Building a Biotechnology Innovation Ecosystem to Mitigate Climate Change

A UIDP Academy Workshop
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Strengthening
University-Industry
Partnerships

Workshop Report

Lead Report Authors
William Joe Sagues and Alex Woodley, North Carolina State University

Organizing Committee
Stephen Eubank and Andrew Warren, University of Virginia
Kelly Gillespie and Phil Taylor, Bayer
Rebecca Irwin, William Joe Sagues, and Alex Woodley, North Carolina State University

Workshop Series Organizer
Anthony Boccanfuso, UIDP

Project Director
Michael Brizek, UIDP

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Contents

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- Joshua Tewksbury, Smithsonian Tropical Research Institute
- Craig Allen, Center for Resilience in Agricultural Working Landscapes
- Thomas Whitham, Northern Arizona University
- Paul Blum, University of Nebraska
- Marie-Odile Fortier, University of California Merced
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Executive Summary

Anthropogenic greenhouse gas emissions continue to rise globally, driving urgency to mitigate climate impacts on our ecosystems, economy, public health, and future wellbeing. Food production accounts for 26% of global emissions, and within that segment, livestock, crop production and land use account for 82% of emissions.[1] Agriculture is both a contributor to climate change and directly affected by its impacts. While current policies strive to curb some emissions, broad implementation and adoption of further technological advancements is required to achieve emission targets to limit warming to 1.5°C to 2°C.[2]

More than 100 participants from the academic, corporate, government, and nonprofit sectors convened virtually for two days to discuss potential research and technology needs for biotechnology innovation ecosystems to mitigate climate change. The invited scientists and researchers were strategically selected to ensure that diverse perspectives and expertise were represented in the workshop deliberations. Participants explored themes related to systems analysis, managed systems, natural systems, and bioengineering/synthetic biology to identify the best opportunities. Topics discussed include regional considerations and risks, identified challenges to scaling up nascent solutions, implementation and adaptive management approaches, and supply chain and market considerations for new technology.

Purpose of the Workshop

Participants gathered to identify the primary levers by which climate change can be slowed or reversed using biotechnological or synthetic biology innovations that enhance the adaptation, resilience, preservation, and restoration of natural and managed ecosystems in response to climate change. The workshop provided a forum for interdisciplinary conversations around the promising, yet underdeveloped, potential of coupling nature-based practices with synthetic biology tools to guide the development and implementation of biotechnological solutions to climate change. Participants were challenged to address the following questions:

- What are the primary levers by which climate change can be slowed or reversed using biotechnological or synthetic biology innovations?
- How might biotechnology be used to enhance the adaptation, resilience, preservation, and restoration of natural and managed ecosystems in response to climate change?
- How can natural systems and nature-based solutions complement and guide the development and implementation of biotechnological solutions to climate change?

Workshop Findings in Brief

- **Mitigating the worst effects of climate change will require intensive research, development, and demonstration of biotechnological solutions.** These solutions must integrate into existing systems that are highly complex, including natural ecosystems, managed lands for agriculture and forestry, and centralized bio-industrial systems.

- **Monitoring the efficacy of biotechnological solutions that are implemented over large spatial domain.** Techniques used in natural ecosystems and managed lands will require standardized protocols and computational tools that enable streamlined data curation and distribution.

- **Carbon sequestration additionality and permanence** are two metrics that must be closely monitored, and at low cost and with high confidence.

- **Genetic engineering and adaptive evolution of microbes, crops, and synergistic systems.** The identified system has the potential to significantly reduce net greenhouse gas emissions through innovation in carbon dioxide (CO2) and methane (CH4) assimilation, nitrous oxide (N2O) degradation, and lignocellulose valorization, to name a few.

- **The biotechnology workforce should be thoroughly informed of the beneficial impacts their skills and existing infrastructure can play in mitigating climate change.** This would justify the consideration of new outreach programs at pre-professional and professional levels.

- **Leveraging existing biotechnological knowledge and infrastructure will require strong partnerships.** This involves fluid communication between emerging innovators and existing operators, from both the public and private sectors.

- **Risks inherent to biotechnology scale up** are limited if such collaboration amongst various stakeholders between academia, industry, and government is not achieved and maintained over long time frames.

- **Caution is warranted in public-private scale ups.** This should be considered in relation to aggressive timelines and those that rely on unstable policy incentives.

- **The large-scale and rapid implementation of biotechnological solutions to mitigate climate change will be resource-intensive and potentially socio-economically biased.** Stakeholders at the community level must be engaged throughout the implementation timeline to ensure such bias is avoided and benefits are equitable.

- **Resiliencies in biotechnologies.** Particularly centralized industrial biosystems, will require resilient and sustainable supply chains to ensure long-lasting climate benefits.

- **Biotechnological solutions to climate change are immature** and will require coordinated efforts at global, national, and local scales across public and private sectors to achieve their exciting potential.

Critical Topics and Necessary Advancements

The critical topics and necessary advancements to achieving large-scale climate change mitigation via biotechnological solutions are summarized below.

SYSTEMS ANALYSIS

- Standardization
- Streamlined data acquisition
- Reliable and accurate monitoring
- Long-lasting benefits
- Regional to global impact translation

BIOENGINEERING

- Crop genetics for carbon sequestration
- Crop genetics for climate resilience
- Engineered microbes for carbon sequestration
- Adaptive evolution
- Transparency and public awareness

NATURAL SYSTEMS

- Ensuring additionality and permanence
- Long-term data acquisition
- Distinction of challenges across system types
- Emphasis of socio-enviro-economic co-benefitpolicy

MANAGED SYSTEMS

- Ensuring additionality and permanence
- Stakeholder engagement
- Appropriate prioritization
- Socio-economic impacts

INDUSTRIAL SYSTEMS

- Leverage existing infrastructure
- Early-stage, long-term partnerships
- Life cycle assessment
- Workforce training and education

RISK ASSESSMENT

- Open source data
- Regional, data-driven decision making
- Accounting for policy uncertainty

SCALE-UP

- Technology-readiness-level considerations
- Reasonable timelines
- Public-private partnerships

IMPLEMENTATION

- Local community engagement
- Simple, low-cost, standardized tools and protocols
- Long-term commitments

SUPPLY CHAIN AND MARKETS

- Carbon market maturation
- Resilience and sustainability
- Circular economy

Figure 1 | Critical topics and advancements matrix (UIDP, 2022)

Conclusions from the Research Landscape

Literature Review and Analysis

Using its substantial data sets on publication and patent trends, research intelligence partner Elsevier performed a review of the research landscape. The review provided insights into biotechnology research that can and has been harnessed to mitigate climate change. The analyses delved into how much research has been done, who the global leaders in the research areas are, what sectors are leading the research, and how the research is being used to support other research and innovations. Additional information from this analysis is found in Appendix A.

Over the past 20 years, global research to mitigate climate change through biotechnology approaches has been growing at a rapid pace (Figure 2). The compound annual growth rate of publications related to the topic was 11.9% over the years 2001 to 2020, which is nearly double the compound annual growth rate of 5.6% observed for all publications. Over the past two decades, publications have grown to represent 0.71 % of all research in 2020, up from 0.24 % of all research in 2001. Growth has been particularly high over the last three years: nearly a quarter of the 233,089 publications since 2001 were published during the years 2018, 2019, and 2020.

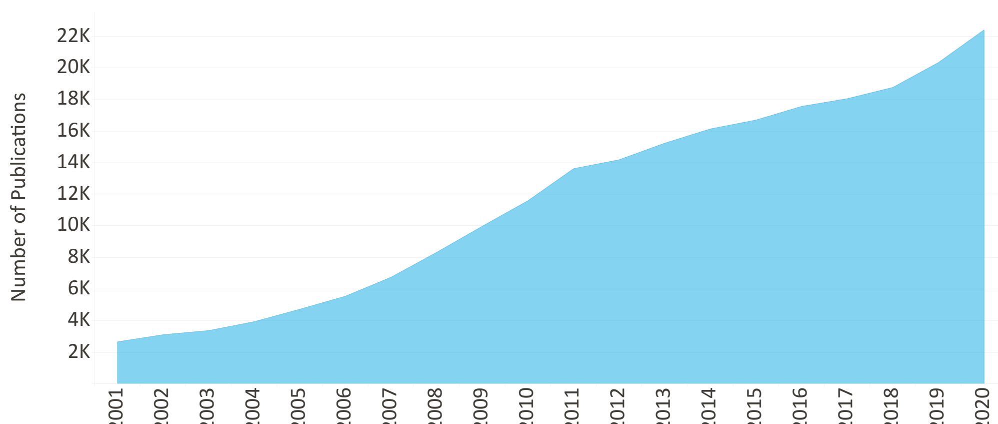

Figure 2 | Number of publications in biotechnology for climate thematic group, 2001–2020. Source: Scopus

This growth in publication output has been driven by continued focus on the research area from many European countries, as well as a rapid increase in publications from China, India, and to a lesser extent, Brazil (Figure 3, upper panel). The EU region displayed the largest output volume between 2001 and 2020 (approximately 64,000 from EU-27; Figure 3, lower panel), with the EU-27 publishing over 5,500 publications in 2020. China is currently closing the gap with EU's research output with 5,200 publications in 2020. It is notable that U.S. publications in this research area have plateaued since 2011, while those of other countries have continued to increase. This has resulted in India having published as many papers as the United States in 2020 (approximately 2,800). If such trends remain in the coming years, it is expected that India's output will surpass that of the United States.

In terms of research priorities and efforts over the past two decades, the EU-27, the United States, and China have each dedicated a similar proportion of their research portfolio in this area accounting for 0.5–0.6% of each country's total output

Of interest, among the top regions publishing research in this area over the past two decades, emerging research nations such as India, Brazil, and Malaysia stand apart as they dedicate 1.2 to 1.6 % of their research portfolio, highlighting the importance of climate change issues in influencing the research portfolio in these countries (Figure 3, lower panel).

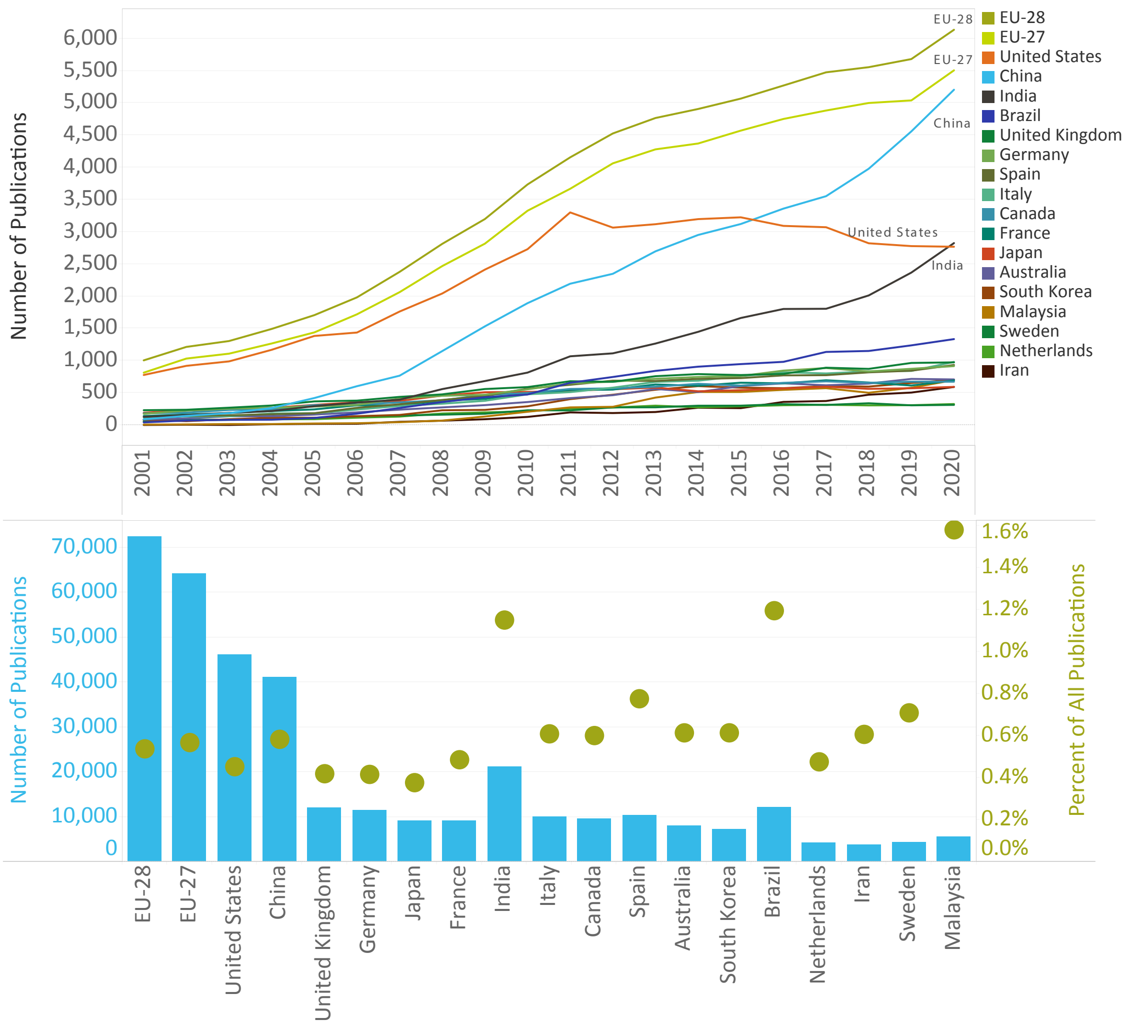

Figure 3 | Top: Trends in the number of research publications by region/country, 2001–2020. Bottom: Overall number of biotechnology for climate change research publications (blue bars) and percent of the regional/country research portfolio represented by biotechnology for climate change research (orange dots), 2001–2020. Source: Scopus

