GEF/STAP/C.55/Inf.02
December 13, 2018

55th GEF Council Meeting
December 18 – 20, 2018
Washington, D.C.

NOVEL ENTITIES
A STAP DOCUMENT

Novel entities

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December 2018

STAP SCIENTIFIC AND TECHNICAL ADVISORY PANEL

An independent group of scientists that advises the Global Environment Facility

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ACKNOWLEDGEMENT
The Scientific and Technical Advisory Panel (STAP) to the Global Environment Facility (GEF) is grateful to all who have contributed to this paper.

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COPYEDITOR:
Caryn M. Davis (Cascadia Editing)

COVER PHOTO:
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SUGGESTED CITATION:
Barra et al. 2018. Novel entities. Scientific and Technical Advisory Panel of the Global Environment Facility. Washington, DC.

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The Scientific and Technical Advisory Panel (STAP) comprises seven expert advisors supported by a Secretariat, who are together responsible for connecting the Global Environment Facility to the most up to date, authoritative and globally representative science. http://www.stapgef.org

ABOUT GEF
The Global Environment Facility was established on the eve of the 1992 Rio Earth Summit to help tackle our planet's most pressing environmental problems. Since then, the GEF has provided over $17.9 billion in grants and mobilized an additional $93.2 billion in co-financing for more than 4500 projects in 170 countries. The GEF has become an international partnership of 183 countries, international institutions, civil society organizations, and the private sector to address global environmental issues. http://www.thegef.org

Design and layout by Phoenix Design Aid A/S, Denmark

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SCIENTIFIC AND TECHNICAL ADVISORY PANEL

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SUMMARY

Novel entities have been broadly defined as, "*things created and introduced into the environment by human beings that could have positive or negative disruptive effects on the earth system and may include new substances or new forms of existing substances such as synthetic chemicals, radioactive materials, nanomaterials, microplastics, as well as modified life forms from technologies like synthetic biology and gene modification*[1]."

The Global Environment Facility (GEF) needs to be aware of the opportunities and potential benefits that new entities and technologies can offer in delivering global environmental benefits, but also needs to be mindful of the potential for novel entities to become major global environmental problems. The Scientific and Technical Advisory Panel (STAP) of the GEF, therefore, commissioned a study to identify novel entities relevant to GEF's work.

Six novel entities were identified based on three criteria: novelty – newness of the entity or new knowledge about the entity; impact – scale, timing, scope, and complexity of its impact; and relevance – how the entity might affect the GEF's work, both positively and negatively. Of these, four are expected to be important to the GEF during the next five years, with the other two likely to be important after this time frame.

The novel entities likely to be important to the GEF over the next five years are:

(i) **Technology-critical elements** (TCEs), including rare earth elements, the platinum group elements, and other scarce metals[2], are used in emerging and green technologies, but can have potentially harmful effects on plants, ecosystems, and human health when released into the environment.

(ii) **Blockchain technology**[3] is a decentralized, intermediary-free, digital log that promotes secure, transparent, and efficient transactions and has possible applications in monitoring chemicals and waste, implementing energy microgrids, reducing illegal fishing, and tracking genetic resources. However, its recent application as an underlying technology for Bitcoin virtual currency has raised concern about its excessive energy consumption, which could adversely impact climate change mitigation.

(iii) **Next generation nanotechnology**[4] is more sophisticated than existing nanotechnology applications and could help increase agricultural productivity, reduce dependence on chemical pesticides, improve soil quality, enhance food preservation, improve freshwater supplies, improve the capture and conversion of solar and waste heat energy, and provide other environmental solutions. However, there could be potential adverse human health and environmental effects if nanomaterials leak into the environment.

(iv) **Gene editing**[5], especially Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), offers the possibility of better control of vector-borne diseases, improved animal husbandry, and helping plants adapt to climate change, but could pose a threat to biodiversity if not well regulated.

The novel entities likely to be important to the GEF beyond the next five years are as follows:

(v) **Cellular agriculture** aims to use novel technologies requiring minimal or no involvement of animals to produce livestock products like meat, leather, and fur that are traditionally produced through livestock rearing. This could help reduce the environmental effects of the current food production system, but there are concerns regarding ethics, socio-economic impacts, governance, and consumer acceptance.

(vi) **New engineered bio-based materials**, which use organic resources enhanced by synthetic biology to produce biofuel, chemicals, plastics, and construction and other materials, could help mitigate the unsus-

tainable use of natural resources, environmental degradation, and global warming. Concerns have been raised, however, regarding the potential socioeconomic impacts of replacing natural indigenous commodities and production processes with bio-based production.

STAP recommends that the GEF should adopt the following strategic posture on these novel entities:

- Technology-critical elements and blockchain technology: focus on managing the risks and harnessing the opportunities.

- Next-generation nanotechnology and gene editing/CRISPR: get a better understanding of these novel entities and consider how the GEF could exploit the opportunities and manage or prevent any negative effects.

- Cellular agriculture and engineered bio-based materials: monitor the development of these entities to determine what further action should be taken.

STAP also recommends some specific actions that can be taken concerning each of these novel entities: for example, support policies towards sustainable extraction, utilization, and recycling of TCEs, including the adoption of circular economy principles in the sector; conduct an assessment of how current trends in nanotechnology may affect the goals of the GEF; explore blockchain technology in GEF strategy and programmatic areas (e.g. for knowledge management and monitoring of global environmental benefits); and support capacity building for regulating gene editing in developing countries.

In addition, STAP offers the following advice on how the GEF might respond more generally to the challenges and opportunities posed by novel entities, innovation, and emerging technologies.

- In the short-term, the GEF should focus on removing bottlenecks to the adoption of environmentally safe and sound technologies, such as poor governance and institutional frameworks and the lack of awareness and capacity; finance demonstration or pilot projects to explore the opportunities offered by some of the novel entities; and leverage investment by others, for example, by providing early investments to help validate new technologies, and motivating further funding by others.

- Looking further ahead, the GEF should stay abreast of developments in novel entities and technologies to take advantage of opportunities and avoid negative consequences. This could include leveraging its convening power to bring together thought leaders from the industry and academia.

1. WHAT IS THE ISSUE?

Human beings have introduced many new substances (novel entities) into the earth's system as solutions to human needs, but some of these substances were later found to have unintended consequences. For example, chlorofluorocarbons (CFCs) were introduced in 1928 as a desirable replacement for toxic refrigerants, but later became a key driver of ozone depletion in the upper atmosphere[6]. Similarly, chemicals such as dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyl (PCBs) were introduced for beneficial use in agriculture, disease control, and industrial manufacturing processes, but were later discovered to have harmful effects on ecosystems and human health and are now classified as persistent organic pollutants (POPs)[7].

Work on the planetary boundaries[8] defined novel entities as, "new substances or new forms of existing substances as well as modified life-forms that have the potential for unwanted geophysical and/or biological effects[9]…."

The Global Environment Facility (GEF) needs to be aware of the opportunities and potential benefits that new entities and technologies can offer in delivering global environmental benefits, but also needs to be mindful of the potential for newly introduced substances or modified life forms to become major global environmental problems. The Scientific and Technical Advisory Panel (STAP) of the GEF therefore commissioned a study[10] to identify novel entities relevant to GEF's work. This study defines novel entities broadly as, "*things created and introduced into the environment by human beings that could have positive or negative disruptive effects on the earth system and may include new substances or new forms of existing substances such as synthetic chemicals, radioactive materials, nanomaterials, microplastics, as well as modified life forms from technologies like synthetic biology and gene modification*[11]."

This definition includes the processes or applications that create the entities, as well as the entities themselves.

A broad range of novel entities was identified. This long list was narrowed down to six entities of interest for this report, based on three criteria: novelty – newness of the entity or new knowledge about the entity; impact – scale, timing, scope, and complexity of its impact; and relevance to the GEF – how the entity might affect the GEF's work[12] and whether it could impede or accelerate the delivery of global environmental benefits, both in the near- and long-term.

The novel entity identification process included the following steps (see Figure 1):

- **Horizon scanning**: a review of relevant literature; interviews with experts, within and outside the GEF, including scientists, social entrepreneurs, representatives from start-ups, and funders; and a two-round Delphi survey[13] involving more than 70 global experts.

- **Timing and impact analysis:** initial prioritization and clustering of findings from the literature review, interviews, and Delphi survey, based on the timing of technological developments (0-5 years and 5-15 years) and their potential impacts.

- **Assessment of relevance to the GEF:** a review of how the identified novel entities might affect GEF's focal areas, and whether this would have a positive or negative effect on GEF's objectives.

- **Strategic posture:** an assessment of what GEF's strategic posture and possible action should be toward each of the novel entities; these were informed by a workshop that brought together experts from several disciplines and sectors and included the GEF Secretariat and the GEF's Independent Evaluation Office.

The six entities are as follows: technology-critical elements (TCEs), next-generation nanotechnology, blockchain technology, gene editing/CRISPR, cellular agriculture, and engineered bio-based materials. This is not a com-

plete list. Other novel entities were identified but did not meet the selection criteria, and there may be others which could be of interest to the GEF. The background report of the study, which provides more detailed information about the process and the long list of novel entities, is available on STAP's website[14].

