CLEAN AIR TASK FORCE

Decarbonizing the agriculture sector: What role can bioenergy play?

Highlights from a Clean Air Task Force virtual learning workshop

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Introduction

In June 2024, Clean Air Task Force (CATF) hosted a two-part virtual learning workshop—titled "Decarbonize–Recarbonize Agriculture with Bioenergy"—to better understand the role that advanced bioenergy systems[1] might play in reducing atmospheric greenhouse gas concentrations and mitigating climate change. This brief summarizes insights and key takeaways from the virtual workshop, which will inform CATF's ongoing research, analysis, and development of policy and advocacy strategies around potentially beneficial bioenergy systems.

The term "Decarbonize–Recarbonize Agriculture" in the workshop title refers to the opportunity to simultaneously reduce carbon dioxide, methane, and nitrous oxide emissions from the agriculture sector while also increasing the amount of carbon stored away from the atmosphere in ecosystems, durable products, and geologic reservoirs. Ideally, well-designed bioenergy systems deployed to this end will also benefit soil health, improve ecosystem functioning, enhance food security, and help transform energy systems.

Workshop participants included nine leading experts from academia and industry who shared their expertise and perspectives on the potential role of different bioenergy technologies in decarbonizing agriculture (see the Workshop Presenters section at the end of this report for a list of experts).

[1] Here we use the term "advanced bioenergy systems" to describe systems that are at varying stages of research, development, and commercialization that utilize the lignocellulosic components of wastes and nonfood biomass feedstocks and deploy carbon capture and storage or other biomass carbon removal and storage technologies.

Background

The agriculture sector[2] faces three primary, concurrent challenges in the decades ahead: rapidly reducing emissions; realizing opportunities to permanently remove carbon dioxide (CO_2) from the atmosphere; and meeting the food, energy, and material needs of a growing global population. Rapidly reducing or avoiding *new* emissions can slow the trajectory of climate change but cannot reverse it. Options for removing and permanently storing CO_2 that is already in the atmosphere are critical as a means for counterbalancing residual emissions and slowing the pace and scale of climate impacts. A further challenge is that new technologies and systems for reducing emissions and removing CO_2 must scale alongside necessary growth in agricultural production. Ideally, efforts to advance emissions reductions, food and energy production, and CO_2 removal (CDR) will also have benefits for water, air, and soil quality, biodiversity, and the prosperity of rural communities. However, these widely agreed-upon goals of ensuring sustainability and providing social and environmental benefits are not guaranteed.

The need to rapidly reduce emissions

Agrifood systems are estimated to account for approximately one-third of overall global anthropogenic greenhouse gas (GHG) emissions.[3] More than half of this contribution is estimated to result from land use changes, predominantly CO_2 emissions from forest conversion; other major sources include on-farm energy use, methane emissions from enteric fermentation, and nitrous oxide emissions from agricultural soils.[4] Globally, agriculture is estimated to account for more than 50% of anthropogenic methane emissions and 75% of nitrous oxide emissions.[5] The remaining sectoral emissions (predominantly in the form of CO_2) come from pre- and post-production activities such as the manufacture of agrochemical inputs like fertilizer, supply-chain energy consumption (e.g., to harvest and transport crops), and the management of food and animal waste streams.[6]

The need to achieve carbon capture, storage, and removal

As decarbonization efforts proceed in other sectors of the economy, agriculture is expected to be a significant contributor to remaining, residual GHG emissions. Changes in manufacturing (e.g., electrifying synthetic nitrogen fertilizer production), electric power production, and transportation technologies will reduce some agricultural supply chain emissions, but other sources of emissions in this sector, including especially non-CO_2 emissions from on-farm activities, will likely continue to grow as global population growth increases demand for farm products. In this context, options for permanently removing carbon from the atmosphere are needed to counterbalance residual emissions from agriculture and other sectors that cannot be technically or economically avoided. Studies also project a need for CDR to return the atmosphere to a safer operating space when the 1.5°C Paris target is breached.[7]

[2] Here we use the term "agriculture sector" in place of "land sector": *Agriculture, Forestry, and Other Land Use* and distinguish it from "agrifood systems" that include farm and forestry activities and land use change and other activities upstream and downstream in the value chain that are not captured in the land sector but do affect the ability of the agriculture sector to produce.

[3] Crippa et al. 2021 https://doi.org/10.1038/s43016-021-00225-9; Tubiello et al. 2021 https://doi.org/10.1088/1748-9326/ac018e; FAO (2020) www.fao.org/3/ca8389en/CA8389EN.pdf

