Accounting Considerations for Capturing the GHG Consequences of BECCS

Christopher S. Galik
Associate Professor, Department of Public Administration, North Carolina State University
csgalik@ncsu.edu

Justin S. Baker
Associate Professor, Department of Forestry and Environmental Resources, North Carolina State University
jsbaker4@ncsu.edu

Ann Bartuska
Former Deputy Undersecretary, United States Department of Agriculture
Bartuska@rff.org

Robert C. Abt
Carl Alwin Schneck Professor Emeritus, Department of Forestry and Environmental Resources, North Carolina State University
bobabt@ncsu.edu

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About the Authors

Christopher S. Galik

Christopher Galik joined NC State in August 2016 as a Chancellor's Faculty Excellence Program cluster hire in Sustainable Energy Systems and Policy (SESP). Galik is a professor in the Department of Public Administration and is primarily interested in the areas of institutions and the portability of governance systems. He brings an interdisciplinary perspective to his work, leveraging expertise in institutional theory, economics, and the natural sciences to address energy and environmental management and policy challenges. Recent research includes an evaluation of institutional stability in environmental governance, the influence of historical transitions on the adoption of sustainable practices at the local level, and the contribution of voluntary actions to climate change mitigation objectives.

Justin S. Baker

Justin Baker is an Associate Professor of Forest Resource Economics at NC State University. Dr. Baker has extensive experience developing economic models that capture spatiotemporal relationships between socioeconomic and environmental systems. His research focuses on forestry and agricultural sector modeling, bioenergy and carbon policy assessment, analysis of adaptation to global change, and integrated hydro-economic modeling for food-energy-water nexus applications. Prior to joining the faculty at NC State, Dr. Baker was a senior economist at RTI International and a research economist at the Nicholas Institute for Environmental Policy Solutions. Dr. Baker currently holds a guest researcher affiliation at the International Institute for Applied Systems Analysis (IIASA).

Ann Bartuska

Ann M. Bartuska is a former Deputy Under Secretary for Research, Education and Economics from USDA, a position she held from 2010 to 2017. Prior to USDA, Dr. Bartuska held a host of leadership positions, including Deputy Chief for Research and Development of the US Forest Service. She also has served in several appointments, including to the advisory board of the National Science Foundation and as executive director of The Nature Conservancy's Invasive Species Initiative and president of the Ecological Society of America. She is currently a Senior Advisor at Resources for the Future and a Senior Contributing Scientist at the Environmental Defense Fund.

Robert C. Abt

Dr. Abt is Carl Alwyn Schenck professor emeritus in the College of Natural Resources at NC State University where he taught natural resource management and forest economics. He has over 25 years of experience in bio-economic modeling of southern forest resources and markets and is co-founder of the Southern Forest Resource Assessment Consortium (SOFAC) at NC State. In the last decade he has focused on the potential impact of bio-energy demand on forest carbon and forest product markets. Dr. Abt has provided consultation on this topic to the National Academy of Sciences, EPA Science Advisory Boards, Department of Energy, and the USDA Forest Service. Non-governmental consultations include the Packard Foundation, Natural Resources Defense Council, Southern Environmental Law Center, Environmental Defense Fund, Pinchot Institute, Heinz Center, Environmental and Energy Study Institute, and the Duke University Climate Change Partnership.

Executive Summary

This paper highlights the relevant management, market, and policy attributes that influence the observed GHG balance of bioenergy with carbon capture and storage (BECCS) systems. Drawing from both the scientific literature and examples of both public and private governance approaches to account for the greenhouse gas (GHG) benefits of BECCS in practice, the paper concludes with a review of unanswered scientific and policy questions for further deliberation and analysis. Although there is a great deal of agreement on various aspects of BECCS carbon accounting throughout the entire life cycle, other elements (e.g., feedstock production and associated indirect effects) remain contentious. This paper provides a summary of the unresolved issues and provides references for readers who would like to dig deeper into specific subjects. It is not meant as a roadmap for policy action in and of itself, but by highlighting areas for additional research and analysis that could inform policy, contributes to subsequent policy blueprint development by the EFI Foundation and others.

BECCS: A Source of Critical but Uncertain GHG Mitigation Potential

Deep decarbonization will likely require significant contributions from carbon dioxide removal (CDR) pathways like BECCS. Deployment of BECCS at the scale of projected estimates has thus far failed, however. As first and foremost a strategy for deep decarbonization, future deployment of BECCS will require confidence in the GHG mitigation potential associated with its use, both in terms of scientific understanding and treatment under relevant policy. Development of such an accounting framework for BECCS has also thus far failed. While it is indeed true that the capture and storage of emission streams make carbon accounting of BECCS systems different from that of conventional bioenergy systems, the challenges that have thus far plagued bioenergy accounting are still present in the case of BECCS, and therefore require resolution if confidence in the technology is to be engendered. These parallels also provide a wealth of literature and practical experience to draw from, shedding additional light on issues to consider when developing a BECCS GHG accounting framework, as well as the policy precedents into which such a framework could be incorporated into or based upon.

BECCS GHG Accounting: The State of the Science

Within the available literature, a subset of factors and system attributes emerge as particularly important to resolve owing either to continued uncertainty or the potential to strongly influence emissions associated with BECCS deployment. For instance, while supply chain emissions are generally well understood, the choice of system boundary strongly influences the net GHG emissions attributable to BECCS, particularly given the variety of inputs into, and multi-functionality of, BECCS pathways. Expanding the project boundary to include indirect effects also necessitates additional layers of explicit assumptions to be made and documented. A failure to include these indirect effects, however—implicitly assuming that effects observed within a narrow system boundary are representative of broader impacts—requires an assumption that direct effects include all major changes. Feedstock production likewise commands a great deal of attention in the literature due to the potential for market interactions and land-use change, processes that are capable of leading to both positive and negative GHG outcomes. Although the potential complexity of supply chains feeding a given BECCS facility—from feedstock production, to transport, to energy or fuel production, to carbon capture— presents a logistical challenge to estimation of emissions stemming from process emissions, feedstock transportation, and feedstock storage, the phenomena giving rise to (and the processes of accounting for) these emissions are generally well-understood and well-documented in the existing literature.

GHG Accounting: Policy and Practice

A variety of approaches have been developed to account for carbon removal under various CDR pathways, including BECCS. The existence of approaches does not imply agreement among them, however. On one hand, there exist examples of state, federal, or international policies that have established GHG accounting processes for particular products or projects. Though not devoid of controversy, these existing approaches demonstrate how complex elements like feedstock production and any associated land-use change might be estimated, as well as how emissions and/or credits might be allocated to particular products along a particular supply chain. At the same time, uncertainty over how to properly account for biogenic emissions remains. The benefit of previous implementation experience is that efforts to craft an accounting scheme for BECCS can benefit not only from existing policy precedent, but also from an appreciation of the issues that remain unresolved and the availability of multiple monitoring programs to help track changes in on-the-ground conditions.

As is the case with state, federal, and international programs, there are multiple third-party programs and processes underway from which BECCS GHG accounting guidelines may be adopted or adapted. While some do not currently contain carbon accounting provisions, they have the benefit of widespread familiarity and even adoption by potential feedstock producers. Other processes are already integrated with existing policy frameworks, potentially facilitating their wider adoption. Given the recent emergence of multiple efforts to develop new or revised GHG accounting processes, questions remain as to how to build on or align competing frameworks.

Conclusions and Recommendations

Our review of the scientific literature underscores widespread agreement and experience with certain elements of BECCS accounting, but also the continued relevance of flashpoints that have long existed in policy deliberations. Choice of methodology is important, as is definition of system boundary and baseline within that methodology. Inclusion of both upstream (i.e., land use and land-use change) and downstream (i.e., energy displacement) emissions emerge as particularly important determinants of net BECCS GHG balance. Process, feedstock transport, and feedstock storage emissions, while potentially still in need of further study, are fairly well-understood and have a history of being accounted for in both research and practice.

Our review of existing approaches to account for the GHG consequences of BECCS and its constituent elements identified both examples of programs that have established GHG accounting processes for particular products or projects, and also initiatives that have failed to do so. Despite the lingering uncertainty of how best to appropriately account for biogenic emissions, these existing approaches demonstrate how complex elements like feedstock production (and associated land-use change) might be assessed. In light of these observations, we offer the findings and recommendations below, assessing alignment between the available literature and existing BECCS GHG accounting policies and programs to identify near-term policy and research needs:

- **BECCS GHG accounting shares accounting challenges with other CDR and renewable pathways.** The deployment of BECCS as an energy generation source may have downstream effects on the power sector similar to deployment of other renewable technologies like wind or solar. By potentially affecting land use through demand for feedstock, BECCS may contribute to indirect land use change similar to other natural climate solutions like afforestation or improved forest management. Consistent treatment is thus important across technologies and practices to avoid implicitly favoring one approach over another (e.g., crediting only sequestration while excluding emissions displacement).
- **BECCS GHG accounting is comprised of both low- and high-uncertainty components.** Supply chain emissions—those associated with feedstock transport, energy or fuel production processes, and potentially direct emissions associated with feedstock production—are generally well-understood; the impact on biogenic carbon stocks owing to indirect market-scale effects is less clear and requires resolution.
- **Emphasize work on those attributes central to BECCS GHG balance.** The implication of the two findings above is that efforts to resolve BECCS GHG accounting should emphasize a subset of accounting issues. As a technology that spans energy and land-use sectors, particular attention should be given to consistent accounting of BECCS at all scales, from inclusion or exclusion of indirect effects to treatment under national inventories. As indirect effects stemming from the production or use of certain feedstocks have the potential to transition a BECCS system from net-negative emissions to net-positive (or vice-versa), their accounting likewise requires attention in the near-term.
- **Avoid easy answers and use unambiguous language.** Consistent framing is necessary given the important contributions from multiple disciplines, each of which use different terminology. A credible accounting regime requires acknowledgement of

the complexities of biomass accounting, even if an ultimate policy decision is made to include or exclude a particular element (e.g., indirect land-use change). In the interim, existing policy and implementation experience demonstrates that simplified accounting approaches might be deployed for particular BECCS pathways that have clear baseline conditions and potentially minimal indirect, market-level effects (e.g., wastes and residues that arise from or are secondary to the production of some other primary commodity).