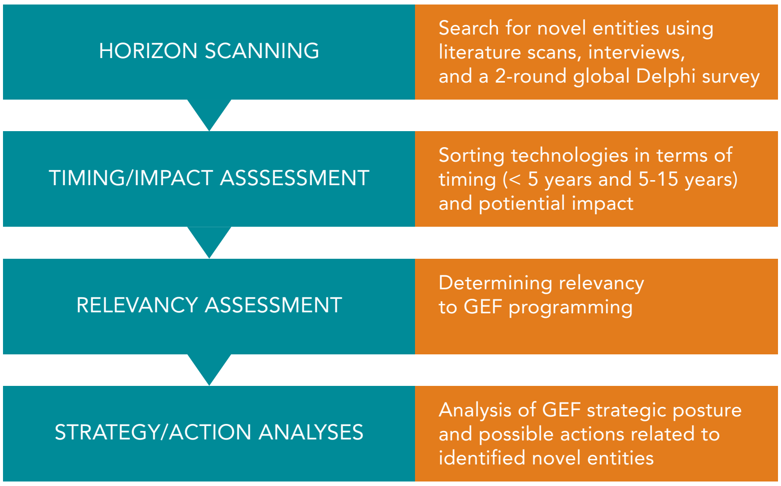


Figure 1. Identification process for novel entities

2. WHAT DOES THE SCIENCE SAY?

2.1 Novel entities likely to be important to the GEF over the next five years

(i) Technology-critical elements

Technology-critical elements (TCEs) include most rare-earth elements (a group of 17 elements including the 15 lanthanides and scandium and yttrium); the platinum group elements (platinum, palladium, rhodium, ruthenium, iridium, and osmium); and the elements gallium, germanium, indium, tellurium, niobium, tantalum, and thallium. TCEs are critical to a renewable energy future and for other green and emerging technologies; hence, global demand, especially for rare earth elements, is increasing and has been projected to grow at a rate of 5% annually by 2020[15]. As a result of their increased use, however, TCEs are being released into the environment[16] including during extraction and processing, during production, and through the disposal of products containing them. The impacts of releasing TCEs are not yet well understood, but research suggests that there may be adverse effects on human beings, plants, and the environment[17].

Products containing TCEs, such as electric cars, wind turbines, and solar cells, help to mitigate climate change, but the mining and processing of TCEs are a source of greenhouse gas emissions. Extraction and refining of TCEs may cause land degradation, water contamination, waste pollution, and the release of radioactive materials, and could also lead to deforestation and biodiversity loss. One study found that up to 300 square meters of vegetation and topsoil were removed for every tonne of rare earth oxide extracted, generating 1000 tonnes of contaminated wastewater, and discarding 2000 tonnes of tailings into adjacent valleys and streams[18]. Another study reported that a planned rare-earth mine in Madagascar may result in the loss of surrounding rainforest, including a protected area that is home to endangered lemurs and other unique wildlife[19]. Currently, less than 1% of rare earth elements (REEs) are recycled[20] – an inefficient use of valuable natural resources. The few cases where REEs have been recycled have been linked to the emission of harmful pollutants, including dioxins (classified as persistent organic pollutants[21] under the Stockholm Convention) due to poor recycling technology.

(ii) Blockchain technologies

A blockchain is a digital ledger that decentralizes data and eliminates intermediaries typically required to validate transactions. It uses a distributed database to store information securely, transparently, and efficiently, thereby improving processes that require secure sending, storing, accessing, or verification of information[22].

Blockchain offers a wide array of potential applications. It has been applied in digital contracting, management of healthcare records and personal identification information, supply chain management, emissions trading, and banking. Applications are also being explored in microfinance, tracing resources through supply chains, and securing land tenure rights for people who lack adequate representation. Blockchain technology could also be used to track and improve environmental practices and policies[23]; to provide consumers with information on the source of materials and their environmental impacts, thereby improving monitoring and transparency[24]; and to track carbon emissions, for example, from power plants for regulatory and carbon accounting purposes[25].

Blockchain could also be used in microgrids in both rural and urban areas to create a local virtual marketplace for peer-to-peer buying and selling of electricity, for example, from solar home systems and other local renewable energy sources[26]. This has already been applied in the USA (in Brooklyn, New York, and in Texas) and in Australia[27] and could contribute to GEF's objective of "promoting innovation and technology transfer for sustainable energy breakthroughs[28]." It could also be used for tracking marine and other resources, and for reducing illegal exploitation, for example, the World Wildlife Fund has used blockchain to mitigate the illegal fishing of tuna[29]. Blockchain could improve urban planning, transportation, smart buildings, and energy use and distribution by providing a cross-cutting platform connecting different city services and enhancing transparency and security for those processes[30].

However, blockchain is the underlying technology for Bitcoin virtual currency[31]; this has raised concerns about its energy consumption, which is high because each transaction occurs over a network of users expending a large amount of computing power. Energy consumption by Bitcoin, as at August 2018, was estimated to be equivalent of the power required by more than 6.8 million U.S. households, with each transaction consuming an estimated 924 KWh of electricity – equivalent to a carbon footprint of 35,830 $ktCO_2$ per transaction[32]. Another analysis indicated that Bitcoin used as much energy as that needed to provide power to 159 countries in 2017[33]. The need to satisfy the energy demands of Bitcoin mining has been linked to the reopening of a coal-fired power plant in Australia[34]. A recent study indicates that if Bitcoin usage is adopted at the same rate as other technologies, its carbon emissions could push warming above 2 °C within less than three decades[35].

(iii) Next-generation nanotechnology

Nanotechnology is the branch of technology that deals with very tiny dimensions and tolerances of less than 100 nanometers. It often involves the manipulation of individual atoms and molecules and has been applied across diverse fields including chemistry, physics, material science, and engineering. It has a wide variety of applications, for example, in healthcare, electronics, agriculture, aerospace, energy production and storage, water treatment, food processing, and the production of electronics and consumer products.

Recent advances are leading to the development of a new generation of nanotechnology that uses active, rather than passive, nanostructures, as well as molecular and integrated nanosystems[36]. Passive nanostructures have steady structures and behavior, which are used to improve the properties and function of existing materials[37], whereas active nanostructures can change their composition and behavior in order to deliver the desired function[38]. Integrated nanosystems bring together different nanoscale components to form complex and functional products by using various syntheses and assembling techniques, such as bio-assembling and robotics, while molecular nanosystems behave like a biological system in which each molecule has a specific structure

that plays its role[39]. This next-generation of nanotechnology (active, integrated and molecular nanosystems) will allow innovative functions. For example, researchers recently created three-dimensional nanostructures with 10,000 components that self-assemble, with potential application in structural biology, biophysics, synthetic biology, and photonics[40].

Several nanotechnology products could potentially deliver environmental benefits. For example, nanocomposites and nanofluids can improve the electrical, thermal, and optical conductivity of solar energy systems[41]. Cells created from carbon nanotubes can also improve efficiency with much less weight than conventional copper wires[42]. Hybrid nanocrystals cells have been demonstrated to provide efficiencies that approach the theoretical maximum of close to 100%[43]. Energy utilization efficiency can be improved with nano-sized semiconductors that allow for increased use of the infrared spectrum, enabling the conversion of both visible and invisible lights to power, which is usually not possible with conventional systems[44]. Additionally, nanotechnology offers possibilities for harvesting energy from low-value heat sources, even body heat, which could be used to supply electricity to cell phones, sensors, or other smart devices through nano-enabled "wearable thermoelectric generators[45]." Nano-based thermoelectric devices can also convert waste heat from heat-producing machines and devices, like cooking stoves, to electricity at increasing efficiencies and scales[46]. Future solar cells, based on nanoscale carbon (graphene) instead of silicon, promise to reduce costs, increase accessibility, and expand markets with the availability of flexible polymer substrates cells that can be integrated directly into building materials or even painted on surfaces[47]. Manufacturing photovoltaics by using nano-engineered materials, such as colloidal quantum dots, and shifting from high-cost, energy-intensive photolithography to high-yield printing for future nanoscale solar cell applications, will also save energy and reduce the environmental impacts associated with the current energy and material-intensive processing of silicon and other PV materials[48].

Biodegradable nanomaterial from wood, with enhanced insulating properties, could replace existing insulators and provide energy-efficient buildings with climate benefits[49]. Nanoscale water treatment including desalination of saltwater using less energy compared to traditional methods could help to provide freshwater[50]. Nanomaterials can also be applied for the remediation of contaminated lands and mitigation of air pollution[51].

In agriculture, biosensors can be built from nanomaterials for the detection and prevention of crop diseases and food contamination[52]. Smart delivery systems using nanoparticles can also be used for the controlled release of agrochemicals, genetic materials, and soil enhancers[53]. Other applications include nano-based fertilizers, pesticides, herbicides, and soil enhancers which offer alternatives to current agrochemicals[54]. These advances could increase agricultural productivity, reduce dependence on harmful chemicals (including pesticides regulated by the chemicals conventions), and reduce the adverse effects of agricultural practices on the environment and human health, thus promoting sustainable intensification[55].

There are questions, however, about the potential environmental impacts that nanomaterials might have if they unintentionally leak into the environment. There is a dearth of knowledge on their fate, transport, and behavior in the environment. Studies suggest that while some nanomaterials are beneficial to plants, some (e.g. silver nanoparticles used extensively in antimicrobial agents, shampoo, soap, toothpaste, fabric, detergents, paints, etc) could adversely impact plant growth at high concentrations[56]. They could also be toxic to aquatic resources, ecosystems, and other sources of biodiversity[57]. Some studies suggest that nanoparticles are more toxic in human bodies than larger particles of the same material, and that their inhalation or transport through the bloodstream may lead to cardiovascular, respiratory tract, and other extrapulmonary effects[58]. Concerns have also been raised regarding the risk to human health from the interaction between active nanostructures or nanosystems and human tissues or the nervous system[59].

There are also concerns that next-generation nanosystems could affect social lifestyle, human identity, and cultural values. For example, there are fears that integrated or molecular nanosystems could lead to self-repli-

cating machines that may spread across the biosphere, thereby affecting human life[60]. There is also the potential effect on human identity if nano-based devices were to influence human behavior when incorporated into the brain, as well as the intrusion of privacy by pervasive nano-based computing devices[61]. There is not an adequate governance structure for managing the passive nanoparticles already being used in commerce or the potential emerging risks from next-generation nanotechnology.

(iv) Gene editing/CRISPR

Gene editing involves the addition, removal, or alteration of the DNA nucleotides (the basic structural unit and building block of DNA) of a cell or an organism, resulting in a change in the characteristics of the cell or organism. Recently, a gene-editing technique, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), was demonstrated to be more precise, cost less, and relatively easier to learn than earlier methods. CRISPR promises to open 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 threats[62].