[4] FAO (2020) www.fao.org/3/ca8389en/CA8389EN.pdf

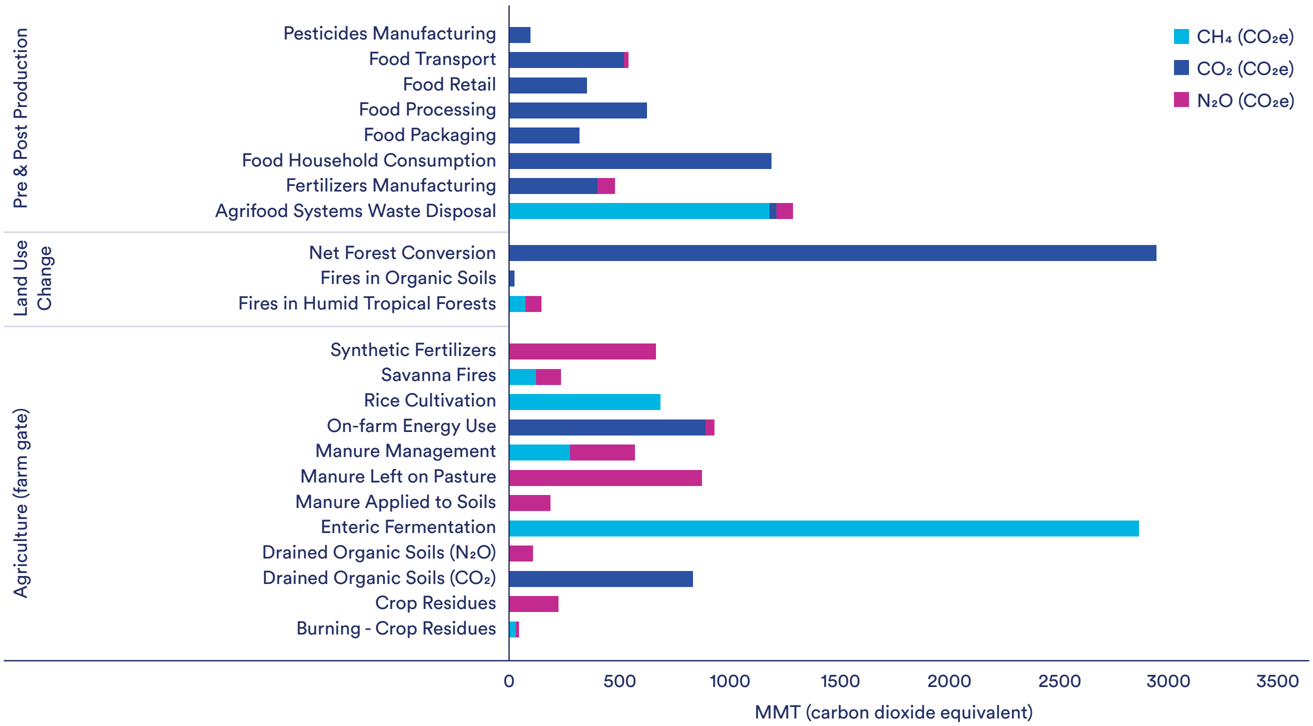
[5] Crippa et al. 2021 https://doi.org/10.1038/s43016-021-00225-9; Tubiello et al. 2021 https://doi.org/10.1088/1748-9326/ac018e; FAO (2020) www.fao.org/3/ca8389en/CA8389EN.pdf

[6] FAO (2020) www.fao.org/3/ca8389en/CA8389EN.pdf

[7] https://crsreports.congress.gov/product/pdf/R/R48258

Figure 1: Global agrifood system greenhouse gas emissions (CO_2e)

Source: FAO (2021); https://www.fao.org/



The need to meet growing societal needs

GHG reductions and removals will have to occur alongside expected growth in global demand for food, feed, fiber, energy, biomaterials, and biochemicals.[8] The agriculture sector's ability to meet these needs in different contexts will be constrained by biomass supply, land area, water and nutrient availability, fertilizer cost, access to capital and labor, and climate change impacts, which are expected to increase the sector's exposure to adverse weather events and crop loss. Improving efficiency and increasing circularity in agrifood systems can help meet increased demand and reduce constraints by avoiding some of the significant losses of inputs that occur in current systems. Examples include nitrogen fertilizers that are applied to agricultural lands but not used by crops[9] and the 14% of global food production that is estimated to be wasted post-harvest, before reaching consumers.[10] Substantially reducing these inefficiencies will require many transformational changes, including significant changes in land management, large-scale adoption of new technologies and practices by farmers, and the development of entirely new value chains.[11]

8 van Dijk, M., Morley, T., Rau, M.L. et al. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nat Food 2, 494–501 (2021). https://doi.org/10.1038/s43016-021-00322-9

9 Basso, B., Shuai, G., Zhang, J. et al. Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. Sci Rep 9, 5774 (2019). https://doi.org/10.1038/s41598-019-42271-1

10 FAO. 2019. The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Rome. Licence: CC BY-NC-SA 3.0 IGO.

11 Schulte, L.A., Dale, B.E., Bozzetto, S. et al. Meeting global challenges with regenerative agriculture producing food and energy. Nat Sustain 5, 384–388 (2022). https://doi.org/10.1038/s41893-021-00827-y

The potential role of biomass and bioenergy in meeting these concurrent needs

Bioenergy systems can reduce carbon dioxide, methane, and nitrous oxide emissions from the agriculture sector by capturing biomass emissions, sustainably intensifying existing cropland, shifting cropping systems, processing carbon in biomass for permanent storage, producing low- or zero- carbon energy, and soil amendments that might displace emitting alternatives.

Biomass resources encompass a wide variety of organic (carbon-based) materials from living or recently living plants, including crops, trees, crop and forest residues, animal wastes, and bioproduct wastes. These resources are the basis for innumerable agricultural products, including food and feed, bioenergy, and other bioproducts (chemicals and materials), as well as invaluable ecosystem services such as clean air and water, soil fertility, and biodiversity.

CDR can be achieved by using biomass feedstocks in systems that store more carbon atoms than they emit on a lifecycle basis, taking into account all upstream and downstream supply chain emissions. All plants use the process of photosynthesis to capture carbon from the atmosphere and convert it to storable chemical energy in the form of carbon-containing compounds like sugar, cellulose, and starches. These plant materials are used for human food, animal feed, bioenergy, and other bioproducts.[12] Bioenergy with carbon capture and storage is an example of an engineered system that can move biomass carbon atoms to geologic reservoirs for permanent storage. These systems do not automatically or always result in CDR and may not necessarily be optimized for CDR over bioenergy production, but they do offer the potential to accomplish both CDR *and* energy production.

