EBRC

Climate & Sustainability Roadmap

Interim Report

November, 2021

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Introduction

Engineering biology to tackle climate and sustainability challenges

Engineering biology – a convergence of biology, chemistry, computer science, and engineering – enables scientists and engineers to design and modify biological systems faster, cheaper, and more precisely than ever before. Engineering biology comprises many powerful technologies that enable the predictive engineering of living organisms and their constituent parts, from modifying DNA in cells, to engineering microorganisms to produce chemicals and materials, to conferring new abilities to plants and animals. These technologies could potentially transform emissions-intensive sectors like agriculture and heavy-duty transportation, complement nature-based solutions to help the world adapt to a changing climate, and mitigate environmental damage from industrial processes.

About EBRC

The Engineering Biology Research Consortium (EBRC) is a non-profit, public-private partnership dedicated to bringing together an inclusive community committed to advancing engineering biology to address national and global needs. We showcase cutting-edge research in engineering biology, identify pressing challenges and opportunities in research and application, articulate compelling research roadmaps and programs to address them, and provide timely access to other key developments in engineering biology.

About the roadmap and interim report

The Climate and Sustainability Roadmap aims to identify research opportunities that respond to the urgency of the climate crisis, explore ambitious research goals for precipitating a greener future, and discuss the ethical and social implications of engineering biology for climate and sustainability.

With this technical roadmap, EBRC hopes to establish a resource for the research and research-support community including educators, policymakers, and funding bodies. For engineering biology researchers, the roadmap identifies climate and sustainability challenges where engineering biology innovations could make significant impacts. For researchers working in climate-related fields, the roadmap presents emerging opportunities and approaches that could be added to our arsenal to fight climate change. Importantly, we hope this roadmap will provide an opportunity to spark cross-disciplinary collaborations, which are critical for tackling these multifaceted challenges. For policymakers and funding bodies, the roadmap highlights potential funding directions in which engineering biology intersects with climate and sustainability, and where advancing the state-of-the-art could have major impacts toward reaching climate goals.

This interim report provides an overview of the current structure and major themes of the Climate and Sustainability Roadmap. The content and structure of the roadmap is likely to change as we continue to draft the roadmap and receive contributions and input from more subject-area experts and stakeholders. The interim report highlights the two overarching topics of the roadmap (Climate Mitigation & Adaptation and Environment & Sustainability), the major technical themes we are considering within each topic, and potential goals, breakthrough capabilities, and milestones that will accompany those technical themes.

With this interim report, we hope to engage new contributors to the roadmap, including a wider group of engineering biology experts, in the themes and goals highlighted in the roadmap, as well as experts from the broader research community working on climate change and environmental sustainability, experts focusing on the social dimensions where impacts of technology advancement and climate change are felt, and other stakeholders who are invested and impacted by these topics.

Roadmap Structure

This roadmap is divided into two technical sections: *Climate Change Mitigation and Adaptation* and *Environment and Sustainability*. The first section on Climate Change Mitigation and Adaptation consists of three Technical Themes: 1) Enabling Large-scale Biosequestration of Greenhouse Gases; 2) Application Sector-specific Opportunities for Climate Mitigation and Adaptation, which covers three industry sectors - Food and Agriculture, Transportation and Energy Production, and Materials Production; and 3) Conservation of Ecosystems and Biodiversity. The second section on Environmental and Sustainability consists of two Technical Themes: 1) Enabling Sustainable Industrial and Chemical Processes; and 2) Mitigating Pollution. A final section is devoted to discussing the *Social Dimensions and Policy Levers* important to the technical topics explored in the roadmap.

Each technical theme covers a series of transformative tools and technologies that will have a significant impact on revolutionizing the field. These potentially transformative technologies (and how to develop them) are articulated in the form of aspirational Research Goals that drive the progression of research and development. Within each research goal, the roadmap delineates a series of short-term, mid-term, and long-term milestones. Short-term milestones are objectives intended to be reached with current funding paradigms, existing infrastructure, facilities, and resources. The mid-term and long-term milestones are more ambitious achievements that require increased funding and resources, and new or improved infrastructure, but result in significant technical advancements. The final roadmap will include specific timeframes for each milestone (e.g., 5, 10, 20 years), which are not included in this interim report. These timeframes will also be adjusted to account for the time constraints posed by urgency of the climate crisis.