- **Consider building on existing approaches.** The constituent elements onto which BECCS pathways are built have the benefit of significant precedent and practical implementation experience. While potentially biasing against new and potentially superior approaches, existing techniques to monitor and account for GHG emissions have the benefit of experience and buy-in. Such approaches may have arisen to address different objectives, however (e.g., attributional lifecycle analysis of a given supply chain versus estimation of national GHG inventories), requiring attention to the appropriateness of a particular approach for a given purpose.
- **Consider the interplay of accounting approach, scale, and time.** Governance of BECCS will drive investment and operation of individual facilities, with potential global implications. Scaling up of deployment may require translation and disaggregation to provide proper incentives at all stages of accounting, from individual facility supply chain management to country-driven national inventories and Nationally Determined Contributions (NDCs).
- **Build on existing research to expand systems-level knowledge of BECCS.** The literature contains multiple examples of LCA- and systems-level modeling to assess the GHG consequences of BECCS deployment. While informative, more true-to-life projections of BECCS are needed, particularly as they pertain to complex energy and feedstock production systems, infrastructure needs to support all aspects of a BECCS supply chain at scale, and the associated societal impacts of BECCS deployment. Validating model assumptions and projections with in situ data is likewise necessary to have confidence in model projections.

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1. Introduction

Deep decarbonization will likely require significant contributions from carbon dioxide removal (CDR) pathways like bioenergy with carbon capture and storage (BECCS).[1,2] For instance, previous analysis of pathways to meet a 1.5°C warming target estimated potential emission reductions from BECCS to range from 3.0 and 6.8 $GtCO_2e$ per year by 2050.[3] Though resource tradeoffs between water consumption, land use, and land-use change are expected to be exacerbated as global BECCS mitigation targets increase, annual global emission removals from BECCS could still reach 2.5 $GtCO_2e$ over the next three decades.[4,5] Estimates for removals in the U.S. alone could range from 0.3 to 2.2 $GtCO_2e$ per year, or between 5 and 36% of U.S. 2018 net emissions.[6]

Despite the projected contributions of BECCS to meet national and international climate targets, deployment of BECCS has thus far fallen short.[7,8,9] As first and foremost a strategy for deep decarbonization, future deployment of BECCS will require confidence in the GHG mitigation potential associated with its use, both in terms of scientific understanding and treatment under relevant policy.[10,11,12,13] As highlighted by the EFI Foundation, however, BECCS currently lacks such an accounting framework owing to inconsistent treatment of emission sources, the complexities of emission and removal patterns over time, and debates over system boundaries.[14]

Here, we provide an overview of the factors either associated with the greatest controversy or uncertainty, or those with the greatest potential to influence the net GHG balance of BECCS. We follow this review with a brief overview of BECCS GHG accounting as it currently exists in public policy, third-party, and private self-governance approaches. We conclude the analysis with a short list of recommendations, assessing alignment between the available literature and existing BECCS GHG accounting policies and programs to identify near-term policy and research needs. Throughout, our intent is to provide a concise summary of the major factors affecting BECCS GHG accounting and how extant policies have (or have not) addressed these. We do not intend to provide a roadmap for direct policy action, but rather to provide ideas for future research and analysis while contributing to subsequent policy blueprint development by the EFI Foundation and others.

2. BECCS GHG Accounting: An Overview

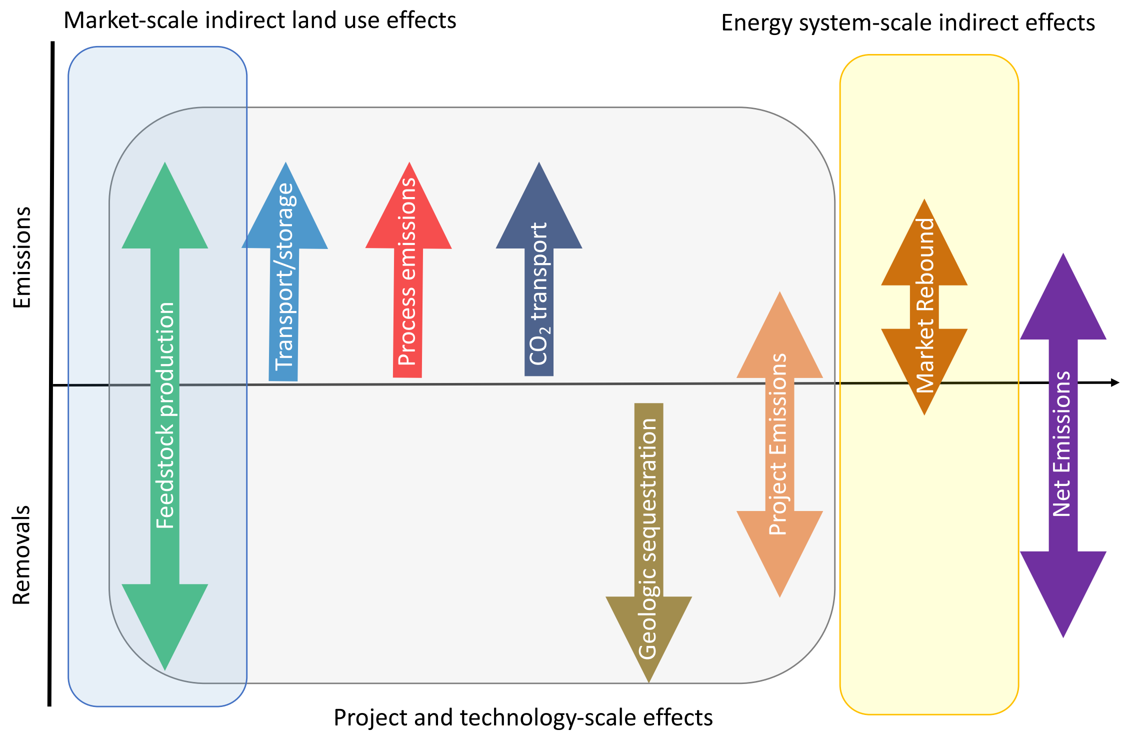
Any discussion of GHG accounting requires clarity of terminology. Particularly within the natural and physical sciences, GHG accounting is often described in terms of life-cycle analysis, assessment, or accounting (collectively, LCA). Within the broader category of LCA are what are often described as attributional and consequential approaches. Attributional LCA approaches seek to estimate emissions across elements of a supply chain. For these reasons, attributional life-cycle analyses (LCA) are less able to assess system-wide changes owing to their inability to capture the influence of processes that fall outside of the designated system boundary (e.g., international trade, indirect land-use change, or reduced oil prices from enhanced oil recovery).[15,16] Consequential LCA approaches, meanwhile, seek to determine the larger emissions implications of a particular action or decision that deviates from the status quo, and are thus better suited to capturing indirect effects attributable to things like expanded feedstock production or fossil fuel substitution.[17]

Elsewhere, particularly in the social sciences, accounting is sometimes described in terms of project- versus market- or landscape-level effects.[18,19] In this context, project-level accounting can be understood as the discrete GHG emissions directly associated with operational decisions of a particular facility (e.g., feedstock harvest, fossil displacement). Market-or landscape-level effects are those emissions that arise from the actions of discrete project or projects, but that are indirect in nature and play out across a larger area owing to their effects on land, feedstock, or energy markets. In this way, both project- and market-level accounting can be seen as adopting a consequential LCA approach, the key distinction being the scope of analysis.

Regardless of approach, the net GHG balance of BECCS can be thought of as a function of emissions and removals from feedstock production, transport of feedstock from farm to facility, on-site emissions from industrial processes, emissions from transport, geological sequestration, and potentially energy system-scale changes and, in the case of fuel production (i.e., ethanol), downstream uses. Each component has location-specific factors that could increase or decrease relative emissions. Building on the existing literature, we can therefore describe an individual BECCS pathway (or project) as a set of project-specific choices and a generic emissions profile (Figure 1).[20,21,22,23] These project-specific components can either generate net emissions or net removals as indicated by the direction of shaded columns in this stylized. In such a scenario, net emissions from system-wide BECCS deployment will be equal to the sum of net emissions across all projects.

In practice, BECCS is not a singular technology, but rather is comprised of multiple feedstock production, conversion, and end-use pathways.[24,25] Within a given pathway, GHG balance may vary over place and time, necessitating mechanisms for tracking and crediting cross-sectoral and intertemporal emissions changes.[26] Stages of the BECCS supply chain must themselves be linked to transmit policy or market incentives to achieve negative emissions all the way from biomass production to end use or storage.[27] As reviewed further below, BECCS deployment has the potential to trigger indirect large-scale land-use and energy system-scale effects that are difficult to observe, while the “multi-functionality” of CDR pathways like BECCS introduce additional complexity in accounting for net GHG removals.[28,29,30,31,32]

Figure 1. Conceptual diagram of GHG emissions or removals from a BECCS pathway.



In this stylized example, project-specific components can either generate net emissions or net removals as indicated by the direction of shaded columns. Note that, for some effects (e.g., feedstock production, energy system market rebound) emissions or removals could include both direct and indirect effects.

