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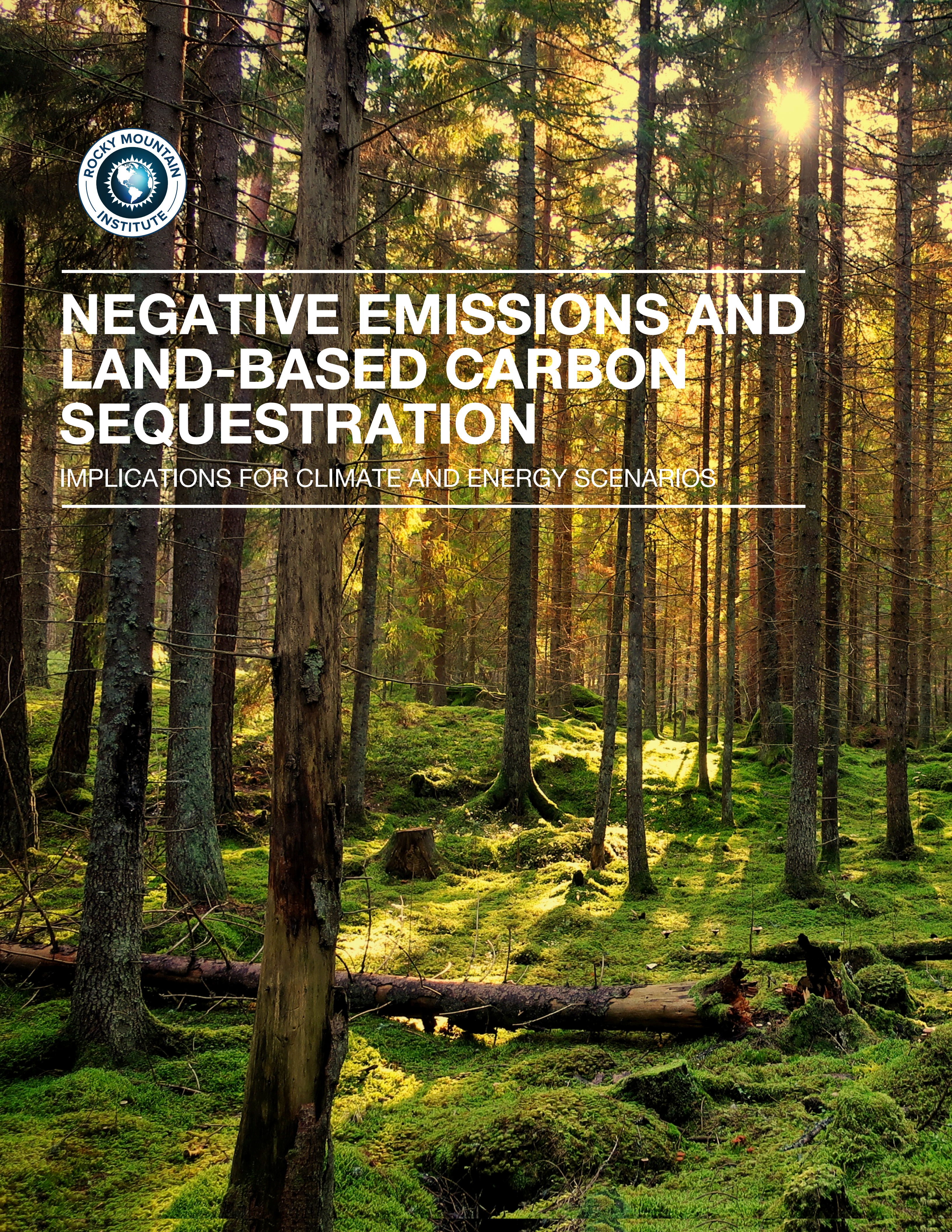
NEGATIVE EMISSIONS AND LAND-BASED CARBON SEQUESTRATION

IMPLICATIONS FOR CLIMATE AND ENERGY SCENARIOS



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SUGGESTED CITATION
Emily McGlynn and Aman Chitkara. *Negative Emissions and Land-Based Carbon Sequestration: Implications for Climate and Energy Scenarios*. Rocky Mountain Institute, 2018. http://www.rmi.org/insight/negative-emissions-carbon-sequestration

This report was updated on November 8, 2018.

ACKNOWLEDGMENTS
The authors acknowledge Thomas Dinwoodie, a member of RMI's Board of Trustees, whose generous support and valuable insights made this report possible.

The authors also thank the following individuals/organizations for offering their insights and perspectives on this work.

