[76] For example, IBM, JD.com, Walmart and Tsinghua University National Engineering Laboratory for E-Commerce Technologies recently implemented a project to track the origin, safety and authenticity of food, using blockchain technology to provide real-time traceability throughout the supply chain. The project will promote accountability and give suppliers, regulators and consumers greater insight and transparency into the safety and environmental impact of food commodities[77].

Another potential use of blockchain is to track carbon emissions from sources like power plants, allowing public agencies and consumers to more easily determine the amount of carbon from various energy producers. Blockchain could also provide information on the carbon footprint of goods or services, which could improve consumer decision-making and create a new way of incentivising sustainability. Blockchains can also be used to support micro-energy grids that create local energy markets[78]. For example, they are now being used to run small solar micro-grids in Brooklyn NY, Texas and Australia, providing a local solution that allows neighbours to buy and sell electricity from each other, either within an existing power grid or independently, without a utility serving as an intermediary[79].

Relevance to the GEF: Within each of the GEF's programme areas, efficient blockchain use could spur better analytics and knowledge management. Access to better data and real-time impact values could enhance the GEF's work and improve its audit of environmental resources and other benefits from its investments.

Blockchain may be particularly relevant to the GEF's Chemicals and Waste programme area. It can be used to track the movement of chemical products, including their makeup and how wastes are managed. This will contribute to achieving its goal of "ensuring that products crossing national borders are free of global priority substances that otherwise enter into markets and recycling chains"[80].

Blockchain enabled microgrids are a potential solution for energy challenges in rural developing countries, by creating a peer-to-peer marketplace for the production of electricity, for example, from solar home systems and other local renewable energy sources, which is currently booming in sub-Saharan Africa[81]. The proliferation of such system could contribute to the GEF's climate change objective of "promoting innovation and technology transfer for sustainable energy breakthroughs"[82].

Related to the GEF's work on international waters, specifically the 'blue economy' and the need for a more sustainable use of marine and coastal resources, blockchain can be used as a tool for monitoring and tracking marine resources and preventing illegal exploitation. For example, the World Wildlife Fund has used blockchain to mitigate illegal fishing of tuna.[83] Blockchain may also be relevant to the GEF's work on illegal wildlife trade. Better tracking of poaching practices would advance the goal of reducing illegal trade via the enhancement of "anti-poaching tracking and intelligence operations."

Blockchain technology has also been proposed as a possible backbone for achieving smart and sustainable cities[84] – one of the GEF's integrated approach programmes (IAP)[85]. Blockchain can improve urban planning, transportation, smart buildings, energy use and distribution, as well as the sharing and flow of resources and information within a city, by serving as a cross-cutting platform that connects the cities' different services and enhances transparency and security in all processes[86]. For example, Ford, Autonomic, Qualcomm and Waze are currently building a blockchain-based smart city platform that could improve transportation in cities and encourage sharing, which could consequently reduce transportation carbon footprint[87].

How can the GEF respond? Though blockchain technologies diverge the furthest from the definition of novel entities, it is recommended that the GEF exploit their potential as an enabling platform with reach across its programmatic areas and internal strategy including for knowledge management. The GEF should not wait for blockchain technology to become well established before getting involved as it may miss the opportunity to help shape blockchain applications and prevent negative consequences. This could start with a detailed assessment of relevance to GEF focal areas to identify areas for immediate action.

The GEF could also explore blockchain application for creating efficient microgrids that support peer-to-peer energy transactions in small communities using renewable energy resources as discussed earlier. Existing experiments in the US and Australia should be studied to determine their viability in the context of developing countries.

Within the context of the Convention on Biodiversity and the Nagoya Protocol, blockchains could play a critical role in tracking the provenance of genetic resources and support more effective benefit-sharing. Additionally, there are new efforts to use blockchains to publicly record and globally verify property rights and individuals' claims, which could help low-income individuals in developing countries capture the value of their land.[88] This type of application can be explored to determine its relevance to the GEF's work on agriculture, food security, land degradation, and biodiversity.

Lastly, the GEF should also review other emerging uses of blockchain technology that present possible opportunities, like using blockchain-based crowdfunding to supplement GEF funds for projects, especially pilots. A new Ethereum blockchain-based platform called Acorn is open-access and commission-free (most commercial crowdfunding platforms charge 3-5 percent) and is designed specifically to, "create an open, global community and marketplace for crowdfunding, opening it up to new participants such as those living in developing countries."[89] The goal of the Acorn Collective is to democratise crowdfunding.[90]

3.4. CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) and Gene Editing – ANTE UP

impacts: Biodiversity, Climate Change, Chemicals & Waste, Forests, Food Security

Overview: Genome editing or gene editing techniques for the addition, removal, or alteration of DNA nucleotides go back to early discoveries in 1991 (Zinc Finger) and 2009 (TALEN)[91]. In 2012, *Clustered Regularly Interspaced Short Palindromic Repeats*, or CRISPR, was demonstrated and described as both "molecular scissors" and a "Swiss Army knife" for biological engineering.[92] CRISPR is a gene editing technique that is precise, inexpensive, and relatively easy to learn. It is rapidly advancing in research and applications (Figure 9) and promises to open up new opportunities to solve problems, ranging from providing better control of vector-borne diseases to improving animal husbandry, and helping plants defend themselves against infection, drought, and other climate-change-related issues.[93]

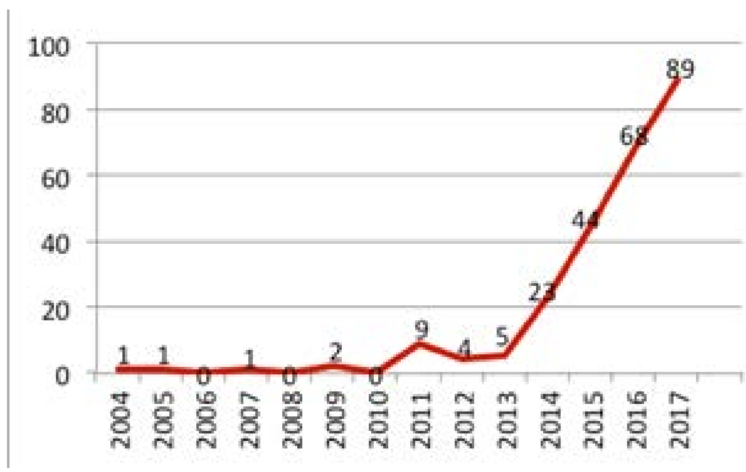

Figure 9. Publications with "gene editing" in the title from 2004 to 2017

(based on a Web or Science search)

Potential Impacts: Researchers at the University of California - Berkeley are using gene editing to alter cacao plants to help them survive if climate change warms and dries their native rainforest habitat. [94] This work is funded by Mars, the candy company, as part of a $1 billion commitment to reducing their carbon footprint. Other critical cash crops, such as coffee[95], are also being threatened by climate change and might benefit from gene editing approaches.