Overall, research in biotechnology for climate change covers the entire spectrum of R&D, spanning from basic science to applied technology (Figure 4). In the United States, over the last two decades, most publications (32%) fall within the category of Basic Science, while Engineering-Technological Mix represented the largest category at the world level, the EU and China.

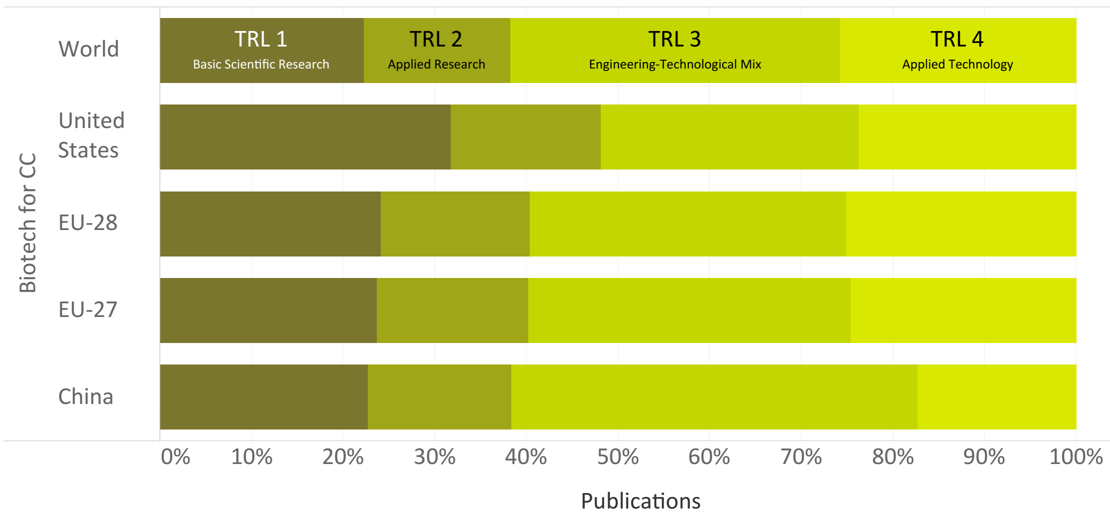

Figure 4 | Biotechnology for climate change research categorized across the basic to applied spectrum of research. 2001–2020. Source: Scopus

Review and Analysis – Key Takeaways from the Research Landscape

- Between 2001 and 2020, global research focused on biotechnology for climate change has grown at a rapid pace, with 233,000 research publications produced globally.
- During this same period, the United States was the leading research country in this field. However, in the last decade, the publication output of the United States has remained stable, while that of other countries continued to increase.
- Since 2001, global research output change in this field grew at a compound annual growth rate of 11.9%, outpacing the compound annual growth rate of overall global research output by over 6 percentage points.
- Globally, more activity is concentrated at the later stages of research (Engineering-Technological Mix and Applied Technology), while at the level of the United States, activity is more concentrated in basic science.
- Academic institutions represent approximately 90% of the United States' publications in this topic area. Patent applications submissions suggest that research involving corporations leads to innovation in the field, despite their limited publications output.

Pre-Event Perspectives on Mitigating Climate Change

A pre-event survey was distributed to participants prior to the workshop to identify key opportunities for each of the critical topics to be explored: systems analysis, managed systems, natural systems, and bioengineering. For each critical topic, participants were asked to rank the importance of several innovations and developments on a scale of 0 (not important) to 5 (very important). Weighted averages of the responses from the participants (n = 27) are shown below.

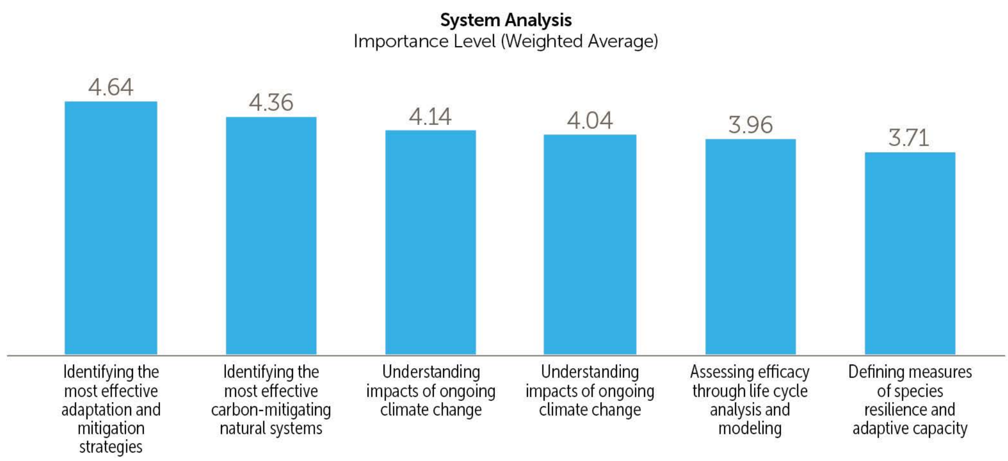

Figure 5 | Survey results measuring the level of importance and significance of factors that contribute to adverse impacts of climate change within analysis of analytical systems design (weighted average of results).

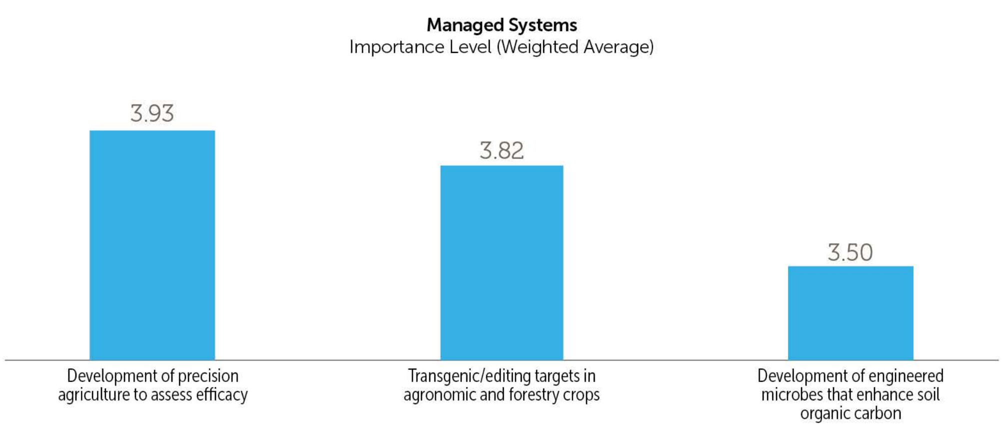

Figure 6 | Survey results measuring the level of importance and significance of factors and events that contribute to adverse impacts of climate change under the domain of managed systems (weighted average of results).

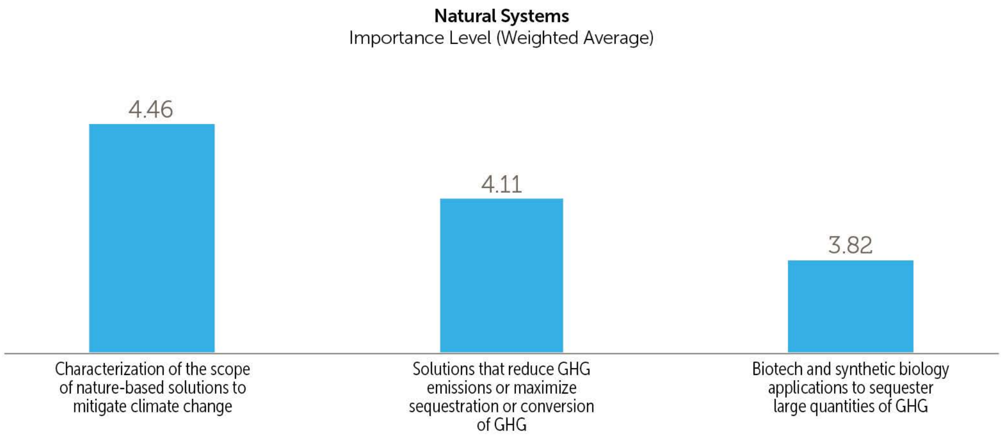

Figure 7 | Survey results measuring the level of importance and significance of factors and events that contribute to adverse impacts of climate change under the domain of natural systems (weighted average of results).

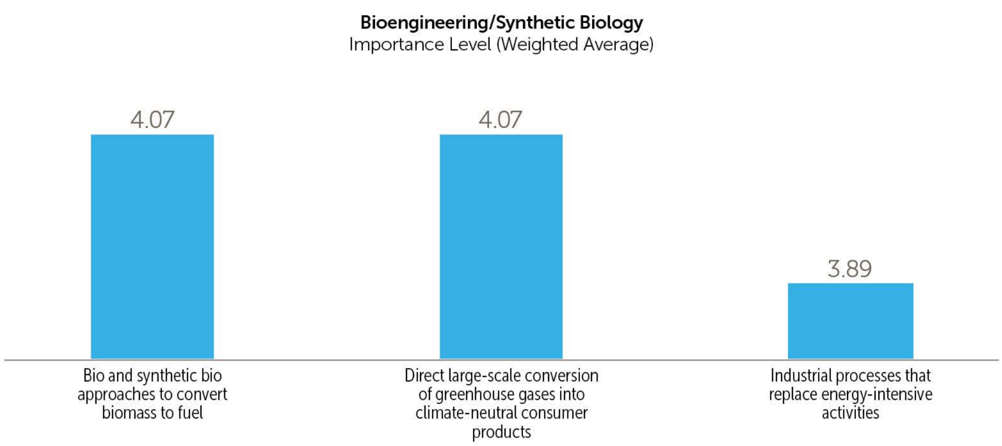

Figure 8 | Survey results measuring the level of importance and significance of factors that contribute to adverse impacts of climate change within analysis of bioengineering and synthetic biological design (weighted average of results).

Session Highlights from Day 1: Defining Key Barriers to Mitigating Climate Change

The first day of the workshop focused on defining the key barriers to mitigating climate change, describing the state-of-the-art technologies available, and identifying the remaining gaps in knowledge. After participants discussed the workshop charge, they were placed into four breakout groups and asked to address five questions as they related to the group's designated topic:

1. What are the best opportunities to implement biotechnological solutions to address climate change?
2. What are the most pressing problems that need to be addressed?
3. What are the research questions and outcomes needed to have a measurable impact on the effects of climate change?
4. What is the current state of commercial implementation of climate solutions? What are the unexplored opportunities?
5. What are the barriers to translation of new research and adoption in the marketplace?