CRISPR technology is being tested to improve the ability of cacao and maize plants to adapt to climate change[63] and to allow plants to produce some of their nitrogen fertilizer[64]. This will reduce the need for fertilizers and the associated energy and environmental effects of synthetic fertilizer production and use. CRISPR was recently used to alter the gene of an algae strain, resulting in a significant increase in algae-based biofuel production[65]. Gene editing is also being applied in the reduction of enteric methane emissions from ruminants – produced through their digestive processes – which constitute the single most significant source of agricultural methane emissions. CRISPR has also been proposed as a technique for saving endangered species and eradicating invasive or harmful species[66].

However, concerns have been raised that the widespread use of gene editing could become a major threat to biodiversity, as the technology can be used to eliminate plant and animal species, including undesirable insects. For example, CRISPR was recently used to eliminate malaria-carrying mosquito species in a laboratory experiment[67]. The Convention on Biological Diversity has called for a moratorium on the use of genetic technologies (gene drive) as a tool for eradicating undesirable species[68]. The emergence of CRISPR has raised ethical concerns about the possibility of market-based eugenics, the advent of novel bioweapons, and the danger of genetic alterations, given the inadequacy of current regulation and governance structures[69]. Concern has also been expressed that the approval of genetically-modified salmon could endanger wild salmon populations[70] if captive fish escape into oceans and rivers.

2.2 Novel entities likely to be important to the GEF beyond the next five years

(v) Cellular agriculture

Cellular agriculture is an emerging technology for producing livestock products from cell cultures without the animal itself[71]. Research is focusing on creating meat substitutes from plant-based protein; engineering microbes to produce dairy products like milk; and making other products, such as leather and fur[72].

Cellular agriculture could help to achieve a more sustainable food production system and significantly reduce the environmental impacts of the current system. This is particularly important, given the increasing global demand for animal protein. Analyses show that producing 1000 kg of cultured meat requires approximately 99% less land and 82%–96% less water, compared with conventionally produced European livestock[73]. Cellular agriculture could also improve food safety and transparency, animal welfare, and the nutritional composition of food, and lead to increased product shelf life[74]. Moreover, if scaled-up and made widely accessible, cellular agriculture could help reduce the protein nutritional deficit in developing countries.

However, the energy and climate benefits from cellular agriculture are still debated. While one analysis indicates that it requires less energy and emits less greenhouse gas compared to conventional livestock[75], another indicates that it could increase greenhouse gas emissions because replacing biological functions with chemical and mechanical equivalents requires significant energy inputs[76]. The current understanding suggests that chicken and plant-based proteins have a lower energy impact than cultured meat, but cultured meat has a lesser impact compared to beef and possibly pork[77]. There are also issues about product regulation, intellectual property, ethical concerns, and public acceptance[78]. Questions have also been raised about the feasibility of scaling-up production and ensuring affordability and accessibility[79], as well as about the socioeconomic effects on livestock and dairy farmers[80]. There are also concerns that cellular agriculture could encourage excessive meat consumption, which could be unhealthy[81].

Subject to resolving these issues, cellular agriculture could yield benefits including: mitigating climate change; protecting biodiversity; reducing the degradation of land, forests, and international waters; and reducing chemicals and waste production by diverting livestock production from the current resource-intensive system.

(vi) New engineered bio-based materials

Recent advances in synthetic biology have expanded the range of products that can be engineered from organic materials through the programming of metabolic processes in biological systems[82]. This is paving the way for engineered microorganisms to complement or replace plant- or fossil-fuel-based technologies, for example, engineered yeast to produce biofuels, food additives, and drugs such as opioids[83]; engineered microbes to produce alternatives to biodegradable plastics[84]; and engineered bacterium to produce chemicals and fuels[85]. Work is underway to use biological approaches for on-site manufacturing of construction materials that could replace bricks and cement[86], thereby reducing greenhouse gas emissions and other environmental impacts of cement production.

However, some have raised concerns that the continuous introduction of new engineered bio-based materials that are incompatible with existing industrial feedstocks could lead to the contamination of product waste streams, thereby making recycling more difficult and consequently constraining the current push towards a more circular economy[87]. The pace of the development of regulatory and governance frameworks for managing new bio-based materials is also believed to lag behind the rate at which these materials are being introduced, especially chemicals[88]. This needs to be addressed in order to avert possible impacts on environmental or human health. Concerns have also been raised regarding the potential socioeconomic impacts of replacing natural indigenous commodities and production processes with synthesized bio-based production[89].

3. WHY IS THIS IMPORTANT TO THE GEF?

Technology-critical elements: products containing TCEs, for example, electric cars, wind turbines, and solar cells, are important for climate change, but their unsustainable mining, processing, and disposal practices could adversely affect the GEF's objectives in chemicals and waste, land degradation, forestry, and biodiversity. The increasing demand for TCEs[90] may lead to mining being shifted to African countries where the GEF implements projects, including in South Africa, Kenya, Tanzania, and Madagascar, all of which have deposits of TCEs[91].

Blockchain technologies: blockchain technology offers opportunities to improve the GEF's knowledge management and auditing of global environmental benefits from its investments. It could be deployed for tracking the movement of chemical products, their makeup, and waste management practices; reducing illegal exploitation of marine resources; meeting energy needs; and tracking genetic resources. However, the energy consumption of blockchain technologies could impact the GEF climate change focal area.

Table 1. Description of the six novel entities, their impact, and relevance to the environment

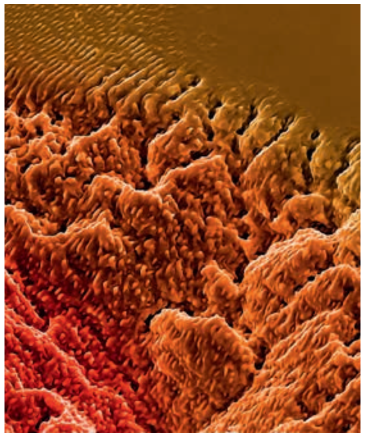
Novel entity	Description	Impacts and relevance
 Technology-critical elements (TCEs)	TCEs include rare earth elements and platinum group elements that are used in emerging green technologies, some of which may help mitigate the impacts of climate change.	• Products containing TCEs provide ways to mitigate or adapt to climate change, but unsustainable extraction practices can result in land degradation, water contamination, waste pollution, radioactive material release, deforestation, and biodiversity loss. • Up to 300 sqm of vegetation and topsoil can be removed for every tonne of rare earth oxide extracted, generating 1000 tonnes of contaminated wastewater and 2000 tonnes of tailings. • Low levels of recycling for TCEs wastes natural resources, and inadequate methods for recycling can lead to pollution, including emission of dioxins.
 Blockchain technology	Blockchain is a decentralized, intermediary-free, digital log that promotes secure, transparent, and efficient transactions, with possible applications in several environment-related fields.	• Blockchain can be used to track and improve environmental practices and policies, as well as provide information on products and their associated environmental footprints, including chemicals relevant to the GEF. • Blockchain can be used to improve knowledge management within the GEF, as well as the auditing of global environmental benefits from GEF investments. • It has been applied to support the operation of local microgrids for renewable energy, for tracking and mitigating illegal fishing, and as a platform for sustainable cities. • The advent of Bitcoin, which uses blockchain technology, has revealed the very high energy consumption of blockchain, which could increase greenhouse gas emissions.
 Next-generation nanotechnology	The next-generation of nanotechnology (which uses active nanostructures, as well as integrated and molecular nanosystems) promises additional diverse, innovative applications such as self-assembly applications, smart-delivery systems, nano-enabled energy, and provide environmental benefits and energy efficiencies.	• Nano-enabled energy technologies could promote a low-carbon, user-centric, local energy future. • Hybrid nanocrystal cells were demonstrated to provide sunlight energy conversion efficiency close to the theoretical maximum of 100%, and nano-enabled thermoelectric generators can be used to convert waste heat to electricity, for example from the human body, or from cookstoves. • Nano products can be used in disease detection, pest control, and precision agriculture, as well as in fertilizers, herbicides, and soil enhancers, thereby enabling increased productivity and reduced chemical use. • New biodegradable nanowood can replace existing building insulators, providing energy efficiency and climate benefits. • Nanoscale water treatment, including desalination of salt water with fewer energy requirements, could help meet freshwater needs. • However, the potential ecological and human health impacts of the unintended release of nanomaterials into the environment needs to be considered. • The absence of a governance structure to manage risks needs to be addressed.

Table 1. Description of the six novel entities, their impact, and relevance to the environment (continued)

Novel entity	Description	Impacts and relevance
 Gene editing/CRISPR	Clustered regularly interspaced short palindromic repeats (CRISPR) is a precise, inexpensive, and relatively easy gene-editing technique that could help address environmental problems.	• Gene editing is currently being explored to help the cacao plant adapt to climate change. • Research is ongoing on using CRISPR to develop crops that fix nitrogen, which could reduce the need for synthetic fertilizers and the associated environmental impacts. • CRISPR has been used to engineer algae to increase biofuel production. • Gene editing is also being explored as a solution for reducing methane emissions from ruminants – the single most significant source of agricultural methane emissions. • There are concerns, however, that gene editing could threaten biodiversity. • There are also concerns related to the adequacy of existing regulatory frameworks for managing ethical concerns and the use of the technology for developing novel bioweapons and for species alterations.
 Cellular agriculture	Cellular agriculture aims to produce livestock products from cell cultures without the animal itself. It focuses on creating meat substitutes, dairy products, and materials like leather and fur.	• Cellular agriculture can help to achieve a more sustainable food production system and reduce the environmental impacts of the current system. • It can also improve food safety, transparency, animal welfare, nutrition, and product shelf life. • It is a potential solution for protein deficiencies in developing countries, while avoiding the negative effects of livestock production. • However, the energy use and climate change impact of cellular agriculture still needs to be properly assessed to ascertain its feasibility. • There remain challenges with scaling-up, affordability, and accessibility; and the impact on the livelihoods of farmers needs to be considered.
 New engineered bio-based materials	Biologically engineered organic resources may be used to meet human material needs while significantly reducing the environmental impacts associated with the production of several materials.	• Examples of engineered bio-based materials include biofuel from engineered yeast, chemicals and fuels from an engineered bacterium, plastics alternatives produced from engineered microbes, and on-site manufacture of construction materials using a biological approach to replace bricks and concrete. • A successful scale-up could provide sustainable alternatives to plant- and fossil-fuel-based production, thereby reducing adverse environmental impacts. • The continuous introduction of new bio-based materials that are incompatible with existing industrial feedstocks could, however, constrain the current push towards a more circular economy. • The potential socioeconomic impacts of replacing natural indigenous commodities and production processes with synthesized bio-based production need to be addressed.