The roadmapping process

EBRC's roadmapping is an iterative process of brainstorming and discussion, drafting, review, and revision. To create the roadmap, EBRC has hosted a number of writing workshops since July 2021, and will continue to hold drafting workshops through February 2022. Roadmap contributors participate in workshops and collaborative writing sessions, building on the work of their colleagues and bringing new ideas and approaches to each strategy laid out in the roadmap's milestones and technical achievements.

The climate crisis presents complex and multifaceted challenges. As we develop this roadmap, we are excited to engage with EBRC members and the broader research community on this important roadmapping effort. We welcome contributions from academic, industry, and government scientists and engineers, research & development leadership, students and postdocs, and other stakeholders.

The final release of this roadmap will include an interactive website, hosted within the roadmap.ebrc.org domain, a printable PDF version, and associated figures and graphics. We anticipate online publication of the full roadmap in April, 2022. Any questions about the roadmap, or suggestions for content or contributors, can be directed to roadmapping@ebrc.org.

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Climate Change Mitigation & Adaptation

The climate crisis demands the rapid decarbonization of our economy and transformations across multiple industry sectors to eliminate and prevent further emissions of greenhouse gases. Additionally, analysis by the IPCC shows that carbon dioxide removal (CDR), the process of removing CO_2 from the atmosphere and sequestering it away, will be a crucial component for keeping global warming under 1.5°C and achieving U.S. and global emissions reduction targets by 2050[1]. Engineering biology approaches considered in Climate Change Mitigation & Adaptation include technologies to capture, convert, and remove greenhouse gases; applications to reduce emissions and address climate challenges associated with specific economic sectors, including sustainable food and agriculture systems, energy production and transportation, and industrial bioprocesses for chemical and materials production; and approaches to mitigate climate events and perturbations to improve biodiversity and ecosystem resilience. While potentially impactful, many of the research paths presented here will take significantly longer to deploy than existing technologies, and all require concerted effort, investment, and cross-disciplinary collaboration to bear fruit. As such, the research proposed here should be developed as part of a broad suite of climate solutions and in the context of their impacts and usefulness toward different geographies, cultures, and economies.

Technical Theme: Enabling Large-scale Biosequestration of Greenhouse Gases

The biosphere is one of the largest carbon sinks on the planet. But partly due to climate change, the capacity for the biosphere to capture carbon is shrinking. Engineering biology could restore or even increase the biosphere's carbon uptake. **Enabling Large-Scale Biosequestration of Greenhouse Gases** focuses on achieving two research goals: 1) the at-scale capture, storage, and utilization of greenhouse gases (GHGs) by engineered organisms; and, 2) how to use engineering biology to enhance natural systems for carbon capture and to mitigate warming.

Under the first goal, the roadmap will explore several research milestones for **engineering photosynthetic organisms to be more efficient at CO_2 uptake**. For example, near-term milestones include engineering key components involved in carbon fixation to improve the CO_2 uptake efficiency in plants, and transplanting CO_2 concentrating mechanisms (CCMs) from cyanobacteria and algae into plants and model organisms. The roadmap will also outline milestones to **enable GHG storage and utilization by organisms**, including the research needed to engineer organisms to convert CO_2 and methane into compounds for long-term storage (e.g., as calcium carbonate or commodities like bioplastics). Finally, the roadmap will focus on the means to **scale up biosequestration technologies**, for example, by addressing challenges to improve gas fermentation technology, with the long-term goal of enabling organisms to capture different types of GHGs from concentrated streams and ambient air.

Under the second goal, the roadmap will focus on **engineering biology for enhancing natural systems to increase carbon uptake and mitigate warming.** Land and ocean together are responsible for absorbing roughly 50% of annual global CO_2 emissions[2], but these carbon sinks are projected to become less effective over time (i.e., taking up a smaller portion of total emissions)[3]. The roadmap will address improving soil carbon sequestration via engineering biology, with milestones on engineering crop plants to store more carbon in their root systems, engineering soil microbiome to increase carbon sequestration, and engineering organisms to slow down the degradation of wetlands, a massive natural carbon sink. Milestones towards enhancing ocean carbon capacity will include designing and engineering organisms (e.g., microbes, phytoplankton, algae) and systems (e.g., viral shunts) for carbon capture and sequestration on the ocean surface and in the deep ocean, and for mitigating ocean acidification. This section will also include research paths to mitigate warming, such as developing ice-nucleating microbes, which could be deployed on land to maintain snowpack, create more reflective surfaces in alpine and polar environments, and preserve permafrost and prevent carbon release.