Marshall Abramczyk, Rocky Mountain Institute
Austin Brown, UC Davis, Policy Institute for Energy, Environment, and the Economy
Martha Campbell, Rocky Mountain Institute
Long He, Syntech Bioenergy
James Newcomb, Rocky Mountain Institute
Brian von Herzen, Climate Foundation

ABOUT ROCKY MOUNTAIN INSTITUTE
Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

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EXECUTIVE SUMMARY

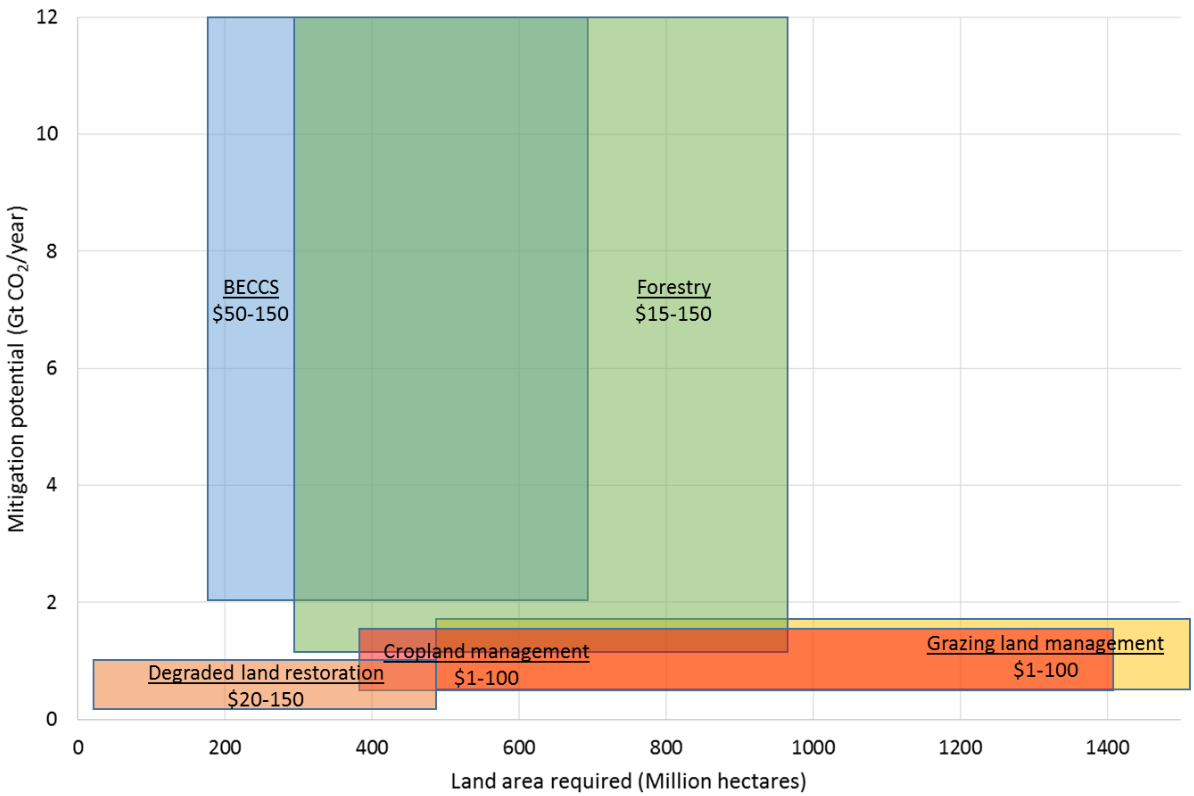
"Negative emissions," or strategies for removing carbon dioxide from the atmosphere, will be indispensable for meeting long-term global climate goals. Rocky Mountain Institute has elaborated in a recent report how a rapid global energy transition, together with changes in agriculture and land use practices, could limit global average temperature increase to 1.5–2.0 C°[i] above preindustrial levels.[1] This paper examines ways to sequester carbon in landscapes and through emerging technologies, identifying key challenges, research needs, and policy priorities in line with this vision.

Deploying land-based carbon sequestration and other "negative emissions" technologies at scale is critical for addressing climate change. Approximately 10–20 Gt CO_2 of negative emissions, or atmospheric CO_2 removal, will be required annually by 2100, equivalent to 25–50 percent of today's global annual fossil fuel emissions. To achieve this goal, aggressive research, development, and deployment incentives are needed.

There are many different negative emissions technologies at various stages of maturity. Although a large portion of negative emissions are projected to come from such engineered solutions as bioenergy with carbon capture and storage (BECCS) or direct air capture (DAC), increased carbon sequestration in forests and soils will also contribute. Non-carbon capture and storage, carbon-beneficial bioenergy may also support mitigation targets. Many of these options compete for land use, making it critical to balance land-based climate mitigation with broader social needs for food production, housing and human settlement, and conservation. There are real trade-offs between carbon mitigation and land-use, as demonstrated in Figure 1, which shows the global mitigation potential for key negative emissions technologies and their corresponding land area required.

[i] While most people are familiar with the expression "degrees Celsius" (°C), that expression signifies an absolute temperature that represents the coolness or warmth of something. The expression "Celsius degrees" (C°) refers to an interval between two measured temperatures, which in this paper denotes temperature rise above preindustrial levels.