Biomass-based systems that maximize climate and other benefits by optimizing for CDR over the production of other bio-outputs (like liquid, solid, or gaseous bioenergy) are called biomass carbon removal and storage.[13] Mitigation pathways modeled by the Intergovernmental Panel on Climate Change (IPCC) that rely on CDR to limit future warming call for bioenergy with carbon capture and storage (BECCS) systems to contribute approximately half—or 2.75 gigatonnes (Gt)—of the permanent CDR required annually by 2050.[14] Globally, plants in natural and managed ecosystems capture hundreds of gigatonnes of CO_2 yearly.[15] This flux exceeds by ten-fold the quantity of CO_2 released by human use of fossil fuels on an annual basis. However, most of the carbon captured by photosynthesis returns to the atmosphere within a relatively short timeframe when plants (or the things that eat plants) respire and eventually decompose or burn. BECCS provides an opportunity to interrupt the flux of carbon captured via photosynthesis back to the atmosphere and beneficially use or move some of this carbon to permanent storage. Additionally, opportunities exist to capture more atmospheric carbon through additional plant growth on existing lands, such as seasonally fallow cropland.

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12 Comparing the concentration of CO_2 in the atmosphere, at approximately 420 parts per million (ppm) or 0.000420, to the concentration of carbon in plant material, at approximately 500,000 ppm or 0.5, provides a sense of the carbon concentrating power of photosynthesis. See https://sdg-action.org/harnessing-the-power-of-photosynthesis-for-negative-emissions/

13 https://www.osti.gov/biblio/1763937

14 M. Pathak, R. Slade, P.R. Shukla, J. Skea, R. Pichs-Madruga, D. Ürge-Vorsatz,2022: Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002. Across the scenarios limiting warming to 2°C (>67%) or below, cumulative volumes of BECCS reach 328 (168–763) $GtCO_2$, CO_2 removal from AFOLU (mainly A/R) reaches 252 (20–418) $GtCO_2$, and DACCS reaches 29 (0–339) $GtCO_2$, for the 2020–2100 period. Annual volumes in 2050 are 2.75 (0.52–9.45) $GtCO_2\ yr^{-1}$ for BECCS, 2.98 (0.23–6.38) $GtCO_2\ yr^{-1}$ for the CO_2 removal from AFOLU (mainly A/R), and 0.02 (0–1.74) $GtCO_2\ yr^{-1}$ for DACCS. (Box TS.10) {12.3, Cross-Chapter Box 8 in Chapter 12}.

15 Figure 5.12 in IPCC, 2021: Chapter 5. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi: 10.1017/9781009157896.007.]

By supplying energy needs that would otherwise be met using fossil-based fuels, heat, and power, bioenergy systems can also avoid the release of carbon from geologic storage back into the biosphere.[16] Further climate benefits are potentially achievable if biomass that would otherwise become a source of emissions can be converted to non-emitting energy products, such as hydrogen, using processes and technologies that allow for effective carbon capture and storage.[17]

Insights and takeaways from the virtual learning workshop

An overarching focus of discussion at the workshop was the value of a circular,[18] carbon-negative bioeconomy that achieves emissions reductions and CDR while also reducing inputs to and losses from existing agricultural systems and meeting societal needs. Carbon-negative refers to processes which store an amount of gross carbon that surpasses the total greenhouse gasses emitted throughout the process's supply chain, over its lifecycle. In a carbon-negative bioeconomy, increased production has the potential to help reverse climate change by increasing the amount of atmospheric carbon captured and stored with each unit of bioenergy or bioproduct delivered, *if* carbon in the biomass resources consumed is permanently stored. In this way, carbon-negative[19] circular bioeconomies[20] can be viewed as economic opportunities that produce products that can be sold and consumed rather than *just* pollution prevention opportunities, as may be the case with other forms of CCS or other forms of CDR.

The concept of a circular bioeconomy also holds promise for reducing the agriculture sector's reliance on external emissions-intensive inputs and reducing the detrimental environmental effects associated with system losses. Scaling a carbon-negative circular bioeconomy may require an organized approach where initial incentives for new farm-based biomass resource production and existing systems for collecting agricultural wastes and residues are designed to support land-sector emission reductions and increased land carbon storage while infrastructure and markets for advanced bioenergy systems with CCS and other systems are being built and tested. It will also be necessary to connect often disparate fields of expertise and nurture partnerships between bioenergy researchers and companies, CDR proponents, agronomic research institutions, policy experts, and farm communities.

The following sections summarize the opportunities, synergies, risks, and challenges associated with utilizing advanced bioenergy systems to decarbonize agriculture identified by workshop participants.

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16 Although the sustainable use of bioenergy resources does not increase the total amount of carbon circulating in the biosphere, it can lead to localized impacts from other types of pollutant emissions (e.g., from combusting wood or crop residues). Different feedstock choices and system designs can have different implications for air and water quality and other impacts of concern.

17 The use of thinnings from well-managed forests, for example, could also reduce wildfire risk, another major source of CO_2 emissions. Other potential bioenergy feedstocks include biogenic wastes that would otherwise decompose anaerobically and produce methane, a more potent greenhouse gas than CO_2.

18 Select resources on the circular economy or circular bioeconomy: https://cbsi-asabe.org/; https://www.ellenmacarthurfoundation.org/articles/time-to-act-seizing-the-potential-of-us-circular-economy-innovation; Khanna et al. (2024) https://www.nature.com/articles/s43247-024-01663-6

19 "Carbon-negative" refers to when the amount of carbon stored during a process surpasses the total greenhouse gas emissions produced throughout the system's supply chain over its lifecycle.