2.1 BECCS GHG Accounting by Constituent Element

Revisiting Figure 1, emissions and removals attributable to BECCS can be broken out into feedstock production, feedstock transportation and storage, industrial processes (e.g., electricity generation and carbon capture), CO_2 transport, and geological sequestration. While several of these constituent elements of the BECCS supply chain are generally well-understood and can be modeled or measured directly (e.g., feedstock transport, energy or fuel production processes, and potentially direct emissions associated with feedstock production), others face continued uncertainty, have the potential to turn a system from net-negative emissions to net-positive, or both (e.g., indirect effects from feedstock production). It is these pivotal and/or unresolved elements that we emphasize here.

The section below provides a brief overview of the state of debate within the literature on GHG accounting within individual supply chain elements of a typical BECCS system. Many GHG accounting considerations discussed here and elsewhere are not unique to BECCS, but are challenges faced by other CDR pathways or other renewable technologies. This is particularly true for concerns related to fugitive loss from geologic storage (common to other CDR pathways like direct air capture, or DAC), market-induced energy-system effects (common to other renewable energy technologies), or land-use or land-use change concerns (common to other natural climate solution approaches like afforestation, improved forest management, or bioenergy production). As a pathway capable of contributing to both CDR and renewable energy objectives, resolution of other considerations like how to allocate or credit removals will determine the extent to which BECCS competes with alternative GHG mitigation pathways like DAC. Without minimizing these considerations, we instead emphasize aspects of accounting characterized by greatest uncertainty and/or greatest impact on BECCS net carbon balance, noting where appropriate the commonalities with other CDR pathways or renewable technologies.

Choice and Articulation of Accounting Approach

The choice of attributional or consequential LCA is the first of many decisions that must be made when accounting for the net GHG balance of BECCS. The decision to adopt one or the other will influence the relevance of other choices, as well. For example, establishment of a baseline is of paramount importance in consequential-type LCA approaches. In attributional LCA, definition of system boundary is of critical importance. The decision of whether to adopt either is entirely dependent upon the objectives of the accounting exercise: to aggregate the discrete emissions associated with a given supply chain, to assess the aggregate direct and indirect emissions associated with BECCS deployment, or to somehow connect the two. The aforementioned connection between GHG accounting and the markets and policies to facilitate BECCS deployment suggest that a consequential approach will be most appropriate to consider when developing GHG accounting standards for BECCS. From the perspective of an individual facility operator or supply chain manager, attributional approaches might nonetheless remain relevant for reporting and performance-improvement purposes.

System Baseline

Consequential LCA approaches require consideration of the change relative to what would have otherwise occurred under a business-as-usual scenario. Choice of counterfactual, or system baseline, can affect the net GHG implications of the BECCS pathway – a system baseline may assume zero BECCS adoption, or just the absence of a particular pathway component (e.g., a single-facility). In the presence of direct and indirect effects, determination of an appropriate baseline counterfactual (system baseline in the absence of the BECCS pathway) is needed to estimate net change attributable to the policy or market intervention; observation of standing carbon stocks is insufficient to make claims of net change.[33] There is a substantial literature that has applied systems modeling techniques to project the potential indirect land-use change implications of agricultural feedstock production from biofuel policies.[34,35,36] Conversely, modeling of forest bioenergy systems suggests the potential for negative leakage (emission reductions) should market-induced investment in the forest resource base counteract emissions from direct removals.[37,38,39,40,41]

The collection of empirical data to verify such modeling approaches and baseline assumptions is an important step to better understanding the linkages between feedstock production systems and net carbon dynamics and ensuring a credible, systematic accounting system. First-generation liquid biofuel and biomass-based energy have been implemented at scale in the U.S. for decades, providing an opportunity to assess their impact on markets. The clearest signal of market impacts is price increases for feedstocks. Higher commodity prices driven by energy policy have the potential to affect land use and management across regional and national boundaries.[42,43] A meta-analysis of the impact of ethanol policy on corn prices, for example, found mixed evidence but concluded that a billion-gallon expansion of ethanol production would lead to a four percent increase in corn prices.[44] In a market-based land economy like the U.S. South, changes in commodity prices can change both land use and land management dynamics. Since the U.S. South is the world's largest timber producer, changes in forest product markets have global implications. Research suggests, however, that nascent pellet markets have led to very small changes—or even increases—in forest carbon in the region.[45,46]

System Boundary and Timing

While most relevant to attributional approaches, distinctions between project-level and market-level effects often considered in the literature requires consideration of system boundary in consequential approaches, as well. As shown in Figure 1, system boundary—the decision to include or exclude particular elements—can have a strong influence on the net GHG balance of BECCS.[47] Of particular relevance is the inclusion or exclusion of direct and indirect land-use change, found to play a particularly strong role in the resulting carbon footprint of biomass feedstock as well as the overall emissions reduction potential of a hypothetical BECCS facility.[48] Also important are the substitution benefits and downstream emissions potentially contributed by BECCS. For example, a failure to recognize the possible fossil emissions displaced by implementation of BECCS reduces the benefits attributable to the pathway, forcing the technology to directly compete with other fossil abatement strategies.[49] As indicated in existing research on bioenergy GHG accounting, assumptions about which fuel source is displaced can strongly influence the net GHG benefits associated with deployment.[50]

In a related sense, the end-use of captured CO_2 can greatly influence the net GHG balance of a given BECCS pathway. Depending on the application, CO_2 capture and use (CCU) (e.g., the use of CO_2 as a feedstock in fuels, chemicals, building materials, or for the purpose of Enhanced Oil Recovery [EOR]) might represent true reductions or simply a delay in emissions, depending on the application (e.g., quantity and carbon intensity of displaced product, duration of storage). For example, conversion of captured carbon into a cement material that would be a substitution for current cement fabrication (a significant producer of CO_2 emissions) could result in storage of carbon in an inert form while also allowing a producer to benefit economically from the creation of a value-added product. Alternatively, captured CO_2 may be used for EOR, increasing the production of fossil fuel over what would have otherwise occurred, contributing downstream emissions.

Accounting in the context of EOR is particularly relevant in the near-term given the large representation of EOR in currently-operating storage sites, outpacing both dedicated capture capacity by approximately three-to-one.[51] As deployment data suggests, EOR is also among the more cost-effective uses of captured CO_2 and is eligible for inclusion under existing policies in the U.S. (e.g., California's Low Carbon Fuel Standard and the 45Q tax credit, reviewed further below). Recent assessment of the GHG balance of EOR activities finds that net carbon balance can be strongly influenced by the choice of system boundary, injection strategy, timing, and the availability of displacement credits for replacement of fossil power sources.[52] Nuñez-López et al. also find that storage efficiency depends on injection strategy and that net emissions shift over time, with early-year negative emissions shifting to net-positive should credits for fossil displacement not be awarded.[53] In this way, EOR can be seen as a use opportunity to improve the economics of a BECCS system, and which may provide permanent sequestration if careful monitored, but only if accompanied by dynamic accounting practices capable of reflecting variation in the production of an input (e.g., feedstock) or output (e.g., oil) over project lifetime.

This, in a way, also highlights the importance of timing considerations in GHG accounting. As discussed further in Box 1 below, timing has been and continues to be a point of contention in the biogenic accounting debate. A feedstock- or process-based approach might be appropriate under a policy-agnostic perspective, in which relevant changes in emissions and sequestration can be tracked over the lifecycle of whatever is being produced. In the presence of policy interventions (or market interventions that are being encouraged through policy), however, it is the response of the system to the intervention that is of interest. Rotation length might change in response to economic conditions created by increased demand for forest biomass, for example. In this situation, timescales should be scalable or attributable to the intervention in question. An annual reporting requirement would require annual GHG balance attributable to a given facility, for example, requiring either the tracking of annual flux or metrics that collapse a stream of estimated or observed annual fluxes into a single reportable year.[54]

Similar to other CDR pathways and technologies capable of affecting broader energy markets, the choice of system boundary is tremendously important in determining BECCS net GHG balance, particularly given the variety of inputs into, and multi-functionality of, BECCS pathways. Expanding the project boundary to include indirect effects also necessitates additional layers of explicit assumptions to be made and documented. A failure to include these indirect effects, however—assuming that all effects can be observed within a narrowed system boundary— requires the implicit assumption that there are no interactions or feedbacks at market scale capable of changing the net balance. The timescale over which GHG balance is calculated is likewise relevant, both to appropriately capture the phenomenon of interest and to allow for necessary reporting to comply with the policy or market intervention that encouraged that phenomenon.