Other research is being undertaken to allow plants to produce their own nitrogen, which could significantly reduce the energy and environmental impacts associated with the production and use of nitrogen-based fertilisers.[96] Three to five percent of the world's natural gas production is consumed in the Haber Process used to produce fertilisers, equivalent to about 1–2% of the world's annual energy supply[97]. Models run at the International Institute for Applied Systems Analysis showed that self-fertilisation could significantly increase maize yields in parts of Africa while reducing climate and land use impacts.[98] Another interesting line of research focuses on improving the health of our prime pollinators, honey bees, by engineering bee species that obsessively clean their hives to remove sick and infected bee larvae[99]. Jennifer Doudna, one of the inventors of CRISPR, has noted that the biggest impact of the technology may not be on humans, but on the food we eat. [100]

The appearance of CRISPR has, however, been accompanied by warnings of ethical concerns, market-based eugenics, novel bioweapons, planetary extinction, and general admonitions about the dangers of unregulated genetic determinism.[101] CRISP was classified as a potential weapon of mass destruction in a 2016 annual United States worldwide threat assessment report[102].

There has been concern among scientists, policymakers and other stakeholders about the availability of an appropriate governance and regulatory framework for these technologies and how and when the public should be engaged[103]. The genetic alteration of plants without the need to transfer genes between species challenges many of the regulatory frameworks originally put in place decades ago to address transgenic modifications. Innovations like CRISPR also often bring up issues of intellectual property. How will these technologies be developed and disseminated to achieve benefits in the developing world given the large investments of private firms like Mars or Bayer? Also, if the resources for genetic modifications come directly from developing countries, the benefits will need to be shared under the Nagoya Protocol, but the details of such sharing mechanisms still need to be developed.[104]

Relevance to the GEF: Gene editing technologies present particularly compelling avenues for responding to some of the threats of global anthropogenic climate change, especially helping crops adapt to climate change impacts. It is also a promising technology for reducing the negative impacts of food production. For example, researchers are attempting to apply gene editing in the reduction of enteric fermentation methane emissions from ruminants[105], which constitute the single largest source of agricultural methane emissions. Also, researchers were able to alter the gene of an algae strain resulting in a significant increase in biofuel production[106]. Scaling up this research could make the algae a significant source of renewable energy in the nearest future. Success in these will contribute to the GEF's work on climate change mitigation and adaptation.

However, the possible negative outcomes of widespread use of gene editing also necessitate vigilance in monitoring and evaluating impacts. While gene editing has been suggested as a technique for saving endangered species or eradicating invasive species[107], the widespread use of gene editing could become a major threat to biodiversity. For example, researchers have developed gene editing techniques that can be used to eliminate some insect species[108]. The UN Convention on Biological Diversity – one of the

Conventions served by the GEF, has called for the establishment of a moratorium on genetic extinction technologies because of the potential threat to biodiversity[109]. Several consumer and environmental groups have also raised concerns about the approval, by the US Food and Drug Administration, of genetically modified food, such as salmon, because of possible escape into oceans and rivers, and consequent endangering of wild salmon populations[110].

How can the GEF respond? Given the rapid advances in the applications of gene editing and the range of potential negative and positive impacts from gene editing innovations like CRISPR, there is an impetus for the GEF to proactively keep track of ongoing developments in the field and attune its programming and resources accordingly.

It is important that the GEF stay on top of gene editing techniques that could adversely impact the achievement of global environmental benefits; and help promote, where possible, the ethical use of techniques that have been scientifically proven, and globally accepted, to contribute positively to meeting environmental objectives. Possible areas of focus could include applications in the area of food security and climate change adaptation such as the development of crops that are more resistant to climate change, and in climate change mitigation such as nitrogen fixation techniques in crops, and methane emission reduction in ruminants.

In the near term, the GEF could also consider supporting capacity building among developing countries, especially as it relates to global and national governance and regulation of gene editing technology.

3.5. New Engineered Bio-based Materials – ANTE UP

Impacts: Biodiversity, Chemicals & Waste, International Waters, Forests , Food Security, Sustainable Cities

Overview: For many years, the discussion of bio-based materials has focused on the development and commercialisation of plastics and composites that can compete with petroleum-based products. Recent advances in synthetic biology have, however, dramatically expanded the range of products that can be engineered from organic materials through the programming of metabolic processes in biological organisms such as yeast[111]. These approaches allow a vast number of complex molecules to be created for both commercial and local on-demand production, while reducing both research and development costs and times. Going forward, advances in synthetic biology will allow engineered microorganisms to complement and replace plant-based production systems altogether. Interesting recent examples include the use of engineered yeast to produce biofuels, vanilla and even opioids.[112] However, significant advances are still needed in the field in order to deliver commercial-scale yields with sustainable benefits, which can provide viable substitutes for materials already in commerce. For example, the existing generation of bio-based plastics has not solved or reduced the accumulation of plastics in our environment and their impacts.[113] More research is needed on next generation bio-based materials that provide long-term solutions and benefits.