Facilitated Breakout Sessions

Systems Analysis

The impacts of ongoing climate change on ecosystem composition are vast and function at the full range of spatial scales, from genes to ecosystems. This breakout group explored advantages and disadvantages of state-of-the-art, system-level modeling techniques and strategies for enhancing the adoption and implementation of climate change mitigation and adaptation efforts. Participants identified critical thresholds of environmental, agricultural, and industrial responses to extreme events, and discussed measures of species resilience, and adaptive capacity to changing environments across diverse domains of life.

Key Takeaways

Develop robust multiscale models. These should include heterogeneous actors and methods for quantifying interactions between system components and are needed on both regional and global scales.

Establish modeling methods that allow for ease of translation. These should range from regional to global impact, thereby guiding transfer of best practices.

Develop system-level analysis guidance. This is needed for rapid implementation of available high technology-readiness-level (TRL) applications at scale for climate change mitigation, while at the same time identifying promising, yet underdeveloped low TRL technologies for further research and development.

Improve data collection and distribution. This should be implemented at large-scale, be streamlined, and systematic to enable efficient, effective interdisciplinary collaborations.

Emphasize adaptation and resilience to climate changes. This should be led and communicated by leading scientists in academia and industry in parallel to mitigation approaches.

Managed Systems

Participants examined biotechnological innovations to help stabilize climate-impacted managed systems in agronomic, forestry, and aquaculture settings. Specific innovations of interest included engineered microbes to enhance soil organic carbon, or gene editing targets in agronomic and forestry crops to enhance stress tolerance or increase the efficiency of resource acquisition and utilization. The group also discussed application of precision agriculture to monitor and maintain efforts to mitigate climate change in managed systems.

Key Takeaways

Prioritize new technology development by potential for mitigation gains. Technology evaluation strategies must be designed in a manner that places the highest priority on potential for climate change mitigation relative to incumbent technologies.

Fund non-technology solutions. Ethical, socio-economic, and cultural impacts of climate change mitigation technologies deserve more consideration by funding bodies managing relevant research grant programs.

Social barriers to new technical solutions must be addressed. Non-technological barriers to implementation of climate change mitigating biotechnology, such as public acceptance and insufficient funding levels, are larger than most perceive. Like the social barriers of genetically modified organisms in food production, coordinated efforts in public education can help improve the acceptance of biotechnology in climate change mitigation.

Natural Systems

Participants focused on bio-inspired, nature-based solutions that can lead to net reductions in global emissions of greenhouse gases (GHG), including biotechnological and synthetic biology applications that enhance the establishment and performance of organisms that sequester large quantities of GHG. The scope of nature-based solutions to mitigate climate change and efforts to ensure permanent, long-lasting impacts were factors discussed.

Key Takeaways

Consider the big-picture, long-term perspective. Each natural system—including forests, wetlands, nearshore "blue carbon" environments, and deep oceans—have its own research and implementation challenges and opportunities. Overall, there is insufficient attention to long-term data, data trajectories, and the potential of existing, intact natural systems to support continued and additional carbon sequestration. A long-term perspective is necessary to ensure solution effectiveness over many decades.

Develop crosscutting methods. Additionality and permanence for natural systems must be developed aggressively.[3] Examples would include advancements in carbon sequestration technology applied to adaptive processes and techniques.

Quantify the positive impacts of mitigation solutions. Co-benefits to natural system innovation and management, such as clean water and reduced air toxicity, are critical, but better strategies to quantify their environmental, social, and economic impacts are needed.

Regional approaches are needed. Scaling and managing natural system climate benefits will require a diverse mix of regional strategies given that most natural systems are geographically constrained.

Bioengineering/Synthetic Biology

Biotechnologies that can be deployed in an industrial or factory setting, with a particular emphasis on synthetic biology approaches to indirectly utilize and/or sequester atmospheric carbon via biomass conversion to fuels or other bioproducts, were explored by this group. Innovations of particular interest included industrial processes that replace GHG- and land-intensive technologies with more efficient biotechnologies.

Key Takeaways

New biochemical pathways are needed. Advancing and scaling technologies for greenhouse gas (GHG) reduction via genetically engineered microbes and synergistic systems will require employing undiscovered or underutilized biochemical pathways to alleviate environmental stresses from traditional approaches to agriculture.

More research is needed on novel microbiological pathways. There is great potential for these to mitigate climate change through direct conversion of C1 carbon sources (including CO2 and CH4), degradation of N2O, and valorization of lignocellulosic biomass.

Regional and global issues related to industrial bioprocessing need clarification. In the context of industrial bioprocessing for climate change mitigation, the interplay between regional and global scales needs to be clarified and issues clearly identified, particularly land use.

Standardize measurement for climate mitigation. The ability to quantify climate benefits through biotechnology, coupled with robust institutional incentives, has the potential to accelerate adoption and implementation by large industrial biotechnology companies.

Employ adaptive evolution strategies. There is intriguing potential to learn from nature by employing adaptive evolution strategies for biotechnological climate change mitigation rather than targeting specific genes for engineering.

Improve training and education. Programs aimed at educating the industrial biotechnology workforce on avenues to climate change mitigation are needed.

Concluding Group Discussion

Each group reported breakout session key takeaways to the larger assembly for further discussion. Key conclusions from this session provided these overarching points:

More robust, publicly available data for the current and potential benefits of biotechnology in natural, managed, and industrial systems is needed.

Standard methods for quantifying climate benefits through biotechnology in natural, managed, and industrial systems are needed to ensure additionality and permanence.

More effective dissemination of information about biotechnological innovations that have potential climate benefits is needed to increase collaboration among relevant researchers in academia and industry. This will advance biotechnology adoption and scale up.

Novel substrates and pathways are needed to alleviate environmental stresses from traditional approaches to agriculture and to advance and scale technologies for GHG reduction via genetically engineered microbes, crops, and synergistic systems.

THE BAYER CARBON INITIATIVE

The Bayer Carbon Initiative was presented as an example of a global strategy to use agricultural soils as a sink for atmospheric carbon through improved carbon sequestration.

Bayer has different regional approaches to the goal, tailored to production systems, current governmental policy and climate. In the U.S. Midwest, soil sequestration is supported through carbon credits to producers; in the EU, Bayer is contributing to EU Green Deal discussions; in Brazil, there is a zero-deforestation initiative; and in India, there is the India Rice Smallholder Assessment. Bayer highlighted the importance of measuring, verifying, and reporting soil carbon sequestration data for consumer confidence, development in carbon markets, and for greenhouse gas inventory.

Climate FieldView™, a digital agriculture platform, is already used in millions of acres in the United States and will be integrated into the Bayer Carbon Initiative. The system supports growers by providing cloud-stored data related to agricultural land management and is a powerful tool to help support 30 regional and global efforts to quantify and track agriculture-related greenhouse gas emissions. It is proposed that the Bayer Carbon Initiative will contribute to reduced greenhouse gas emission, provide additional revenue streams to farmers, and help improve crop yield and yield stability.

Session Highlights from Day 2: Accelerating the Research

Breakout sessions on Day 2 examined opportunities to minimize unanticipated ecological and/or societal negative impacts of biotechnological solutions aimed at mitigating the effects of anthropogenic climate change. Emphasis was placed on balancing potential risks and costs against the benefits of ecosystem resiliency and negative emissions, as well as ensuring long-lasting benefits, particularly for carbon sequestration. After participants discussed the workshop charge, they were placed into four breakout groups and asked to address these questions as they related to the group topic within the timeframe of a two, five, and ten-year period:

1. Where are the most compelling opportunities?
2. How can innovation and discovery be accelerated in this area?
3. How can solutions be implemented on a global scale?
4. Who are the major stakeholders?
5. How can the public be engaged early in the process?
6. How will opposing viewpoints be engaged and accommodated?
7. How can opportunities and benefits be equitably distributed?
8. What are the regional considerations to be made, including coastal/island territories?

Facilitated Breakout Sessions

Risk Assessment and Regional Considerations

Participants discussed the importance of managing risk through access to readily available, open-source data, as well as other tools to mitigate risk. The group also explored ways to ensure that regional stakeholders can engage meaningfully in decision making that has the potential to significantly affect their communities.

Key Takeaways

Standardize data collection and synthesis on a regional level. This data should be made accessible globally via open-source repositories to enable better evidence-based decision making. These data collection and distribution systems will require coordinated, long-term financial and resource support to minimize duplication of effort and to maximize impacts.

Leverage industry approaches for risk assessment. Incorporating these approaches includes identifying compound risks and performing region-specific scenario analyses informed by empirical data. This is an opportunity to identify deployment strategies that lead to better outcomes in long-term climate change mitigation.

Establish stable incentives. These will foster long-term commitment between the public and private sectors and prevent climate benefit reversals. Communication between stakeholders and local communities needs to encompass best practices to disseminate evidence-based information in a concise yet compelling way.

Scale-Up

Participants explored challenges and barriers to implementing biotechnological solutions on a scale that is sufficient to achieve global impacts on mitigating climate change. Emphasis was placed on the roles public and private actors must play to ensure large-scale affects in a timely manner.

Key Takeaways

Engage in thoughtful, meaningful engagement. Such engagement between diverse stakeholders, including the public, throughout the research process will build trust and enable more effective scale up.

Forge cross-sector research partnerships early in the development process. Collaboration between academic and industry partners (and other interested parties such as nonprofits and national labs) allows research to be more dynamic and tailored to end-user needs. Early partnerships also provide an opportunity to enhance educational messaging to the public, specifically around the risks and benefits of genetically modified products.

Engage social scientists in infrastructure development to offset negative impact on marginalized communities. Certain biotechnologies for climate change mitigation will involve significant infrastructure changes and place new demands on resources; this could potentially displace some communities. The approach to scale up of these biotechnologies should include direct involvement of social scientists to ensure marginalized communities are not negatively affected.

Quantify and promote shared benefits and potential losses. This is integral to public acceptance and successful global scale-up. Likewise, quantifying and disseminating potentially negative outcomes should be pursued, including the risk of benefit reversals (e.g., forest fires and releasing sequestered carbon).

Leverage interagency funding programs for scale up. Joint agency funding (e.g., from USDA + NSF) can pair basic with applied researchers for an integrated scaling pipeline from lab bench to field, to consumer.

Fund longer-term, high-risk, high-reward projects. Better and longer-term support is needed for high-risk, high-reward biotechnology research for climate change mitigation. Brief (three-year) grant cycles limit continuity and upscaling.

Accelerate scale-up via private-public partnerships, including support through non-profits. Caution is warranted in public-private scale ups that have aggressive timelines and rely on unstable policy incentives (e.g., the advanced biofuel boom and bust between 2005 and 2015).

Establish a coherent, uniform global regulatory framework for biotechnologies. This will go far in alleviating public mistrust and minimizing financial risk for all sectors.

Implementation and Adaptive Management

Participants delved into the mechanisms needed to ensure solutions are assessed and approaches modified as new data are obtained. Emphasis was placed on the technology and monitoring capabilities needed to determine efficacy and the unique challenges associated with applications in unmanaged or lightly managed systems.

Key Takeaways

Stakeholder engagement is crucial for successful biotechnology implementation. Stakeholders are not only academic, government, industry, and producers/customers, but also include local communities, indigenous communities, NGOs, philanthropies, and advocacy groups. A respectful, equitable co-design process should be established so stakeholders can be engaged for climate change mitigation by co-developing, co-creating, co-designing the project before or after the research ends. Successful engagement includes translating information into accessible language and integration with social and behavioral sciences and humanities. University extension agents will play a critical role in stakeholder engagement, social impact, data collection, and education.

Make key components urgently needed for scaling biotechnologies public and accessible. This includes creation of publicly available data, models, code, tools, and science to create templates or broader frameworks that can inform other systems and where lessons learned are shared. Frameworks and modular approaches that include key regional considerations and draw upon local knowledge are required for global solutions.

Create simple, scalable, ground-level tools to collect and disseminate data from biosystems. These should be provided at low-cost and with wide-spread availability. Particularly, remote sensing tools and hyperspectral data may be useful here.

Tailor strategies to incorporate urban areas. There is opportunity within natural systems found in urban areas, but these operate under different constraints that may require alternative strategies than other natural systems.

Prioritize biotechnology research with the potential to delay natural system tipping points. Further elucidation of the mechanistic forces driving tipping points (irreversible changes) in natural systems will help guide the selection of biotechnological solutions.