Next-generation nanotechnology: there are many applications that can deliver global environmental benefits in areas related to chemicals, waste, and food security, for example in agriculture (e.g., pest control, precision agriculture, delivery of fertilizers, and detection of plant diseases), contaminated land management, and water treatment. Scaling-up nano-enabled energy technologies would help advance a low-carbon, user-centric, local energy future, which would obviate the need for constructing large centralized electricity networks, benefitting the GEF's work on climate change and sustainable energy innovation and technology. However, the leakage of nanomaterials into the environment also has potential risks for terrestrial and aquatic ecosystems and for biodiversity, as well as for human health.

Gene editing/CRISPR: gene editing offers opportunities for improving the adaptation of crops to mitigate the adverse effects of climate change, to reduce greenhouse gas emissions from livestock, and to produce biofuel. However, gene-editing technologies could also pose threats to biodiversity and ecosystems if not adequately regulated.

Cellular agriculture: cellular agriculture could improve food and nutritional security, while significantly reducing land, water, and energy use and greenhouse gas emissions from the current food production system, thereby contributing to the GEF's objectives in climate change, land degradation, international waters, forests, biodiversity, and chemicals and waste.

New engineered bio-based materials: engineered bio-based materials could provide a more sustainable way of producing biofuels, alternatives to biodegradable plastics, and chemicals, and thereby reduce the negative effects associated with current plant- and fossil-fuel-based production systems. This would benefit the GEF's work in climate change, land degradation, biodiversity, international waters, forestry, and chemicals and waste.

4. HOW CAN THE GEF RESPOND?

STAP considered what the GEF's strategic posture should be for each of these novel entities and recommends the following:

- **Focus:** the GEF should focus on managing the risks and harnessing the opportunities offered by these novel entities
  - Technology-critical elements
  - Blockchain technology

- **Ante up:** the GEF should obtain a better understanding of these novel entities and consider how it could exploit the opportunities they present, while managing, or preventing any negative effects:
  - Next-generation nanotechnology
  - Gene editing/CRISPR

- **Track:** the GEF should monitor the development of these entities to determine what further action it should take:
  - Cellular agriculture
  - Engineered bio-based materials

STAP further recommends that the GEF should consider taking the suggested actions presented in Table 2 for each novel entity.

Table 2. STAP's recommended strategic posture and suggested GEF actions for the six novel entities

Novel entity	Suggested strategic posture	Suggested GEF actions
Technology-critical elements (TCEs)	**Focus**	• Consider taking an active role in ensuring the sustainable and healthy production and use of TCEs. • Support the development of policies and actions promoting sustainable extraction of TCEs. • Promote alternative mining, refining, and recycling technologies that minimize environmental damage. • Help facilitate the adoption of circular economy principles in the sector. • Help increase awareness of potential environmental and health impacts of unsustainable mining and use of TCEs. • Support efforts to quantify the demand for TCEs and the implications of their extraction, use, disposal, and uptake into the environment.
Blockchain technology	**Focus**	• Consider exploring blockchain technology as an enabling platform for its strategy, and in programmatic areas. This could include knowledge management, chemicals and waste monitoring, the creation of energy microgrids, reducing illegal fishing, tracking of genetic resources, and ensuring benefit sharing as part of the Convention on Biological Diversity and the Nagoya Protocol. • Consider exploring blockchain-based crowdfunding to supplement GEF funds for projects especially novel pilots, for instance, the Acorn Collective – an open access and free crowdfunding platform[101].
Next-generation nanotechnology	**Ante Up**	• Consider the potential for both beneficial and negative effects of nanotechnology. • Stay abreast of developments in this field, including by conducting a detailed assessment of trends in nanotechnology and how these might affect GEF's goal and objectives. • Support and monitor ongoing research to understand the fate and behavior of nanomaterials in the environment, including the potential threat to humans and ecosystems. • Support and encourage the emerging field of sustainable and green nanomanufacturing[102].
Gene editing/ CRISPR	**Ante Up**	• Consider actively monitoring developments in this field and attune its programme and resources accordingly. • Consider assessing how gene editing could affect goals and objectives. • Consider supporting the ethical use of gene editing in environmental applications that have been scientifically assessed to be beneficial. • Consider supporting awareness-raising efforts addressing gene editing that could adversely affect the environment. • In the near term, consider supporting capacity building in developing countries to regulate and monitor gene editing.
New engineered bio-based materials	**Track**	• Help shape the future bio-economy, including by actively engaging in the global dialogue on the future bio-economy[103]. • Focus engagement on assessing potential environmental impacts and benefits; developing public policy, institutional and financial frameworks; and investing in pilot projects.
Cellular agriculture	**Track**	• Track developments and be part of the global discussion about future protein production and how it will affect the global environment.

STAP also has recommendations for the short- and long-term on how the GEF might respond to the challenges and opportunities posed by novel entities, innovation, and emerging technologies:

In the short-term, the GEF should consider the following actions:

(a) **Focus on bottlenecks to the adoption of technology.** These bottlenecks include inadequate capacity, poor governance and institutional frameworks, lack of awareness, and unfavorable public opinion. For example, a recent workshop on supporting the bio-economy in Africa identified deficits in technical training, poor access to research materials, and lack of strategic national and international partnerships as some of the factors responsible for the slow adoption of new technologies in Africa[92]. In line with two of GEF's influencing models highlighted in its 2020 Strategy[93] – "transforming policy and regulatory environments" and "strengthening institutional capacity and decision-making processes" – the GEF should consider how it might help to alleviate these bottlenecks, for example, by addressing them in components of its funded projects.

(b) **Finance pilot projects aimed at demonstrating new technologies.** This should build on the GEF's track record of fostering risk-taking opportunities[94] and its commitment to supporting innovative and scalable activities[95]. The GEF could also explore options for stimulating innovation and scale-up of novel opportunities using prizes, challenge awards, and other incentives.

(c) **Leverage investment by others.** The GEF should explore areas where early investment could drive follow-on or matching funding from philanthropies, foundations, and individuals. For example, some philanthropies are interested in how blockchain technologies could be applied to global development issues. Small, early investments by the GEF could help validate funding by others[96]. The GEF could also explore emerging financing mechanisms such as crowdfunding, which is now estimated to account for $34 billion in global investments, $25 billion of which is direct peer-to-peer[97].

Looking further ahead, the GEF should consider how to stay abreast of novel developments, to take advantage of opportunities, and avoid negative consequences, through the following actions:

(d) **Scan, convene, and signal.** The GEF should make use of other horizon scanning and innovation systems both inside and outside the UN system that can provide intelligence on emerging technology trends. Furthermore, the GEF could leverage its convening power to bring together thought leaders from a variety of backgrounds. This could be used to signal the GEF's priorities, update and expand on findings from foresight exercises, engage existing and potential new stakeholders in collective efforts to achieve goals, and design better public-private partnerships to leverage funds.

(e) **Engage and support open-source technologies and systems.** These technologies and systems can help provide broad access and knowledge-sharing in developing countries and between developed and developing countries. Engaging existing local, regional, and global networks can help develop or disseminate technological solutions, for example, the Do-It-Yourself biologist network[98], the global Fab Lab Network[99], and other citizen science movements. The GEF could also support the creation of knowledge platforms to aggregate ideas from within and outside the GEF as inputs into innovation processes for emerging technologies[100].

ENDNOTES

1 This definition is based on the definition in Welcome to the Anthropocene, "Novel entities," in *Planetary Boundaries,* http://www.anthropocene.info/pb2.php. The definition has been expanded to include positive impacts of novel entities.

2 Rare-earth elements are a group of 17 elements, including the 15 lanthanides as well as scandium and yttrium. The platinum group elements are platinum, palladium, iridium, osmium, rhodium, and ruthenium. Other technology-critical elements include gallium, germanium, indium, tellurium, niobium, tantalum, and thallium.

3 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, thereby improving processes that require secure sending, storing, accessing, or verification of information.

4 Nanotechnology is the branch of technology that deals with very tiny dimensions and tolerances of less than 100 nanometres (much thinner than a human hair). It often involves the manipulation of individual atoms and molecules and can be applied across diverse scientific fields including chemistry, physics, material science, and engineering. Recent advances are leading to the development of a new generation of nanotechnology that goes beyond current passive nanostructures – which have stable behaviour during their use – to active nanostructures and systems that can change composition and behaviour during use and can be assembled into a system of structures and molecules to achieve specific objectives.

5 Gene editing involves the addition, removal, or alteration of DNA nucleotides (the basic structural unit and building block of DNA) of a cell or an organism, resulting in a change in the characteristics of the cell or organism.

6 See James W. Elkins, "Chlorofluorocarbons (CFCs)" in *The Chapman & Hall Encyclopedia of Environmental Science*, ed. David E. Alexander and Rhodes W. Fairbridge, pp.78-80 (Boston: Kluwer Academic, 1999), https://www.esrl.noaa.gov/gmd/hats/publictn/elkins/cfcs.html.

7 See "What are POPs?" *Stockholm Convention on Persistent Organic Pollutants* (United Nations Environment Programme, 2008), http://chm.pops.int/TheConvention/ThePOPs/tabid/673/Default.aspx; and EPA-United States Environmental Protection Agency, "Persistent Organic Pollutants: A Global Issue, A Global Response" (2002; updated Dec 2009): https://www.epa.gov/international-cooperation/persistent-organic-pollutants-global-issue-global-response.

8 "The planetary boundaries framework defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth system." See: Steffen, W. et al. 2015. Planetary boundaries: Guiding human development on a changing planet. Science, 347, 1259855. DOI: 10.1126/science.1259855

9 This definition is based on the definition in Welcome to the Anthropocene, "Novel entities," in *Planetary Boundaries,* http://www.anthropocene.info/pb2.php. The definition has been expanded to include positive impacts of novel entities.