Potential Impacts: Advances in the development of engineered bio-based materials will contribute to mitigating the unsustainable use of natural resources and global warming. As stated by Marc Palahi, the Director of the European Forest Institute, "if we want to address the urgent challenge of climate change, materials will have to come predominantly from fossil-free sources, basically from renewable biological resources." This implies a shift from a hydrocarbon to a carbohydrate economy, or as some observers had pointed out, a possible return to a time when "plants were the primary raw material in the production of dyes, chemicals, paints, inks, solvents, construction materials, even energy."[114]

Researchers are exploring the use of biological approaches to allow on-site manufacturing of construction materials that would replace existing bricks and cement[115]. This would allow building materials to be made at ambient temperatures with no CO_2 emissions, minimal dependency on natural fossil fuels, and little waste in manufacturing. Today, cement making accounts for around five percent of all industrial fossil fuel emissions and, of the two billion tons of CO_2 emissions created each year by cement production, half come from fossil fuels burned as an energy source for the kilns[116].

However, negative and unintended consequences need to be addressed. For instance, concerns have been raised about impacts on farmers and local supply chains if natural indigenous crops and production processes are replaced in part, or completely, by synthesized bio-based production techniques and products.[117]

Relevance to the GEF: Advances in engineered bio-based material could provide more sustainable alternatives to plant-based production system, thereby reducing their environmental impacts which cut across several of GEF work areas – climate change, land degradation, biodiversity, international waters, forestry, and chemicals and waste. Producing chemicals using engineered bio-based materials combined with green chemistry could help eliminate harmful, petroleum-based chemicals[118]. Likewise, a successful scale-up of biofuel production from engineered yeast could significantly reduce fossil-fuel consumption, thereby reducing greenhouse gas emissions. Also, biological manufacturing of construction materials could significantly reduce the environmental impacts of construction in cities, as well as more rural areas.

How can the GEF respond?: There are significant opportunities for the GEF to help shape the future bio-economy beginning with continuous and high-level engagement in on-going global dialogues such as the annual bio-economy summits or meetings of organisations like Synbiobeta and the synthetic biology innovation network.[119] Additionally, the GEF could identify and highlight emerging applications of synthetic biology with positive environmental, social, and economic impacts for developing countries. Many promising technologies are in the scale-up and early commercialisation phases where public policy frameworks can play important roles in allowing solutions to reach the market. Policy harmonisation between developed countries and within the context of multilateral treaties, such as the Convention on Biological Diversity, the United Nations Convention to Combat Desertification, the United Nations Framework Convention on Climate Change and the Chemical Conventions will play important roles in advancing solutions with high environmental value.

3.6. Nano-Enabled Energy – TRACK

Impacts: Climate Change, Chemicals & Waste, Sustainable Cities

Overview*:* If we capture only 1/1000th of the solar energy striking the Earth, we could have six times more energy than we consume in all forms today. One of the challenges to harnessing solar energy is the difficulty in efficiently capturing and converting solar energy to meet our needs. Currently, crystalline silicon cells, having a conversion efficiency of 12 to 20 percent over a small area, dominate the photovoltaic (PV) cell market, with costs dropping from $30 per watt to under 30 cents per watt today. Researchers and companies are exploring options to boost efficiencies, and values as high as 44 percent have been obtained in experimental settings, such as at the U.S. National Renewable Energy Lab (NREL). Nano-composites can add to the electrical and thermal conductivity of PV cells, and cells created from carbon nanotubes can add efficiency with far less weight than conventional copper wires. Other options involve increasing the use of the infrared spectrum, through nano-sized semiconductors, for electricity production or converting all available light to power equally, which is normally impossible using existing technologies[120].

Future solar cells based on nanoscale carbon (graphene), instead of silicon, promise to reduce costs and expand markets with the availability of flexible polymer cell substrates that can be integrated directly into building materials or painted on surfaces[121]. This could significantly increase market penetration and public acceptance of solar energy. Another nano-enabled energy innovation of the future is the so-called "wearable thermoelectric generator" where solar cells are integrated directly into clothing to harvest energy from body heat to supply electricity to devices such as cell phones, sensors, or other smart devices.[122]

Efficient battery technology also constitutes a major bottleneck in expanding the use of renewables. Nanotechnology has already improved battery energy and power density, cyclability, and safety, especially for electric vehicles and portable devices.[123] Many of the improvements focus on electrode structure and improved surface chemistry. In the longer term, novel future batteries could include self-assembling, 3-dimensional nanostructures.[124]

Potential Impacts: the impacts of nanoscale science and engineering on energy production technologies and systems will cut across multiple areas, including solar, hydrogen, and wind energy, over the next couple of years[125]. For solar energy in particular, nano-bio hybrid cells may allow even greater efficiencies to be achieved that approach theoretical maximums[126]. Nanoscale manufacturing of PVs can also provide direct environmental advantages. For instance, PVs based on colloidal quantum dots can be manufactured at room temperature, saving energy and avoiding environmental impacts associated with the high-temperature processing of silicon and other PV materials[127]. Also, many of the future applications of nano-enabled energy will involve a shift in manufacturing from high-cost and energy-intensive photolithography to high-yield printing, which will provide environmental benefits and may facilitate their uptake in developing countries.[128] As the late Nobel Laureate and nanotechnology scientist Richard Smalley noted, “breakthroughs in nanotechnology open up the possibility of moving beyond our current alternatives for energy supply by introducing technologies that are more efficient, inexpensive, and environmentally sound”[129].

Relevance to the GEF: It is estimated that nearly 1.3 billion people do not have access to electricity. Meeting their energy needs using conventional fossil-fuel based energy sources will exacerbate climate change. Nano-enabled energy technologies could support a low-carbon, user-centric, local energy future that reduces the need for constructing large centralised networks in developing countries, with benefits for the GEF’s work on climate change and sustainable energy innovation and technology. The shift to high-yield printing could also reduce chemical needs of production, with potential benefits for the GEF’s chemical and waste focal area.

How can the GEF respond?: Most future breakthroughs in nano-enabled energy will come from countries like China, the United States, South Korea, Japan, Germany, Taiwan, and the United Kingdom, where research and development investments, patents, and university research levels are the highest.[130] The GEF should, therefore, keep track of technological advances in these countries to identify relevance to developing countries’ energy needs. The GEF, through its investments, could also help facilitate quick access, penetration and acceptance of these new technologies as they become available.