Support long-term monitoring of natural systems. This investment will improve the ability to determine tipping points, enhance resilience to perturbations, and enable dynamic adaptation as ecosystem capacity and function change.

Supply Chains and Markets

Participants discussed ways that supply chains should be modified and/or implemented to ensure that there are sufficient raw materials to achieve production at a scale that can impact climate. They also considered new and existing bioproduct marketing strategies aimed at mitigating climate change.

Key Takeaways

Novel bioproducts and markets pose both enormous potential *and* risk. Examples include industrial biotechnologies that rapidly extract and sequester CO2 from the atmosphere with reliable permanence and minimal land footprint.

Standard policy and regulatory frameworks are needed for carbon markets, globally. Intellectual property advancement is restricted by uncertain policy frameworks.

Resilient, sustainable, and regional supply chains are needed for industrial biotechnologies intended for climate change mitigation. Circularity will enable regionality through recycling of materials. (See the UIDP bioeconomy workshop publication Innovation in the Bioeconomy | World without Waste (2022) for additional contextual information.)

Leverage existing industrial biotechnology infrastructure to mitigate climate change. For example, retrofitting corn ethanol refineries and kraft pulping mills for CO2 capture has the potential to sequester more than 200 million metric tons of biogenic CO2 per year in the United States.

Invest in early-stage cross-sectorial and cross-disciplinary partnerships. Partnerships between industry and academia (and other relevant parties) will help identify opportunities to leverage existing supply chains, infrastructure, and markets. Workforce training is required to educate people about the role biotechnology can play in climate change mitigation, and associated impacts on supply chains, infrastructure, and markets.

CASE STUDY IN TRANSLATION

MySOC > Kristofer Covey, Co-Founder, President, The Soil Inventory Project

Background

The Soil Inventory Project (TSIP) is an independent, science-led not-for-profit organization with a focus on democratizing changes to data related to soil management. To achieve this goal, TSIP is developing a systems approach to measuring, collecting, and managing large-scale data that is publicly accessible so it can be used by a range of stakeholders, such as landowners and land managers.

Quantifying soil carbon changes due to land management at large scale is challenged by several factors. There is a lag time of several years between management change and detectable differences in parameters such as soil carbon, soil aggregation, water-holding capacity and crop yields, and yield stability. This lag time and uncertainty of eventual outcomes can be resolved with robust soil data to quantify these management practices.

Large-scale data inventories are needed to catalyze practice adoption. In addition, high resolution gridded soil sampling for carbon stock status is still a time-consuming and costly endeavor. The difficulty in market adoption of soil carbon sequestration compared to forestry is due in part to a lack of scalable inventory systems and mechanisms for rewarding early adopters of sustainable practices.

Product Development

Kristofer Covey, president and co-founder of TSIP, began developing MySOC at Skidmore College, where his team paired field soil carbon field sampling methods with remote sensing models to provide large-scale surface soil carbon inventories at the Caney Fork Farms. MySOC expanded this approach with a 19-ranch study (17,354 ha) sampling campaign located in Oklahoma and Texas, work done in collaboration with the Nobel Research Institute, TSIP, and Skidmore College. They analyzed 2,800 soil samples for a range of properties and compared these values to results from both an in-field handheld reflectometer (OurSci) and remote sensing models. Using the Caney Fork Farm as an example, Covey showed that integrating these measurement methods can reduce the expense of creating a robust surface soil carbon inventory by 70%.

TSIP developed a fast, low-cost, and standardized soil extraction tool for the MySOC platform, allowing for consistency between users and improved data quality when integrating individual field samples into an aggregate database. The team developed an advanced stratification and automation sampling design application (Stratifi). This application generates maps for landowners with pre-selected sampling points. Using strategic sampling based on the Stratifi application, the number of physical samples is greatly and reduced while maintaining inventory accuracy. Participating landowners are provided a sampling kit send the samples to a MySOC lab partner for analysis. Landowners then receive a farm-scale soil carbon inventory. The data is linked to MySOC' s national field scale inventory, which is held in a public trust. The inventory is published on an open platform to foster collaboration and dynamic improvement to changing models and market activity.

Future uses of MySOC include providing data validation in regulated soil carbon markets and guiding risk-adjusted insurance rates based on agricultural outcomes. In addition, MySOC will help enable access to affordable lending and capital support for BIPOC farmers. Tools such as MySOC have the potential to provide the technical foundation for policies that address changes in agricultural soil carbon sequestration.

Conclusions

- The systems approach to data collection and sharing has a societal benefit beyond the individuals who contribute data.
- Leveraging data already collected at the field scale offers a pathway to link soil and land management to outcomes and encourages innovation.
- The open platform combines novel and existing technologies and offers potential for creation of low-cost national and global inventories, accessible to farms of any size.

Concluding Group Discussion

Facilitators from the breakout groups reported key takeaways to the workshop attendees for further discussion. Below are the conclusions from the second day of deliberation:

Standardized data must be collected and synthesized regionally and made accessible globally via open-source repositories to enable better evidence-based decision making. These data collection and distribution systems will require coordinated, long-term financial support and other resources to minimize duplication of effort and maximize impacts.

Incentives are needed to foster long-term cooperation between industry, academia, and local communities. This will require clear communication across stakeholders and must leverage best practices to disseminate evidence-based information in a concise, compelling way.

Key components are urgently needed to support scaling biotechnologies for climate change mitigation globally. These include creation of publicly available data, models, code, tools and science to create templates/broader frameworks that can inform other systems and share lessons learned. Scaling up via frameworks/franchise/modular approaches with key regional considerations that draw upon local knowledge are required for global solutions.

There is a need for more research into biotechnologies with potential for adaptive management to prevent or delay tipping points in natural systems. Further elucidation of the mechanistic forces driving tipping points will help guide the selection of biotechnological solutions.

Existing supply chains, infrastructure, and markets for industrial biotechnologies must be leveraged to mitigate climate change through workforce development, stable policy frameworks, and cross-sector partnerships.

Conclusion and Charge for Action

This workshop convened a diverse set of leading experts and practitioners from public and private sectors to identify the primary levers to slow or reverse climate change using biotechnological or synthetic biology innovations, with a keen focus on biotechnologies with the potential to enhance the adaptation, resilience, preservation, and restoration of natural and managed ecosystems. To ensure gain without further harm, the existing biotechnology workforce and infrastructure must be delicately and inclusively leveraged through innovation in technical, social, environmental, and economic realms to meet the challenges posed by climate change.

Many ambitious endeavors must be pursued in parallel to take full advantage of the climate change mitigation potential possible through existing and emerging biotechnologies. These endeavors encompass innovations in systems analysis and synthetic biology applied to natural, managed, and industrial systems. Critical topics that must be addressed in these efforts include risk assessment, scale-up, implementation, supply chains, and markets.

Appendix A:
Research Overview by Elsevier

Approach and Key Results

Bibliometric analyses, performed and presented by UIDP research intelligence partner Elsevier, were based on peer-reviewed publications (articles, reviews, and conference papers) and focused on the period 2001 – 2020. The source for all bibliometric data was the Scopus database. Scopus includes data and linkages across 83 million items from 80 thousand affiliations and 17 million authors. It is the largest curated abstract and citation database of peer-reviewed literature and provides a comprehensive view on the research landscape.

Defining the Research Area

The query for defining this research was developed in collaboration with subject matter experts coordinating the workshop. The terms used to search publication title, abstract, and keyword text were extensive and account for a large spectrum of biotechnology research approaches that play a role in climate change mitigation by mechanisms including but not limited to:

- Strengthening resilience and adaptive capacity to climate-related hazards
- Increasing the share of renewable energy in the global energy mix
- Improving energy efficiency
- Expanding infrastructure and upgrading technology to supply modern and sustainable energy services
- Ensuring the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems
- Sustainable management of all types of forests, halting deforestation, restoring degraded forests, and increasing afforestation and reforestation
- Combatting desertification, restoring degraded land and soil, and achieving a land degradation-neutral world
- Conserving mountain ecosystems, including their biodiversity
- Reducing the degradation of natural habitats, halting the loss of biodiversity, and protecting and preventing the extinction of threatened species
- Reducing the impact of invasive alien species on land and water ecosystems
- Managing and protecting marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience and restoration
- Minimizing and addressing the impacts of ocean acidification
- Restoration of fish to levels that can produce maximum sustainable yield as determined by their biological characteristics
- Utilization of genetic resources to maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species
- Sustainable food production and development of resilient agricultural practices to maintain ecosystems that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters and that progressively improve land and soil quality
- Achieving the environmentally sound management of chemicals and all wastes throughout their life cycle and significantly reducing their release to air, water, and soil

- Substantially reduce waste generation and facilitate more sustainable patterns of consumption and production
- Facilitate sustainable patterns of consumption and production

The description of the biotechnology for climate change research landscape is one that is provisional and not definitive. The definition of this research theme, and thus the papers included in the analyses, were determined by the creation and application of multi-factor, multi-term queries created in collaboration with subject matter experts in the relevant research area. Research areas—particularly multidisciplinary ones such as climate change and biotechnology —have ambiguous boundaries and may be defined more narrowly or more broadly by individual scholars or groups of experts. This is an inherent structural factor in the model itself. Nonetheless, the set of papers gathered by this query is a robust, quality representation of the research area overall, and capture both fine-grained details of very specific research questions and paradigms, and a broader overview of the research area.

Results

Research Landscape

Over the past 20 years, global research to mitigate climate change through biotechnology has been growing at a rapid pace (Figure 1). The compound annual growth rate of publications related to the topic was 11.9% over the years 2001–2020, which is nearly double the compound annual growth rate of 5.6% observed for all publications. Over the past two decades, publications have grown to represent 0.71 % of all research in 2020, up from 0.24 % of all research in 2001. Growth has been particularly high over the last 3 years: nearly a quarter of the 233,089 publications since 2001 were published during the years 2018, 2019 and 2020.

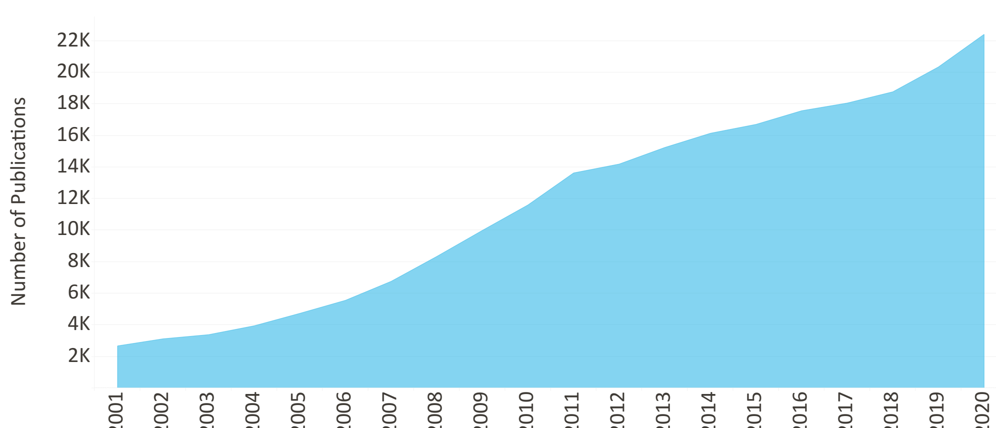

Figure 1 | Number of biotechnology for climate change thematic group, 2001–2020. Source: Scopus

This growth in publication output has been driven by continued focus on the research area from many European countries, as well as a rapid increase in publications from China, India, and to a lesser extent, Brazil (Figure 2, upper panel). The EU region displayed the largest output volume between 2001 and 2020 (~64,000 from EU-27; Figure 2, lower panel), with the EU-27 publishing over 5,500 publications in 2020. China is currently closing the gap with EU's research output with 5,200 publications in 2020. It is notable that the United States publications in this research area have plateaued since 2011, while those of other countries have continued to increase. This has resulted in India having published as many papers as the United States in 2020 (approximately 2,800). If such trends remain in the coming years, it is expected that India's output will surpass that of the United States.