10 http://stapgef.org/novel-entities-and-gef

11 This definition is based on the definition in Welcome to the Anthropocene, "Novel entities," in *Planetary Boundaries,* http://www.anthropocene.info/pb2.php The definition has been expanded to include positive impacts of novel entities.

12 Global Environment Facility (GEF) work areas include biodiversity, chemicals and waste, climate change mitigation and adaptation, forests, international waters, land degradation, fisheries, food security, sustainable cities and more. See: https://www.thegef.org/our-work.

13 For this project, a Real-Time Delphi developed by the Millennium Project (http://www.millennium-project.org/rtd-general/) 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 several 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.

14 http://stapgef.org/novel-entities-and-gef

15 Tanushree Dutta, Ki-Hyun Kim, Minori Uchimiya, Eilhann E.Kwon, Byong-Hun Jeon, Akash Deep, and Seong-Taek Yun, "Global demand for rare earth resources and strategies for green mining," *Environmental Research* 150 (Oct 2016): 182–190. https://doi.org/10.1016/j.envres.2016.05.052.

16 For example, Antonio Cobelo-Garcia, "Technology-critical elements: a need for evaluating the anthropogenic impact on their marine biogeochemical cycles," *Frontiers in Marine Science Conference Abstract: IMMR, International Meeting on Marine Research 2014, Peniche, Portugal, 10-11 July 2014* (published online: 18 Jul 2014), https://www.frontiersin.org/10.3389/conf.fmars.2014.02.00164/event_abstract; P. Nuss and G.A. Blengini, "Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles," *Science of the Total Environment* 613–614 (1 Feb 2018): 569–578, doi: 10.1016/j.scitotenv.2017.09.117 ; W. Gwenzi, L. Mangori, C. Danha, N. Chaukura, N. Dunjana, and E. Sanganyado, "Sources, behaviour, and environmental and human health risks of high-technology rare earth elements as emerging contaminants," *Science of the Total Environment* 15 (15 Sep 2018): 299–313, doi: 10.1016/j.scitotenv.2018.04.235.

17 For example, Mike Ives, "Boom in mining rare earths poses mounting toxic risks," *Yale Environment 360* (28 Jan 2013), e360.yale.edu/features/boom_in_mining_rare_earths_poses_mounting_toxic_risks; Silvio J. Ramos, Guilherme S. Dinali, Cynthia Oliveira, Gabriel C. Martins, Cristiano G. Moreira, José O. Siqueira, and Luiz R.G. Guilherme, "Rare earth elements in the soil environment," *Current Pollution Reports* 2, issue 1 (Mar 2016): 28–50, https://doi.org/10.1007/s40726-016-0026-4; Kyung-Taek Rim, "Effects of rare earth elements on the environment and human health: A literature review," *Toxicology and Environmental Health Sciences* 8, issue 3 (Sep 2016): 189–200, DOI 10.1007/s13530-016-0276-y; Winfred Espejo, Daiki Kitamura, Karen A. Kidd, José E. Celis, Shosaku Kashiwada, Cristóbal Galbán-Malagón, Ricardo Barra, and Gustavo Chiang, "Biomagnification of tantalum through diverse aquatic food webs," *Environmental Science & Technology Letters* 5, no. 4 (2018): 196–201, DOI: 10.1021/acs.estlett.8b00051; EPA-United States Environmental Protection Agency, *Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues*, EPA/600/R- 12/572 (Cincinnati, OH: EPA National Risk Management Research Laboratory, 2012). https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EUBC.PDF?Dockey=P100EUBC.PDF

18 X. Jin Yang, Aijun Lin, Xiao-Liang Li, Yiding Wu, Wenbin Zhou, and Zhanheng Chen, "China's ion-adsorption rare earth resources, mining consequences and preservation," *Environmental Development* 8 (2013): 131–136. http://dx.doi.org/10.1016/j.envdev.2013.03.006

19 See Edward Carver, "Another blow to troubled Madagascar rare earth mine, *Mongabay* (22 Nov 2017). https://news.mongabay.com/2017/11/another-blow-to-troubled-madagascar-rare-earth-mine/

20 UNEP-United Nations Environment Programme, *Recycling Rates of Metals: A Status Report*. (International Resource Panel, United Nations Environment Programme, 2011): http://wedocs.unep.org/handle/20.500.11822/8702

21 EPA, *Rare Earth Elements.*

22 Blockchain Commission, *The Future is Decentralised. Block chains, distributed ledgers & the future of sustainable development* (Blockchain Commission for Sustainable Development, 2018): http://www.undp.org/content/undp/en/home/librarypage/corporate/the-future-is-decentralised.html; and Junaid Rehman, "Difference between centralized, decentralized and distributed processing," *IT Release* (2017): http://www.itrelease.com/2017/11/difference-centralized-decentralized-distributed-processing/.

23 Lisa Walker, "This new carbon currency could make us more climate friendly," *World Economic Forum* (19 Sep 2017). https://www.weforum.org/agenda/2017/09/carbon-currency-blockchain-poseidon-ecosphere/

24 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, see IBM News Release, "Walmart, JD.com, IBM and Tsinghua University Launch a Blockchain Food Safety Alliance in China" (14 Dec 2017): https://www-03.ibm.com/press/us/en/pressrelease/53487.wss.

25 For example, see Vincent Manier, "Blockchain Will Make Carbon Visible for Everybody," *The Next Economy* (26 Jul 2018): https://www.sustainablebrands.com/news_and_views/next_economy/vincent_manier/blockchain_will_make_carbon_visible_everybody; and Walker, "This new carbon currency."

26 George Kyriakarakos and George Papadakis, "Microgrids for Productive Uses of Energy in the Developing World and Blockchain: A Promising Future," *Applied Sciences* 8, no. 4 (2018): 580, doi:10.3390/app8040580.

27 Esther Mengelkamp, Johannes Gärttner, Kerstin Rock, Scott Kessler, Lawrence Orsini, and Christof Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn Microgrid," *Applied Energy* 210 (2018): 870–880, https://doi.org/10.1016/j.apenergy.2017.06.054; Esther Mengelkamp, Benedikt Notheisen, Carolin Beer, David Dauer, and Christof Weinhardt, "A blockchain-based smart grid: towards sustainable local energy markets," *Computer Science - Research and Development* 33 (2018): 207–214, https://doi.org/10.1007/s00450-017-0360-9; Mike Orcutt, "How blockchain could give us a smarter energy grid," MIT Technology Review (16 Oct 2017): https://www.technologyreview.com/s/609077/how-blockchain-could-give-us-a-smarter-energy-grid/; Diane Cardwell, "Solar experiment lets neighbors trade energy among themselves," *New York Times* (13 Mar 2017): https://www.nytimes.com/2017/03/13/business/energy-environment/brooklyn-solar-grid-energy-trading.html; PR News, "World's first micro energy hedging platform to benefit Texas businesses" (2018): https://www.morningstar.com/news/pr-news-wire/PRNews_20180409DA60498/worlds-first-micro-energy-hedging-platform-to-benefit-texas-businesses.html; and Cassandra Sweet, "South Australian businesses launch blockchain app to cut costs, trade local clean energy," *GreenBiz* (20 Mar 2018): https://www.greenbiz.com/article/south-australian-businesses-launch-blockchain-app-cut-costs-trade-local-clean-energy.

28 GEF-7 Replenishment, "Programming Direction," Global Environment Facility (Apr 2018). https://www.thegef.org/council-meeting-documents/gef-7-programming-directions.

29 Candice Visser and Qentin A. Hanich, "How Blockchain is strengthening tuna traceability to combat illegal fishing," *The Conversation*/ABC News (22 Jan 2017): 1-4, http://www.abc.net.au/news/2018-01-22/how-blockchain-is-being-used-to-combat-illegal-fishing/9344376 .

30 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 the transportation carbon footprint. See Warren Karlenzig, "Ford, Siemens use blockchain as the fabric for a sustainable city," *GreenBiz* (11 Apr 2018): https://www.greenbiz.com/article/ford-siemens-use-blockchain-fabric-sustainable-city; and Darrell Etherington, "Ford and Autonomic are building a smart city cloud platform," CES (2018): https://techcrunch.com/2018/01/09/ford-and-autonomic-are-building-a-smart-city-cloud-platform/

31 Bitcoin is a type of digital currency in which encryption techniques are used to regulate the generation of units of currency and verify the transfer of funds, operating independently of a central bank, and can be used anywhere in the world. See Dictionary.com, *Random House Unabridged Dictionary*, https://www.dictionary.com/browse/bitcoin; and Nathaniel Popper, "What Is Bitcoin, and How Does It Work? *New York Times* (1 Oct 2017): https://www.nytimes.com/2017/10/01/technology/what-is-bitcoin-price.html.

32 Digiconomist, "Bitcoin Energy Consumption Index," https://digiconomist.net/bitcoin-energy-consumption.

33 See Dom Galeon, "Mining bitcoin costs more energy than what 159 countries consume in a year," *Future Society* (27 Nov 2017): https://futurism.com/mining-bitcoin-costs-more-energy-159-countries-consume-year/

34 See Akshat Rathi, "Bitcoin mining's growing demand for cheap energy revived a shuttered coal mine," *Quartz* (12 Apr 2018): https://qz.com/1250980/an-australian-coal-power-plant-will-reopen-to-help-mine-bitcoins/

35 Camillo Mora, Randi L. Rollins, Katie Taladay, Michael B. Kantar, Mason K. Chock, Mio Shimada, and Erik C. Franklin, "Bitcoin emissions alone could push global warming above 2°C," *Nature Climate Change* 8 (29 Oct 2018): 931–936. https://doi.org/10.1038/s41558-018-0321-8

36 O. Renn and M.C. Roco, "Nanotechnology and the need for risk governance," *Journal of Nanoparticle Research* 8, issue 2 (Apr 2006): 153–191. DOI 10.1007/s11051-006-9092-7; and Mihail C. Roco, "Affirmation of Nanotechnology between 2000 and 2030," in *Nanotechnology Commercialization: Manufacturing Processes and Products*, ed. Thomas O. Mensah, Ben Wang, Geoffrey Bothun, Jessica Winter, and Virginia Davis (Hoboken, NJ: John Wiley & Sons, Inc., 2018): 1–24.