The GEF could also focus on areas beyond PVs where nanotechnology could reduce climate and environmental impacts, such as novel thermoelectric devices. It is estimated that seventy percent of all energy loss is through heat. Generating 5-10 percent more electricity from that wasted heat could result in significant reductions in power demand and associated carbon emissions, as well as other pollutants[131]. Nanotechnology-based thermoelectric devices using, for instance, carbon nanotubes, can convert waste heat from power plants, automobiles or even cooking stoves directly into electricity at increasing efficiencies and scales,.[132]

The GEF, through the STAP for example, may also help stimulate research into how nano-enabled energy can be developed to fit into developing countries context as well as the development and scaling-up of integrated systems to support individual or household needs. Questions remain, however, about the demand for solar power in the developing world, even if costs drop significantly. Some studies have shown that even at low prices, people tend to favour “real electricity,” i.e., central station grid-connected power that is viewed as reliable and available around the clock.[133] The GEF, through its projects, could support awareness-raising efforts on the benefits of embracing renewable energy from decentralized sources.

3.7. Cellular Agriculture – TRACK

Impacts: Biodiversity, Climate Change, International Waters, Land, Forests, Food Security

Overview: Presently, livestock is responsible for an annual greenhouse gas emission of 7.1 Gigatonnes CO_2, equivalent to 14.5% of total emissions[134]. Additional impacts occur through land-use, water, and nutrient requirements for feed. Hence, the promise of a post-animal economy has recently attracted the attention of funders like Google and Bill Gates; and some start-ups and labs are focused on ways to make edible and attractive protein substitutes for meat through cellular agriculture[135]. Cellular agriculture focuses on livestock products from cell cultures without the animal itself[136]. Researchers are also focused on creating meat substitutes from plant-based protein; engineering microbes to produce dairy products such as milk; and making other products like leather, fur and wood through cellular agriculture[137]. Other researches aim to develop decentralised, small-scale bioreactors for growing plant cells in the home or at a local level. For instance, the Technical Research Center in Finland (VTT) has demonstrated a system for growing plant cells with the same active biomolecules as the plant itself in fermenters, with a capacity of up to 1,000 litres, as well as using in-home bioreactors.[138]

Potential Impacts: Advocates of cellular agriculture are motivated by the belief that the technology could help achieve a more sustainable food production system, and significantly reduce the environmental impacts of food production. These include greenhouse gas emissions, freshwater-use footprint, water pollution, deforestation, biodiversity loss, land degradation, desertification, agrochemical pollution and associated health impacts[139]. This is particularly important with the continuous rise in global demand for animal protein[140]. A life cycle analysis showed that producing 1000 kg of cultured meat requires approximately 99% lower land use, 82–96% lower water use, 78–96% lower greenhouse gas emissions, and 7–45% lower energy use (poultry has lower energy use) compared to conventionally produced European livestock[141].

Apart from the potential environmental benefits, cellular agriculture could also have positive impacts on food safety, reduce antibiotic resistance, improve animal welfare, and result in products with longer shelf life[142]. It may also improve nutritional composition of food products[143] and could be a solution for protein nutritional deficit in developing countries, which can lead to such problems as childhood growth stunting.

However, a more recent life-cycle analysis of energy consumption in cellular agriculture raised concerns about its climate change mitigation benefits. The study indicated that cellular agriculture could intensify greenhouse gas emissions because of the increased industrial energy needed for replacing biological functions with chemical and mechanical equivalent[144]. This point is further buttressed in another study that shows that cultured meat has higher environmental impacts, except for its impact on land use and terrestrial and freshwater pollution, compared to chicken and plant-based, mycoprotein-based, and dairy-based meat alternatives, mostly due high energy requirements[145]. Overall, current understanding seems to suggest that chicken and plant-based proteins have lower environmental impact than cultured meat but cultured meat has less impact than beef, and possibly pork[146]. It is, therefore, important to fully understand the footprint and trade-offs involved before the technology advances further.

There are also issues regarding how products will be regulated, the challenge of intellectual property, ethical concerns, and the looming issue of public acceptance[147]. Moreover, there remain questions of how to scale manufacturing processes to create adequate supplies, and ensure affordability and accessibility, especially in developing countries[148]. It is worth noting that the first lab-grown burger came at a steep price of $300,000.[149] Furthermore, the probable socio-economic effects such as the impact on livestock and dairy farmers need to be considered[150].

Some have also raised concerns that growing meat in the lab would further encourage current excessive meat consumption in some cultures (a causative for several illnesses[151]) instead of promoting behavioural change and sustainable diets that provide benefits for both the environment and human health[152].

Relevance to the GEF: If successfully scaled up, cellular agriculture may significantly reduce the environmental footprints of current food production system. This would yield benefits for several GEF work areas including climate change mitigation, land degradation, international waters, chemicals and waste, forest, and biodiversity. However detailed analysis is still needed to understand the full impact, as well as possible unintended consequences.

How can the GEF respond? Given the potential for cellular agriculture to fundamentally shape our food systems, the GEF should consider what role it can play as the conversation moves forward. The GEF should keep track of technological developments, capabilities, and timing, as well as engage in the expanding conversation on the future of protein, and how it affects the global environment.

3.8. Possible Surprises

Over the course of the next five years, the GEF can expect to be surprised—confronted with new threats and risks or unusual opportunities that may fall outside of the boundaries of a strategic plan or related organisational attention and capacity. The danger implicit in novelty of this type is that disruptive effects may not be discovered until they become a problem at a large scale and cannot be readily reversed or, if the effects are positive, exploited.[153] We have identified three recent novel discoveries that present a range of possible risks and opportunities. These discoveries were identified through the Delphi process or interviews with researchers. All share the characteristic that scientists were not necessarily looking for them when they were discovered.