FIGURE 1: GLOBAL POTENTIAL FOR KEY NEGATIVE EMISSIONS TECHNOLOGIES BY 2100. PRICES REPRESENT RANGES OF CARBON PRICES FOR EACH TECHNOLOGY ($/TON CO_2 SEQUESTERED)[2]



Note: Mitigation potential for forestry in Figure 1 only includes afforestation and reforestation, per Smith et al. 2015, and doesn't include avoided deforestation or management of existing forests. Global numbers for mitigation potential through enhanced forest management are not available.

Critical research and policy needs for responsibly deploying negative emissions technologies include:

- Developing policy frameworks to guide land use and land management across mitigation options and alternative land uses for food, feed, conservation, and other human and ecological needs
- Increasing productivity and efficiency of land use for human needs
- Investing in new agronomic technologies to increase agricultural and forestry climate resilience and mitigation potential
- Putting in place land carbon monitoring and verification systems
- Creating revenue streams to finance negative emissions technologies, mirroring an economy-wide carbon price—this will be a necessary condition for any meaningful negative emissions deployment

This paper focuses primarily on how natural climate solutions could be deployed and contribute to emissions reduction goals in the United States, which has projected negative emissions technologies contributing 0.6–1.4 Gt CO_2 sequestration annually by 2050.[3] This would make up a substantial portion of the estimated annual 7–10 Gt CO_2 global sequestration that could be delivered through landscapes. Table 1 below summarizes US sequestration potential from multiple land-based carbon sequestration technologies and other negative emissions technologies at scale.

TABLE 1: SUMMARY OF POTENTIAL OF LAND-BASED CARBON SEQUESTRATION AND OTHER "NEGATIVE EMISSIONS" TECHNOLOGIES AT SCALE IN THE US.

	Technology	US Potential (Gt CO_2/y, 2050)
Forest-based climate mitigation options	Forest expansion	0.96–1.29[ii]
	Enhanced forest management	0.56–1.59[iii]
	Avoided conversion/ Disturbance	0.09+[iv]
	Wood products and bioenergy	Uncertain (for bioenergy see BECCS below)
Agricultural climate mitigation options	Agroforestry and silvopasture	0.24–1.98[v]
	Soils	0.17–0.27[vi]
	Bioenergy	See BECCS estimate below
Engineered and technological climate mitigation options	BECCS	0.1–0.6[vii]
	Biomass gasification/biochar	.01–0.1[viii]
	Deep-rooted crops	.25–1.2[ix]
	Algae	Uncertain
	Dietary changes	0.26–0.48[x]

The US provides an important case study as the third-largest country in the world, covering 6 percent of the world's land mass, representing more than 250 of the world's 867 ecoregions, and supporting a diverse range of agricultural and forestry industries. This paper seeks to provide climate and energy policy experts with a useful overview of how negative emissions can be incorporated into national climate policy.

[ii] Low is $50/ton CO_2 estimate based on linear extrapolation of literature estimates (see Figure 2), high is maximum literature estimate (Van Winkle et al., 2017).

[iii] Low is $50/ton CO_2 estimate based on linear extrapolation of literature estimates (see Figure 2), high is maximum literature estimate (Van Winkle et al., 2017).

[iv] Assuming US EPA 2017 estimate of LULUCF emissions can be avoided completely, assumed to be a lower bound on avoided disturbance emissions mitigation.

[v] Low based on riparian buffer and alley crop (10 percent of cropland) estimates, high represents low plus 10 percent of all pasture land managed under silvopasture, all based on Udawatta and Jose 2011.

[vi] Low represents Murray et al., $15/ton CO_2 (2005), high based on maximum estimate in Chambers et al., 2016.

[vii] Range based on Limited Sink (low) and Benchmark (high) scenarios in US Mid-Century Strategy for Deep Decarbonization (White House, 2016).

[viii] Range based on Fargione et al. (in prep), with low based on $50/ton carbon price and high based on $100/ton carbon price. Assumes only crop residues are used for biochar production.

[ix] Range based on US Mid-Century Strategy for Deep Decarbonization (White House, 2016), p. 78.

[x] Range based on Stehfest et al., 2009, assuming US can account for 6 percent (202 million hectares of 3.3 billion hectares global grazing lands, FAO, 2017) of global mitigation from phasing out global red meat consumption (low) to all meat consumption (high).