Feedstock Production

Feedstock production involves multiple actors operating over disparate timelines and the potential for direct and indirect effects with global emissions implications. Accounting complexity will itself vary by both feedstock type and the particular location or management regime. Feedstock to supply BECCS operations could include, for example, material derived from forest systems, ethanol waste streams, agricultural residues, perennial and/or energy crops, wastes and various forms of waste derivatives (e.g., landfill gas, biogas, methane from wastewater treatment plants). For the purpose of this review, we focus on those feedstocks and management regimes subject to the greatest GHG uncertainty, particularly those which involve long time scales, for which established markets exist, and/or which are capable of inducing substantial direct and indirect land-use change. Two systems that meet these criteria are corn ethanol and forest biomass, production systems that likewise feature prominently in the scientific literature on GHG accounting and are well-represented in existing BECCS project experience.[55,56,57,58,59,60,61]

Feedstock production can either be a net source of emissions or removals, depending on both project-scale (on-farm/in-forest) and indirect large-scale land-use effects. Farm-scale emissions, tracked by individual cropping unit or area of production for a specific feedstock per farm, could include annual carbon sequestration rates for biomass and soils associated with the feedstock production system, non-CO_2 emissions from chemical and fuel use, and CO_2 emissions associated with on-farm energy use. Uncertainty in farm-scale emissions reflects differences in feedstock production systems and spatial heterogeneity in removal and emissions profiles. Similar considerations are necessary in forest systems, with the selection of appropriate management units taking on particular importance. Evaluation of net emissions can vary based on the scope assumed (e.g., single stand versus entire managed property versus regional), necessitating consideration of the broader management area within which forest management activities and sourcing of woody feedstock are taking place.[62]

In both crop-based ethanol and wood-based bioenergy systems, large-scale effects can be either positive or negative and include indirect land-use change and management responses to the allocation of land to feedstock production.[63,64] While effects of global land-use change are driven by cultural, technological, biophysical, political, economic and demographic factors rather than by a single crop market, many economic models assume market dynamics and resource competition are primary drivers.[65,66,67] As such, the indirect emissions implications of future BECCS deployment would be affected by both the scale of BECCS feedstock production as well as anticipated economic conditions (e.g., market expansion or contraction) that drive the competition for feedstocks and associated resource inputs. Indirect effects are also driven by policy choices (e.g., policy incentives that favor a particular feedstock or production system).

A rational but oversimplifying response to the complexity of feedstock carbon accounting discussed above is to declare certain feedstocks as inherently carbon neutral, a term that itself is subject to different interpretations.[68] Although such an approach conveniently avoids the complexity of analysis, it does so at the expense of promoting or excluding processes from what should be an emerging portfolio of carbon-friendly options as science and technologies evolve. Experience with biofuels and biomass-based energy production systems have demonstrated the potential for complex market interactions that often cross national boundaries, necessitating approaches capable of identifying both positive and negative GHG consequences of BECCS deployment.

While future uncertainties are potentially confounding, modeling nevertheless offers potential insight into the GHG implications of BECCS pathways relative to plausible future conditions, while also reflecting potential management and environmental changes in the baseline that are not static (e.g., harvest, disturbance). Economic conditions potentially influencing both what is produced and how it is produced can change over the period a given feedstock is being produced. Simplifying the scope of an approach to focus on project-scale direct emissions could ignore important opportunity costs of land management alternatives across scenarios. Building these plausible scenario assumptions remains a challenge, especially for technologies not currently adopted at scale like BECCS, because this will result in scenarios that are disconnected from what is and has historically occurred on the ground.

Process Emissions, Feedstock Transport, and Storage

Though there is some geographic overlap between areas of potential feedstock supply and areas of potential geologic storage in the U.S., an expansion of industrial-scale BECCS operations will likely require significant transport of feedstock from one area to another.[69] Seasonal storage will likely also be required due to greater difficulty in harvesting and transporting biomass during certain times of year. The GHG consequences of both storage and transport could be important considerations in a comprehensive GHG accounting framework for BECCS, though some experimental evidence suggests these losses could be insignificant.[70] The high quality of U.S. wood pellets and their relatively lower cost of transportation over water (relative to land) make it attractive to import U.S. wood pellets to Europe, for instance.[71] While transportation across the ocean has been estimated to be the largest source of GHG emissions in the wood pellet supply chain, it is unclear if transatlantic shipments have increased with the wood pellet trade or if tankers are transporting pellets in place of something else (e.g., coal).[72]

The process, feedstock transport, and feedstock storage emissions associated with a given BECCS system are generally associated with lesser controversy than the feedstock production component described above. Certain process and transport emissions are likewise not unique to BECCS and require resolution under any CDR pathway. For example, emission factors might be estimated and applied for different input electricity mixes or shipping on a miles-traveled basis.[73,74,75] Other elements like capture efficiency or parasitic load are functions of system design and can be observed or calculated directly. [76,77] This is relevant to CO_2 transportation and storage, for example, which require additional energy and can therefore reduce BECCS GHG removal potential. Although the potential complexity of BECCS supply chains presents a logistical challenge to estimation of emissions stemming from process emissions, feedstock transportation, and feedstock storage, the phenomena giving rise to (and the processes for accounting for) these emissions are generally well-documented in the existing literature.

2.2 BECCS GHG Accounting in National Inventories

In addition to project scale emissions and aggregation or reporting challenges, indirect, large-scale land-use and energy system-scale effects remain both uncertain and present unique challenges for tracking and reporting emissions at regional and national scales. Indirect, market-scale effects particularly complicate the quantification of net emissions from feedstock production. Large-scale BECCS deployment that displaces a significant quantity of fossil fuel consumption in the electricity system could likewise result in a market rebound effect in energy systems. Similar to leakage in land use systems, the market rebound effect is a market concept whereby policy-driven changes in renewable energy supply are assumed to affect consumption decisions in a way that reduces the emissions displacement potential of the renewable energy source. As with any alternative energy or fuel source, large-scale BECCS deployment could decrease the supply price of a fossil energy source that the bioenergy feedstock is displacing, thereby driving up its demand outside of the project boundaries.

To the extent that BECCS pathways induce indirect land-use change and energy sector spillovers that cross international borders, these indirect effects would likely be accounted for in the balance of the country where emissions are physically taking place. Given the separation of land-use and energy systems accounting under IPCC guidelines, however, some uncertainty remains as to where to record emissions related to, for example, direct and indirect land-use change related to BECCS deployment.[78] There is likewise concern that separate accounting of land use and energy systems will create improper incentives for the deployment of BECCS, particularly in the presence of international trade and different country-level accounting decisions.[79,80]

So while the net emissions effect of a BECCS pathway can be seen as the sum of the project-scale emissions components and the indirect (large scale land-use and energy system-scale) effects, a remaining challenge is how to attribute observed changes in emissions or removals to a particular source or cause. Structural modeling and empirical analysis can be applied to better attribute changes in these emissions accounts to specific BECCS pathways, policy incentives, and macroeconomic conditions. Results of such studies can improve policy design (e.g., establishment of compensatory removal credit trading) so as to encourage investment in BECCS systems that minimize adverse indirect emissions.[81]

3. Public and Private Governance of GHG Accounting

A variety of approaches have been developed to account for carbon removal under various CDR pathways, including BECCS. The existence of approaches does not imply agreement among them, however. Accounting for emissions attributable to CDR pathways, as well as the policies in place to govern its deployment, currently varies widely both internationally and within the U.S. To identify common elements among existing frameworks and to help inform the design of some future unified framework in the U.S., this section reviews select policies, programs, and practices relevant to CDR and different BECCS pathways (e.g., biofuels, biopower), with an emphasis on government, non-profit third-party, and private-sector approaches.[82,83] Though the emphasis throughout is on policies and programs active within the U.S., examples from other contexts are provided (e.g., European Union) when relevant as an example or analog.

3.1 Relevant State, Federal, and International Policies and Programs

There are several existing policies and programs operating at the state, federal, and international levels with the potential to influence how the GHG consequences of BECCS are estimated and allocated across the supply chain.[84] The relative recency of BECCS as compared to traditional forms of bioenergy (e.g., biopower and liquid biofuels) likewise suggests that there is a rich history of accounting policy precedent to draw from to inform the feedstock production and conversion portions of BECCS. Perhaps most developed are GHG accounting approaches for specific products. One early example is the U.S. Renewable Fuel Standard (RFS) program, created under the Energy Policy Act of 2005 (EPAct; P.L. 109-58) and both amended and expanded by the Energy Independence and Security Act of 2007 (EISA; P.L. 110-140). The RFS includes four renewable fuel categories: biomass-based diesel, cellulosic biofuel, advanced biofuel and total renewable fuel. Explicit definitions of qualified renewable fuels promulgated in 2007 considered renewable biomass, and the final rule implementing the expanded RFS program under EISA (RFS2) included a statutorily-required analysis of GHG reductions by fuel category.[85] To be classified as renewable fuel, for example, a pathway must achieve 20% reduction relative to year 2005 conventional fuel emissions. Biomass-based diesel and advanced biofuels require a 50% reduction, whereas cellulosic biofuels require demonstration of a 60% reduction. Notably, compliance with GHG reduction thresholds is to be determined using lifecycle analysis including both direct and significant indirect emissions, such as those stemming from land-use change.[86] A similar approach was adopted under both the UK Renewables Obligation and Renewable Transport Fuels Obligation and EU RED II for bioenergy (Directive (EU) 2018/2001), with the latter specifically requiring 80% reduction from fossil fuels while also requiring a reporting of emissions from land-use change.[87]

Despite the precedent set by the RFS, the determination of emissions associated with biomass use at the federal level has continued to be controversial and associated with multiple legislative and administrative attempts to clarify. Most directly relevant to this analysis is the nearly-decade long effort by the U.S. EPA to determine a scientifically valid process for biogenic carbon assessment. The process and outcomes of that exercise is instructive for the purposes of this analysis (Box 1), as are the areas of emphasis considered throughout the process. Emerging as particularly strong flashpoints throughout that work were the appropriate timescales to use, the specification of spatial scales for assessment, the inclusion of leakage, the choice of baseline, and the need to assess the incremental effect of biomass use on net emissions (i.e., no categorical inclusion or exclusion).

Box 1

Biogenic Carbon Assessment by the U.S. EPA

In 2011 and again in 2014, the U.S. EPA appointed two Science Advisory Board (SAB) peer review processes to evaluate a draft science-based biogenic carbon dioxide (CO_2) assessment method as a potential foundation for future biogenic CO_2 policy. To date, an agreed-upon approach to accounting for biogenic carbon-based emissions associated with the combustion of biomass has not emerged from these deliberations. The summaries of the science, though based on somewhat dated literature, capture the fundamental scientific principles and tradeoffs relevant to any biomass-based (including BECCS) emissions quantification approach. While a lack of consensus on the science is common in a SAB deliberation, the inability to put forward a comprehensive analytical framework is unusual.