20 As described by Khanna et al. (2024), *Definitions of a circular bioeconomy vary across studies but have a common emphasis on reducing the use of virgin materials, recycling and reusing materials, restoring, and regenerating natural systems, and converting the unavoidable wastes and other biological resources into bioenergy or bioproducts to substitute for fossil fuels* https://cbsi-asabe.org/wp-content/uploads/2024/10/Madhu_Zilberman_Hochman_Basso_Circular-Bioeconomy.pdf

Opportunities

Workshop participants identified several strategies for potentially maximizing the climate and non-climate benefits of advanced bioenergy systems. We discuss these opportunities and synergies first before elevating risks and challenges.

Reduce agricultural emissions by utilizing existing biomass resources that are otherwise emitting

Many opportunities exist to interrupt the flux of GHG emissions from biogenic point sources back to the atmosphere and to divert these emissions to permanent storage. These emission sources include existing combustion facilities in the pulp and paper industry that use biomass for stationary heat and power production, ethanol refineries, and anaerobic digesters.[21] One study estimates that advanced bioenergy systems with carbon capture and storage could capture and store approximately 130 million tonnes (Mt) of biogenic CO_2 emissions per year from existing biogenic point sources in geologic reservoirs in Europe.[22]

Additionally, other distributed residue and waste biomass resources could be collected and transported to bioenergy conversion facilities that implement CCS or provide other forms of durable carbon storage.[23] Such resources could include crop residues and forest thinnings harvested to support wildfire resilience, food processing waste, and manure. Crop residue decomposition, manure management, and food waste disposal have been estimated to account for approximately 16% of total greenhouse gas emissions from agrifood systems.[24]

Grow plants and/or increase yields on lands that are currently less productive

Demand for agricultural land fluctuates, but opportunities exist to grow biomass resources on currently underutilized lands, including on field borders and strips[25] where perennial vegetation is needed to reduce nonpoint source water pollution, on the tens of millions of acres of cropland that have been abandoned globally,[26] on existing cropland that is seasonally bare, or fallow (in the U.S. Midwest, for example, more than 90% of land in corn-soy rotations is left fallow during the winter[27]), and on existing cropland that delivers consistently low yields (this category may include as much as one-quarter of the land in the U.S. Midwest[28]) or earns nearly zero economic returns after accounting for the monetized costs of environmental externalities like water quality impairment and habitat loss (sometimes termed socially marginal land).[29]

According to some studies, growing perennials for use as bioenergy with CCS on land that is being transitioned out of crops or pasture and might otherwise be abandoned could achieve greater greenhouse gas mitigation benefits than using these lands for forest and grassland restoration.[30] The climate mitigation potential of growing plants alone will likely decrease as soils' capacity to store organic carbon saturates, while mitigation potential from systems that grow and harvest biomass like bioenergy with CCS will likely increase over time.[31]

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21 Feng and Rosa (2024) https://iopscience.iop.org/article/10.1088/1748-9326/ad1e81; Rosa et al. (2021) https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee00642h; Sanchez et al. (2018) https://www.pnas.org/doi/10.1073/pnas.1719695115

22 Rosa et al. (2021) Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy and Environmental Science. https://doi.org/10.1039/D1EE00642H

23 Feng and Rosa (2024) https://iopscience.iop.org/article/10.1088/1748-9326/ad1e81; Rosa et al. (2021) https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee00642h; Roads to Removal – Options for carbon dioxide removal in the US

24 Rosa and Gabrielli (2023). Achieving net-zero emissions in agriculture: a Review. Environmental Research Letters. https://doi.org/10.1088/1748-9326/acd5e8

25 https://www.nrem.iastate.edu/research/STRIPS/

26 Zheng et al. (2023) https://www.nature.com/articles/s41467-023-41837-y

27 Zhou et al. (2022) https://doi.org/10.1029/2022GL100249

28 Basso et al. (2019) https://www.nature.com/articles/s41598-019-42271-1

29 Khanna et al. (2021) https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12877

30 Field et al. (2020) Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels - PubMed

Cultivating perennial bioenergy crops that are bred or engineered with genes that enhances photosynthetic activity and boosts plant growth[32] may also increase net carbon capture compared to conventional bioenergy crops, particularly if these crops are integrated into field buffers and unprofitable subfield areas where yields are low or unstable. Growing winter crops on seasonally fallow land is another potentially promising option: one study estimated that U.S. cellulosic biofuel production could be tripled using select fallow cropland in a five-state region of the US. Midwest.[33]

Use bioresources strategically for permanent carbon storage and, in hard-to-decarbonize industries