1. SETTING THE STAGE: NEED AND POTENTIAL FOR NEGATIVE EMISSIONS

To avoid the most dangerous impacts of climate change, the global community agreed to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and [pursue] efforts to limit the temperature increase to 1.5°C."[4] To achieve this, the world will need to not only rapidly decarbonize the power, industrial, buildings, and transportation sectors, but also deploy negative emissions or carbon dioxide removal strategies, to actively remove CO_2 from the atmosphere.[xi] Rocky Mountain Institute's (RMI's) Positive Disruption report describes in detail how rapid decarbonization can occur across industrial sectors, driven by existing market forces and increasing rates of innovation, including through negative emissions.[5] Negative emissions will be needed, hand in hand with rapid energy sector decarbonization, for three reasons:

- To offset hard-to-eliminate emissions from sectors such as agriculture, aviation, and heavy-duty transportation
- To counteract the "overshoot" of dangerous CO_2 levels that is likely to occur even with best efforts
- To keep overall costs of climate mitigation low

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report estimates that staying well below 2 C° will require 10–20 Gt CO_2 removal globally per year by 2100, cumulatively reaching 400–800 Gt CO_2.[6] This would be equivalent to removing 25–50 percent of today's global fossil fuel emissions every year. It will be a monumental task, and requires getting to work immediately.

The IPCC indicates that globally land use, land use change, and forestry (LULUCF) could support between 15 and 40 percent of cumulative mitigation by 2100, or approximately 7–10 Gt CO_2e sequestered annually by 2030.[7] At the same time, IPCC scenarios have engineered solutions such as BECCS contributing upward of 12 Gt CO_2 removal globally per year.[8] Similarly, the United States Mid-Century Strategy for Deep Decarbonization indicates US landscapes could sequester up to half of economy-wide emissions by 2050.[9] More recent updates indicate responsible land use and management strategies globally could contribute 23.8 Gt CO_2 of sequestration and avoided emissions annually, accounting for 37 percent of global mitigation required through 2030.[10] These estimates reflect a range of assumptions about the technical and economic potential of proposed solutions, which remain highly uncertain and should be interpreted carefully. They are described here to provide an overall sense of scale and scope.

Natural climate solutions include forest expansion, enhanced forest management, agroforestry, agricultural soil improvement, biomass for carbon-beneficial bioenergy, and opportunities for offsetting fossil fuel emissions such as long-lived wood products. Estimates of the scale of potential for each opportunity vary widely.

Today global land use and land management are the source of one-quarter of total anthropogenic CO_2 emissions.[11] Shifting global landscapes from a net emissions source to a (massive) net sink will require a suite of investments in new technologies and ambitious policy. Key strategies for increasing natural carbon sequestration will also be needed. All of these issues will be discussed further below.
Perhaps most importantly, governments need to create large-scale revenue streams for financing natural climate solution activities such as forest expansion, enhanced forest management, and soil carbon storage in cropland, grazing land, and forests, as well as biomass for carbon-negative bioenergy. Whereas CO_2-emitting facilities such as coal plants will be incentivized to *avoid a carbon price*, many carbon-sequestering activities will require a *carbon payment* to incentivize action.

[xi] Out of the 116 IPCC model scenarios consistent with keeping warming below 2 C°, 87 percent utilize negative emissions technologies (Smith et al., 2015).

A 2005 study indicated that at a $40/ton CO_2 carbon price, US landscapes have the potential to deliver 1.2 billion tons of CO_2e reductions annually (annualized over 2010–2110), if fully funded across forestry and agriculture.[12] Compare this with the estimated 1.2 billion–1.8 billion tons of CO_2e mitigated annually in the energy sector with a $40 to $47 carbon price in 2025.[13]

Consider that under a carbon pricing approach, the energy sector could be given an allowance of achieving 8 percent of its carbon pricing obligation through land-based offsets. This could fund nearly 150 million tons of carbon sequestration in soils and forests annually by 2025, financed by approximately $2.2 billion from the private sector each year (assuming an average $15/ton CO_2e in the land sector). Compare this with the $6.3 billion-plus the energy sector would have had to pay for the most expensive mitigation options, without the ability to use offsets, at $47/ton CO_2e. Here we see the efficiency gains in mobilizing land-based carbon sequestration, as well as the potential for generating multibillion-dollar revenue streams for rural communities.[xii] Local, state, or federal governments will need to develop programs to fund carbon sequestration, whether out of carbon tax, carbon credit auction revenues, or carbon offsetting schemes. Each of these incentive frameworks is discussed in more detail below.

The US provides an important case study for assessing carbon sequestration opportunities and policies. Since 1990, US lands have consistently offset 10–13 percent of annual economy-wide emissions; the majority has been sequestered by tree growth in existing forests.[14] Many analyses indicate great potential for expanding US natural climate mitigation, with some estimates surpassing 1.5 Gt CO_2 of annual sequestration, equivalent to more than 20 percent of current US annual emissions.[15] Achieving this potential, however, would require putting in place carbon sequestration incentives.

Note that in discussing annual mitigation opportunities, we refer to the ability to sequester additional carbon every year and store that carbon on a virtually permanent basis.[xiii] Annual mitigation occurs only if more and more carbon is being added to forests, soils, or geologic storage each year. As a result, it is possible for natural carbon sinks to "saturate," or reach a maximum carbon storage such that additional sequestration (or mitigation) is not possible. However, these "saturation points" are highly dependent on assumptions of how much land use and land management change is possible, and should be carefully interpreted. Saturation is discussed in more detail for specific strategies below.