In the first draft report, EPA proposed a reference point baseline approach to calculate Biogenic Accounting Factors (BAF) where categorical exclusion for woody biomass was applied based on regional forest stock trends, that is if forest carbon stocks were increasing, woody biomass use for energy was assumed carbon neutral. The first Biogenic Carbon Science Advisory Board Ad hoc Panel (a subpanel of experts hired specifically to review EPA's framework, which they would then hand over to the standing Chartered SAB panel for finalization) rejected this framework.

Two years later (2014) the EPA released a revised framework. This report suggested an anticipated (counterfactual) baseline approach in addition to the reference point approach. The SAB Panel also recommended that a general principle for determining the time horizon for BAF calculations should be to select a time horizon that fully accounts for the temporal dynamics for all feedstocks. In 2019, the Charter SAB criticized the revised framework as not being policy specific. Alternatively, the biogenic carbon SAB Ad hoc Panel had focused on the scientific basis for the appropriate time span, recommending selection of a time horizon that fully accounts for the temporal dynamics for all feedstocks, independent of the policy applications and their potentially different timeframes. The Charter SAB also suggested a reference point approach-based tracking of terrestrial carbon stocks, even though the first Chartered SAB and the biogenic carbon Ad hoc Panel had rejected a similar version of the approach.

The absence of consensus is not surprising given the complexities in measuring carbon fluxes over time from a variety of dynamic carbon pools and, in the case of an anticipated future baseline, uncertain future outcomes. EPA's experience in attempting to come to a consensus on biogenic carbon, however, highlights the difficulty of developing policy when the underlying science has no clear answer and where there is uncertainty surrounding the context to which it will be applied. As the scientific literature reviewed in the issuance of the above SAB reports illustrated how the use of wood bioenergy can appear to promote increases in forest extent or lead to the loss of forest stock depending on the baseline (reference point or counterfactual), region, feedstock, and spatial/temporal scale of different accounting approaches—leading to findings of carbon gain or loss relative to alternative fuels—it is not surprising that one area of agreement between the 2012 SAB peer review report and the Chartered SAB pertained to *a priori* assumptions of neutrality. As stated in the 2012 SAB peer review report:

> *Carbon neutrality cannot be assumed for all biomass energy a priori. There are circumstances in which biomass is grown, harvested and combusted in a carbon neutral fashion but carbon neutrality is not an appropriate a priori assumption; it is a conclusion that should be reached only after considering a particular feedstock's production and consumption cycle. There is considerable heterogeneity in feedstock types, sources and production methods and thus net biogenic carbon emissions will vary considerably. Of course, biogenic feedstocks that displace fossil fuels do not have to be carbon neutral to be better than fossil fuels in terms of their climate impact.*[88]

In 2019, the Chartered SAB echoed this finding by asserting "not all biogenic emissions are carbon neutral nor net additional to the atmosphere, and assuming so is inconsistent with the underlying science".[89]

The lack of consensus reached through the U.S. EPA Science Advisory Board (SAB) process—and the corresponding absence of a comprehensive approach to evaluating potential net biogenic CO_2 outcomes associated with the use of biomass for energy—also yielded a variety of legislative and administrative attempts to clarify the issue. From 2017-2021 Congress sought to address the topic by issuing directives for some federal agencies to essentially apply a categorical exclusion for some biomass types. The Consolidated Appropriations Act of 2018, for example, directs agencies to consider and reflect "the carbon-neutrality of forest bioenergy and recognize biomass as a renewable energy source, provided the use of forest biomass for energy production does not cause conversion of forests to non-forest use" (P.L. 115-141, Sec. 431 (2)(A)). A 2018 policy statement by the U.S. EPA clarified that biogenic CO_2 resulting from combustion of material from managed forests would be treated as carbon neutral for the purposes of forthcoming regulatory actions, while also noting that the agency would "continue to evaluate the applicability of this policy of treating biogenic CO_2 as carbon neutral based on relevant information, including data from interagency partners on updated trends in forest carbon stocks. This safeguard, among others, serves to ensure that EPA periodically assesses the need to revisit this treatment in the future".[90]

At the state level, the California Low-Carbon Fuel Standard (LCFS) requires the calculation of lifecycle emissions for certified fuel pathways, including emissions associated with fuel production, transportation, storage, and end-use.[91] As with the RFS2 program, emissions stemming from indirect land-use change are to be included in estimates of fuel pathway emissions. Of particular relevance to BECCS accounting, however, are provisions within the LCFS that allow for crediting of CCS as well as stacking with other benefits (e.g., Section 45Q tax credits, discussed further below). By outlining how credits for CCS are to be allocated along a supply chain, an associated protocol provides a model for how actors across a BECCS supply chain might be linked.[92,93] In excluding oil generated through EOR from receiving credit as a particular project type, the protocol likewise provides a model for how to target incentives to specific activities or activity types. Lastly, the protocol provides an example of how system boundaries can be modified to include or exclude various elements depending on application.

From an individual project perspective, Section 45Q of the US tax code provides a performance-based tax credit for carbon capture projects that can be claimed when an eligible project has securely stored CO_2 in geologic formations, such as depleted oil and gas fields and saline aquifers; or beneficially used captured CO_2 or its precursor carbon monoxide (CO) as a feedstock to produce fuels, chemicals, and products in a way that results in emissions reductions. Final regulations promulgated early in 2021 clarify the requirement for a life cycle assessment, requiring that the LCA must conform with ISO 14044:2006, “Environmental management — Life cycle assessment — Requirements and Guidelines,” and ISO 14040:2006, “Environmental management – Life cycle assessment – Principles and framework”. The ISO standards provide guidelines and a framework for the LCA and permit the use of both direct and indirect data. In all, a taxpayer must demonstrate, based on an LCA, that a utilization process leads to a reduction in carbon dioxide equivalents.

Existing programs address the permanence of stored carbon—relevant not only to BECCS but to multiple other CDR pathways, as well—in several different ways. In some contexts, such as the California LCFS, a portion of awarded credits is set aside to buffer against future leakage.[94] Final regulations issued in support of the 45Q program allow for recapture of credits in the event of documented leakage within a maximum period of five years following claiming of the credit (86 FR 4728; January 15, 2021). Given the potentially long-time periods involved with ensuring that stored carbon remains intact, an alternative approach is to provide for conditional transfer of liability to the state, as is the case under the 2009 EU CCS Directive (Directive 2009/31/EC).[95]

Regardless of pursuing project- or product-level accounting, a variety of monitoring programs exist with the potential to assist in the estimation of both direct and indirect emissions associated with BECCS. The primary accounting system used within the Federal government is the Inventory of U.S. Greenhouse Gas Emissions and Sinks published by the U.S. EPA with input from other Federal agencies based on their mission.[96] The Inventory provides data on CO_2 emissions, as well as other greenhouse gasses. In some cases, the Inventory draws on facility-level information, using emissions data from the U.S. GHG Reporting Program and other sources. In addition, the inventory provides information on the net flux across all sectors, including emissions and sinks (or removals), for carbon, methane, and nitrous oxide. Currently, the report is at a national scale and much of the data are estimates from models, thus are not suitable for localized condition reporting. Exceptions exist, however. For example, the underlying database for forest carbon is the Forest Inventory and Analysis (FIA) Program of USDA Forest Service, that can be used to report at the state or regional (by aggregating) level.[97] While an analogous nationwide inventory for agricultural systems, which would consider non-food/non-forest feedstocks, does not exist, the Economic Research Service (ERS) of USDA produces the U.S. Bioenergy Statistics, which track U.S. ethanol and biodiesel production, consumption, and trade, and highlight the factors that influence demand for agricultural feedstocks for biofuels production.[98] Across programs, an emphasis on aggregate data for national reporting has exposed a gap in site-specific accounting capabilities, giving rise to a 2020 ARPA-E grant opportunity to develop a monitoring approach for field-level estimates.[99]

The brief survey above suggests a complicated but informative GHG accounting landscape. On one hand, there are examples of programs that have established GHG accounting processes for particular products or projects (e.g., RFS2, California LCFS, EU RED II). Though not devoid of controversy, these existing approaches demonstrate how complex elements like feedstock production and any associated land-use change might be quantified, as well as how emissions and/or credits might be allocated to particular products along a particular supply chain. At the same time, the U.S. EPA's assessment of biogenic carbon and subsequent Congressional efforts to resolve uncertainty over the GHG consequences of biomass combustion expose strong and lingering debate over appropriate accounting of biogenic emissions. The benefit of previous implementation experience is that efforts to craft an accounting scheme for BECCS can benefit not only from existing policy precedent, but also from a sense of the issues that remain unresolved (e.g., timing, choice of baseline) and the availability of multiple monitoring programs to help track changes in on-the-ground conditions.