Historically, efforts to promote bioenergy have focused on the opportunity to improve energy security and generally displace fossil fuels. As energy systems transform and add more renewables like wind and solar and clean firm energy options like geothermal and nuclear, decision-makers must think strategically about bioresources uses, bioenergy and system configurations. On farms, advanced bioenergy systems can complement weather-dependent renewables in meeting electricity demands for irrigation, refrigeration, lighting, and heat and displace fossil fuels in operations that require hard-to-electrify heavy machinery (fossil fuel use on farms are estimated to account for 1.03 Gt CO_2-eq or 2% of global anthropogenic GHG emissions in 2020[34]). The opportunity to displace fossil-derived hydrocarbon resources remains important in hard-to-decarbonize industries where carbon or firm energy sources are needed today, like aviation, and where carbon is an intrinsic part of the production process, such as concrete, platform chemicals,[35] steel and iron.[36] One study in Europe estimated agricultural residues and waste used in BECCS supply chains can produce up to 12.5 Mt of biohydrogen annually and remove up to 133 Mt CO_2 per year from the atmosphere (or 3% of European total greenhouse gas emissions) and these resources are collocated near hard-to-electrify industries.[37] Some researchers have proposed combining energy systems to most effectively use the carbon in biomass, e.g., nuclear-assisted biofuels with nuclear energy systems providing heat for bioconversion[38] but some of these ideas may be too complex to pursue or lack economic viability. Others emphasize the thermodynamic efficiency of capturing carbon via photosynthesis compared to other processes and the potential to economically capture carbon from bioenergy conversion pathways that also generate pure CO_2 streams. Bioenergy systems with CCS that move carbon atoms to geologic reservoirs and achieve CDR[39] can be a way to counterbalance residual GHG emissions in a net zero economy and draw down CO_2 levels in the atmosphere. These systems can be optimized for energy production or CDR and researchers suggest that the value of biomass resources for removing carbon exceeds the value of using biomass for energy.[40] Other opportunities representing a likely smaller portion of the solutions portfolio include mineralizing biogenic carbon in concrete and burying nondegradable biopolymers. One study estimates that biogas-concrete supply chains could mineralize 8 Mt of CO_2 per year in recycled concrete aggregates in Europe.[41]

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31 Robertson et al. (2022) https://doi.org/10.1111/gcb.16267

32 https://www.ornl.gov/news/landmark-photosynthesis-gene-discovery-boosts-plant-height-advances-crop-science

33 Malone et al. (2023) Harvested winter rye energy cover crop: multiple benefits for North Central US - IOPscience

34 Rosa and Gabrielli (2023) DOI 10.1088/1748-9326/acd5e8

35 For example, Bhagwat et al. (2021) https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.1c05441

36 For example, Suopajärvi et al. (2017) https://doi.org/10.1016/j.jclepro.2017.02.029

37 Rosa and Mazzotti (2022) https://doi.org/10.1016/j.rser.2022.112123

38 Forsberg and Dale (2022) https://futureofenergyinitiative.org/Pubs/Forsberg-Biofuels.pdf

39 See Chapter 6: https://roads2removal.org/

40 Sandalow et al. (2021) https://doi.org/10.2172/1763937

41 Rosa et al. (2022) https://doi.org/10.1016/j.resconrec.2022.106436

Recycle nitrogen to reduce dependence on synthetic nitrogen fertilizers and decrease nitrogen pollution

In addition to carbon, other constituents in biomass, especially nitrogen, are also valuable for plant growth in the right amounts. Nitrogen is often a limiting nutrient for plant growth, which is why modern agriculture uses large quantities of organic and inorganic nitrogen fertilizers (e.g., manure and ammonia derived from the Haber-Bosch process, respectively).

Fertilizers are a major source of anthropogenic emissions of nitrous oxide, a potent greenhouse gas. They also cause nitrate leaching and other reactive nitrogen losses that are harmful to air and water quality.[42] Synthetic fertilizers are estimated to contribute about 1.01 Gt CO_2e emissions annually, or 2% of global GHG emissions—approximately one-third of this contribution comes from energy use and other inputs to fertilizer production; the remaining two-thirds comes from nitrous oxide emissions when fertilizers are used in agriculture.[43]

Where excess nitrogen from biological processes is available, replacing synthetic nitrogen fertilizers with organic fertilizers can reduce upstream fossil fuel emissions.[44] However, this can require reconnecting currently disconnected crop and livestock systems.[45] Additionally, the performance of organic fertilizers like manure can be less predictable than that of synthetic fertilizers, resulting in over application, and losses such as nitrous oxide emissions, and nitrate-nitrogen leaching which can impair water quality. Bioenergy conversion processes like anaerobic digestion can deliver a more predictable and plant-available nutrient source than unprocessed resources. In well-designed systems, all the nitrogen in the biomass feedstock ends up in the digestate, but even so, not all of the nitrogen will be taken up by plants when land applied, and losses can occur and must be considered.

Changing cropping systems to include bioenergy crops that do not require added nitrogen or have reduced nitrogen requirements relative to the alternative system can reduce fertilizer use and reactive nitrogen losses. Perennial or other crops engineered or bred to have low nitrogen requirements could reduce the need for nitrogen fertilizers, but researchers are still improving crop varieties in the lab and field plots.[46] Growing winter energy crops on fallow land can also reduce reactive nitrogen losses.[47] Emerging studies suggest that some level of nitrogen fertilization may maximize biomass yields for an overall GHG benefit.[48]

Synergies

Workshop participants shared several potential synergies that could deliver broader climate and ecosystem benefits while meeting other agriculture sector needs.

Increase circularity in agriculture

Bioenergy systems can be designed to create beneficial feedback loops with land systems in ways that enhance circularity, improve nutrient recycling, reduce waste emissions, reconnect cropping and livestock systems, and reduce demand for fossil-derived resource inputs and related emissions. To maximize overall benefits, a focus on CDR (i.e., decreasing carbon circularity and instead moving carbon from the biosphere to permanent storage) should be balanced with the reuse of other biomass components.