In terms of research priorities and efforts over the past two decades, the EU-27, the United States and China, have each dedicated a similar proportion of their research portfolio in this area accounting for 0.5–0.6% of each country's total output

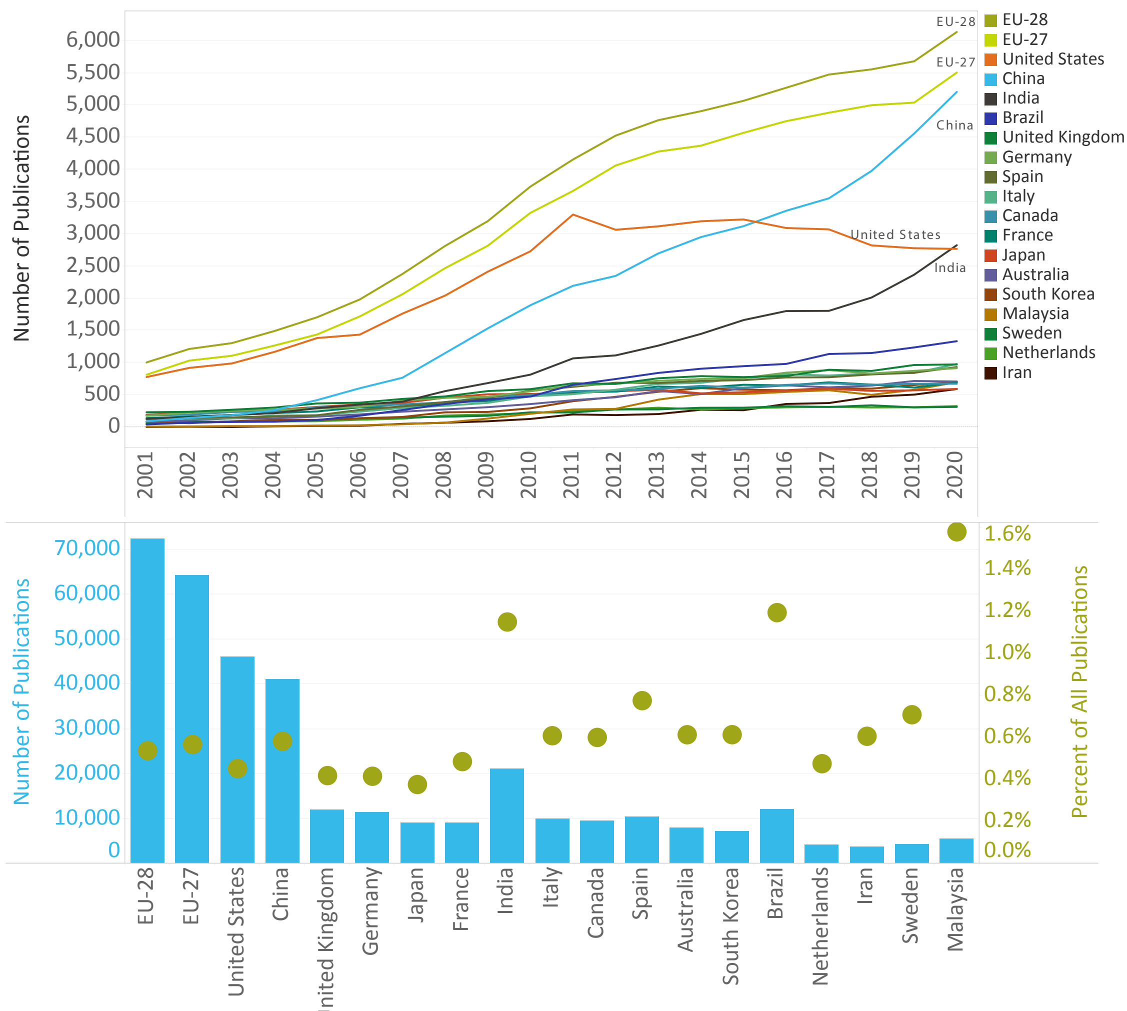

Figure 2 | Top: Trends in the number of research publications on the topic, by region/country, 2001–2020. Bottom: Overall number of research publications (blue bars) and percent of the regional/country research portfolio represented by this research (orange dots), 2001–2020. Source: Scopus

(Figure 2, lower panel, orange data points). Of interest, among the top regions publishing research over the past two decades, emerging research nations such as India, Brazil, and Malaysia stand apart as they dedicate 1.2–1.6 % of their research portfolio, highlighting the importance of climate change issues in influencing the research portfolio in these countries.

Overall, research covers the entire spectrum of R&D, spanning from basic science to applied technology (FIGURE 3). In the United States, over the last two decades, most publications (32%) fall within the category of Basic Science, while Engineering-Technological Mix represented the largest category at the world level, the EU and China.

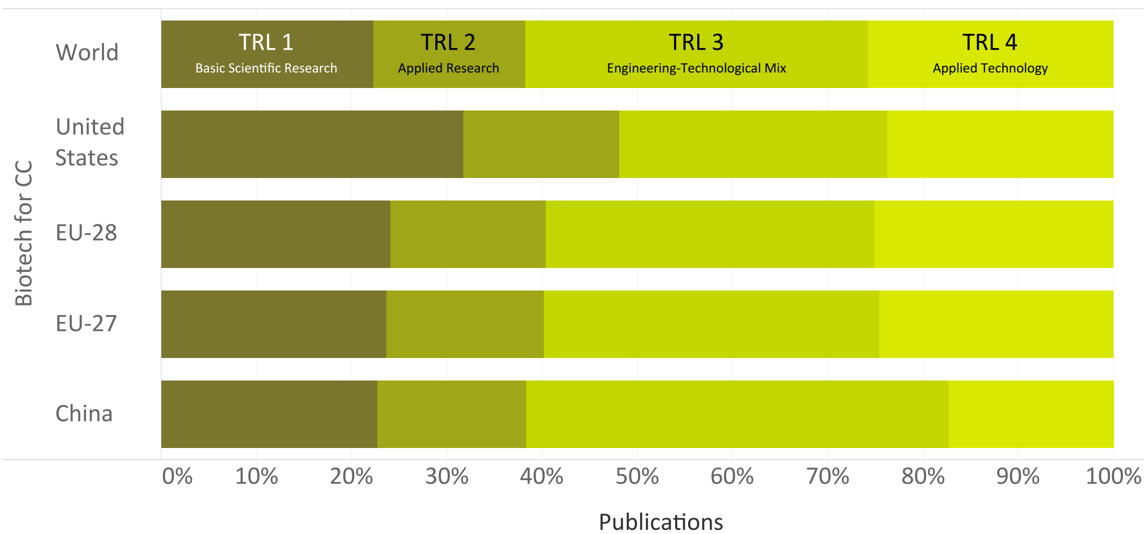

Figure 3 | Research on the theme categorized across the basic to applied spectrum of research. 2001–2020. Source: Scopus

One way of looking into the type of scientific research underlying the field in the United States and globally is by topic modelling of global research using citation pattern-based clustering methods. The resulting topics provides a higher granular perspective of research communities represented in the field. In addition, prominence score, which is calculated based on recent trends in citations to the papers in the topic, the relative frequency with which the publications were viewed in Scopus, and the CiteScore of the journals that the research is being published in. The prominence score can be broadly described as an analogue for the current momentum of the topic, including the level of funding and underlying publication trends over time.

TABLE 1 shows the topics that are most highly represented in the field worldwide. Among those, the United States contributed the most to four Topics: Trichloroethylene; Bioremediation; Groundwater Contamination (U.S. contribution represents 61.5% of global publication output), Genetically Modified Plant; Cellulase; Acidothermus cellulolyticus (U.S. contribution represents

58.0% of global publication output), Techno-Economic Analysis; Jet Engine Fuel; Hydrothermal Liquefaction (U.S. contribution represents 47.8% of global publication output), and Renewable Energy Directive; Agricultural Price; Biodiesel (U.S. contribution represents 41.7% of global publication output).

However, looking at the prominence score trends between 2015 and 2020, and the percent change in prominence percentile, these research topics are losing momentum (see topics highlighted in red, TABLE 1).

Most of the topics covering the bulk of the literature have maintained a stable momentum since 2015 (highlighted in yellow). Of interest, two topics have experienced positive trends (shown in green), indicating that they represent growing areas of interest. These topics are Gas Turbine; Laminar Flame; Fuel Spray and Digester; Anerobic Digestion; Biodiesel. The United States has contributed to 30.5% and 12.2% of publications in these topics, respectively.

Topic	World Pubs	US Pubs	US Pub Share	Prominence Trend	% Change in Prominence Percentile
Gas Turbine | Laminar Flame | Fuel Spray	210	64	30.5%		23.5%
Digester | Anerobic Digestion | Biodiesel	1,097	134	12.2%		6.0%
Ethyl Laurate | Lauric Acid Methyl Ester | Antiknock Rating	550	64	11.6%		2.1%
Nutrient Removal | Activated Sludge | Dechloromonas	2,221	293	13.2%		0.9%
Contaminated Soil | Polycyclic Aromatic Hydrocarbon | Phenanthrene	3,011	411	13.6%		0.4%
Contaminated Soil | Bioaugmentation | Petroleum Derivative	2,790	252	9.0%		0.3%
Fuel Test | Exhaust Emission | Diesel Engine	7,766	473	6.1%		0.0%
Rubber Seed Oil | Cooking Fat And Oil | Transesterification	8,133	527	6.5%		-0.1%
Nannochloropsi | Chlorellum Sorokiniana | Photobioreactor	7,051	986	14.0%		-0.1%
Scenedesmi | Photobioreactor | Nutrient Removal	3,728	657	17.6%		-0.2%
Life Cycle Assessment | Anerobic Digestion | Biodiesel	1,339	172	12.8%		-0.2%
Biohydrogen | Photofermentation | Hydrogen Production	4,799	310	6.5%		-0.2%
Bioanode | Enzymatic Fuel Cell | Bilirubin Oxidase	2,232	602	27.0%		-0.9%
Bioanode | Enzymatic Fuel Cell | Bilirubin Oxidase	1,671	228	13.6%		-0.9%
Renewable Energy Directive | Agricultural Price | Biodiesel	2,251	939	41.7%		-1.7%
Triacylglycerol Lipase | Transesterification | Pseudozymum Antarctica	1,253	63	5.0%		-2.4%
Municipal Solid Waste | Leachate | Waste Disposal Facility	934	119	12.7%		-4.8%
Social Inclusion | Castor Bean | Biodiesel	192	20	10.4%		-12.8%
Euphorbiacea | Female Flower | Jatropha	1,244	67	5.4%		-17.8%
Bacteria Contamination | Distillery | Ethanol Fermentation	257	58	22.6%		-22.8%
Trichloroethylene | Bioremediation | Groundwater Contamination	270	166	61.5%		-23.1%
Growth Hormone | Oryzia Dancena | Oncorhynchus Kisutch	432	86	19.9%		-26.8%
Techno-Economic Analyse | Jet Engine Fuel | Hydrothermal Liquefaction	113	54	47.8%		-27.4%
Biodiesel | Transesterification | Sewage Sludge	118	20	16.9%		-39.6%
Genetically Modified Plant | Cellulase | Acidothermi Cellulolyticu	119	69	58.0%		-53.5%

Table 1 | Topics of Prominence represented in this theme in the literature, 2001–2020. Prominence trend and percent change shown for 2015-2020. Source: Scopus

Cross-Sectoral Collaboration

FIGURE 4 illustrates trends in cross-sector collaboration in research in the United States and in the rest of the world (excluding the United States) over the period 2016–2020. The data show that just over half of all publications in the field resulted from efforts of academic institutions alone, while approximately 37% of all publications resulted from cross-sectoral collaboration that included academic institutions with some combination of governmental institutions, NGOs or corporate entities. It is noteworthy that the level of academic-corporate collaboration is low, given the high percentage of applied research in the field (see FIGURE 3), although corporate entities are more highly represented in U.S. research than research in the rest of the world. Moreover, the academic-government and academic-NGO collaborations are quite high. Unlike in many fields, governments are not only major funders of research, but they are also major contributors and authors of publications in this area of research.