- **Titanium Sub-Oxides: A nanoscale pollutant:** In 2014, a team of scientists studying arsenic in the Dan River coal ash spill site in North Carolina discovered a new nanoscale version of titanium oxides that had never been seen before (Ti_6O_{11}). Testing found that unlike normal titanium dioxide, which is photoactive and damaging to zebrafish embryos in sunlit conditions, these particles were reactive and toxic to zebrafish in dark conditions, which has significant implications for humans inhaling particles into the dark depths of their lungs. How much has been emitted into the earth's atmosphere through coal combustion since the beginning of the Industrial Revolution? Initial calculations result in a figure of around one billion tons. Understanding the long-term toxic effects of titanium sub-oxides to humans is important and will require much more study into their transport and fate, mechanisms of action, and short- and long-term impacts from exposure.[154]

- **Pandoraviruses:** In 2003, large viruses were discovered quite accidentally in Chile and Australia that lacked any similarity to previously described organisms suggesting that they may represent a fourth domain of life. DNA analysis of the viruses found a near absence of Pandoravirus-like sequences in existing databases (only 7% of their genes matched known viruses) and suggested that their ecological niche and role has not been studied by scientists. It remains unclear what the implications of the discovery will be, though scientists noted that they may have to revise their notions of what a virus looks like and that one should expect 'surprises' from future study.[155]

- **New antibiotic without apparent resistance:** In 2015, scientists at Northeastern University identified teixobactin, an antibiotic produced by previously undescribed soil microorganisms. Teixobactin kills pathogens by preventing peptidoglycan biosynthesis, effectively preventing the synthesis of cell walls. It is significant because it is without detectable resistance—a quality desperately sought in the current context of rapidly spreading antibiotic resistance. Bacteria will someday develop resistance to teixobactin, but scientists are optimistic that this may occur in decades, rather than years. Of perhaps more import than the teixobactin itself is the tool used to isolate and identify the compound: the iChip. The iChip is an assembly of plastic plates and membranes containing hundreds of holes, which allows researchers to isolate antibiotic compounds with far greater sensitivity, potentially enabling the discovery of more compounds like teixobactin in the future.[156]

It is likely that with the proper surveillance mechanisms and situational awareness, the GEF will see the emergence of novelty of this type. The challenge then will be how to respond. An extensive study of 88 environmental issues by the European Environmental Agency discovered that only four early warnings constituted true "false positives" — US swine flu, saccharin, food irradiation, and the Southern leaf corn blight.[157] In a majority of cases, early warnings provided by scientists and others proved correct. In many cases, though, risks and trade-offs continued to be studied, and actions were delayed. Research has shown that addressing these types of surprises, some predictable, is often delayed or avoided in organisations because it would require effort in the present and because it is easier to maintain the status quo and avoid departing from organisational plans.[158] Consequently, it makes sense for the GEF to create "organisational slack"—some excess capacity maintained to respond to highly novel, emerging issues like those highlighted above.[159]

4. Further Recommendations

In the preceding section, we described the identified novel entities, their relevance to the GEF, and we provided specific recommendations on how the GEF may respond. In this section, we provide supplementary and broader advice on approaches that the GEF could adopt in responding to the challenges and opportunities posed by the identified novel entities.

Scan, Signal, and Convene: In order to stay on top of emerging trends, this type of horizon scanning should be encouraged and repeated on a regular basis. The GEF should also explore ways of learning from and leveraging other horizon scanning systems that can provide intelligence on emerging technology trends. For instance, in 2013 UNICEF set up a "near-future sensing team" to provide information on rapidly emerging issues and threats, and inform investments in innovative technologies[160]. The global network of innovation labs and projects that are part of UN Global Pulse might also provide relevant data[161]. Anticipatory analyses by the European Commission Joint Research Center and the Organization for Economic Co-operation and Development (OECD) could also be used, as well as private sector and NGO efforts, such as the Millennium Project's Global Futures Intelligence System[162].

A key to future success will be the GEF's ability to identify and understand the implications of so-called "weak signals[163]" and to send indications to the outside world regarding strategic priorities and intent[164]. Future scanning should employ both bottoms-up approaches to prioritise developing world needs and top-down mechanisms to identify possible technological solutions. The GEF should act as a "convener," which could be used to signal GEF priorities, update and expand on findings from foresight exercises, engage existing and potentially new stakeholders in collective efforts to achieve goals, and design better public-private partnerships to leverage funds. For instance, if there are questions about how best to apply blockchain technologies to developing country challenges, the GEF, probably through the STAP, could convene experts around the topic "blockchains for development."

Focus on removing bottlenecks to technology adaptation. These bottlenecks could include cost and financing shortfalls, public opinions affecting market penetration of new technologies, political resistance; lack of infrastructure; privacy concerns; natural resource constraints, research and development investment, education and literacy; inadequate technical capacity; and political stability. A recent workshop on supporting the bio-economy in Africa made the point that "these new technologies are relatively low-cost, but their adoption in Africa is limited by deficits in technical training, poor access to new research materials, inadequate laboratory facilities, and lack of strategic partnerships with other African and international research institutions."[165] Some of the required infrastructure could be technological, but limits may be imposed by the lack of a trained workforce, poor physical infrastructure, cultural norms, inadequate or non-existent regulations or policy that support innovation, or limited financing options. The GEF may consider the use of 'bridge' technologies to provide interim solutions for bottlenecks as other solutions requiring more time and investment are developed and scaled up. For instance, steam autoclaving of municipal solid waste using existing technologies could provide a means to divert and convert considerable amounts of waste as more advanced biologically-based systems are developed.[166]

Seek Early Successes and Make them Visible: It is important to showcase early wins as a means of building and sustaining momentum by picking a few priorities that can be tackled in a reasonable amount of time with a high probability of success. For example, the GEF cannot tackle the challenge of greening the rare earth metal production system, but it could pilot innovative ways to reduce waste, emissions, and human exposures. Supporting early successes can use a number of strategies:

- Disaggregate large projects with ambitious, multi-year goals into achievable pieces.
- Make someone responsible, for instance, by creating a 'technology and innovation' lead within the GEF partnership (or within STAP) who can drive change and organise cross-functional efforts.
- Run pilot projects using small grants to explore solutions, and, if these fail, integrate learning and move on. Use these pilots to test novel organisational and/or funding models.
- Develop standardised procedures to quickly evaluate and learn from pilots.
- Report on progress frequently both within the UN system and to the outside world, not waiting for the next planning cycle, and use a variety of means, including social media venues, talks at conferences, and press releases.