42 https://www.unep.org/resources/report/global-nitrous-oxide-assessment

43 Menegat et al. (2022) https://www.nature.com/articles/s41598-022-18773-w

44 Menegat et al. (2022) https://www.nature.com/articles/s41598-022-18773-w

45 https://ltar.ars.usda.gov/research/ltar-working-groups/manureshed/

46 https://www.ornl.gov/news/landmark-photosynthesis-gene-discovery-boosts-plant-height-advances-crop-science

47 https://iopscience.iop.org/article/10.1088/1748-9326/acd70; https://acsess.onlinelibrary.wiley.com/doi/pdf/10/2134/ael2017.11.0041

48 Malone et al. (2017) https://acsess.onlinelibrary.wiley.com/doi/10.2134/ael2017.11.0041; Ruan et al. (2014) https://lter.kbs.msu.edu/pub/3539

Advance land and biomass resource configurations that promote biodiversity and return value to land systems

Cultivating new perennial biomass resources on underutilized land can improve biodiversity, including crop diversity, support healthy populations of beneficial insects and birds, and help manage harmful pests on that land.[49] Even if the focus of future bioenergy deployment efforts is climate change mitigation, other potential benefits such as biodiversity, soil health, water quality, and resilience to flood, drought, pests, and wildfire are critically important and could themselves result in climate benefits. Planting certain perennial bioenergy feedstocks, for example, can reduce fertilizer requirements and improve water quality via reduced reactive nitrogen losses,[50] while also increasing biodiversity,[51] making the land more resilient to disturbances, enhancing soil carbon stocks, and reducing wildfire risk. These synergies highlight the potential of bioenergy systems, coupled with durable carbon storage, to mitigate climate change while delivering a broad array of other environmental benefits.

Bioenergy systems might also be configured to return value to land systems from which biomass resources were removed. Concerns about the impacts of harvesting residues that otherwise support ecosystem functioning are warranted; in these cases, strategies to mitigate potential tradeoffs—for example, by returning soil amendments to the lands from which residues are taken—may be appropriate.[52]

Realizing these synergies is not without challenges, however, and will require safeguards alongside robust policies and stakeholder collaboration. Increased support for non-climate land system functions (like water quality and biodiversity) that may result in climate co-benefits may need to be prioritized sometimes over a myopic focus on carbon in these conversations.

Risks

Ensuring sustainability and avoiding other social or environmental harms are widely agreed *goals* of decarbonize-re-carbonize agriculture with bioenergy—they are not guarantees. The environmental tradeoffs involved in scaling bioenergy systems should be understood, transparently shared, and carefully weighed by decision-makers and stakeholders, including communities in areas that supply biomass feedstocks and/or host bioenergy conversion facilities and carbon storage. It will be important to identify potential unintended consequences and pursue policies, regulations, and implementation practices that mitigate risks and address potential tradeoffs.

Avoid increased use of nitrogen fertilizer beyond crop needs

Expanded applications of fertilizer to purpose-grown perennial biomass crops can result in emissions of upstream CO_2 and nitrous oxide and increase nitrate-nitrogen runoff and leaching, potentially negating some of the climate benefits achieved through bioenergy-based CDR and impairing water quality. Land managers must take care to optimize the amount of nitrogen applied to bioenergy crops without increasing reactive nitrogen losses and associated GHG emissions.

Limit methane leakage from anaerobic digesters

Anaerobic digesters, which produce biomethane and biogas, were discussed at length at the workshop, given their ability to process a diverse array of biomass feedstocks and be resilient to changes in biomass supply. A key point in the discussion was the need to tightly limit methane leaks from these types of facilities to ensure

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49 Werling et al. (2014) https://lter.kbs.msu.edu/docs/robertson/Werling_et_al._2014_PNAS.pdf

50 Malone et al. (2018) https://acsess.onlinelibrary.wiley.com/doi/full/10.2134/ael2017.11.0041; Malone et al. (2023) Harvested winter rye energy cover crop: multiple benefits for North Central US - IOPscience

51 Werling et al. (2014) https://lter.kbs.msu.edu/docs/robertson/Werling_et_al._2014_PNAS.pdf

52 Soil application of high-lignin fermentation byproduct to increase the sustainability of liquid biofuel production from crop residues - IOPscience

that an increase in methane emissions does not outweigh any climate benefit achieved by capturing carbon that would otherwise be released as CO_2 if the biomass feedstocks used were instead allowed to decompose aerobically. Implementing best engineering designs and management practices and robust leak detection can support limiting leakage. Needing policies to treat avoided methane emissions differently than actual net-negative emissions or carbon dioxide removal was also discussed.

Reduce the risk of detrimental land use changes that would *reduce* land-based carbon storage

Land use changes can be beneficial or detrimental, and intentionally growing biomass resources for bioenergy can directly or indirectly affect land use in both directions. Examples of detrimental land use changes include deforestation; the conversion of more carbon-dense land, such as wetlands, to less carbon-dense land; and land use changes that reduce or destroy biodiversity. Intensifying the use of current croplands might help reduce these detrimental land use change risks.

Design policy mechanisms to reduce the risk of negative unintended outcomes

Misaligned incentives risk creating perverse outcomes, such as rewarding larger polluters, encouraging agricultural producers to maximize waste streams for use as bioenergy feedstocks (potentially competing with other uses such as animal feed), generating additional new methane, or discouraging diversity in cropping systems. A BECCS system that moves carbon atoms in biogenic material to durable geologic storage may not achieve net climate benefits overall if it leads to increased GHG emissions elsewhere in the supply chain. And if carbon credits with improper accounting are used to offset fossil emissions, the effect may be to deter necessary investments in alternative technologies.

Address equity and environmental justice concerns

Bioenergy projects could disproportionately impact disadvantaged communities or exacerbate existing inequities. Workshop participants cited several concerns, including community impacts related to truck traffic, storage leaks, wastewater discharge, demand for freshwater, and non-GHG air pollutant emissions. Workshop participants also discussed potential benefits to communities, such as reduced odor, improved air quality, and jobs.