In the United States, several institutions appear key among the community of research. The network analysis shown in Figure 5 highlights the collaboration patterns in the United States between institutions contributing to research that have been involved in at least two collaborations and published at least two publications during the period 2016–2020. The analysis shows that the top 2 governmental organizations in terms of output, the U.S. Department of Agriculture, and the U.S. Department of Energy, are central to the network. These federal agencies have contributed to more publications related to this topic than any single university. The U.S. Department of Energy is strongly connected to several academic institutions and to many other governmental institutions. Its strongest academic links are with the University of Wisconsin-Madison and the University of California at Berkley, and its strongest governmental links are with the Lawrence Berkeley National Laboratory and the Argonne National Laboratory. The U.S. Department of Agriculture is connected to several academic institutions, and fewer governmental institutions compared to the U.S. Department of Energy, with the strongest connections to the University of Illinois at Urbana-Champaign and the University of Wisconsin-Madison. The latter university is thus strongly connected to both the U.S. Department of Agriculture and the U.S. Department of Energy. The University of Illinois at Urbana-Champaign, on the other hand, is connected to many more universities. Other highly connected institutions in the network include Cornell University and the University of California at Berkley.

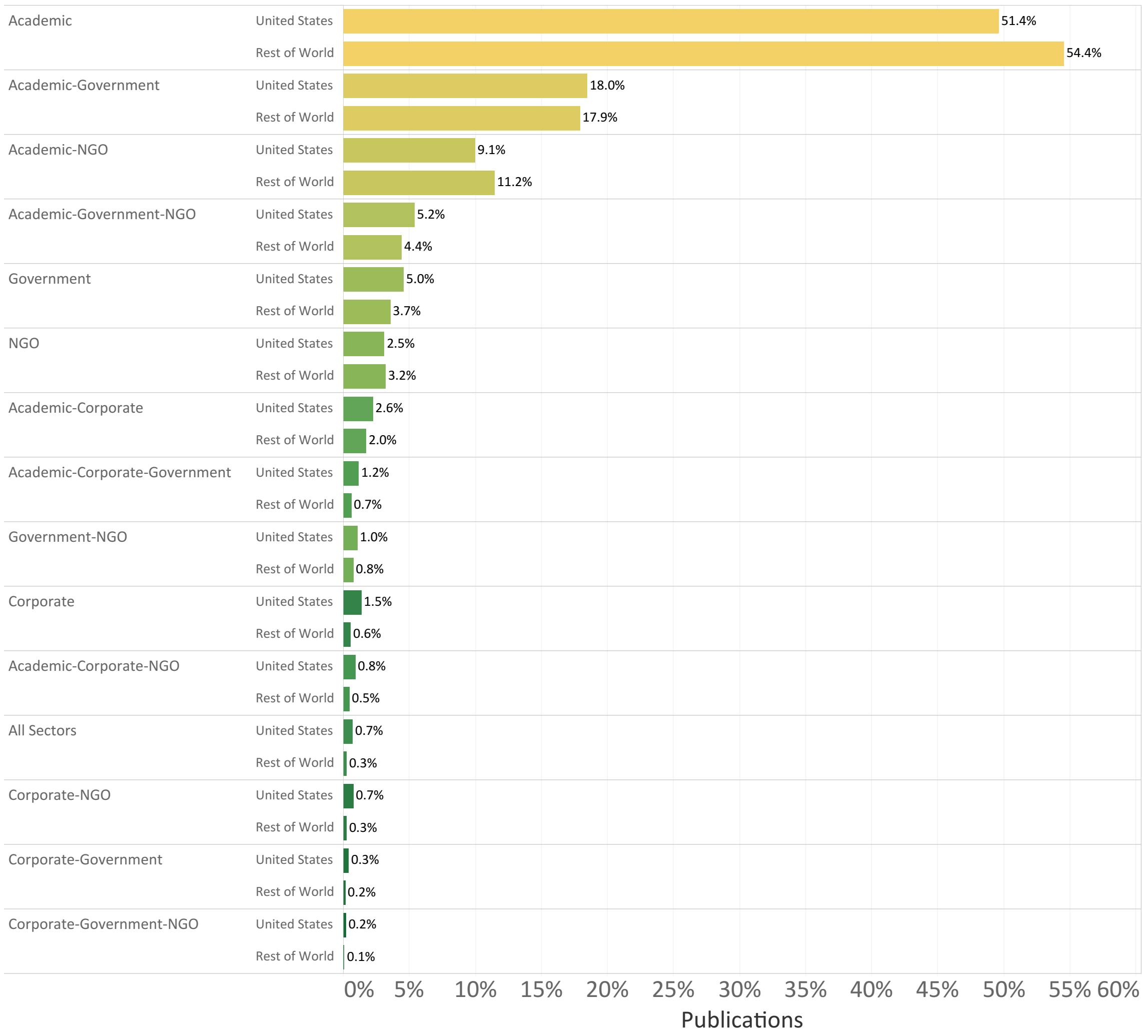

Figure 4 | Research in this topic in publications from the U.S. and the rest of the world (excluding the U.S.) published from 2016–2020 and categorized according to the sectors represented in the author byline. Source: Scopus

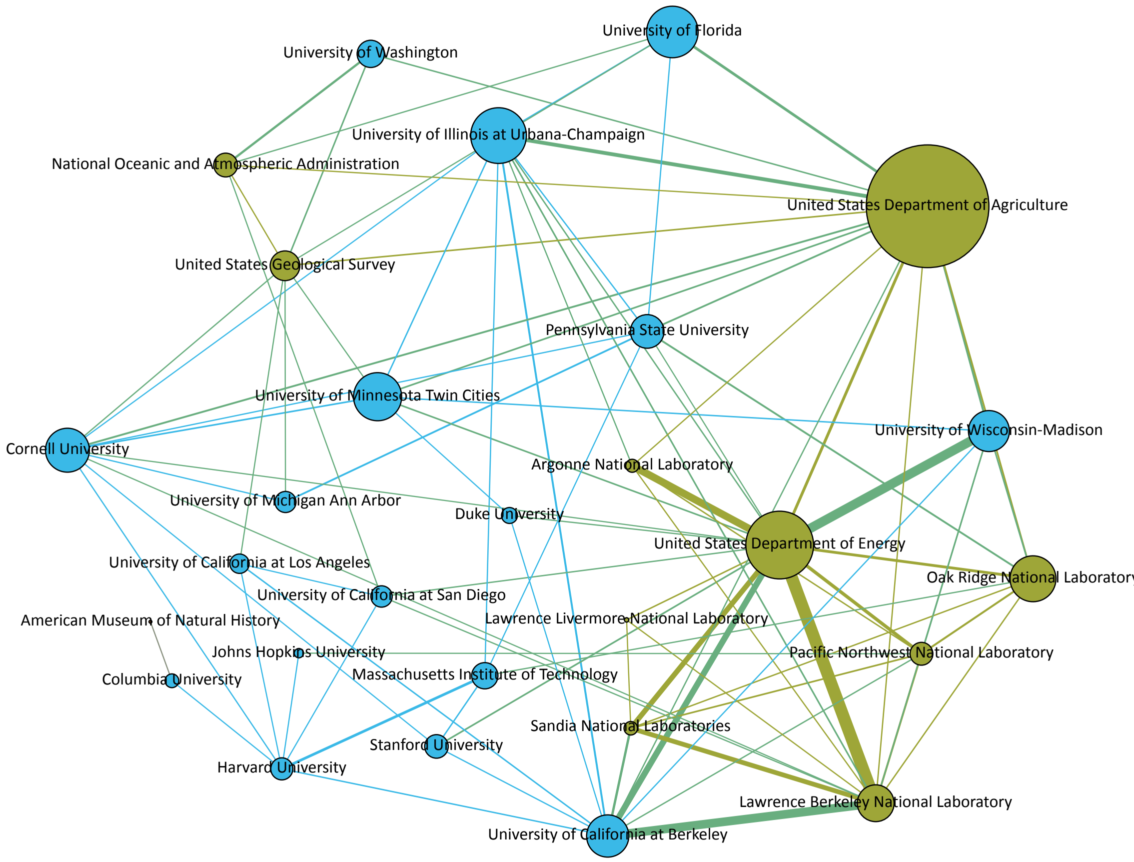

Figure 5 | Network collaboration map based on the 20 U.S. institutions in each of activity sector (academic, government and corporate), according to their output in research from 2016–2020. The map is limited to institutions that have published at least 2 publications in collaboration with at least 2 other institutions. Academic institutions are shown in pink and governmental institutions are shown in green. Circle size represents publication output during the period 2016–2020 and the thickness of connecting lines represents the number of publications co-authored by the connected institutions. Source: Scopus

Of note, although publications involving the private sector accounted for 8.0% of all U.S. research in this field, no corporate institutions were tied to the network map (Figure 5), indicating that corporate entities were not connected to two or more institutions in the network by at least two collaborative publications. The top ten corporate institutions in the U.S. based on the number of publications from 2001–2020 are indicated in Table 2.

Dow Chemical is the leading corporation in terms of output in this research area, having contributed to 80 publications between 2001–2020. SAIC and General Electric follow Dow Chemical with 56 and 53 publications, respectively. Except for Boeing and Schlumberger, all the corporations among the top ten have published research that was cited in patents. Among them, IBM, Pfizer and Merck have, respectively, 57%, 40% and 33% of their papers cited in patents, highlighting a high degree of their research uptake into innovation. In addition, these corporations as well as others, such as SAIC and Genentech incorporated, have published a high proportion of high quality and impactful research papers –each of these corporations has at least 30 % of their papers that are among the top 10% most highly cited worldwide.

	Publications				
Institution	All CB	Cited in USPTO patents	Cited in WTO patents	Among top 10% most cited	Field-weighted citation impact
Dow Chemical	80	9	5	16	2.2
SAIC	56	1	0	17	1.4
General Electric	53	1	1	9	1.5
General Motors	41	1	1	8	1.7
Schlumberger	32	0	0	1	1.5
Merck	30	5	5	11	4.8
IBM	21	7	5	11	3.1
Pfizer	20	4	4	6	1.4
Boeing	19	0	0	1	1.0
Genentech Incorporated	18	2	1	9	1.6

Table 2 | Top 10 corporate institutions publishing research in the United States, 2001–2020. Indicators show the number of publications cited in patents and among the top 10% most cited worldwide. Source: Scopus

When assessing all U.S. research, no specific sector stands apart with regards to the percentage of publications cited in USPTO patents: 7–8% of publications with at least one author from the academic, governmental or corporate sectors were cited in patents. However, when assessing the sectoral data according to the combination of collaborators, some combinations are revealed to be more likely to be cited in patents (FIGURE 6). These include publications consisting only of governmental institutions (11% of publications cited in patents) and publications resulting from either academic-corporate collaborations or academic-corporate-government collaborations (10% of publications cited in patents).

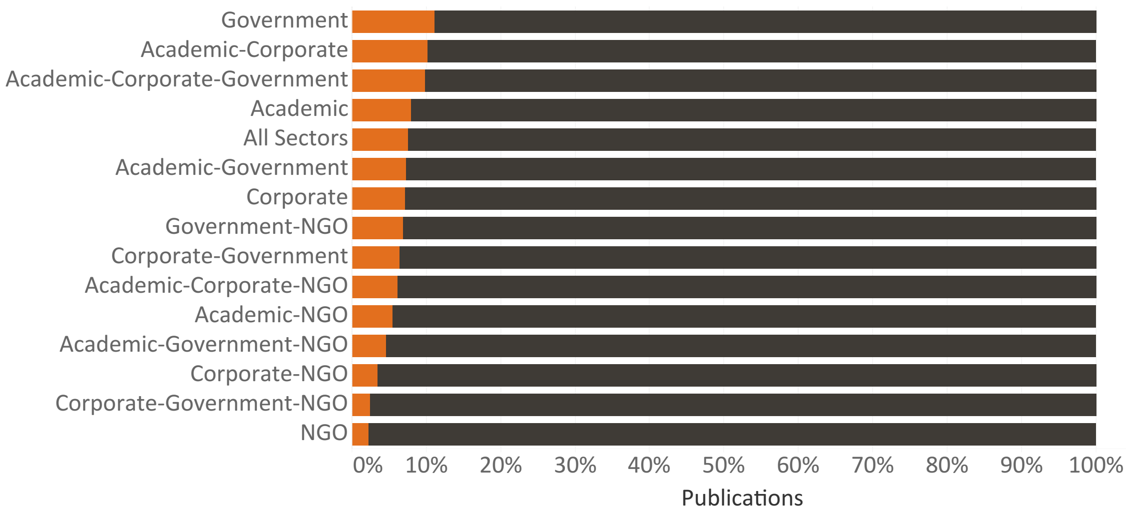

Figure 6 | Percent of U.S. research in this topic during the period 2001–2020, that has been cited in USPTO patents, categorized according to cross-sector collaboration. Source: Scopus

Categorization of Global Biotechnology Research for Climate Change

Publications can be classified into four key categories that reflect different scientific approaches and innovations in biotechnology research: Systems Analysis, Managed Systems, Natural Systems, and Bioengineering/Synthetic Biology. Note that these categories are not mutually exclusive, and therefore publications may be classified to more than one category. The trends in output for each category show that the number of publications in the U.S. have increased at different rates over the past two decades (FIGURE 7). These trends reveal a shift in research in that Natural Systems and Bioengineering/Synthetic Biology research represented less than 25% of research in 2001 and has grown to represent over 40% of research in 2020. Conversely, Managed Systems and Systems Analysis research declined in their representation in the research by 27 and 13 percentage points respectively during the same period. Further differences between the categories of research concentrations can also be seen across the spectrum of basic to applied research (FIGURE 8). Publications in Managed Systems and in Systems Analysis primarily focus on basic research, while Natural Systems and Bioengineering and Synthetic Biology primarily focus on applied research for technological innovation (Applied Technology). Accordingly, publications in Natural Systems and Bioengineering and Synthetic Biology are more represented in USPTO patent applications, with about 10% of publications in each category being cited in patents (FIGURE 9).