Leverage investment by others, particularly philanthropies, governments, and individuals, in areas where synergies exist. For instance, the GEF could explore how to leverage funds from investments to support the Sustainable Development Goals[167], the Global Protein Challenge 2040[168], or Earth Bank of Codes.[169] The GEF could also explore areas where early investment could drive follow-on funding from foundations or others funders. For instance, some philanthropies are interested in how blockchain technologies could be applied to global development issues. Small, early investments by the GEF could validate funding by others.[170] As mentioned earlier, the GEF should leverage its ability as a visible, international institution to 'signal' strategic intent to outside observers in ways that could engage new partners, align objectives between organisations, and leverage investments. It could also explore emerging financing mechanisms such as crowdfunding, which is now estimated to account for $34 billion in global investments, $25 million of which are peer-to-peer.[171]

Support open source technologies and systems that can provide wide access and knowledge-sharing in developing countries and between the developed and developing worlds. As scholars have pointed out, "open source is a way of organising production, of making things jointly"[172]. The GEF can support the creation of production platforms that can exploit ideas external and internal to the GEF as inputs into innovation and production processes around emerging technologies[173]. The rapidly expanding Do-It-Yourself (DIY) movement is global and has created open source systems for knowledge and tool-sharing that can be applied to the creation of local solutions to local problems[174]. Also, an explosion in citizen science activities has occurred over the past decade supported by better broadband communications, smart networked mobile platforms, inexpensive sensors, and cloud computing that has enabled citizens (citizens as sensors) to make important contributions to environmental health, biology, and epidemiology[175]. This phenomenon is global and could be leveraged by the GEF.

Experiment with new organisational models. Transformational changes on the ground will be a result of the right combination of novel technologies and business models shaped by contextual understanding. The GEF should continually engage outsiders from industry and academia, along with people who have visceral and first-hand knowledge of what is needed on the ground in developing countries. Incremental changes are difficult to delegate, so the engagement of GEF leadership will be needed to shape and validate organisational experiments. [176]

Run experiments and pilot projects to test new organisational, leadership, and funding models. This builds on one of the key strategies of the GEF since its inception: to simulate experimentation and risk-taking through piloting innovative approaches to deal with existing and emerging complex challenges facing the global environment. The real world is an expensive environment in which to run experiments, so these should be small, data-intensive, and well evaluated. One model is to use a lean start-up approach—a temporary organisation designed to search for repeatable and scalable models. This approach "favours experimentation over overelaborate planning, customer feedback over intuition, and iterative design over traditional 'big design up front' development."[177] The GEF could also explore the use of prizes and challenges to stimulate innovation, an approach that has received considerable public and private sector attention over the past decade. However, it is important to understand under what conditions such mechanisms work and recognise and address their downsides[178]. Tackling grand challenges requires more than just dedicated funding. This endeavour should be viewed as an open-ended mission "concerning the socio-economic system as a whole," even including strategies for system transformation, including social innovations.[179]

5. Appendix

A. Summary of the Delphi Survey Demographics and Results

The Environmental Law Institute and the Scientific and Technical Advisory Panel (STAP) of the Global Environmental Facility (GEF) partnered with The Millennium Project to collect information on "Novel Entities," defined as things created and introduced into the environment by humans that could have a disruptive effect—positive or negative—on the global environment and the earth system in general.

The Millennium Project, an independent non-profit founded in 1996 that connects futurists from across the world to improve global foresight, facilitated the first round of the Delphi survey.[180] The existing expert network of the Millennium Project was expanded to include other experts recommended by the STAP and people interviewed for the project or identified through literature searches.

The results presented here are the responses collected from experts during the first round of the Delphi process.[181] Experts from a wide array of professional backgrounds, locations, ages, and affiliations submitted their responses to questions on novel entities via an online survey in November 2017.

Round 1 of the Delphi Survey

The first round of the survey included eight open-ended questions. The first six asked respondents to supply answers about which novel entities they thought should be included in the following categories: Biological Entities, Synthetic Chemical Entities, Radioactive Entities, Genetically Modified Organism Entities, Nanomaterial Entities, and Plastic-related Entities. The seventh question allowed respondents to supply any Novel Entities that might not fall into these categories. In each category, respondents were asked to provide answers in two different time frames: novel entities of interest between the present and the next five years, and novel entities of interest over the next five to fifteen years. An eighth question prompted respondents to provide any additional commentary they would like.

The Round 1 Delphi received responses from 78 experts. These individuals hailed primarily from Europe and North America—34 and 24 respondents respectively. About 20% of respondents were from Latin America, Africa, West Asia, or Asia Pacific. Most of the respondents were between the ages of 36 and 74.

Suggested novel entities include:

- New man-made virus or pathogen created, possibly through mistakes from biological hobbyist/DIYer, or intentionally as bio-weapon.
- Biological engineering creates a new invasive species (with introduction into novel location and bio-region).
- Creation of biological means to quickly eat waste.
- Inexpensive and effective DNA barcoding to track products in supply chains or species.