The remainder of this paper will (1) provide an overview of key US negative emissions solutions, highlighting critical considerations for implementation and research needs for each, and (2) discuss considerations for incorporating land use and land management into US climate and energy policy. Ways to address uncertainty and manage controversial topics such as competing land use needs and bioenergy are highlighted.

2. REVIEW OF US NATURAL CLIMATE SOLUTIONS OPTIONS

This section breaks down the climate mitigation potential across forestry, agricultural, and technological solutions supported by US lands, reflecting the scale of potential, mitigation costs, and implementation considerations.

[xii] Assumptions for mitigation scale and costs based on Climate Leadership Council 2017, Hafstead & Kopp scenario.

[xiii] Note that different carbon accounting programs (American Carbon Registry, Voluntary Carbon Standard, California Low Carbon Fuel Standard, EPA Draft Biogenic Accounting Framework, and others) use a range of 30–100 years to account for land management and land use changes. There is literature and policy debate about how "permanent" carbon sequestration must be to qualify for incentives. For purposes of mitigation effectiveness, any lost carbon, whether due to human activities or natural causes, will need to be compensated with additional sequestration. Carbon-trading mechanisms tend to address this challenge through "buffer" or "insurance" pools that carbon market participants must pay into through generated carbon credits. However, the longest these programs account for any lost carbon is 100 years.

Forests

US forests are efficient carbon sequestering landscapes and the largest contributor to the national carbon sink, covering over 750 million acres.[16] Each year as forests grow and trees age, they fix atmospheric CO_2 into long hydrocarbon chains. Once fixed, undisturbed trees can store a substantial amount of this carbon for 800 years or more, both above and below ground.[xiv] Some of the carbon will cycle more quickly in and out of the atmosphere through (1) respiration of CO_2 as part of the living processes of the trees themselves (a "fast" process, similar to how humans breathe in oxygen and breathe out CO_2) and (2) decay of leaves and small woody debris (a "slow" process). Some of the decayed material gets incorporated into the forest soil and can be sequestered nearly permanently. As stands of trees age, the CO_2 emissions from respiration and decay can catch up to the amount of carbon sequestered each year. At this point, a forest is considered to have reached carbon saturation. Researchers debate how long it takes forests to reach saturation, particularly as increasing atmospheric CO_2 concentrations create a "fertilization effect" by spurring plant growth and potentially deferring saturation points.[17] It can take from decades to centuries for a new forest to reach saturation.

Forests can be managed so they sequester greater amounts of carbon in a number of ways; these include forest expansion, EFM, avoided forest disturbance, and the offsetting of fossil fuels through the use of wood products and bioenergy.

Forest Expansion

Following extensive deforestation in the 18th and 19th centuries coinciding with European settlement, US forests have made a comeback, regrowing at a rate of approximately 1 million acres per year over the past 30 years.[18] These relatively new forests, both naturally regrowing and replanted, can sequester large amounts of carbon. Yet they have contributed only 10 percent of the US land carbon sink since 1990. Discussed further below, the much larger carbon sink is from growth in existing forests.

Potential for future US forest expansion (afforestation or reforestation) has been discussed largely in the context of how much mitigation can be delivered at various levels of carbon pricing (see Figure 2). Van Winkle et al. indicate across a dozen studies that 1 Gt CO_2 of annual forest carbon sequestration could be achieved at \$50/ton CO_2. The US Mid-Century Strategy for Deep Decarbonization (MCS) indicates that 40–50 million acres of forest expansion might be required to maintain the current annual forest sink until 2050.

Although these modeled results are useful, there has been much less assessment of where and how forest expansion might take place, and whether or not these projections are socially and economically realistic. More research is needed to tailor these estimates using geospatial analysis. To date, this type of work has been limited owing to political and budget constraints, and going forward, there are likely to be strong concerns about how to identify "appropriate" areas for converting private land to forest. Thus the most feasible strategy for garnering more accurate estimates is to put in place forest expansion carbon incentives and undertake econometric analysis.

The two active US carbon incentive programs, the California cap and trade system and the Regional Greenhouse Gas Initiative (RGGI), have incentives in place for afforestation. However, because of legal uncertainty and low carbon credit prices, they have produced negligible forest expansion activity—an indication that forest expansion will be a more expensive mitigation option than other forest management tools.

This is partially due to the fact that forest expansion, unlike enhanced forest management, has the potential to compete with other land uses, particularly agriculture. Identifying strategies for multiple land uses, such as agroforestry and silvopasture (wherein trees are integrated with crop and pasture systems), can reduce competitive effects on land use and head off potential food cost increases. The US MCS indicates there is

[xiv] Nearly 75 percent of US forest carbon is stored in soils, but the largest annual sink is attributed to growth in live trees ("US Forest Carbon Accounting Framework," Domke et al., 2015).

potential for 50 million acres of agroforestry in the United States, which could go a long way in supporting mitigation goals and reducing competitive impacts.