37 For example, the addition of nanoparticles to a matrix to form a nanocomposite with improved properties.

38 They are used for their biological, mechanical, electronic, magnetic, photonic, and other effects by incorporating into microscale devices and systems. Example include bioactive uses as targeted drugs, biodevices, and artificial muscles and physico-chemical active uses such as amplifiers, actuators, adaptive structures, and 3-D transistors. See Roco, "Affirmation."

39 See *Human Paragon*, "The four generations of nanotechnology" (2 Feb 2017): https://humanparagon.com/four-generations-of-nanotechnology/; and K.Eric Drexler, "Toward Integrated Nanosystems: Fundamental Issues in Design and Modeling," *Journal of Computational and Theoretical Nanoscience* 3, no. 1 (Feb 2006): 1–10, DOI: https://doi.org/10.1166/jctn.2006.001.

40 Luvena L. Ong, Nikita Hanikel, Omar K. Yaghi, Casey Grun, Maximilian T. Strauss, Patrick Bron, Josephine Lai-Kee-Him, Florian Schueder, Bei Wang, Pengfei Wang, Jocelyn Y. Kishi, Cameron Myhrvold, Allen Zhu, Ralf Jungmann, Gaetan Bellot, Yonggang Ke, and Peng Yin, "Programmable self-assembly of three-dimensional nanostructures from 10,000 unique components," *Nature* 552 (7 Dec 2017): 72–77, https://www.nature.com/articles/nature24648

41 K.S. Reddy, Nikhilesh R. Kamnapure, and Shreekant Srivastava "Nanofluid and nanocomposite applications in solar energy conversion systems for performance enhancement: a review," *International Journal of Low-Carbon Technologies* 12, issue 1 (Mar 2017): 1–23. doi:10.1093/ijlct/ctw007; and Y. Li, Y.A. Samad, K. Polychronopoulou, S.M. Alhassan, and K. Liao, "Highly Electrically Conductive Nanocomposites Based on PolymerInfused Graphene Sponges," *Scientific Reports* 4 (2014): 4652. doi:10.1038/srep04652.

42 Maogang Gong, Tejas A. Shastry, Yu Xie, Marco Bernardi, Daniel Jasion, Kyle A. Luck, Tobin J. Marks, Jeffrey C. Grossman, Shenqiang Ren, and Mark C. Hersam, "Polychiral semiconducting carbon nanotube–fullerene solar cells," *Nano Letters* 14, no. 9 (2014): 5308–5314. DOI: 10.1021/nl5027452.

43 M. Tabachnyk, B. Ehrler, S. Gélinas, M.L. Böhm, B. Walker, K.P. Musselman, N.C. Greenham, R.H. Friend, and A. Rao, "Resonant energy transfer of triplet excitons from pentacene to PbSe nanocrystals," *Nature Materials* 13, no. 11 (Nov 2014): 1033–1038, doi:10.1038/nmat409; University of Cambridge, "Hybrid materials could smash the solar efficiency ceiling," *Research News* (9 Oct 2014): https://www.cam.ac.uk/research/news/hybrid-materials-could-smash-the-solar-efficiency-ceiling; and James Trew, "Scientists create first solar cell with over 100% quantum efficiency," *EnGadget* (19 Dec 2011): https://www.engadget.com/2011/12/19/scientists-create-first-solar-cell-with-over-100-percent-quantum/.

44 Takashi Asano, Masahiro Suemitsu, Kohei Hashimoto, Menaka De Zoysa, Tatsuya Shibahara, Tatsunori Tsutsumi, and Susumu Noda; "Near-infrared–to–visible highly selective thermal emitters based on an intrinsic semiconductor," *Science Advances* 2 (23 Dec 2016): e1600499, DOI: 10.1126/sciadv.1600499; and Kyoto University, "A big nano boost for solar cells," *Science News* (18 Jan 2017): https://www.sciencedaily.com/releases/2017/01/170118082439.htm.

45 Hiroaki Jinno, Kenjiro Fukuda, Xiaomin Xu, Sungjun Park, Yasuhito Suzuki, Mari Koizumi, Tomoyuki Yokota, Itaru Osaka, Kazuo Takimiya, and Takao Someya, "Stretchable and waterproof elastomer-coated organic photovoltaics for washable electronic textile applications," *Nature Energy* 2, no. 10 (Oct 2017): 780–785, https://www.nature.com/articles/s41560-017-0001-3; and Jhonathan P. Rojas, Devendra Singh, Salman B. Inayat, Galo A. Torres Sevilla, Hossain M. Fahad, and Muhammad M. Hussain, "Review—micro and nano-engineering enabled new generation of thermoelectric generator devices and applications," *ECS Journal of Solid State Science and Technology* 6, issue 3 (2017): N3036-N3044 N3036–N3044, doi: 10.1149/2.0081703jss.

46 H. Liu, X. Shi, F. Xu, L. Zhang, W. Zhang, L. Chen, Q. Li, C. Uher, T. Day, and G.J. Snyder, "Copper ion liquid-like thermoelectrics," *Nature Materials* 11, no. 5 (11 Mar 2012): 422–425, doi:10.1038/nmat3273; and Dexter Johnson, "Thermoelectric materials turning increasingly towards nanotechnology," *IEEE Spectrum* (23 March 2012), https://spectrum.ieee.org/nanoclast/semiconductors/nanotechnology/thermoelectric-materials-turning-increasingly-towards-nanotechnology.

47 See work at Stanford: Gary C. Bjorklund and Thomas M. Baer,"Organic Thin-Film Solar Cell Research at Stanford University," *BAO Research* (2007): https://baogroup.stanford.edu/index.php/research-highlights/41-organic-thin-film-solar-cell-research-at-stanford-university.

48 Joel Jean, Sehoon Chang, Patrick R. Brown, Jayce J. Cheng, Paul H. Rekemeyer, Moungi G. Bawendi, Silvija Gradečak, and Vladimir Bulović, "ZnO Nanowire Arrays for Enhanced Photocurrent in PbS Quantum Dot Solar Cells," *Advance Materials* 25, issue 20 (28 May 2013): 2790–2796, https://doi.org/10.1002/adma.201204192. See also David L. Chandler, "New solar-cell design based on dots and wires," *MIT News* (25 Mar 2013): http://news.mit.edu/2013/nanowires-quantum-dots-solar-cell-0325; Sharaf Sumaiya, Kamran Kardel , and Adel El-Shaha "Organic solar cell by inkjet printing—an overview," *Technologies* 5, no. 3 (2017): 1–18, doi:10.3390/technologies5030053 / https://digitalcommons.georgiasouthern.edu/manufact-eng-facpubs/11 ; and Michael Berger, "Complete solar cells printed by inkjet," *Nanowerk* (16 June 2014): https://www.nanowerk.com/spotlight/spotid=36042.php.

49 Tian Li, Jianwei Song, Xinpeng Zhao, Zhi Yang, Glenn Pastel, Shaomao Xu, Chao Jia, Jiaqi Dai, Chaoji Chen, Amy Gong, Feng Jiang, Yonggang Yao, Tianzhu Fan, Bao Yang, Lars Wågberg, Ronggui Yang, and Liangbing Hu"Anisotropic, lightweight, strong, and super thermally insulating nanowood with naturally aligned nanocellulose," *Science Advances* 4, no. 3 (2018), 1–9. DOI: 10.1126/sciadv.aar3724. See also, Amina Khan, "This is 'nanowood,' an invention that could reduce humanity's carbon footprint," *Los Angeles Times* (12 March 2018), https://phys.org/news/2018-03-nanowood-humanity-carbon-footprint.html.

50 Jonathon Brame, Qilin Li, and Pedro J.J. Alvarez, "Nanotechnology-enabled water treatment and reuse: emerging opportunities and challenges for developing countries," *Trends in Food Science & Technology* 22, issue 11 (2011): 618–624, https://doi.org/10.1016/j.tifs.2011.01.004; and Jijo Abraham, Kalangi S. Vasu, Christopher D. Williams, Kalon Gopinadhan, Yang Su, Christie T. Cherian, James Dix, Eric Prestat, Sarah J. Haigh, Irina V. Grigorieva, Paola Carbone, Andre K. Geim, and Rahul R. Nair, "Tunable sieving of ions using graphene oxide membranes," *Nature Nanotechnology* 12 (2017): 546–550, doi:10.1038/nnano.2017.21. See also, "Graphene sieve turns seawater into drinking water," *Phys.Org* (3 Apr 2017): https://phys.org/news/2017-04-graphene-sieve-seawater.html; and Frans Møller Christensen, Anna Brinch , Jesper Kjølholt, Paul D. Mines , Nana Schumacher, Torben Højbjerg Jørgensen, and Reto Michael Hummelshøj, "Nano-enabled environmental products and technologies - opportunities and drawbacks," Miljøprojekt nr. 1803 (Copenhagen K: Danish Environmental Protection Agency, 2015).

51 Kumar Suranjit Prasad and Vivek Kumar, "Nanotechnology in sustainable agriculture: Present concerns and future aspects," *African Journal of Biotechnology* 13, no. 6 (Feb 2014): 705–713, DOI: 10.5897/AJBX2013.13554; and Christensen et al., "Nano-enabled environmental products and technologies."

52 See for example, Nadejda Sertova, "Application of nanotechnology in detection of mycotoxins and in agricultural sector," *Journal of Central European Agriculture* 16, no. 2 (2015): 117–130, DOI: 10.5513/JCEA01/16.2.1597; Alexandru Grumezescu, ed., *Food Preservation: Nanotechnology in the Agri-Food Industry* (London: Academic Press - Elsevier, 2016); and María L. Zambrano-Zaragoza, Ricardo González-Reza, Néstor Mendoza-Muñoz, Verónica Miranda-Linares, Tania F. Bernal-Couoh, Susana Mendoza-Elvira, and David Quintanar-Guerrero, "Nanosystems in edible coatings: A novel strategy for food preservation," *International Journal of Molecular Sciences* 19, no. 3 (Mar 2018): 705, doi:10.3390/ijms19030705.