- Discovery of entirely new biological organisms, such as pandoraviruses (discovered in 2013).
- New genetically modified crops designed for disease/insect resistance, to withstand higher temperatures and greater drought conditions, increase yields, and/or provide greater nutritional benefits.
- Cellular agriculture (plant and/or meat based) to provide protein with reduced environmental impacts.
- Re-emergent diseases or novel organisms from melting permafrost or deep-sea mining.
- Biological production of hydrogen.
- Re-genesis of extinct animals or other biological organisms with unintended results.
- Gene drives or other methods used to successfully control invasive species or vector-borne diseases.
- The release of completely novel engineered synthetic organisms with no natural referent
- 3-D printed organisms, replacement body parts, artificial blood, or other bio-materials.
- Gene edits on humans for disease prevention or enhancement (novel traits).
- Nano-scale agricultural applications such as crop nutrients, growth stimulants, pesticide delivery systems.
- Nano-scale monitoring of human and other biological organisms at the molecular level.
- Nanobots that can break down plastics or other pollutants.
- Increased bioaccumulation of nanoparticles in consumer goods and industrial products pose health problems.
- Discoveries of entirely new nano-scale materials, such as titanium sub-oxides.
- Nanotechnologies dramatically improve the efficiency of batteries, solar cells, catalysts by 5-10x.
- Nanoparticles are used to combat global warming effects, i.e., weather control (solar radiation management) and acidification of the oceans (fertilisation).
- Nano pollinators.
- Materials with programmable functions appear (can change colour, conductivity, optical characteristics, etc. in response to external stimuli).
- Nano-scale additive manufacturing appears.
- Fukushima like accidents.
- Black market diversions of existing radioactive materials result in contamination.
- Dirty bomb.
- Nuclear exchange contaminates significant part of the Earth's surface.
- Early demonstrations of nuclear fusion provide clean energy path.
- Chemicals used in fracking, underground sequestration of carbon, or used to change the viscosity of liquids for pumping cause environmental problems.
- Nanomaterials such as graphene, nanotubes, nano-metal hybrids, may be found increasingly in industrial and consumer products.
- Continued problems with endocrine disruptors.
- Synthetic plastics in marine environment including new forms from 3-D printing and nano plastics
- Chemicals used in geoengineering.
- Nano-bio hybrid materials with novel properties and risks.

- Autonomous robots of plastic-eating organisms that clean up plastics.
- New generations of bio-degradable plastics and plastic substitutes.

Round 2 of the Delphi Survey

The responses produced during the first Delphi round were then analysed and used to build the second round of the survey. In this round, respondents were asked to rate a selection of the novel entities that had been submitted to the first survey from 1 to 5 by relevance to the work of the GEF. 1 would indicate low relevance, and five would indicate high relevance.

The survey instructions elaborated on what "relevance to the GEF" meant by providing the following: "The criteria for rating the relevance to the GEF are: the linkage between the identified entity and GEF's work areas (biodiversity, climate change mitigation, land degradation, international waters, chemicals and waste, sustainable forest management, fisheries, food security, sustainable cities) and the extent to which the entity can affect the ability of the GEF to achieve its objectives, positively or negatively, both in the near- and long-term."

The survey further elaborated on what it might mean to bolster the ability of the GEF to "achieve its objectives" by explaining that "the 2020 vision for the GEF is to be a champion of the global environment, building on its role as a financial mechanism of several multilateral environmental conventions (MEAs), supporting transformational change, and delivering global environmental benefits on a larger scale. To achieve this vision, the GEF will do the following: *Address the drivers of environmental degradation*… *Support innovative and scalable activities*… [and] *Deliver the highest impacts, cost-effectively*."

In this survey, respondents were provided examples of novel entities from the following categories: Biological Entities, Nanotechnology Entities, Radioactive Material Entities, Synthetic Chemical Entities, and Additional Entities. The categories Genetically Modified Organism and Plastic-related Entities from the first round of the survey were folded into Biological Entities and Synthetic Chemical Entities, respectively.

Within each of the above five categories, examples of novel entities were offered within two timeframes: novel entities of relevance between the present and the next five years, and novel entities of relevance over the next five to fifteen years.

Respondents were given the opportunity to rank and to provide any explanatory commentary on each novel entity. Questions at the end of the survey also allowed respondents to provide any additional novel entities that had not been included in the survey and to provide any additional commentary. Once the survey was completed, a respondent was allowed to see others' answers.

Respondents from Round 2

The Round 2 Delphi survey received responses from 62 experts. Most respondents marked that they were between the ages of 36 to 74. The respondents hailed from across the world. Europe received the greatest representation with 19 respondents. 12 respondents were from Latin America or the Caribbean, ten were from Asia Pacific, nine were from North America, seven were from Africa, and one was from West Asia (Figure A1).

The Round 2 survey also collected information on professional affiliations and background. Many respondents—26—were affiliated with universities or academia. 13 were with NGOs, 11 were independent of any affiliation, five were in business, and four were in government. Most respondents marked that their work aligned most closely with the social sciences.

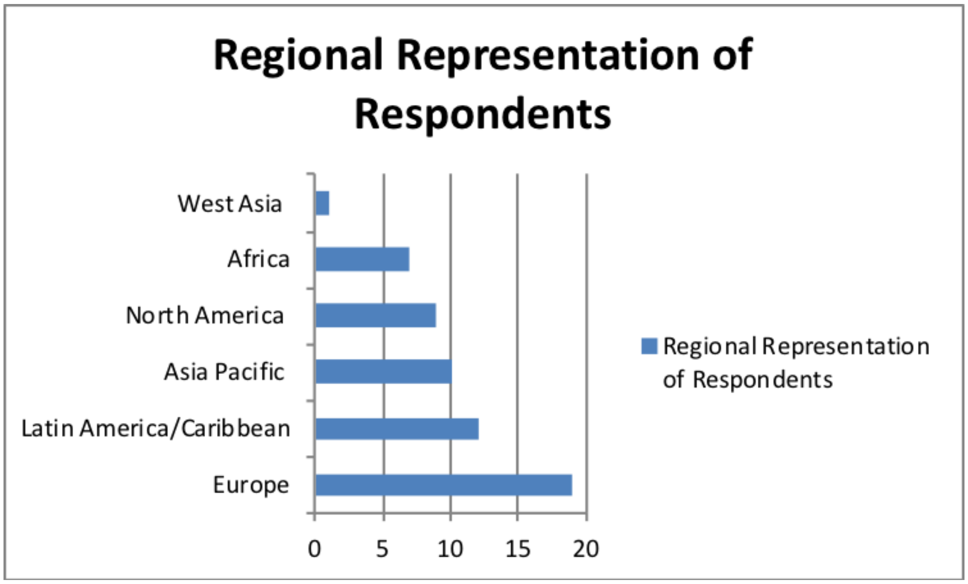

Figure 1. Regional representation of respondents to Round 2 of the Delphi.