Growth in Existing Forests

In the US, existing forests account for more than 85 percent of carbon sequestration, making them by far the largest contributor to the US carbon sink. Enhancing carbon sequestration in existing forests usually takes the form of enhanced forest management (EFM) (often described as improved forest management [IFM]) in carbon accounting programs), such as lengthening the rotation periods, or amount of time between timber harvests. To understand this mitigation strategy, note that 58 percent of US forests are privately owned and that private forests provide 90 percent of the nation's wood products.[19] The timeline for harvesting and regrowing trees depends on the target wood product market, and often the owner of a private forest is growing for multiple wood products at once, with small-diameter thinnings supporting low-value markets such as bioenergy, larger-diameter trees supporting mid-value pulp and paper products, and, later in the growth cycle, the largest-diameter trees supporting high-value products such as timber and telephone poles.

Van Winkle et al. have synthesized literature estimates that indicate enhanced forest management could contribute upward of 1.5 Gt CO_2 sequestration annually, but most scenarios indicate potential for 500 million tons of CO_2 at carbon prices of less than $60/ton. Note that many of these studies assume national implementation of a carbon price, minimizing risk of leakage within the US.

Leakage refers to the risk that reducing harvests in one area can increase harvests somewhere else owing to market drivers. That is, although increasing rotation lengths can increase standing carbon in one area, it also results in lowered wood product supply and thus can increase wood prices and drive increased harvesting elsewhere. Studies indicate harvest leakage can range from less than 10 percent to more than 90 percent of total carbon mitigation.[20] This means that although enhanced forest management can be an effective sequestration tool, it needs to be implemented on a broad geographic basis to ensure effectiveness.

There is disagreement about the ability of US forests to continue sequestering carbon in the coming decades. Some models indicate forest aging will result in slower growth, compounded by changes in land use, to result in a weakened sink.[21] Others project forests have the potential to be managed more intensively to serve both the wood products markets and carbon demand, keeping the forest sink strong.[22] Natural disturbances such as forest fire, drought, insect infestation, and hurricanes will also determine the future carbon sink. Thus, even though existing forests have carried the US carbon sink to date, the future is highly uncertain.

Avoided Forest Carbon Loss From Conversion and Natural Disturbance

Once carbon is stored in forests, soils, or geologic formations, it is important that it stay there virtually permanently, otherwise it cannot be considered a lasting climate mitigation solution. If it cannot be guaranteed to be permanent, there must be some understanding of how its eventual emission would be offset by some additional sequestration in the future (for example, in a natural forest system, predictable harvest and regrowth may be consistent with net carbon sequestration over time). As we discuss further below, "permanence" may be less critical if humans don't seek to represent land carbon sequestration as a permanent offset to fossil fuel emissions. Regardless, avoiding emissions from natural and human-made impacts to forests both reduces future climate impacts and ensures mitigation to date remains effective.

Unfortunately, a changing climate is likely to result in greater natural disturbances such as wildfires, droughts, and insect infestations. Wildfires have gone from affecting 3 million acres nationwide in 1985 to affecting more than 10 million acres in 2015.[23] Rocky Mountain–region tree mortality due to mountain pine beetle infestation has increased by 92 percent since the 1990s.[24] It is difficult to predict the future extent of these impacts, but decision makers must plan for this uncertainty in projections of the future land carbon sink, and assess the ability of these disturbances to undo best efforts in managing forest resources.

Conversion of forests to agriculture and settlement is another major contributor to loss of land carbon. Although the US has seen a net annual gain of forest area for several decades, conversion of forests to cropland and settlements emits some 90 million tons of CO_2 annually, reducing the net land carbon sink by 10 percent.[25]

Reducing forest conversion to settlement can be supported by stricter zoning, smart urban design, and dense, integrated communities. However, since these efforts require long-term policy planning and urban investment, the costs of avoiding forest conversion are likely to be higher than those of other forest carbon opportunities. Carbon-based incentives alone will be insufficient, needing to be paired with regulatory guidance and easements that create value for standing forest.

Addressing natural disturbances will be more challenging. Forest management stakeholders have proposed thinning forests that are "overstocked," or that have more trees than a historical baseline, to reduce the impacts of forest fires, insects, and the compounding effects that drought can have on these disturbances. However, knowing where, when, and how much to thin is challenging, particularly when one of the objectives is reduced carbon loss. Natural disturbances occur unpredictably across landscapes. Depending on what happens to the thinned wood (whether it is used in long-lived products, used for bioenergy, or simply burned on site), the net effect of thinning trees compared with disturbance-related emissions can be a wash or even potentially negative for the climate.[26] Further research and fieldwork is needed to better calibrate thinning toward carbon outcomes while supporting ecological, hydrological, and other objectives.