Challenges

Many of the challenges discussed in connection with BECCS have been discussed in the cellulosic bioenergy community for decades.[53] Critical factors that have affected and continue to affect the deployment and scale-up of cellulosic bioenergy systems *without* CCS can also be expected to affect efforts to scale “net negative and circular” BECCS systems that use cellulosic feedstocks and include durable or permanent carbon storage.[54] Issues associated with greenhouse gas accounting and uncertainty in lifecycle and technoeconomic analyses must also be addressed.[55]

Address the need for a reliable and sustainable biomass supply that matches bioconversion capacity and product demand

There are two types of bioenergy conversion facilities—those that rely on consistent supplies of particular feedstocks and those that can accept a diversity of biomass resources and are, therefore, resilient to changes in feedstock supply. Two system designs currently being researched at the Center for Bioenergy Innovation

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53 https://pubs.aip.org/physicstoday/article/75/7/22/2848574/Whatever-happened-to-cellulosic-ethanol

54 Davison et al. (2015) https://scijournals.onlinelibrary.wiley.com/doi/10.1002/bbb.1549

55 BioSTEAM was presented as a quantitative sustainable design (QSD) tool that can help quantify uncertainty and attribute sensitivity and uncertainty to model inputs and characterize lifecycle environmental impacts and financial viability. https://biosteam.readthedocs.io/en/latest/index.html

shared during the workshop—carbohydrates-first via consolidated bioprocessing with cotreatment and lignin-first via reductive catalytic fractionation—are examples of conversion pathways that have highly specific feedstock requirements. Anaerobic digestion, by contrast, can accommodate a wide range of feedstocks. Today, bioenergy conversion facilities may face challenges in terms of securing adequate, reliable supplies of feedstocks or, in other cases, of being potentially oversupplied and having to turn some resources away, which can pose challenges in the region if conversion facilities are limited. Contingency plans may be needed for facilities that cannot handle diverse feedstocks in the case of supply disruptions. Where oversupply is more likely (as in the cases described by workshop presenters in parts of California today), processing capacity would need to scale rapidly to take full advantage of resources that are currently described as underutilized. Given the likely variable supply of feedstock (over time), locations are likely to end up with situations like limited processing capacity and *too much* biomass in some years, leading to the possibility that facilities may turn biomass away. Therefore, policies should be designed so that processing capacity can be built and remain viable even when operating at less than 100% of design capacity.

Reduce barriers related to high capital costs and uncertain economic viability

Many existing bioenergy systems depend on subsidies or incentives to be economically competitive, in part because capital costs for these systems remain high. The business case for new projects is also highly dependent on policy decisions in several areas, such as biofuel standards and carbon markets. The CDR market is still emerging, and it remains unclear whether the economics of future BECCS or other biomass carbon removal and storage deployment will be primarily driven by land system benefits, demand for bioenergy products, demand for durable carbon storage, or some combination of these factors.

Facilitate needed infrastructure siting

A challenge for systems that incorporate CCS is public opposition to the siting of pipelines to transport captured CO_2 from bioenergy conversion facilities to geologic storage sites. A general rule of thumb shared during the workshop holds that conversion facilities should be sited near the biomass resource to be used if less than half the carbon in the biomass is captured for durable storage at the facility. Alternatively, if more than half the carbon is going to be captured, the bioenergy conversion facility should be located near the geologic sites that will be used for CO_2 storage. The BioSiting Tool was shared as an example of a geospatial interface for analyzing bioeconomy resources and infrastructure. The Roads to Removal report was shared as an example of a national-scale analysis of biomass carbon removal and storage systems outlining regional opportunities. Because transportation costs are often substantial, proximity to feedstocks, geologic carbon storage, and existing infrastructure is important for the economic viability of BECCS systems. Policies are needed to facilitate related investments, both in CO_2 transport infrastructure and in distributed systems, to reduce environmental burdens on disadvantaged communities. Siting policies must incorporate environmental justice criteria to avoid disproportionate impacts on historically burdened populations and ensure that benefits (e.g., jobs, cleaner air) are distributed fairly.

Invest in Research, Development and Demonstration (RD&D) to address the low technological readiness of cellulosic bioenergy conversion systems and supply chain infrastructure

Many of the technologies needed to implement BECCS are still in the research, development, and demonstration stages. These technologies need RD&D support and must be scaled carefully with environmental and social safeguards to avoid the mistakes that have undermined previous attempts to scale cellulosic bioenergy.

Needs

Policies can be a significant driver and must be designed to avoid unintended consequences. Tools are also needed to quantify impacts and to monitor and verify the sustainability of BECCS supply chains. Lessons learned from failed efforts to deploy cellulosic bioenergy provide insights and a starting point for developing more successful business models.

Center the discussion on improving land systems

The land systems that sustain biomass resources must be at the center of discussions about how to develop a sustainable, climate-beneficial bioenergy industry. Energy market demand is important but should not be the sole driver of decisions about land uses, research priorities, and policy design. Rather, the focus should be on reducing emissions, enhancing CDR, and improving the health and resilience of land systems to sustain their ability to continue providing climate benefits.

Improve biomass traceability and verification

Robust biomass chain-of-custody and traceability requirements and verification will be critical to ensuring beneficial outcomes. Strong standards and protocols in bioenergy (solid, liquid, and gas) and biomass carbon removal and storage markets are needed.