As with other CDR technologies, biobased carbon capture is neither a replacement for drastic emissions reduction nor a justification for delaying climate actions, and must be developed in conjunction with other approaches to deep decarbonization. In addition, engineering biology-enabled carbon capture in ecosystems faces unique environmental implications that must be addressed, including the biocontainment of engineered organisms and the potential of competition between engineered organisms and non-engineered, native species.

Technical Theme: Combating Climate Change in Application Sectors

I. Food and Agriculture

The agricultural sector is the largest source of anthropogenic methane. Reducing this GHG is now a top priority as part of the pathway to combat climate change[4]. Current agricultural practices also generate other GHGs such as nitrous oxide (N_2O) from synthetic fertilizer usage, which leads to run-offs and eutrophication of ecosystems. This roadmap will set out **engineering biology research goals to enable the production of food and crops with lower GHGs.**

The Haber process is a cornerstone of modern agriculture. During this process, inorganic nitrogen in the air is combined with hydrogen (mostly from natural gas) to produce ammonia, which is used to makes nitrogen fertilizers that supply vital nutrients for crop growth. However, the Haber process is energy intensive, relies on natural gas, and generates large amounts of N_2O — a potent and long-lived GHG with 300 times the warming potential of CO_2. Here, the roadmap will focus on developing more sustainable biobased fertilizer alternatives that reduce the need for water, enable the use of marginal land for plant growth, and prevent ecological disruption caused by run-off of water-soluble nitrates. An important research goal is to **engineer crops to more effectively assimilate nitrogen, phosphorus, and other nutrients** vital for crop growth, by identifying microorganisms and pathways for nutrient fixation and incorporating symbiotic bacteria like rhizobia into non-legume plants. Another goal is to **restore soil health and facilitate crop growth on marginal lands**. Milestones toward this goal include modifying plant root systems to store more nutrients in the soil and engineering soil microbiomes to improve water retention and nutrient uptake.

To tackle emissions from livestock - in particular, those of domestic ruminants, the roadmap will explore approaches to **engineer ruminant gut microbiomes** to inhibit methane production (e.g., by colonizing the ruminant gut with methanotrophs via feed or inoculation) and to **improve the nutrient profiles of animal feed**, such as enabling microbes to synthesize nutrients (e.g., essential amino acids, micronutrients, vitamins) not naturally found in unprocessed feed.

Alternative meats and proteins offer another means to continue feeding a growing global population, while reducing the consumption of land, water, fertilizers, and pesticides. The roadmap will explore how to **enable**

alternative meats and proteins to compete on taste, price, safety, and accessibility with their conventional counterparts. This includes advancing protein engineering to improve the texture and the nutritional value of cellular meats, developing microbes and fermentation processes to add complex flavors and textures to plant-based proteins, lowering the cost of key ingredients (e.g., flavorings, enzymes) through biosynthesis, and developing novel, low-cost feedstocks for cellular agriculture. Long-term milestones envision new food production platforms including novel protein sources with calibrated nutritional content and flavor palettes, and food produced through a completely circular process (e.g., microbes that convert industrial or agricultural side-streams into food).

Engineering biology can help the food and agriculture sector better adapt to a changing climate. More intense and frequent droughts and heat waves have decimated agricultural output in all parts of the world, but have been especially detrimental to the Global South[1]. The roadmap will focus on **engineering biology research to help build crop resistance to biotic and abiotic stresses**, including improving drought and flood tolerance in plants by engineering leaves and root systems, designing soil microbiomes to improve plant health and help plants survive under stressful environmental conditions (e.g., heat, high salinity), and increasing crop resistance to pathogens without using environmentally harmful pesticides. Other milestones toward a climate resilient agriculture include developing algae and kelp aquaculture and advancing urban and indoor farming.

Climate change also threatens global food supply chains by disrupting food transportation and increasing the likelihood of food spoilage. The roadmap will present research goals to **mitigate spoilage and ensure food security**. Milestones will include developing food-safe coatings to lengthen the shelf life of produce, enabling food suppliers to detect and control when produce ripen, and creating biosensor systems to indicate the presence of pathogens or early signs of spoilage.

II. Transportation and Energy Production

Almost three quarters of today's anthropogenic GHG emissions come from energy production[5]. The roadmap will focus on two goals to mitigate these emissions: 1) developing engineering biology approaches to reduce emissions from aviation and shipping; and, 2) enabling biology to supplement renewable energy sources.