3.2 Relevant Third-Party Certifications

As noted above, compliance with 45Q provisions require conformance to ISO standards for lifecycle analyses. Under the auspices of Technical Committee 207, a variety of standards are currently under development pertaining to both life cycle analysis, as well as broader GHG management and related activities.[100] Elsewhere, the recently-launched CCS+ Initiative intends to develop what it refers to as a "modular methodological framework" under the Verified Carbon Standard to guide CDR pathway accounting.[101] As of this writing, a concept note outlining the methodology has been submitted to the VCS oversight body, Verra. Efforts likewise continue under the auspices of the WRI GHG Protocol and Science Based Target Initiative (SBTi) for Forest, Land and Agriculture (FLAG) to develop standards and tools to aid in GHG accounting by private sector entities.[102] Though a final protocol for bioenergy has yet to be issued, available materials suggest that attention is being paid to many of the issues raised above, including both direct and indirect emissions, separate consideration of carbon removal and storage (sequestration), allocation of removals and emissions across the supply chain, and alignment with existing national and private-sector accounting approaches.[103]

Also of potential relevance are the multiple forest and agricultural carbon offset programs and protocols in use at the present time. An inherent advantage of these programs and protocols is that they are largely project-based, meaning that they seek to account for the net GHG balance of individual interventions, and could thus serve as a model for BECCS deployment decisions. Programs and protocols offered in association with state-level regulatory initiatives, such as California's compliance offset program, or with voluntary initiatives under the auspices of Verra, the American Carbon Registry, or other organizations and registries, offer examples for how to consider challenging accounting elements like indirect effects (e.g., leakage) and project baseline.[104,105] Even so, concerns have been raised about the integrity of offset projects generally, relitigating many of the challenges raised above.[106]

Lastly, there are a variety of third-party verification entities that evaluate and certify the sustainability of forests which operate in the United States as well as globally (e.g., the

Sustainable Forestry Initiative or Forest Stewardship Council), although they do not currently have a carbon monitoring component. These certification systems could be the framework for third-party verification in the future. An analogous system for other biomass feedstocks does not exist, but agricultural-based systems do have familiarity with certification systems, generally (e.g., USDA's Organic Agriculture certification). At the state-level, Best Management Programs (BMP) have been established to meet U.S. Clean Water Act requirements. Every state has some form of regulatory requirements concerning one or more aspects of forest management, and while implementation and compliance varies, BMPs provide an existing policy framework upon which biomass monitoring could be incorporated and possibly quantified. The value of these certification systems is that they provide external, data-supported, and audited processes to validate and verify GHG reduction claims, with the potential to further expand scope to include a variety of systems or regions.

As is the case with state, federal, and international programs, third-party programs and processes can provide examples from which BECCS GHG accounting guidelines may be adopted or adapted. While some of the examples reviewed above do not currently contain carbon accounting provisions, they have the benefit of widespread familiarity and even adoption by potential feedstock producers. Other processes are already integrated with existing policy frameworks (e.g., ISO conformance requirements under 45Q), potentially facilitating their wider adoption. A remaining challenge, particularly given the recent emergence of multiple efforts to develop new or revised GHG accounting processes, is how to build on or align competing frameworks.

3.3 Relevant Private and Self-Governance Initiatives

The private sector serves an important role in the maturation of BECCS. Sustained demand for long-lived carbon removal credits can help facilitate deployment of CDR pathways like BECCS.[107] In practice, the approach for doing so varies widely. Companies like Shopify have expressed a preference for seeding pre-commercial endeavors by paying price premiums and prepaying for carbon removals. Purchases in these situations could rely on existing GHG monitoring and verification protocols—where they exist—but also help to facilitate the development of new protocols through additional research and data gathering.[108]

As a potential buyer of negative emission credits, the private sector can also be an important driver for the adoption of standards in nascent markets, providing demand for a level and well-understood playing field while also helping to define the particulars of eventual standards. Microsoft, for example, has specified its requirements for CDR procurement bids, including demonstrated legal and financial additionality, as well as the use of a counterfactual baseline.[109] Requirements specific to proffered biomass procurements also include identification of alternative fates of biomass resources used in the project, the use of a cradle-to-grave LCA with temporal considerations (e.g., biomass growth/emissions), and a demonstration that leakage has been avoided and/or a conservative accounting of any leakage. Though these are but two examples, they demonstrate how private, self-governance approaches can both help to inform accounting through research and experience while also setting the terms for eventual widespread adoption of specific standards.

4. Conclusions

BECCS is portrayed as a critical element in pathways to reach global warming targets, but creation of a credible accounting regime remains an important prerequisite. When even general terms like "negative emissions" or "carbon neutral" are subject to inconsistent use or different interpretations, the GHG mitigation potential of BECCS must be well-understood to craft policies and incentives that maximize reductions while avoiding negative social or environmental trade-offs. Confidence in accounting is also a prerequisite to encourage investment in the pathway.[110,111,112]

In general, this analysis underscores the previous findings put forward by the EFI Foundation regarding BECCS accounting—the inconsistent treatment of emission sources, the challenges created when assuming that biomass combustion leads to no energy-sector emissions, the importance of well-defined system boundaries, and the complexities of emission and removal patterns over time.[113] Here, we build on these observations and delve deeper into the scientific literature on GHG accounting as it pertains to BECCS, with an emphasis on areas of continuing uncertainty or the potential to strongly influence BECCS GHG balance. We likewise assess the alignment between that literature and existing U.S. policies and programs for GHG accounting relevant to BECCS, and in doing so make recommendations for near-term policy and research needs.

While implicitly recognizing areas of understanding and agreement, our review of the scientific literature also underscores the continued relevance of flashpoints that have long existed in policy deliberations. Choice and clarity of approach is an important and necessary first step. This will determine the relevance of other considerations, such as system baseline or system boundary. Inclusion of both upstream (land use and land-use change emissions) and downstream (energy displacement or fuel use) are relevant to determination of net GHG consequences of BECCS deployment, but are likewise common to other CDR pathways and renewable energy technologies, making their resolution an important part of any mitigation strategy. Of particular relevance to BECCS, inclusion of both direct and indirect effects of feedstock production is important and is well-represented in existing policy. Process and feedstock transport, and feedstock storage emissions, while potentially in need of further study in some respects, are fairly well understood and are accounted for in both research and practice.

Our review of existing approaches to account for the GHG consequences of BECCS and its constituent elements identified both examples of programs that have established GHG accounting processes for particular products or projects, and also government-led initiatives that have failed to do so. These existing approaches demonstrate how complex elements like feedstock production (and associated land-use change) might be estimated, but also the lingering uncertainty of how best to appropriately account for biogenic emissions. In a similar sense, multiple third-party programs and processes exist or are under development with the potential to inform or facilitate BECCS GHG accounting. Questions remain, however, as to whether separately developing initiatives will converge into a single agreed-upon set of standards, or whether divergence in emphasis or approach will further perpetuate uncertainty. At the confluence of these developments lie private, self-governance approaches, which could both inform accounting through research and experience while potentially facilitating the eventual widespread adoption of specific standards.

In light of these observations, we offer the findings and recommendations below, assessing alignment between the available literature and existing BECCS GHG accounting policies and programs to identify near-term policy and research needs. Given the limited purview of this analysis, we do not intend to provide a roadmap for direct policy action, but rather to provide a point of departure from which such policy could be deliberated upon, while also providing ideas for future research and analysis.

4.1 Findings and Recommendations

BECCS GHG accounting is comprised of both low- and high-uncertainty components. Supply chain emissions—those associated with feedstock transport, energy or fuel production processes, and potentially direct emissions associated with feedstock production—are generally well-understood and can be estimated or measured directly; the impact on biogenic carbon stocks owing to indirect market-scale effects is less clear and requires resolution. Although much is already known and subject to a great degree of agreement, resolution of remaining uncertainty is likely to be challenging and has proved contentious in the past.

BECCS GHG accounting shares accounting challenges with other CDR and renewable pathways. The deployment of BECCS as an energy generation source may have downstream effects on the power sector similar to deployment of other renewable technologies like wind or solar. By potentially affecting land use through demand for feedstock, BECCS may contribute to indirect land-use change similar to other nature-based solutions like afforestation or improved forest management. Resolution of these accounting challenges is therefore not unique to BECCS, and consistent treatment is important across technologies and practices to avoid implicitly favoring one over another. A failure to recognize displacement of fossil emissions by BECCS deployment reduces the benefits attributable to the pathway, forcing it directly compete with other fossil abatement strategies.

Emphasize work on those attributes central to BECCS GHG balance. The implication of the two findings above is that efforts to resolve BECCS GHG accounting should emphasize a subset of accounting issues. Much is already known of the constituent elements of BECCS, and some remaining challenges will require resolution regardless of the CDR pathway chosen. As a technology that spans energy and land-use sectors, however, particular attention should be given to consistent accounting of BECCS at all scales, from inclusion or exclusion of indirect effects to treatment under national inventories. As indirect effects stemming from the production or use of certain feedstocks have the potential to transition a BECCS system from net-negative emissions to net-positive (or vice-versa), their accounting likewise requires attention in the near-term.

Avoid easy answers and use unambiguous language. Consistent framing is necessary given the important contributions from multiple disciplines and the accompanying use of different terminology. Furthermore, carbon neutral, carbon positive, or carbon negative are not universally true and suggest a certainty that does not currently exist. A credible accounting regime requires acknowledgement of the complexities of biomass accounting, even if an ultimate policy decision is made to include or exclude a particular element (e.g., indirect land use change). Alternatively, existing policy and implementation experience demonstrates that simplified accounting approaches might be deployed for particular BECCS pathways that have clear baseline conditions and minimal indirect, market-level effects (e.g., wastes and residues that arise from or are secondary to the production of some other primary commodity).

Consider building on existing approaches. Though still nascent in terms of deployment, the constituent elements onto which BECCS pathways are built have the benefit of significant precedent and practical implementation experience. While potentially biasing against new and potentially superior approaches, existing techniques to monitor and account for GHG emissions have the benefit of experience and buy-in. Existing approaches have also arisen to address different objectives (e.g., attributional lifecycle analysis of a given supply chain, estimation of national GHG inventories) requiring attention to the appropriateness of a particular approach for a given purpose.