The Offsetting of Fossil Fuels Through the Use of Wood Products and Bioenergy

Rather than storing carbon, forest products can offset fossil fuels. Although this can result in short-term forest carbon emissions into the atmosphere, if forests are appropriately managed for carbon outcomes, these emissions can be re-sequestered much more quickly than fossil carbon. Science-based carbon accounting protocols are needed to estimate net carbon outcomes from wood product and bioenergy use, including the likelihood and scale of fossil fuels offset and timing for re-sequestration.

Long-lived wood products, generally used in construction, are likely to represent a strong mitigation opportunity, if sourced from responsibly managed forests and if offsetting fossil fuel–intensive products like steel and concrete. Given that the life of a building is 80 years or more, long-lived wood products can store carbon much longer than short-lived wood products such as paper or bioenergy, and can create robust market incentives for expanding forests. Wood products as a carbon solution may be attractive because these markets already exist at scale and drive a substantial number of US forest management decisions. Long-lived wood product use could be expanded through greater deployment of multifamily, multistory, and large-scale commercial wood buildings. Wood is already commonly used in residential homes, but it is much less common in apartment buildings, skyscrapers, malls, and department stores. Several 10-plus-story wood buildings are under development in the US today, but new building codes and community ordinances will be needed to deploy tall commercial wood buildings at a larger scale.

However, this opportunity needs to be managed carefully. Whether or not wood products and bioenergy can truly be considered a mitigation option depends on both the context in which the product is made and the forest management regime. Studies have shown that increasing demand for wood products is correlated with forest area growth or stability, counteracting market forces that might otherwise convert forests for development or agricultural uses.[27] This dynamic is particularly relevant for forests on the margin of agricultural and urban areas. Transitioning from harvest regimes focused on lower-value, short-lived wood products, which are likely to be supported by short rotation cycles, to long-lived and higher-value wood products is also likely to have a positive carbon effect, in that harvest rotations would be lengthened. Forest owners are also likely to benefit from greater revenue, supporting rural economies. If long-lived wood products offset carbon-intensive alternatives such as steel or concrete, the net carbon benefits are sizable.[28]

For instances that do not meet the above criteria, and for forests that would otherwise stay undisturbed, increasing harvesting could result in greater carbon emissions to the atmosphere than would otherwise occur.

Harvesting of old-growth trees and previously undisturbed forests is likely to result in negative carbon impacts, potentially for centuries, regardless of wood product end markets.[29]

For these reasons, bioenergy demand might have a perverse effect on carbon outcomes, by reducing harvest rotations in order to serve a lower-value market. Given the immediate combustion of carbon and release into the atmosphere, the time line for re-sequestering forest carbon and thus reaching "carbon neutrality" could be decades (note that although this is still an improvement from fossil carbon emissions, it is considered by many to be suboptimal compared with other renewable energy options). Yet there are sources of woody biomass that can be considered "carbon beneficial," such as those that meet the various criteria described above, as well as harvest residues and short rotation woody crops. Furthermore, a number of studies have pointed to the potential for bioenergy to, like other wood products markets, drive forest expansion and enhanced forest management.[30] If this is the case, forest bioenergy could represent a sizable and cost-effective mitigation opportunity—additional empirical evidence to verify this market dynamic would be instructive.

Thus, the calculation of net carbon effects from wood products and bioenergy is complex, and should be carefully considered. If carbon incentives are used to drive these markets, additional empirical research and carbon accounting protocols need to be put in place to account for the above dynamics.

Summary

Table 2 summarizes the forest mitigation opportunities described above along with supportive research and policies needed to deploy each.

TABLE 2: SUMMARY OF US FOREST-BASED CLIMATE MITIGATION OPTIONS.

	US potential (Gt CO_2/y, 2050)	Research needs	Policy needs (+ carbon payments)
Forest expansion	0.96–1.29[xv]	"Hot spot" geospatial analysis of potential Assessment of potential to combine EFM with bioenergy, wood products Intermodel comparison to reduce projection uncertainty	Based on research and accounting protocols, incentivize forest products markets that drive forest expansion, enhanced management
Enhanced forest management	0.56–1.59[xvi]		
Avoided conversion/ disturbance	0.09+[xvii]	Improved thinning practices, monitoring Climate-resilient breeding/planting	Conservation easements Urban planning Funding for responsible thinning/disaster management
Wood products and bioenergy	Uncertain (for bioenergy, see BECCS in Table 3)	Carbon accounting methods RD&D for wood building materials	Updated building, zoning codes to allow taller/commercial wood buildings

[xv] Low is $50/ton CO_2 estimate based on linear extrapolation of literature estimates (see Figure 2), high is maximum literature estimate (Van Winkle et al., 2017).

[xvi] Low is $50/ton CO_2 estimate based on linear extrapolation of literature estimates (see Figure 2), high is maximum literature estimate (Van Winkle et al., 2017).