The first research goal focuses on **reducing emissions from transportation.** Aviation, marine shipping, and heavy-duty transport together contribute to 7.4% of global emissions, but are hard to decarbonize because current technologies are unable to provide the energy density needed. Biofuels may offer large GHG emission reductions and in some cases can be used as a 'drop-in' fuel, requiring very little alteration to the incumbent engines[6]. **The roadmap will outline research needed to advance the current state of the art to make biofuels more sustainable, scalable, and affordable.** Short-term milestones include enabling feedstock crops (e.g., switchgrass, sorghum) to grow on marginal lands (i.e., land with poor irrigation or fewer nutrients in soil) and improving carbon utilization from feedstocks (e.g., more efficient ways to degrade lignocellulose). Mid-term milestones will focus on improving the fermentation of feedstocks to enable industrial-scale production of sustainable biofuels. These include reducing the processing times during fermentation, engineering organisms to utilize all available carbon sources, selecting and optimizing organisms for each stage of the fermentation process, and engineering extremophiles to convert biomass into hydrocarbons at an industrial scale. Long-term milestones will aim to address the oxidation and degradation of biofuels during storage, and improving biofuel lubricity and conductivity. For marine shipping specifically, the roadmap will also explore biobased applications to improve shipping efficiency, such as reducing hydrodynamic drag on ships by coating hull surfaces with environmentally friendly antifouling biomaterials.

The second research goal will focus on **enabling biological systems to store and produce energy.** Milestones will aim to explore how to leverage engineering biology to supply rare-earth elements needed for renewable energy production, and drive advances in biobased fuel cells and biomass energy storage (e.g., converting excess electricity from renewable energy sources into biomass). A final set of milestones will focus on reducing emissions from existing energy infrastructure, such as engineering organisms to detect and patch methane leaks in natural gas pipelines.

III. Materials Production

The manufacturing of materials consumes large amounts of energy and is a substantial source of global GHG emissions[7]. Materials Production focuses on **replacing emissions-intensive and environmentally damaging materials with sustainable biobased alternatives.** These materials include cement and other building materials, plastics, and textiles. The list of materials here is not exhaustive and may be expanded in the final roadmap.

The manufacturing of building materials is energy and carbon intensive - steel and cement productions already account for 10% of global GHG emissions[5] and are projected to grow in the coming decades[8]. The roadmap will focus on a goal of using **engineering biology to facilitate the production of sustainable building materials**, such as low-carbon concrete and high-density wood. Milestones toward this goal include engineering biocementing microbes to grow faster and produce stronger (i.e., more load bearing) biocement, engineering trees to produce denser wood for construction, scaling up the production of sustainable biobased wall materials (e.g., mycelium-based thermal insulation), developing organisms to repair buildings via biomineralization, and synthesizing novel biomaterials (e.g., engineered spider silk) to reinforce construction materials.

Another research goal aims to **advance solutions in biobased alternatives to replace fossil fuel derived plastics**. Globally, 380 million tons of plastic are produced every year[9], almost all of which are derived from fossil fuels and emit GHGs at every stage of their production. To address this, short-term milestones will focus on lowering the cost and improving the performance of biobased packaging materials (e.g., using biopolymers or mycelium), so they may fully replace conventional plastic packaging. Medium-term milestones will outline the research needed to make bioplastics for a wide range of applications (e.g., electronics) using various feedstocks, develop carbon-negative bioplastic manufacturing processes, and produce biopolymers that will not persist in the environment as waste.

The roadmap will also focus on **reducing the environmental footprint of the textile industry through engineering biology.** It has been estimated that the textile industry is responsible for 3-10% of global GHG emissions, in addition to consuming massive amounts of water and generating chemical waste[10]. Milestones will aim to make biobased textiles and dyes more affordable, sustainable, and better-performing than existing products. Short- to medium-term milestones include enabling the synthesis of various types of biopolymers to make textiles, engineering microbes to produce long-lasting bio-pigments, and scaling up the production of biomaterials like engineered spider silk and mycelium-based leather alternatives.

Technical Theme: Conservation of Ecosystems and Biodiversity

Climate change threatens ecosystems and biodiversity, and is a key driver of biodiversity loss[11]. Meanwhile, it is becoming increasingly clear that intact ecosystems are essential to human well-being and to mitigating and adapting to climate change. This part of the roadmap focuses on engineering biology approaches that could complement nature-based solutions to restore and protect biodiversity and ecosystems, with additional research goals on addressing the issues of biocontainment.