Connect carbon dioxide removal (CDR) and bioenergy policy discussions

A major takeaway from the learning workshop was that biomass resources have special value as a tool for CDR. Biomass is not as efficient as solar panels for producing electricity, but it is more efficient at concentrating dilute CO_2 in the atmosphere than other CDR technologies available today. Awareness of this value outside the bioenergy community, however, remains low. Experts and advocates in the areas of CDR and bioenergy must become better connected as there is currently not enough overlap in policy discussions about these topics.

Develop performance-based standards that prioritize CDR to drive innovation

Policies that drive innovation in land management, biomass resource use, and bioproducts are needed. Policies must also be designed to distinguish between reduced or avoided emissions and permanent carbon dioxide removal or net negative greenhouse gas emissions. Current transportation policies, including California's Low Carbon Fuel Standard (LCFS), provide strong incentives for anaerobic digestion by assigning negative carbon intensity scores to systems that do not result in CDR but rather only avoid emissions (based on a calculated baseline), which appears problematic. Another issue is that many policies encourage the use of "cellulosic" biomass resources in an effort to exclude food crops. However, this term excludes winter crops like rye, which are inedible, and includes manure from animals that may have been fed food crops. Most current policies still mainly direct biomass resources toward energy production and do not prioritize CDR or the potential to improve land or agrifood systems.

Support farmers and local communities

Mechanisms to support small landowners/farmers/producers are needed to ensure that bioenergy and BECCS policies avoid disproportionately benefiting large landowners or farmers. Workshop participants shared that there are nodes in the value chain where sufficient scale already exists to invest in the expertise and analysis needed to implement better agricultural practices in bioenergy supply chains. Building the policies needed to capture these opportunities is critical. Another need is to consider how policies can support the use of soil amendments and biofertilizers from bioenergy systems when and where their use will reduce emissions and improve land systems.

Design policies to support systems at different stages of development

Well-designed policies tailored to different stages of development are critical for successfully scaling the biomass resources and bioconversion technologies discussed in this learning series. Many systems are not yet commercially viable, so efforts to promote their deployment at scale must be undertaken with care and with the backing of robust RD&D.

Conclusion

Opportunities exist to build a carbon-negative, circular bioeconomy at scale and to use bioenergy conversion systems with durable carbon storage to reduce agricultural emissions, achieve carbon dioxide removal, and improve land systems. However, much caution is needed to avoid unintended consequences and detrimental social and environmental tradeoffs. Regionally specific studies that prioritize biomass resources and assess energy and carbon removal needs over time and tradeoffs (both local and global) are needed to guide policy advocacy. For starters, the mature and increasingly comprehensive knowledge base that exists in academia and industry about these opportunities must be connected to decision-makers, NGOs, and stakeholders who are likely to be affected by decisions related to BECCS systems. Much knowledge resides in silos like bioenergy or CDR research communities. Given the emerging interest in biomass resources from land for carbon dioxide removal, connecting the bioenergy and CDR communities across academic, industry, and policy advocacy can support the design and deployment of climate-beneficial advanced bioenergy systems.

Workshop presenters

Tom L. Richard, Professor Emeritus of Agricultural and Biological Engineering, Penn State University; Finance Committee Chair, Global Council Science and the Environment (GSCE) Board of Directors; Immediate Past Chair, GCSE Board of Directors

Presentation title: *Decarbonization/ReCarbonization: Harnessing Photosynthesis for a Carbon Negative Bioeconomy*

Phil Robertson, Distinguished Professor of Ecosystem Science, Michigan State University; Science Director, Great Lakes Bioenergy Research Center (GLBRC)

Presentation title: *Sustainable Bioenergy, The role of bioenergy for reducing CO_2 emissions and enhancing CO_2 removal in the ag sector*

Brian Davison, Corporate Fellow and Chief Scientist, Systems Biology and Biotechnology, Oak Ridge National; Chief Science Officer, Center for Bioenergy Innovation (CBI)

Presentation title: *Bioenergy Research Centers, path to sustainable aviation fuels, The Center for Bioenergy Innovation*

Corrine Scown, Deputy Director for Research, Energy Analysis and Environmental Impacts (EAEI) Division Lawrence Berkeley National Lab (LBNL); Vice President and founder, Lifecycle, Economics, and Agronomy Division (LEAD) at the Joint BioEnergy Institute (JBEI); Head of Sustainability, Energy and Biosciences Institute (EBI)

Presentation title: *Biomass Resource Availability and Siting Considerations for a Circular Bioeconomy*

Juliana Vasco Correa, Assistant Professor of Agricultural and Biological Engineering, Penn State University

Presentation title: *Bioenergy solutions for a changing climate: rethinking bioenergy*

Jeremy Guest, Associate Professor of Civil & Environmental Engineering, University of Illinois Urbana-Champaign (UIUC); Associate Director, Research for the Institute for Sustainability, Energy, and Environment, UIUC; Sustainable Design Lead, the Center for Advanced Bioenergy and Bioproducts Innovation (CABBI)

Presentation title: *Prioritization of research, development, and deployment of technologies for a circular bioeconomy*

Lorenzo Rosa, Principal Investigator, Carnegie Science; Assistant Professor (by courtesy), Doerr School of Sustainability, Stanford University

Presentation title: *Biomethane, nitrogen recovery, and carbon dioxide removal from anaerobic digestion of waste biomass*

Lauren Ray, Agricultural Sustainability and Energy Engineer, Cornell PRO-DAIRY

Presentation title: *Dairy manure based anaerobic digestion trends and economics*

Neil Renninger, Founder and Chief Executive Officer, Ample Carbon

Presentation title: *Gigaton scale carbon removal while supporting rural communities*

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