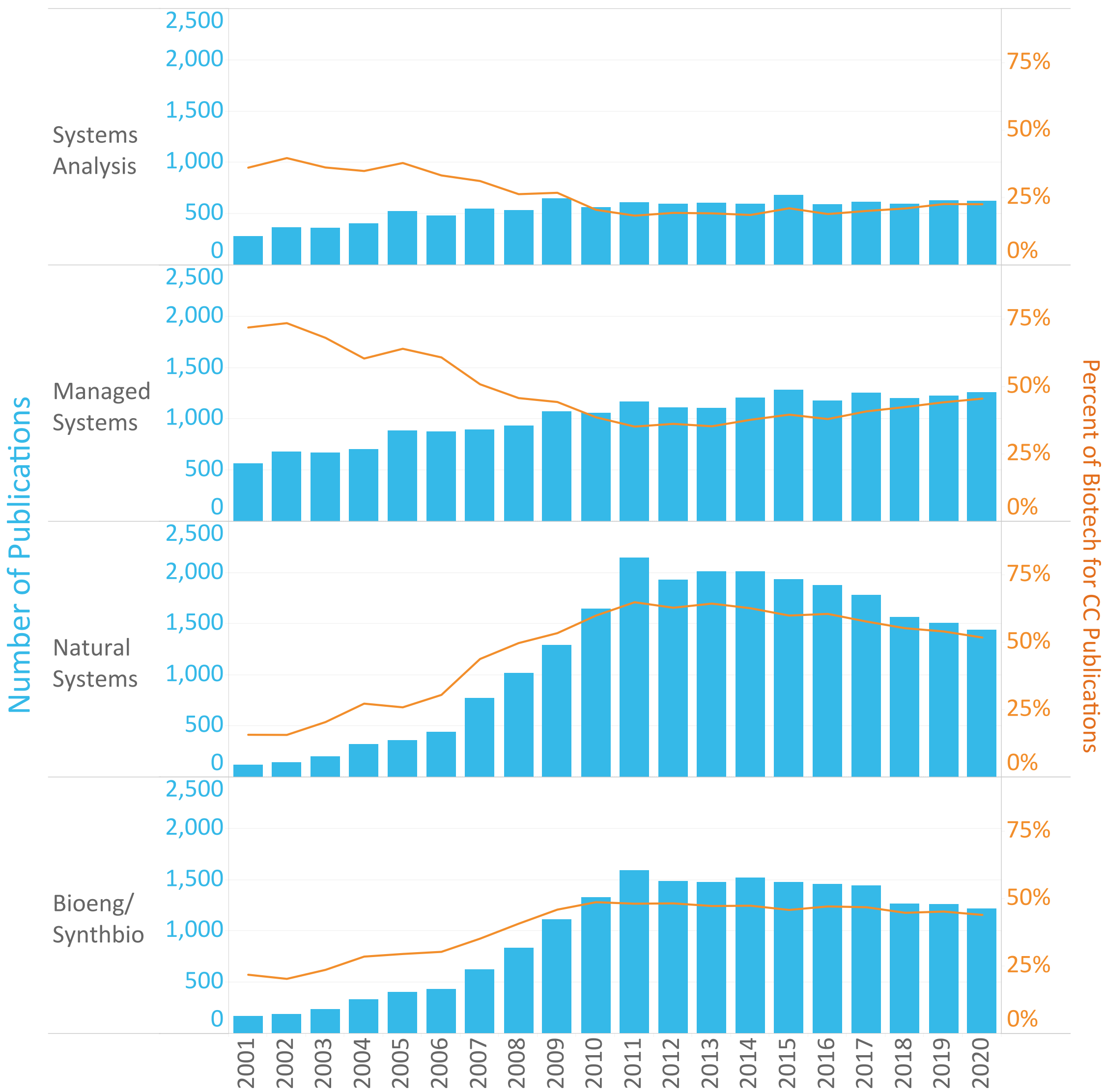

Figure 7 | Trends in subcategories of U.S. research in this topic. Annual number of publications (blue bars) and percent of each subcategory's output (orange line) among U.S. research, 2001–2020. Source: Scopus

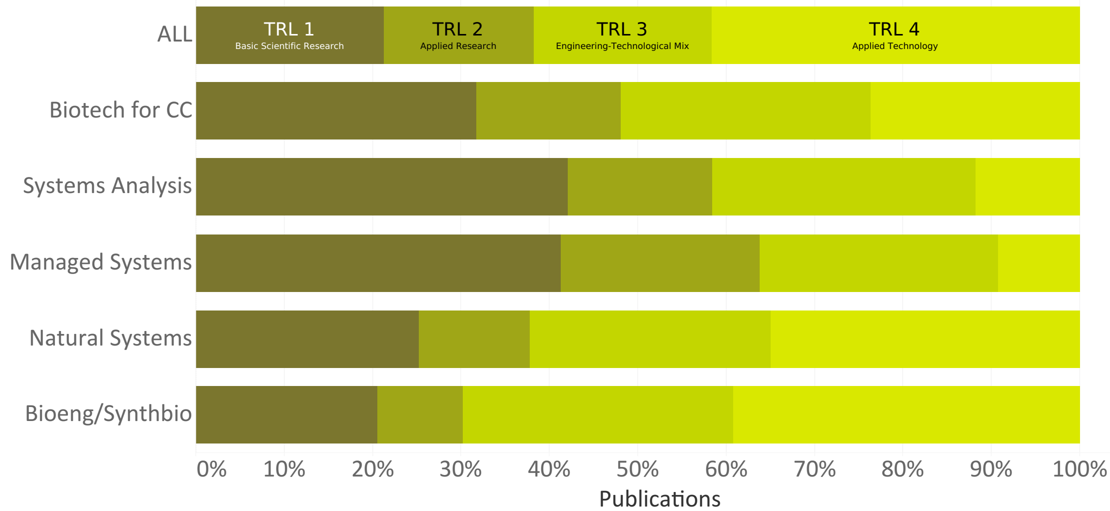

Figure 8 | Percent of U.S. publications on this theme and subcategories during the period 2001–2020 classified across the basic to applied spectrum of research. Source: Scopus

Figure 9 | Percent of U.S. publications on this theme and subcategories during the period 2001–2020 among the top 10 percent most cited and cited in USPTO. Source: Scopus

Conclusions

Over the past two decades, global research has grown at a rapid pace, with 233,000 research publications produced globally over the period 2001–2020. Since 2001, global research output change in this field grew at a compound annual growth rate of 11.9%, outpacing the compound annual growth rate of overall global research output by over 6 percentage points. Between 2001 and 2011, the United States was the leading research country in this field, with a constant growth in output and a slightly lower output volume than the European Union as a whole. Since 2011, however, the publication output of the United States has remained stable, while that of other countries continued to increase. Currently, the European Union continues to publish the most, but China is poised to become the leading country in the field if recent trends continue. The United States' output is now comparable to that of India, an emerging leader in this field that is likely to surpass the United States in the coming years. India, as well as other developing countries such Brazil and Malaysia, dedicate a greater percentage of their research portfolio in this research than the United States, European countries, or China, allocating more that 1.2% of their research portfolio to the field of study. This highlights the high priority status of research as a means of mitigating climate change through biotechnology in those countries.

Since 2015, the United States contributed to several research topics within the corpus of research on the theme of biotechnology for climate change. These include:

- Trichloroethylene; Bioremediation; Groundwater Contamination, Genetically Modified Plant; Cellulase.
- Acidothermus Cellulolyticus, Techno-Economic Analysis; Jet Engine Fuel.
- Hydrothermal Liquefaction, and Renewable Energy Directive; Agricultural Price; Biodiesel.

These topics are not the most significant in terms of global output, and they have been research areas of declining interest over the past few years. Among the most represented topics in research, only two have been areas of growing research interest worldwide – Gas Turbine; Laminar Flame; Fuel Spray, and Digester; Anerobic Digestion; Biodiesel. The United States' contribution to these growing topics accounted for 30.5% and 12.2% of publications, respectively.

Research dedicated to this theme spans across all stages of R&D. Globally, but also at the level of the EU and China, more activity is concentrated at the later stages of research (Engineering-Technological Mix and Applied Technology), while at the level of the United States, activity is more concentrated in basic science. In addition, research spans across various sectors of activity, with academic institutions represented in approximately 90% of the United States' publications. In the United States, two federal government institutions appear central among top publishing institutions. The Department of Agriculture has contributed the most to publications, followed by the Department of Energy. These federal institutions are connected to many other top publishing governmental and academic institutions. Among academic institutions, the University of Illinois at Urbana-Champaign, the University of Wisconsin-Madison, Cornell University, and the University of California at Berkley are important hubs within the network of top publishing American institutions in this field of research.

In contrast to the large contribution of governmental and academic institutions involved in the research topic, corporate organizations have contributed less. However, publications involving corporate organizations were highly represented in USPTO patent applications, to a similar degree as those involving governmental or academic institutions. This suggest that this research involving corporations leads to innovation in the field, despite their limited output.

Appendix B: Mitigating Climate Change Agenda

Tuesday, October 12, 2021

11–11:10 a.m.	**Workshop Introduction** Anthony Boccanfuso, UIDP Theresa Good, The National Science Foundation Stephen DiFazio, The National Science Foundation
11:10–11:30 a.m.	**Opening General Framing Session** Kelly Gillespie, Bayer Science Crop R and D Charge to participants, workshop rules, and goals. Organizers will introduce the main theme of Day 1, which is how we can integrate the four key themes.
11:30 a.m.–12:30 p.m.	**Review of the Current R&D Landscape** Bamini Jayabalasingham, Elsevier Daniel Calto, Elsevier Elsevier will provide findings from their review of the nation's current sustainable agriculture capabilities and benchmark against global activities.
1–2:30 p.m.	**Concurrent Breakout Sessions: Key Workshop Themes** Participants will be assigned to groups prior to workshop. Groups will be interdisciplinary and from different industries. Each group will determine the state-of-the-art methods in each field, discuss limitations/gaps, and determine how to integrate biological and computational methods toward desired outcomes in mitigating climate change.
1–2:30 p.m.	**Systems Analysis** Stephen Eubank, University of Virginia (Facilitator) Shweta Singh, Purdue (Assessor) Discussion on understanding the impacts of ongoing climate change on ecosystem composition and function at all spatial scales, from genes to ecosystems; defining critical thresholds of environmental responses to extreme events, and defining measures of species resilience and adaptive capacity to changing environments across diverse domains of life; identifying the most effective carbon-mitigating natural systems; identifying the most effective adaptation and mitigation strategies; assessing efficacy through life cycle analysis and modeling.
1–2:30 p.m.	**Managed Systems** Diane Pataki, Arizona State University (Facilitator) Paul Vincelli, University of Kentucky (Assessor) Discussion on development of biotechnology and synthetic biology innovations to help stabilize climate-impacted managed systems including agronomic, forestry, and aquaculture contexts. This might include development of engineered microbes that enhance soil organic carbon, or transgenic or editing targets in agronomic and forestry crops that enhance stress tolerance or increase the efficiency of resource acquisition and utilization; development of precision agriculture and approaches that facilitate implementation and assessment of efficacy.