Consider the interplay of accounting approach, scale, and time. Governance of BECCS, be it by national and subnational governments, third-party non-profits, or the private sector, will drive investment and operation of individual facilities, with potential global implications. Scaling up of deployment may require some degree of translation and disaggregation to provide proper incentives at all stages of accounting, particularly given the present emphasis on country-driven Nationally Determined Contributions (NDCs). The expected scale of BECCS and its potential impact on global supply chains thus requires that accounting be congruent at the project, domestic policy, and international levels. The manner in which emissions or reductions are best recorded may depend on the scope of the program to which it is applied, however. Attention to allocation of credits for emission reduction is also necessary to avoid double-counting of individual activities within a given supply chain in the presence of project-based incentives.

Build on existing research to expand systems-level knowledge of BECCS. The existing literature contains multiple examples of LCA- and systems-level modeling to assess the

GHG consequences of BECCS deployment. While informative, several questions remain. As detailed above, an initial priority is to develop more true-to-life projections of BECCS mitigation potential. As part of these efforts, it is necessary to better ascertain the relationship between the GHG removals achieved by (and the related incentives for deployment of) BECCS in integrated energy and feedstock production systems that are already influenced by multiple policy drivers at the state and federal levels (e.g., incentives or requirements for renewable energy generation, feedstock production incentives). These projections could likewise inform a more sophisticated understanding of infrastructure needs to support all aspects of a BECCS supply chain at scale, which are critical to appreciate the societal impacts of BECCS deployment, both from a siting perspective and potential equity issues as well as land use and feedstock production. Lastly, a more comprehensive understanding is needed between BECCS deployment at various scales, the aggregate impacts on net GHG flux, and related long-term environmental change that can alter ecosystem processes, resource availability, and feedstock production patterns.

References

1 H. de Coninck et al., “Strengthening and implementing the global response.” In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte et al. (eds.), (2018): 313-443.

2 Energy Futures Initiative (EFI Foundation). “Workshop Summary: The Critical Role of CCUS: Pathways to Deployment at Scale.” Washington, D.C. (2021).

3 J. Rogelj et al., “Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development.” In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte et al., (eds.). (2018).

4 M. Fajardy et al., "Investigating the BECCS resource nexus: delivering sustainable negative emissions." Energy & Environmental Science, 11 (2018): 3408-3430.

5 S.V. Hanssen et al., "The climate change mitigation potential of bioenergy with carbon capture and storage." Nature Climate Change, 10 (2020): 1023-1029.

6 Energy Futures Initiative (EFI Foundation). “Surveying the BECCS Landscape.” Washington, D.C. (2022).

7 M. Bui et al., “Carbon capture and storage (CCS): the way forward.” Energy & Environmental Science, 11 (2018): 1062-1176.

8 C.S. Galik. "A continuing need to revisit BECCS and its potential." Nature Climate Change, 10 (2020): 2-3.

9 C. Gough et al., "Understanding Negative Emissions From BECCS." Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions (2018): 3.

10 H. de Coninck et al., “Strengthening and implementing the global response.” In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte et al. (eds.), (2018): 313-443.

11 A. Torvanger. "Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement." Climate Policy, 19 (2019): 329-341.

12 E. Cox and N.R. Edwards. "Beyond carbon pricing: policy levers for negative emissions technologies." Climate Policy, 19 (2019): 1144-1156.

13 C.S. Galik. "A continuing need to revisit BECCS and its potential." Nature Climate Change, 10 (2020): 2-3.

14 Energy Futures Initiative (EFI Foundation). “Surveying the BECCS Landscape.” Washington, D.C. (2022).

15 M. Brander et al., “Carbon accounting for negative emissions technologies.” Climate Policy, 21 (2021): 699-717.

16 P. Thornley and A. Mohr. "Policy frameworks and supply-chain accounting." Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions (2018): 227-250.

17 F. Cherubini and A.H. Strømman. “Life cycle assessment of bioenergy systems: state of the art and future challenges.” Bioresource Technology, 102 (2011): 437-451.

18 C.S. Galik and R.C. Abt. "The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass." Biomass and Bioenergy, 44 (2012): 1-7.

19 V. Colomb et al., “Selection of appropriate calculators for landscape-scale greenhouse gas assessment for agriculture and forestry.” Environmental Research Letters, 8 (2013): 015029.

20 P. Zakkour et al., "Incentivising and accounting for negative emission technologies." Energy Procedia, 63 (2014): 6824-6833.

21 A. Torvanger. "Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement." Climate Policy, 19 (2019): 329-341.

22 P. Thornley and A. Mohr. "Policy frameworks and supply-chain accounting." Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions (2018): 227-250.

23 M. Brander et al., “Carbon accounting for negative emissions technologies.” Climate Policy, 21 (2021): 699-717.

24 M. Fajardy et al., “BECCS deployment: a reality check.” Grantham Institute Briefing Paper. (2019): 28.

25 Energy Futures Initiative (EFI Foundation). “Surveying the BECCS Landscape.” Washington, D.C. (2022).

26 A. Gilbert and B.K. Sovacool. "Emissions accounting for biomass energy with CCS." Nature Climate Change, 5 (2015): 495-496.

27 P. Thornley and A. Mohr. "Policy frameworks and supply-chain accounting." Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions (2018): 227-250.

28 T. Searchinger et al., “Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change.” Science, 319 (2008): 1238-1240.

29 R.J. Plevin et al., “Greenhouse gas emissions from biofuels’ indirect land use change are uncertain but may be much greater than previously estimated.” Environmental Science and Technology, 44 (2010): 8015–8021.

30 A. Mosnier et al., “Alternative US biofuel mandates and global GHG emissions: The role of land use change, crop management and yield growth.” Energy Policy, 57 (2013): 602-614.

31 K.G. Austin et al., “A review of domestic land use change attributable to US biofuel policy.” Renewable and Sustainable Energy Reviews, 159 (2022) : 112181.

32 U. Singh and L.M. Colosi. “The case for estimating carbon return on investment (CROI) for CCUS platforms.” Applied Energy, 285 (2021): 116394.

33 M. Brander et al., “Carbon accounting for negative emissions technologies.” Climate Policy, 21 (2021): 699-717.

34 T. Searchinger et al., “Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change.” Science, 319 (2008): 1238-1240.

35 R.J. Plevin et al., “Greenhouse gas emissions from biofuels’ indirect land use change are uncertain but may be much greater than previously estimated.” Environmental Science and Technology, 44 (2010): 8015–8021.

36 A. Mosnier et al., “Alternative US biofuel mandates and global GHG emissions: The role of land use change, crop management and yield growth.” Energy Policy, 57 (2013): 602-614.

37 G.S. Latta et al., "A multi-sector intertemporal optimization approach to assess the GHG implications of US forest and agricultural biomass electricity expansion." Journal of Forest Economics, 19 (2013): 361-383.

38 C.S. Galik and R.C. Abt. "Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the southeastern United States." GCB Bioenergy, 8 (2016): 658-669.

39 S.J. Kim et al., “Cumulative Global Forest Carbon Implications of Regional Bioenergy Expansion Policies.” Resource and Energy Economics, 53 (2018): 198-218.

40 J.S. Baker et al., “Potential Complementarity between Forest Carbon Sequestration and Bioenergy Expansion Policies.” Energy Policy, 126 (2019): 391-401.

41 A. Favero et al., “Forests: Carbon sequestration, biomass energy, or both?” Science Advances, 6 (2020): eaay6792.

42 A. Mosnier et al., “Alternative US biofuel mandates and global GHG emissions: The role of land use change, crop management and yield growth.” Energy Policy, 57 (2013): 602-614.

43 T.J. Lark et al., “Environmental outcomes of the US Renewable Fuel Standard.” Proceedings of the National Academy of Sciences, 119 (2022): e2101084119.

44 N. Condon et al., "Impacts of ethanol policy on corn prices: A review and meta-analysis of recent evidence." Food Policy, 51 (2015): 63-73.

45 K. Abt et al., “Effect of bioenergy demands and supply response on markets, carbon, and land use.” Forest Science, 58 (2012): 523-539.

46 E.S. Parish et al., “Dataset of timberland variables used to assess forest conditions in two Southeastern United States' fuelsheds.” Data in Brief, 13 (2017): 278–290.

47 S.E. Tanzer and A. Ramírez. “When are negative emissions negative emissions?” Energy & Environmental Science, 12 (2019): 1210-1218.

48 M. Fajardy and N. Mac Dowell. “Can BECCS deliver sustainable and resource efficient negative emissions?” Energy & Environmental Science, 10 (2017): 1389-1426.

49 IEAGHG. “Biomass and CCS—Guidance for accounting for negative emissions.” (2014). https://ieaghg.org/docs/General_Docs/Reports/2014-05.pdf (last accessed March 7, 2022).

50 C.S. Galik et al., "The environmental and economic effects of regional bioenergy policy in the southeastern US." Energy Policy, 85 (2015): 335-346.

51 Global CCS Institute. “Global Status of CCS, 2021: CCS Accelerating to Net Zero.” (2021).

52 V. Nuñez-López et al., “FINAL REPORT: Carbon Life Cycle Analysis of CO2-EOR for Net Carbon Negative Oil (NCNO) Classification.” Submitted to U.S. Department of Energy under agreement DE-FE0024433. (2019).

53 V. Nuñez-López et al., “FINAL REPORT: Carbon Life Cycle Analysis of CO2-EOR for Net Carbon Negative Oil (NCNO) Classification.” Submitted to U.S. Department of Energy under agreement DE-FE0024433. (2019).

54 C.S. Galik and R.C. Abt. "The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass." Biomass and Bioenergy, 44 (2012): 1-7.

55 T. Searchinger et al., “Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change.” Science, 319 (2008): 1238-1240.

56 U.S. Environmental Protection Agency (U.S. EPA), "Renewable fuel standard program (RFS2) regulatory impact analysis." (2010).