Extreme climate events - wildfires, droughts, heat waves, and floods - are already impacting communities and are poised to become even more frequent and intense as the planet continues to warm[4]. The roadmap will **explore engineering biology approaches to help mitigate risks from these extreme climate events**. Milestones will include, but not limited to, seeding trees with engineered organisms to increase water retention, improving bio-recycling of detritus and undergrowth to prevent wildfires, engineering soil microbiomes to reduce soil erosion, and developing measures to mitigate algal blooms near coastal communities.

Another roadmap research goal will focus on **leveraging engineering biology to prevent, limit, or reverse biodiversity loss.** Short- and mid-term milestones will look to advance a variety of technologies to limit biodiversity loss, such as increasing heat or low pH tolerance of corals (e.g., by engineering symbiotic algae), helping coastal vegetation (e.g., mangroves) better adapt to rising sea levels, expanding DNA sequencing to rapidly catalog existing biodiversity, and increasingly replace wild-sourced and unsustainable natural products with synthetic alternatives (e.g., synthetic palm oil, ivory, squalene). Long-term milestones will look to potentially restore ecosystem balance and reverse biodiversity loss, such as (re)assembling ecosystems and “reviving” extinct species lost to climate change and human activities.

The roadmap will outline research to reduce pathogen transmission and the spread of invasive species exacerbated by climate change, with milestones including developing gene drives to limit the spread of disease vectors, engineering the microbiome of honey bees and other pollinators to protect them against pathogens and pesticides, engineering soil microbiome to resist introgression from invasive plant species, and deploying advanced sensor networks to monitor the spread of pathogens and invasive species.

Finally, it is paramount to ensure biocontainment to prevent negative environmental impact. Milestones toward creating robust biocontainment measures include developing the capacity to monitor organisms post-release and detect signs of biocontainment breach, designing failsafe systems to ensure engineered organisms will not survive outside the intended environment, and identifying the ecological impacts of gene drives, such as any adverse effects the gene drive might have on non-target populations.

Environment & Sustainability

This section focuses on advancing engineering biology for long-term sustainable development, to the benefit of people and the planet. In this section, we ask the question, if the climate crisis were resolved, what sustainability challenges would remain? And how could engineering biology help tackle those challenges? Broadly, the research goals in this section focus on the technologies and tools needed to enable deployment of bioengineered systems to protect the environment through waste reduction, environmental remediation, and environmental monitoring.

Technical Theme: Enabling Sustainable Industrial and Chemical Processes

Modernizing industrial and chemical processes is important for transitioning to a more sustainable economy that is less damaging to the health of people and the environment. This technical theme focuses on three areas where engineering biology could make significant impacts in the near future: chemical synthesis, plastic waste, and mining.

Chemical production underpins multiple industry sectors, including textiles, electronics, and cosmetics, but as a result, releases large quantities of hazardous waste into the environment every year. Recently, the UN has called for urgent actions to minimize the impacts of chemicals on human health and the environment[12]. The roadmap presents **research paths for engineering biology to reduce the environmental impacts of chemical production**. Milestones include enabling organisms to produce chemical precursors at an industrial scale, lengthening the shelf life of biocatalysts and making them cheaper and more robust, and identifying and deploying enzymes to degrade toxic chemicals during the production process. Additional milestones will aim to address chemical waste within the biotechnology industry, such as moving away from chemical synthesis of DNA, which produces many toxic chemicals, and toward enzymatic DNA synthesis.

Plastic pollution has major impacts across multiple ecosystems, from the Great Pacific Garbage Patch to microplastics in Antarctica. Because of their long hydrocarbon polymer chains, plastics are highly resistant to degradation. **Engineering biology provides solutions to tackle plastic waste in two ways: 1) developing novel bioplastics and 2) creating new processes to degrade and upcycle plastic waste.** The former is covered under the Materials Production part of the Climate Mitigation and Adaptation section, as almost all plastics production is derived from fossil fuels; this section targets the latter. Research milestones include developing microbes capable of degrading common types of plastics with high efficiency, enabling the efficient breakdown of mixed waste plastics (e.g., multi-layer plastics such as those found in carpets or shoes), engineering organisms to degrade plastics in different ecological niches (e.g., in the soil, on the ocean floor), and developing organisms and bioprocesses to convert waste plastics into high value products.