53 Sandhya Mishra, Chetan Keswani, P.C. Abhilash, Leonardo F. Fraceto, and Harikesh Bahadur Singh, "Integrated approach of Agri-nanotechnology: Challenges and future trends," *Frontiers in Plant Science* 8 (4 Apr 2017), doi: 10.3389/fpls.2017.00471; and Dae�Young Kim, Avinash Kadam, Surendra Shinde, Rijuta Ganesh Saratale, Jayanta Patra, and Gajanan Ghodake, "Recent developments in nanotechnology transforming the agricultural sector: A transition replete with opportunities," *Journal of the Science of Food and Agriculture* 98, issue 3 (Feb 2018): 849–864, https://doi.org/10.1002/jsfa.8749.

54 For example, Joginder Singh Duhan, Ravinder Kumar, Naresh Kumar, Pawan Kaur, Kiran Nehra, and Surekha Duhan , "Nanotechnology: The new perspective in precision agriculture," *Biotechnology Report* 15 (Sep 2017): 11–23, doi: 10.1016/j.btre.2017.03.002; M. Rai and A. Ingle, "Role of nanotechnology in agriculture with special reference to management of insect pests," *Applied Microbiology and Biotechnology* 94, no. 2 (Apr 2012): 287–293, doi: 10.1007/s00253-012-3969-4; V. Ghormade, M.V. Deshpande, and K.M. Paknikar, "Perspectives for nano-biotechnology enabled protection and nutrition of plants," *Biotechnology Advances* 29, no. 6 (Nov-Dec 2011): 792–803, doi: 10.1016/j.biotechadv.2011.06.007; Kim et al., "Recent developments in nanotechnology"; and Sahayaraj Kitherian, "Nano and Bio-nanoparticles for Insect Control," *Research Journal of Nanoscience and Nanotechnology* 7 (2017): 1–9, DOI:10.3923/rjnn.2017.1.9.

55 Leonardo F. Fraceto, Renato Grillo, Gerson A. de Medeiros, Viviana Scognamiglio, Giuseppina Rea, and Cecilia Bartolucci, "Nanotechnology in agriculture: Which innovation potential does it have?" *Frontiers in Environmental Science* (22 Mar 2016): doi: 10.3389/fenvs.2016.00020.

56 For example, Anshu Rastogi, Marek Zivcak, Oksana Sytar, Hazem M. Kalaji, Xiaolan He, Sonia Mbarki, and Marian Brestic, "Impact of metal and metal oxide nanoparticles on plant: A critical review," *Frontiers in Chemistry* 5 (12 Oct 2017):78, doi: 10.3389/fchem.2017.00078; and S.C.C. Arruda, A.L. Silva, R.M. Galazzi, R.A. Azevedo, and M.A. Arruda, "Nanoparticles applied to plant science: A review," *Talanta* 131 (Jan 2015): 693–705. https://doi.org/10.1016/j.talanta.2014.08.050; and Mishra et al., "Integrated approach of Agri-nanotechnology."

57 Darryl Macer, "Nanotechnology and Biodiversity," in *In Pursuit of Nanoethics*, ed. Bert Gordijn and Anthony Mark Cutter (Dordrecht: Springer, 2014), 73–88; and Gonçalo Vale, Kahina Mehennaoui, Sebastien Cambier, Giovanni Libralato, Stéphane Jomini, Rute F. Domingos , "Manufactured nanoparticles in the aquatic environment – Biochemical responses on freshwater organisms: A critical overview," *Aquatic Toxicology* 170 (Nov 2015): 162–174. http://dx.doi.org/10.1016/j.aquatox.2015.11.019.

58 See OECD, *Small sizes that matter: Opportunities and risks of nanotechnologies,* Report in Co-operation with the OECD International Futures Programme (Organization for Economic Co-operation and Development (OECD, 2004), and references cited therein. See also K. Tomar, "Nanotechnology: recent developments, applications, risk and techniques," *International Journal of Engineering Science and Computing* 7 (2017): 14264–14268, and references cited therein; and International Risk Governance Council, *Policy Brief: Nanotechnology Risk Governance. Recommendations for a global, coordinated approach to the governance of potential risks* (2007), https://www.irgc.org/IMG/pdf/PB_nanoFINAL2_2_.pdf

59 Renn and Roco, "Nanotechnology."

60 Renn and Roco, "Nanotechnology"; and OECD, *Small sizes that matter*.

61 Renn and Roco, "Nanotechnology"; International Risk Governance Council, *Policy Brief*; K. Pathakoti et al., "Nanostructures: Current uses and future applications in food science," *Journal of Food and Drug Analysis* 25 (2017): 245–253, https://doi.org/10.1016/j.jfda.2017.02.004; and G. Miller and M. Kearnes, "Nanotechnology, ubiquitous computing and the internet of things: challenges to rights to privacy and data protection," Draft Report to the Council of Europe (2013): https://rm.coe.int/168067f7f5.

62 Sara Reardon 2016. Welcome to the CRISPR Zoo. Nature, 531, https://www.nature.com/news/welcome-to-the-crisprzoo-1.19537; E. Dolgin, "CRISPR hacks enable pinpoint repairs to genome, *Nature News* (25 Oct 2017): https://www.nature.com/news/crispr-hacks-enable-pinpoint-repairs-to-genome-1.22884; and Heidi Ledford, "CRISPR, the disruptor," *Nature News* (3 June 2015): https://www.nature.com/news/crispr-the-disruptor-1.17673.

63 K. Yin, C. Gao, and J.L Qiu, "Progress and prospects in plant genome editing," *Nature Plants* 3, (31 July 2017): 17107. DOI: 10.1038/nplants.2017.107; and UC Berkeley Public Affairs, "CRISPR Put To Work to Save Chocolate from Devastation," *UC/Berkeley Research News* (2 Jan 2018), http://news.berkeley.edu/story_jump/crispr-put-to-work-to-save-chocolate-from-devastation/.

64 Caixia Gao, "The future of CRISPR technologies in agriculture," *Nature Reviews Molecular Cell Biology* 19 (2018): 275–276: doi:10.1038/nrm.2018.2; and S. Adams, "Bayer and Ginko Bioworks, A Startup, Aim to Make Crops Produce Their Own Nitrogen Fertilizer," *Forbes* (14 Sep 2017): https://www.forbes.com/sites/susanadams/2017/09/14/new-venture-aims-to-make-crops-produce-their-own-nitrogen-fertilizer/#f5b55611db0e.

65 Imad Ajjawi, John Verruto, Moena Aqui, Leah B. Soriaga, Jennifer Coppersmith, Kathleen Kwok, Luke Peach, Elizabeth Orchard, Ryan Kalb, Weidong Xu, Tom J Carlson, Kristie Francis, Katie Konigsfeld, Judit Bartalis, Andrew Schultz, William Lambert, Ariel S. Schwartz, Robert Brown, and Eric R Moellering, "Lipid production in *Nannochloropsis gaditana* is doubled by decreasing expression of a single transcriptional regulator, *Nature Biotechnology* 35 (2017): 647–652. DOI: 10.1038/nbt.3865.

66 Kathiann Kowalski, "Can DNA editing save endangered species? *Science News for Students* (6 Mar 2018): https://www.sciencenewsforstudents.org/article/can-dna-editing-save-endangered-species; Emma Marris, "Process of Elimination," Wired (20 Feb 2018): https://www.wired.com/story/crispr-eradicate-invasive-species/; and Hillary Rosner, "Tweaking Genes to Save Species, *New York Times* (17 April 2016), https://www.nytimes.com/2016/04/17/opinion/sunday/tweaking-genes-to-save-species.html

67 Kyros Kyrou, Andrew M. Hammond, Roberto Galizi, Nace Kranjc, Austin Burt, Andrea K Beaghton, Tony Nolan, and Andrea Crisantit., "A CRISPR–Cas9 gene drive targeting *doublesex* causes complete population suppression in caged *Anopheles gambiae* mosquitoes," *Nature Biotechnology* (2018): DOI: 10.1038/nbt.4245.

68 See SynBioWatch, "Common Call for a Global Moratorium on Genetically-engineered Gene Drives" (5 Dec 2016): http://www.synbiowatch.org/gene-drives/gene-drives-moratorium/.

69 For example, Megan Molteni, "This gene editing technique may be too dangerous to unleash," *Wired* (16 Nov 2017) : https://www.wired.com/story/this-gene-editing-tech-might-be-too-dangerous-to-unleash/; David King, "Editing the human genome brings us one step closer to consumer eugenics," *The Guardian* (4 Aug 2017): https://www.theguardian.com/commentisfree/2017/aug/04/editing-human-genome-consumer-eugenics-designer-babies; and J.R. Clapper, *Statement for the Record, Worldwide Threat Assessment of the U.S. Intelligence Community* (Senate Armed Services Committee, 9 Feb 2016). https://www.dni.gov/files/documents/SASC_Unclassified_2016_ATA_SFR_FINAL.pdf

70 Pollack, A. 2015. Genetically engineered salmon approved for consumption. *New York Times* (20 Nov 2015): https://www.nytimes.com/2015/11/20/business/genetically-engineered-salmon-approved-for-consumption.html.

71 New Harvest, "Cellular Agriculture": https://www.new-harvest.org/cellular_agriculture.

72 Sasha Mandy and Érika Bergeron-Drolet, "Cellular agriculture – an introduction," *Cultivate: Food and Agribusiness Newsletter* 13 (Jul 2017): 02-03, http://www.nortonrosefulbright.com/files/cultivate-issue-13-154880.pdf.

73 Hanna L. Tuomisto and M. Joost Teixeira de Mattos, "Environmental impacts of cultured meat production," *Environmental Science & Technology* 45, no. 14 (2011): 6117–6123. DOI: 10.1021/es200130u. This finding is also supported by the study, Hanna Tuomisto and Avi Roy, "Could cultured meat reduce environmental impact of agriculture in Europe?" *8th International Conference on LCA in the Agri-Food Sector, Rennes, France, 2-4 October 2012*: https://www.researchgate.net/publication/255179690_Could_cultured_meat_reduce_environmental_impact_of_agriculture_in_Europe.