57 R.J. Plevin et al., “Greenhouse gas emissions from biofuels’ indirect land use change are uncertain but may be much greater than previously estimated.” Environmental Science and Technology, 44 (2010): 8015–8021.

58 A. Daigneault et al., "Economic approach to assess the forest carbon implications of biomass energy." Environmental Science and Technology, 46 (2012): 5664-5671.

59 C.S. Galik and R.C. Abt. "The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass." Biomass and Bioenergy, 44 (2012): 1-7.

60 S.J. Kim et al., “Cumulative Global Forest Carbon Implications of Regional Bioenergy Expansion Policies.” Resource and Energy Economics, 53 (2018): 198-218.

61 M. Fajardy et al., “BECCS deployment: a reality check.” Grantham Institute Briefing Paper. (2019): 28.

62 C.S. Galik and R.C. Abt. "The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass." Biomass and Bioenergy, 44 (2012): 1-7.

63 T. Searchinger et al., “Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change.” Science, 319 (2008): 1238-1240.

64 C.S. Galik and R.C. Abt. "Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the southeastern United States." GCB Bioenergy, 8 (2016): 658-669.

65 H.J. Geist and E.F. Lambin. "Proximate Causes and Underlying Driving Forces of Tropical Deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations." BioScience, 52 (2002): 143-150.

66 E.F. Lambin et al., "Dynamics of land-use and land-cover change in tropical regions." Annual Review of Environment and Resources, 28 (2003): 205-241.

67 P.E. Kauppi et al., "Returning forests analyzed with the forest identity." Proceedings of the National Academy of Sciences, 103 (2006): 17574-17579.

68 G. Berndes et al., “Forest biomass, carbon neutrality and climate change mitigation.” From Science to Policy, 3 (2016): 3–27.

69 E. Baik et al., “Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States.” Proceedings of the National Academy of Sciences, 115 (2018): 3290-3295.

70 X. Qin et al., “Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment.” Clean Technologies and Environmental Policy, 8 (2006): 233-249.

71 J. Beckman, J. “Biofuel use in international markets: the importance of trade.” EIB-144. U.S. Department of Agriculture, Economic Research Service. (2015). https://www.ers.usda.gov/publications/pub-details/?pubid=44012 (last accessed March 7, 2022).

72 P. Dwivedi et al., “Quantifying GWI of wood pellet production in the southern United States and its subsequent utilization for electricity production in The Netherlands/Florida.” Bioenergy Research, 4 (2011): 180-192.

73 S. Bello et al., “BECCS based on bioethanol from wood residues: Potential towards a carbon-negative transport and side-effects.” Applied Energy, 279 (2020): 115884.

74 M. Langholtz et al., "The economic accessibility of CO2 sequestration through bioenergy with carbon capture and storage (BECCS) in the US." Land, 9, (2020): 299.

75 M. Freer et al., "Carbon optimal bioenergy with carbon capture and storage supply chain modelling: How far is too far?" Sustainable Energy Technologies and Assessments, 47 (2021): 101406.

76 T. Falano and P. Thornley. "Life Cycle Assessment." Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions (2018): 117.

77 M. Bui et al., “Carbon capture and storage (CCS): the way forward.” Energy & Environmental Science, 11 (2018): 1062-1176.

78 T. Falano and P. Thornley. "Life Cycle Assessment." Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions (2018): 117.

79 A. Gilbert and B.K. Sovacool. "Emissions accounting for biomass energy with CCS." Nature Climate Change, 5 (2015): 495-496.

80 M. Brander et al., “Carbon accounting for negative emissions technologies.” Climate Policy, 21 (2021): 699-717.

81 M. Fajardy and N. Mac Dowell. “Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal.” One Earth, 3 (2020): 214-225.

82 P. Zakkour et al., "Incentivising and accounting for negative emission technologies." Energy Procedia, 63 (2014): 6824-6833.

83 F. Schenuit et al., "Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases." Frontiers in Climate, 3 (2021): 7.

84 IEAGHG. “Biomass and CCS—Guidance for accounting for negative emissions.” (2014). https://ieaghg.org/docs/General_Docs/Reports/2014-05.pdf (last accessed March 7, 2022).

85 U.S. Environmental Protection Agency (U.S. EPA), “EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels.” (2009). https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100B3F8.pdf (last accessed January 30, 2022).

86 U.S. Environmental Protection Agency (U.S. EPA), “EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels.” (2009). https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100B3F8.pdf (last accessed January 30, 2022).

87 M. Fajardy et al., “BECCS deployment: a reality check.” Grantham Institute Briefing Paper. (2019): 28.

88 Science Advisory Board (SAB). “SAB Review of EPA’s Accounting Framework for Biogenic CO2 Emissions from Stationary Sources (September 2011).” United States Environmental Protection Agency, Office of the Administrator, Washington, D.C. EPA-SAB-12-011. (2012).

89 Science Advisory Board (SAB). “SAB review of Framework for Assessing Biogenic CO2 Emissions from Stationary Sources (2014).” United States Environmental Protection Agency, Office of the Administrator, Washington, D.C. EPA-SAB-19-002. (2019).

90 U.S. Environmental Protection Agency (U.S. EPA), “EPA’s Treatment of Biogenic Carbon Dioxide (CO2) Emissions from Stationary Sources that Use Forest Biomass for Energy Production.” (2018). https://www.epa.gov/sites/default/files/2018-04/documents/biomass_policy_statement_2018_04_23.pdf (last accessed January 30, 2022).

91 California Air Resources Board (CARB). “Detailed Analysis for Indirect Land Use Change.” (2015). https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/iluc_assessment/iluc_analysis.pdf (last accessed January 30, 2022).

92 California Air Resources Board (CARB). “Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard.” (2018). https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf (last accessed January 30, 2022).

93 California Air Resources Board (CARB). “Low Carbon Fuel Standard, Frequently Asked Questions. Carbon Capture and Sequestration Project Eligibility.” (2019). https://ww2.arb.ca.gov/resources/fact-sheets/carbon-capture-and-sequestration-project-eligibility-faq (last accessed January 30, 2022).

94 California Air Resources Board (CARB). “Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard.” (2018). https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf (last accessed January 30, 2022).

95 A. Torvanger. "Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement." Climate Policy, 19 (2019): 329-341.

96 U.S. Environmental Protection Agency (U.S. EPA), "Inventory of U.S. Greenhouse Gas Emissions and Sinks." (2021). https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (last accessed January 30, 2022).

97 U.S. Forest Service, "Forest Inventory and Analysis (FIA)." (2020). https://www.fia.fs.fed.us/ (last accessed January 30, 2022).

98 U.S. Economic Research Service (ERS). "U.S. Bioenergy Statistics." (2022). https://www.ers.usda.gov/data-products/u-s-bioenergy-statistics/ (last accessed February 2, 2022).

99 ARPA-E. "Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management." (2020). https://arpa-e.energy.gov/technologies/programs/smartfarm (last accessed February 2, 2022).

100 The International Organization for Standardization (ISO). "Standards by ISO/TC 207: Environmental management." (2022). https://www.iso.org/committee/54808/x/catalogue/p/0/u/1/w/0/d/0 (last accessed January 30, 2022).

101 CCS+. "New carbon market initiative to scale-up carbon capture and storage solutions" (2021). https://ccsplus.org/wp-content/uploads/2021/06/FINAL_Announcement_CCS_Initiative_16June2021.pdf (last accessed January 30, 2022).

102 Science Based Targets Initiative (SBTi). "Launch Webinar: SBTi Forest Land and Agriculture (FLAG) Sector Development." (2020). https://sciencebasedtargets.org/resources/legacy/2020/03/20200225-SBTI-FLAG-overview_v1.1.pdf (last accessed January 30, 2022).

103 World Resources Institute/World Business Council on Sustainable Development (WRI/WBCSD). "Greenhouse Gas Protocol, Land Sector and Removals Initiative: Project Overview." (2021). https://ghgprotocol.org/sites/default/files/standards/LSR_Overview.pdf (last accessed January 7, 2022).

104 The American Carbon Registry. "The American Carbon Registry Standard: Requirements and Specifications for the Quantification, Monitoring, Reporting, Verification, and Registration of Project-Based GHG Emissions Reductions And Removals." Version 7.0. (2020).

105 Verra. "Module for Estimating Leakage from ARR Activities." (2022). https://verra.org/methodology/leakage-tool-for-afforestation-reforestation-and-revegetation-project-activities/ (last accessed March 7, 2022).

106 G. Badgley et al., "Systematic over-crediting in California's forest carbon offsets program." Global Change Biology, 28 (2022): 1433-1445.

107 M. Allen et al., "The Oxford Principles for Net Zero Aligned Carbon Offsetting," University of Oxford, Oxford, UK (2020).

108 Shopify. "How to Kick-Start the Carbon Removal Market: Shopify's Playbook." (2021). https://cdn.shopify.com/static/sustainability/How-to-Kick-Start-the-Carbon-Removal-Market_Shopifys-Playbook.pdf (last accessed January 8, 2022).

109 Microsoft. “Microsoft carbon removal: Lessons from an early corporate purchase.” (2021). https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDlc (last accessed March 7, 2022).

110 G. Berndes et al., “Forest biomass, carbon neutrality and climate change mitigation.” From Science to Policy, 3 (2016): 3–27.

111 S.E. Tanzer and A. Ramírez. “When are negative emissions negative emissions?” Energy & Environmental Science, 12 (2019): 1210-1218.

112 C.S. Galik. "A continuing need to revisit BECCS and its potential." Nature Climate Change, 10 (2020): 2-3.

113 Energy Futures Initiative (EFI Foundation). “Surveying the BECCS Landscape.” Washington, D.C. (2022).