Metals extracted from mining are used in everything from consumer electronics to wind turbines and solar panels to electric vehicles. Mining for new metals causes severe and lasting damage to the environment, and is increasingly becoming a source of geopolitical tensions. Meanwhile, precious metals worth billions of dollars are lost every year in un-recycled electronic waste[13]. To address these challenges, the roadmap will aim to drive research to **develop biotechnologies to extract and recover metals from metal ores and waste materials**. Short-term milestones include increasing metal uptake in organisms currently used in biomining and engineering microbes to extract rare-earth elements at low concentrations. Mid-term milestones will aim to develop a broad range of biological systems to accumulate different types of metal and enable biological systems to extract precious metals from electronic waste. Longer-term milestones include engineering biological systems to detect and degrade highly toxic pollutants on-site, such as cleaning up mining byproducts and even nuclear waste.

Technical Theme: Mitigating Environmental Pollution

The previous technical theme explored ways to reduce waste produced during industrial processes. Here, the focus will be on approaches to mitigate pollution that have already been released into the environment.

A roadmap research goal will aim to **improve the detection of pollutants using biosensors.** Compared to conventional sensors, biosensors are more affordable and portable, and could potentially detect a wider range of contaminants. Short-term milestones will focus on developing biosensors able to detect water contaminants at or below EPA limits, provide fast readouts, and perform detection of multiple contaminants simultaneously. Mid-term milestones include engineering biosensors to be more compatible with digital infrastructure (e.g., electrochemical biosensors), integrating biosensors into connected sensor networks, and making biosensors more robust against fouling and degradation. Additionally, many microorganisms are able to sense environmental pollutants. Relevant milestones will explore how to leverage this ability for pollution detection, while also addressing issues of biocontainment.

The roadmap will also focus on **advancing the state-of-the-art in bioremediation.** Milestones will include increasing the cost-effectiveness of current bioremediation methods, identifying new enzymes and microbes for cleaning up heavy metals and oil spills, engineering macroalgae to bind toxins in marine environments, and enabling organisms to withstand the accumulation of toxins (e.g., engineering organisms to have strong uptake systems). Bioremediation also helps to ensure safe drinking water, especially in places vulnerable to flood and storm runoffs. Milestones will delineate the research needed to develop biological systems to capture fecal coliforms, degrade nutrient runoffs from agriculture and aquaculture, reduce antibiotics and insecticide contamination, and track the dissemination of waste in water systems. Additional milestones will focus on engineering biobased filters to desalinate water and remove pollutants.

Social Dimensions and Policy Levers

As we draft this roadmap, it will be important to question how engineering biology is utilized to address global problems and the ways that novel technologies might create new problems or exacerbate existing social and political inequalities. To maximize the possibility of positive outcomes, technological pursuits will need to be coupled with ongoing study and negotiation of the social, cultural, political, and economic landscapes for which they are being designed. Doing this will require leveraging expertise in disciplines beyond science and engineering, including the arts, humanities, and social and behavioral sciences.

This section will outline the challenges, knowledge gaps, and potential solutions to some of the social, economic, and ethical implications of applying biotechnology to address climate and sustainability issues. In addition, we hope to continue these discussions in a more in-depth format, such as policy papers that articulate specific needs and recommendations.

The topics outlined here have been collected from the workshops held to date. We expect both the depth and breadth of these topics to be expanded as we continue to draft the roadmap. These topics can be roughly grouped into three areas pertaining to: the research enterprise, public engagement, and regulatory guidance.

All research paths proposed in the roadmap will necessitate knowledge sharing and collaboration across multiple research disciplines. To tackle the technical challenges laid out in the roadmap, this section will make recommendations to help the engineering biology community develop coherent research ecosystems with relevant disciplines and remove barriers to collaboration. These improvements will be useful for assessing the effectiveness of proposed solutions to lower emissions, and for evaluating the impacts they could have on society and the environment.

Public engagement is an important aspect to the successful uptake of new biotechnologies. We should work to develop biotechnologies sustainably, such that we do not incur further damage to the environment, and equitably, such that these technologies and the products derived from them are affordable and accessible. The roadmap will explore ideas on how to clearly communicate the benefits and drawbacks of biotechnologies to the public in the context of climate change and sustainability, and how to incorporate local consent and community stakeholders in intervention decisions.

Finally, the roadmap will examine policy levers and regulatory frameworks that will help accelerate engineering biology innovations to fight climate change and promote sustainable growth. The roadmap will outline some potential approaches to questions such as what financial incentives could be put into place to accelerate R&D and application (e.g., carbon pricing, new funding structures); how we can integrate the bioeconomy with a circular economy (e.g., biotechnology for green urban planning); and how international governance frameworks for engineering biology could be updated to reflect current state-of-the-art and anticipate future advances in the field.

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