Highlights from Round 2

Among those novel entities in the **5-year range,** the following received mean ratings of 3.45 or higher for relevance to the work of the GEF:

- New man-made virus or pathogen created, possibly through mistake from biological hobbyist/DIYer, or intentionally as bio-weapon.
- Nanobots that can break down plastics or other pollutants.
- Increased bioaccumulation of nanoparticles in consumer goods and industrial products pose health problems.
- Discoveries of entirely new nanoscale materials, such as titanium sub-oxides.
- Fukushima-like accidents.
- Black market diversions of existing radioactive materials result in contamination.
- Synthetic plastics in marine environment including new forms from 3-D printing and nano-plastics.

Among those novel entities in the **5-15 year range,** the following received mean ratings of 3.5 or higher for relevance to the work of the GEF:

- New genetically modified crops designed for disease/insect resistance, to withstand higher temperatures and greater drought conditions, increase yields, and/or provide greater nutritional benefits.
- Cellular agriculture (plant and/or meat based) to provide protein with reduced environmental impacts.
- Gene drives or other methods used to successfully control invasive species or vector-borne diseases.
- 3-D printed organisms, replacement body parts, artificial blood, or other bio-materials.
- Nanotechnologies dramatically improve the efficiency of batteries, solar cells, catalysts by 5-10 times.
- New generations of bio-degradable plastics and plastic substitutes.

Additional Novel Entities

When provided the option to mention any additional novel entities that might have been left out of the survey, comments included the following:

- Artificial Intelligence
- Development of new industrial materials
- Blockchain technologies
- Geoengineering

B. Experts Interviewed for this Project

Science & Technology

1. Honda Chen, PhD, National Program Leader for Bioprocess Engineering and Nanotechnology at National Institute of Food and Agriculture (NIFA), US Department of Agriculture [https://nifa.usda.gov/staff-contact/hongda-chen-phd]
2. William Orts, PhD. Research Leader, Bioproducts, Western Regional Research Center. US Department of Agriculture [https://www.ars.usda.gov/people-locations/person?person-id=4240]
3. Tom Graedel, PhD. Professor Emeritus of Industrial Ecology and Chemistry, School of Forestry and Environmental Studies, Yale University [https://environment.yale.edu/profile/graedel/]
4. Jason White, PhD. Vice Director, Department of Analytical Chemistry, The Connecticut Agricultural Experiment Station. [http://www.ct.gov/caes/cwp/view.asp?a=2812&q=345092]
5. Mike Roco, PhD. Senior Advisor for Science and Engineering, National Science Foundation [https://nsf.gov/staff/staff_bio.jsp?lan=mroco]
6. Barbara Harthorn, PhD. Professor of Anthropology; Director, NSF Center for Nanotechnology in Society; Group leader, NSF/EPA UC Center for Environmental Implications of Nanotechnology [http://www.cns.ucsb.edu/people/barbara-herr-harthorn-0.html]

7. Michael Hochella, PhD. Professor of Geosciences, Virginia Tech. [http://www.geochem.geos.vt.edu/hochella/hochella.html]
8. Paul Anastas, PhD. Director, Center for Green Chemistry and Green Engineering, School of Forestry & Environmental Studies, Yale University. [http://ursula.chem.yale.edu/faculty/anastas.html]
9. Julie Zimmerman, PhD. Associate Professor of Chemical & Environmental Engineering & Forestry & Environmental Studies, Yale University [http://seas.yale.edu/faculty-research/faculty-directory/julie-zimmerman]
10. Drew Endy, PhD. Associate Professor of Bioengineering, Stanford University [https://profiles.stanford.edu/drew-endy]

Horizon Scanning

11. Jonathan Peck, President and Senior Futurist, Institute for Alternative Futures [http://www.altfutures.org/about-iaf/futurists-and-associates/jonathan-peck/]
12. James Goodman, Director of Futures & Projects, Forum for the Future, UK [https://www.forumforthefuture.org/siteusers/james-goodman]
13. Evan Michelson, Director, Energy & Environment Program, Alfred P. Sloan Foundation [https://sloan.org/about/staff/evan-s-michelson]
14. Kevin O'Neil, Associate Director for Strategic Research, Rockefeller Foundation [https://www.rockefellerfoundation.org/people/kevin-oneil/]

Social Entrepreneurship, Innovation

15. Thane Kreiner, PhD. Executive Director, Miller Center for Social Entrepreneurship. Howard and Alida Charney University Professor of Science and Technology for Social Benefit, Santa Clara University [https://phonebook.scu.edu/Thane-Kreiner]
16. Katharine Kreis, Director of Strategic Initiative for International Development, PATH [http://www.path.org/news/press-room/666/]

Other

17. John Cumbers, PhD Founder and CEO, SynbioBeta [https://synbiobeta.com/about/team/john-cumbers/]
18. Isha Datar, CEO, New Harvest, [http://www.new-harvest.org/nh2016_isha_datar]
19. Ginger Dosier, CEO, Bio Mason, [https://www.linkedin.com/in/ginger-krieg-dosier-7281027/]
20. Perumal Gandhi, Co-Founder, Perfect Day, [https://www.linkedin.com/in/perumal-gandhi-83550488/]
21. Byrne Stanton, PhD, Program Director, Gingko Bioworks [https://www.linkedin.com/in/brynne-stanton-98a399a7/]

6. Endnotes and References

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[10] those interviewed include scientific and technical experts, CEOs and founders of startup firms, members of the GEF and other multilateral funders (such as the World Bank), and people in the private and philanthropic sectors who have conducted and/or utilized horizon scanning and other foresight techniques (listed in Appendix A).

[11] For this project, a Real-Time Delphi developed by the Millennium Project was adopted. It taps into an existing global network of over 50 nodes around the globe. This group was supplemented through the addition of experts identified by the STAP and ELI. Round one was designed to collect a number of technologies trends in two temporal clusters: present to five years, and beyond five years, while the second round focused on prioritizing these trends. The output of the Delphi was designed to inform, but not necessarily constrain, the selection of a smaller group of novel entities for further study.

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[181] The Delphi technique was developed by RAND in the early 1960s. Background can be found at: https://www.rand.org/topics/delphi-method.html

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