Tuesday, October 12, 2021

1–2:30 p.m.	**Natural Systems** Josh Tewksbury, Smithsonian Tropical Research Institute (Facilitator) Craig Allen, Resilience in Agricultural Working Landscapes (Assessor) Discussion on bio-inspired design and nature-based solutions that lead to net reductions in global emissions of greenhouse gases (GHG). This can include biotechnological and synthetic biology applications that enhance the establishment and performance of organisms that sequester large quantities of GHG. It may also include solutions that reduce GHG emissions or maximize sequestration or conversion of GHG into benign products in natural settings; characterization of the scope of nature-based solutions to mitigate climate change and innovations to preserve and deploy them.
1–2:30 p.m.	**Bioengineering and Synthetic Biology** Paul Blum, University of Nebraska (Facilitator) Natalie Kofler, Harvard University (Assessor) Discussion on development of solutions that can be deployed in an industrial or factory setting, including biological and synthetic biology approaches to convert biomass to fuel and other bioproducts; industrial processes that replace energy-intensive activities such as displacing livestock with cultivated meat products; or direct large-scale conversion of greenhouse gases into climate-neutral consumer products using engineered organisms or bio-inspired processes.
3–4:15 p.m.	**Breakout Session Report Outs** Phil Taylor, Bayer R and D
4:15–5 p.m.	**Concluding Session/Identification of Key Takeaways** Becky Irwin, North Carolina State University Come together as a group to summarize answers from each of the breakout topics and identify key takeaways from Day 1.

Wednesday, October 13, 2021

11–11:30 a.m.	**Welcome and Day 1 Recap** Kelly Gillespie, Bayer
11:30 a.m.–12:30 p.m.	**Translational Case Study** Kris Covey, MySOC
1–2:30 p.m.	**Concurrent Breakout Sessions:** **Translating Basic and Use-Inspired Research**
1–2:30 p.m.	**Risk Assessment/Regional Considerations** Marie-Odile Fortier, UC Merced (Facilitator) Kate Lyons, University of Nebraska–Lincoln (Assessor) Discussion on how to minimize the chances of unanticipated ecological and/or societal negative impacts of biotechnological solutions to mitigate the effects of anthropogenic climate change; how the potential risks and costs can be balanced against the benefits of ecosystem resiliency and negative emissions.
1–2:30 p.m.	**Scale-Up** Om Parkash Dhankher, University of Massachusetts Amherst (Facilitator) Christine Wittich, University of Nebraska-Lincoln (Assessor) Discussion on identifying the challenges and barriers to implementing solutions on a scale that is sufficient to achieve global impacts on atmospheric composition, as well as the technologies needed to support and reduce the cost of delivering solutions to practitioners in the field.
1–2:30 p.m.	**Implementation and Adaptive Management** William Anderreg, University of Utah (Facilitator) Bill Yu Case, Western University (Assessor) Discussion on how to evaluate the effects of interventions; identifying the mechanisms needed to ensure that solutions are assessed, and approaches modified as new information is obtained; which technology and monitoring capabilities are needed to determine efficacy; and the unique challenges that are associated with applications in unmanaged or lightly managed ecosystems.
1–2:30 p.m.	**Supply Chains and Markets** Andrew Warren, University of Virginia (Facilitator) Paul Blum, University of Nebraska (Assessor) Discussion on how supply chains will be implemented to ensure sufficient raw materials to achieve production at a scale that can impact climate and what new products will be created and how to market them.

Wednesday, October 13, 2021

3–4:15 p.m.	**Report Outs and Discussion** Phil Taylor, Bayer R and D
4:15–5 p.m.	**Concluding Group Discussion** Becky Irwin, North Carolina State University Come together as a group to summarize answers from each of the breakout topics and identify key takeaways from Day 2.

Appendix C: Participant List

Senay Agca, George Washington University

Craig Allen, University of Nebraska

William Anderegg, University of Utah

Chris Barrett, Biocomplexity Institute at University of Virginia

Joerg Bauer, BASF Corp

Michael Betenbaugh, Johns Hopkins University

Solomon Bililign, North Carolina A&T State University

Paul Blum, University Nebraska-Lincoln

Arpita Bose, Washington University in St. Louis

Adam Briggle, University of North Texas

Nicole Buan, University of Nebraska-Lincoln

Siu Hung "Joshua" Chan, Colorado State University

Lily Cheung, Georgia Institute of Technology

Adam Costanza, NCASI

Taraka Dale, Los Alamos National Laboratory

Jason Delborne, North Carolina State University

Charles Delisi, Boston University

Om Parkash Dhankher, University of Massachusetts Amherst

Jazz Dickinson, UC San Diego

Gamal El Afandi, Tuskegee University

Stephen Eubank, Biocomplexity Institute & Initiative, University of Virginia

Souleymane Fall, Tuskegee University

Marie-Odile Fortier, University of California, Merced

Eric Corey Freed, CannonDesign

Dan Friess, National University of Singapore

Katerina Georgiou, Lawrence Livermore National Laboratory

Robin Gerlach, Montana State University

Kelly Gillespie, Bayer Crop Science

Ian Graham, University of York

Mark Green, Case Western Reserve University

Anna Greenaway, University of Cambridge

Andrew Gregory, University of North Texas

Laura Gunn, Cornell University

Maureen Hanson, Cornell University

Calvin Henard, University of North Texas

Andrea Hicks, University of Wisconsin-Madison

Gloria Ho, BASF

Andrea Hodgson, Schmidt Futures

Guanyu Huang, Spelman College

Rebecca Irwin, North Carolina State University

Christopher Johnson, National Renewable Energy Laboratory

Lauren Junker, BASF

Ramanitharan Kandiah, Central State University

Erica Key, Future Earth

Seunghee Kim, University of Nebraska-Lincoln

Natalie Kofler, Harvard University

Joel Kostka, Georgia Institute of Technology

Robert Last, Michigan State University

Kristy Lewis, University of Central Florida

Jonathan Losos, Washington University

Chenfeng Lu, Fybraworks Foods

Sarah Luppino, M Ventures (Merck KGaA, Darmstadt, Germany)

Kate Lyons, University of Nebraska – Lincoln

Michael Mascia, Conservation International

Mary Maxon, Schmidt Futures

Donald Miles, Ohio University

Tae Seok Moon, Washington University in St. Louis

Wellington Muchero, Oak Ridge National Laboratory

Ashok Mulchandani, University of California Riverside

Navdeep Mutti, Corteva Agriscience

Robert Nairn, University of Oklahoma

Lucy Ngatia, Florida A&M University

Matthew Niemiller, The University of Alabama in Huntsville

Steve Palumbi, Stanford University

Diane Pataki, Arizona State University

Keith Paustian, Colorado State University

Sophia Perdikaris, University of Nebraska-Lincoln

Gary Peter, University of Florida

Caitlin Petro, Georgia Institute of Technology

Brian Pfleger, University of Wisconsin-Madison

Alexandra Ponette-Gonzalez, University of North Texas

Danny Reible, Texas Tech University

Leighton Reid, Virginia Tech

Annette Rowe, University of Cincinnati

Ron Runnebaum, University of California, Davis

Jennifer Russell, Virginia Tech

Paul Russo, CH4 Global

Joe Sagues, North Carolina State University

Daniel Sanchez, University of California-Berkeley

Daniel Segre, Boston University

Sheldon Shi, University of North Texas

Shweta Singh, Purdue University

Jennifer Smith, Scripps Institution of Oceanography

Laura Solitare, Texas Southern University

Liz Specht, The Good Food Institute

Stuart Strand, University of Washington

Mark Svoboda, National Drought Mitigation Center/University of Nebraska-Lincoln

Phil Taylor, Bayer Crop Science US

Joshua Tewksbury, Smithsonian Tropical Research Institute

Deborah Thompson, NC State University

Srinivasan Venkatramanan, University of Virginia

Paul Vincelli, University of Kentucky

Timothy Volk, SUNY ESF

Marc von Keitz, Grantham Foundation

Kim Waddell, University of the Virgin Islands

Matthew Wallenstein, Colorado State University

Andrew Warren, Biocomplexity Institute at UVA

Cathleen Webb, Western Kentucky Climate Center

Karrie Weber, University of Nebraska—Lincoln

Tom Whitham, Northern Arizona University

Mark Wilkins, University of Nebraska

Michael Willey, Elsevier

Christine Wittich, University of Nebraska-Lincoln

Alex Woodley, North Carolina State University

Kelly Wrighton, Colorado State University

Xiong Yu, Case Western Reserve University

Appendix D: Workshop Observers

Sandra Cruz-Pol, The National Science Foundation

Stephen DiFazio, The National Science Foundation

Theresa Good, The National Science Foundation

Bruce Hamilton, The National Science Foundation

Manju Hingorani, The National Science Foundation

Deborah Jackson, The National Science Foundation

Maureen Kearney, The National Science Foundation

Jaroslaw Majewski, The National Science Foundation

Clifford Weil, The National Science Foundation

Appendix E: Pre-Event Survey

We look forward to your participation at the upcoming “Mitigating Climate Change” workshop. Our goal is to convene stakeholders from multiple sectors and disciplines to discuss potential research and technological innovation areas needed for biotechnology innovation ecosystems to mitigate climate change. We will focus on four theme areas:

1. Systems analysis
2. Managed systems
3. Natural systems, and
4. Bioengineering/synthetic biology.

So our exploration of each of those themes is efficient and productive, we ask that you give us your feedback on the following. We also welcome your written comments below.

Please help us set the stage for the workshop by completing the survey. Please respond by Tuesday, October 5, 2021.

For each theme below, please rate the importance of the topics for industry and academia to collaboratively expand knowledge in and remove barriers to mitigating climate change.

Systems Analysis	Not Important	Slightly Important	Moderately Important	Important	Very Important
Understanding the impacts of ongoing climate change on ecosystem composition and function at all spatial scales, from genes to ecosystems	○	○	○	○	○
Defining critical thresholds of environmental responses to extreme events	○	○	○	○	○
Defining measures of species resilience and adaptive capacity to changing environments across diverse domains of life	○	○	○	○	○
Identifying the most effective carbonmitigating natural systems	○	○	○	○	○
Identifying the most effective adaptation and mitigation strategies	○	○	○	○	○
Assessing efficacy through life cycle analysis and modeling	○	○	○	○	○

Managed Systems	Not Important	Slightly Important	Moderately Important	Important	Very Important
Development of engineered microbes that enhance soil organic carbon	◯	◯	◯	◯	◯
Transgenic or editing targets in agronomic and forestry crops that enhance stress tolerance or increase the efficiency of resource acquisition and utilization	◯	◯	◯	◯	◯
Development of precision agriculture and approaches that facilitate implementation and assessment of efficacy	◯	◯	◯	◯	◯

Natural Systems	Not Important	Slightly Important	Moderately Important	Important	Very Important
Biotechnological and synthetic biology applications that enhance the establishment and performance of organisms that sequester large quantities of GHG	◯	◯	◯	◯	◯
Solutions that reduce GHG emissions or maximize sequestration or conversion of GHG into benign products in natural settings	◯	◯	◯	◯	◯
Characterization of the scope of nature-based solutions to mitigate climate change and innovations to preserve and deploy them	◯	◯	◯	◯	◯

Bioengineering/Synthetic Biology	Not Important	Slightly Important	Moderately Important	Important	Very Important
Biological and synthetic biology approaches to convert biomass to fuel and other bioproducts	◯	◯	◯	◯	◯
Industrial processes that replace energy-intensive activities such as displacing livestock with cultivated meat products	◯	◯	◯	◯	◯
Direct large-scale conversion of greenhouse gases into climate-neutral consumer products using engineered organisms or bioinspired processes	◯	◯	◯	◯	◯

Please offer any additional relevant topics or additional comments you'd like to share.

Notes

References

[1] Poore, J., Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987–992. https://doi.org/10.1126/science.aaq0216

[2] IPPC Special Report 2018 - Technical Summary. (2018). IPCC, (October).

[3] Additionality refers to assurance that carbon sequestration would not have happened without some sort of intentional intervention to the system, and permanence refers to the assurance that carbon will be sequestered for a long duration (typically > 100 years).

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