74 A. Rorheim, A. Mannino, T. Baumann, and L. Caviola, "Cultured meat: An ethical alternative to industrial animal farming," Policy paper by *Sentience Politics* 1, (2016): 1–14, https://sentience-politics.org/files/cultured-meat-revision.pdf; and C. Purdy, "A tech startup is making convincing cow-free milk by genetically engineering yeast," *Quartz* (20 Dec 2017): https://qz.com/1161955/perfect-day-is-making-convincing-cow-free-milk-by-genetically-engineering-yeast/.

75 Tuomisto and Teixeira de Mattos, "Environmental impacts of cultured meat production."

76 Carolyn S. Mattick, "Cellular agriculture: The coming revolution in food production," *Bulletin of the Atomic Scientists* 74, issue 1 (2 Jan 2018), https://doi.org/10.1080/00963402.2017.1413059; C.S. Mattick, A.E. Landis, B.R. Allenby, and N.J. Genovese, "Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States," *Environmental Science & Technology* 49, no. 19 (6 Oct 2015): 11941–11949, DOI: 10.1021/acs.est.5b01614; and Sergiy Smetana, Alexander Mathys, Achim Knoch, and Volker Heinz, "Meat Alternatives: Life cycle assessment of most known meat substitutes," *The International Journal of Life Cycle Assessment* 20, no. 9 (2015): 1254–1267, https://doi.org/10.1007/s11367-015-0931-6

77 Neil Stephens, Lucy Di Silvio, Illtud Dunsford, Marianne Ellis, Abigail Glencross, and Alexandra Sexton, "Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in Cellular Agriculture," *Trends in Food Science & Technology* 78 (Aug 2018): 155–166, https://doi.org/10.1016/j.tifs.2018.04.010.

78 Mandy and Bergeron-Drolet, "Cellular agriculture – an introduction"; Ahmed Khan, "Cellular Agriculture: The Obstacles Ahead," *CellAgri* (25 Jan 2018): https://medium.com/cellagri/cellular-agriculture-the-obstacles-ahead-83ecd77115ac; and Stephens et al., "Bringing cultured meat to market."

79 Stephens et al., "Bringing cultured meat to market."

80 Khan, "Cellular Agriculture"; and Emma Cosgrove,"What do farmers think about cultured meat? *AgFunder News* (12 Oct 2017): https://agfundernews.com/what-do-farmers-think-about-cultured-meat.html.

81 Oron Catts, "Opinion: Weighing up lab-grown steak—the problems with eating meat are not Silicon Valley's to solve," *Phys.Org* (12 Oct 2017). https://phys.org/news/2017-10-opinion-lab-grown-steakthe-problems-meat.html

82 For example, see R.A. Le Feuvre and N.S. Scrutton, "A living foundry for Synthetic Biological Materials: A synthetic biology roadmap to new advanced materials," *Synthetic and Systems Biotechnology* 3 (2018), 105–112. https://doi.org/10.1016/j.synbio.2018.04.002; A.K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable Bio-Composites from Renewable Resources: Opportunities and Challenges in the Green Materials World," *Journal of Polymers and the Environment* 10, nos. 1 /2 (April 2002): 19-26, https://doi.org/10.1023/A:1021013921916; and National Research Council, *Biobased Industrial Products: Research and Commercialization Priorities* (Washington, DC: The National Academies Press, 2000): https://doi.org/10.17226/5295.

83 S. Galanie, K. Thodey, I.J. Trenchard, M. Filsinger Interrante, and C.D. Smolke, "Complete biosynthesis of opioids in yeast," *Science* 4 (4 Sep 2015): 349 (6252): 1095–1100. doi:10.1126/science.aac9373; S.H.M. Azhar, "Yeasts in sustainable bioethanol production: A review," *Biochemistry and Biophysics Reports* 10 (2017): 52–61. https://doi.org/10.1016/j.bbrep.2017.03.003; F.H. Lam, "Engineering alcohol tolerance in yeast," *Science* 346 (2014): 71–75. DOI: 10.1126/science.1257859 ; and Nethaji J. Gallage and Birger Lindberg Møller, "Vanillin-Bioconversion and Bioengineering of the Most Popular Plant Flavor and Its *De Novo* Biosynthesis in the Vanilla Orchid," *Molecular Plant* 8, issue 1 (5 January 2015): 40–57, https://doi.org/10.1016/j.molp.2014.11.008 .

84 Víctor de Lorenzo, Kristala L.J .Prather, Guo‐Qiang Chen, Elizabeth O'Day, Conrad von Kameke, Diego A Oyarzún, Leticia Hosta‐Rigau, Habiba Alsafar, Cong Cao, Weizhi Ji, Hideyuki Okano, Richard J Roberts, Mostafa Ronaghi, Karen Yeung, Feng Zhang, and Sang Yup Lee, "The power of synthetic biology for bioproduction, remediation and pollution control," *EMBO Reports* (2018) e45658. DOI 10.15252/embr.201745658.

85 Judith Becker and Christoph Wittmann, "Advanced Biotechnology: Metabolically Engineered Cells for the Bio-Based Production of Chemicals and Fuels, Materials, and Health-Care Products," *Angewandte Chemie - International Edition* 54, issue 11 (Mar 2015): 3328–3350, doi:10.1002/anie.201409033; and K.A. Baritugo , H.T. Kim, Y. David, J.I. Choi, S.H. Hong, K.J. Jeong, J.H. Choi, J.C. Joo, and S.J. Park, "Metabolic engineering of Corynebacterium glutamicum for fermentative production of chemicals in biorefinery," *Applied Microbiology and Biotechnology* 102, no. 9 (May 2018): 3915–3937, https://doi.org/10.1007/s00253-018-8896-6.

86 BioMason, https://biomason.com/technology/.

87 Luc Alaerts, Michael Augustinus, and Karel Van Acker, "Impact of bio-based plastics on current recycling of plastics," *Sustainability* 10 (2018), 1487, doi:10.3390/su10051487.

88 J.C. Philp, "Biobased chemicals: the convergence of green chemistry with industrial biotechnology," *Trends in Biotechnology* 31 (2013): 219–222, https://doi.org/10.1016/j.tibtech.2012.12.007.

89 ETC Group, *Synthetic Biology, Biodiversity & Farmers: Case studies exploring the impact of synthetic biology on natural products, livelihoods and sustainable use of biodiversity,* ETC Communiqué #116 (April 2016): http://www.etcgroup.org/sites/www.etcgroup.org/files/files/etc_synbiocasestudies_2016.pdf.

90 A. Greenfield and T.E. Graedel, "The omnivorous diet of modern technology," *Resource Conservation Recycling* 74 (2013): 1–7. http://dx.doi.org/10.1016/j.resconrec.2013.02.010; and P. Nuss and G.A. Blengini, "Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles," *Science of the Total Environment* 613–614 (2017): 569–578. https://doi.org/10.1016/j.scitotenv.2017.09.117.

91 See *Financial Times*, "Africa holds promise of rare earth riches" (6 Mar 2017): https://www.ft.com/content/88abbe52-0261-11e7-aa5b-6bb07f5c8e12; Xiang Huang, Guochun Zhang, An Pan, Fengying Chen, and Chunli Zheng, "Protecting the environment and public health from rare earth mining," *Earth's Future* 4, issue 11 (Nov 2016): 532–535, doi:10.1002/2016EF000424; and Winfred Espejo, Cristóbal Galbán-Malagón and Gustavo Chiang Merimoyu, "Risks from technology-critical metals after extraction," *Nature* 557 (23 May 2018): 492, https://www.nature.com/articles/d41586-018-05234-6.

92 Open Plant Project 2017, *Bakubung Workshop Report: Capacity Building for the Bioeconomy in Africa* (Cambridge: Cambridge University Press, 2017). http://www.haseloff-lab.org/resources/SynBio_reports/Bakubung-FinalReport-Web.pdf

93 GEF Secretariat, *GEF 2020: Strategy for the GEF* (Global Environment Facility, 1 Aug 2015): https://www.thegef.org/publications/gef-2020-strategy-gef.

94 GEF-7 Replenishment, "Programming Direction."

95 GEF Secretariat, *GEF 2020 Strategy for the GEF.*

96 See OECD Conference, *Innovating the Public Sector: from Ideas to Impact, Paris, 12–13 November 2014* (Paris: OECD Conference Centre, 2014).

97 Data from Fundly, "Crowdfunding Statistics" (https://blog.fundly.com/crowdfunding-statistics/).

98 DIYBio - An Institution for the Do-It-Yourself Biologist: https://diybio.org/.

99 The Fab Foundation, http://fabfoundation.org/.

100 Annabelle Gawer and Michael A. Cusumano, *Platform Leadership: How Intel, Microsoft, and Cisco Drive Industry Innovation* (Boston: Harvard Business School Press, 2002); and Henry Chesbrough, "Open Platform Innovation: Creating Value from Internal and External Innovation," *Intel Technology Journal* 7, no. 3 (Aug 2003): 5–9, https://www.semanticscholar.org/paper/Creating-Value-from-Internal-and-External-Innovati-Chesbrough/033c06f4208502481eba35e71123a496ad24f398

101 See for example, Acorn Collective, "Blockchain for Funding: Acorn Collective Helping Crowdfunding for Startups" (8 May 2018), https://themerkle.com/blockchain-for-funding-acorn-collective-helping-crowdfunding-for-startups/

102 M.S. Hull, Sustainable Nanotechnology: A Regional Perspective, in *Nanotechnology Environmental Health and Safety, Second Edition*, ed. Matthew Hull and Diana Bowman (Norwich, NY: William Andrew - Elsevier, 2014): 395–424. https://doi.org/10.1016/B978-1-4557-3188-6.00016-5

103 This could involve organizing bio-economy summits (https://2018.synbiobeta.com/) or attending meetings of organizations like the Synthetic Biology Innovation Network - SynbioBeta (https://synbiobeta.com/).

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