[xvii] Assuming US EPA 2017 estimate of LULUCF emissions can be avoided completely, assumed to be a lower bound on avoided disturbance emissions mitigation.

Agriculture

US agriculture supports two-thirds of the world's commodity crop calories, spanning a diverse range of activities with varying carbon intensities, across row cropland for corn, soy, wheat, and rice; orchards and specialty crops; and pasture and rangeland for grazing livestock. Cropland covers 400 million acres, and pasture and rangeland over 500 million acres, together covering 41 percent of the United States. Currently these landscapes contribute less than 5 percent of the US land carbon sink, with croplands sequestering 18 million tons of CO_2 annually (this is generated almost entirely by cropland retired through the Conservation Reserve Program) and grasslands sequestering another 20 million tons.[31] The question is whether agricultural lands can be reliably managed to sequester more carbon while preserving and increasing their ability to support global fuel, feed, and fiber.

Strategies for increasing carbon storage on agricultural land include agroforestry and silvopasture (integrating trees into agriculture), enhanced soil carbon management, and supplying biomass for bioenergy.

Agroforestry and Silvopasture

Agroforestry and silvopasture are methods for integrating trees into agricultural systems. These include planting trees along field borders and stream banks, in the "alleys" between rows of crops, and in low-producing areas of fields and pasture, as well as more regularly distributing them throughout pasture to support shade for livestock. Udawatta and Jose estimate that riparian buffers, alley cropping, and silvopasture can sequester nearly 2 Gt CO_2 annually (with the majority coming from silvopasture), but this would require alley cropping on 10 percent of all cropland and integrating grazing with forestry across 133 million acres.[32] Furthermore, much of this estimate likely overlaps with forest expansion mitigation estimates.

Farmers and ranchers to date have been reluctant to integrate more trees into their operations due to cost and not wanting the trees to compete with their primary agricultural outputs. Further research is needed to understand the economic incentives required to scale up agroforestry practices and to understand logistical and ecological constraints to these initial estimates. If truly feasible, this will be an especially attractive mitigation option owing to the reduced competition with food production.

Enhanced Soil Management

Since European settlement, US agricultural soils have lost more than one-third of the original carbon they contained.[33] Recovering lost soil carbon could represent a substantial mitigation opportunity. The key is to understand more confidently how much carbon sequestration is possible through changes in management practices and whether the carbon storage is relatively permanent. Although research on these topics has been ongoing for decades, there is still much uncertainty regarding the net carbon benefits of soil management practices across regions, soil types, and climates.

Enhancing soil carbon requires increasing inputs of below-ground (through roots) and above-ground (through residues or cover crops) plant matter into the soil, and then minimizing soil disturbance to encourage "aggregates" (clumps of soil) that can protect soil from erosion and also reduce carbon emissions from the soil. Practices such as leaving crop residues on the field, growing cover crops, and growing more deeply rooting plants such as perennial grasses can all support increased plant matter inputs. Less common but especially effective practices include manure or biochar application, which can substantially increase carbon inputs to the soil (though life-cycle carbon analysis is required to understand where the manure or biochar comes from and whether carbon storage is truly new and additional). Reducing or eliminating tillage, referred to as following "no-till" practices, helps ensure that carbon remains stored.

That said, there are substantial uncertainties with respect to the level and permanence of these practices as carbon mitigation tools. Issues such as soil carbon baseline, appropriate depth of measurement, potential for saturation, and other issues create large uncertainties in soil carbon models.

Some studies have indicated that no-till practices may increase carbon storage near the soil surface, but reduce deep carbon, having a net zero effect on total carbon storage, and that they can also result in increased N_2O emissions.[34] Uncertainties with respect to the sequestration potential of no-till practices must be resolved in order to better understand the scale of potential for soil carbon storage from improved soil management. In sum, if future research can reduce uncertainty and increase confidence in soil carbon dynamics, it could add significantly to negative emissions mitigation potential. Chambers et al. suggest US agricultural soils could sequester 270 million tons CO_2 annually by 2050, and Murray et al. suggest 168 million tons of potential at a $15 carbon price.[35]

Investing in field research, improved models, and enhanced field operations will help improve decision makers' ability to plan for the future and understand how much soil carbon storage can contribute to climate mitigation.

Agriculture and Bioenergy

Similar to the case with forests, there is potential for trade-offs but also synergies between carbon sequestration on agricultural landscapes and bioenergy. The main agricultural biomass sources are crop residues and energy grasses.

Removing large amounts of crop residues for bioenergy has potential to degrade soil carbon.[36] The literature shows wide-ranging effects of residue removal on soil carbon, and generally indicates highly productive soils can support greater residue removal than low-quality soils. Additional research and analysis can help guide residue removal to minimize soil carbon loss, but in any case residue removal will need to be managed carefully according to soil type, climate, management regime, and other factors.

Conversely, growing high-yield perennial grasses for bioenergy could substantially increase soil carbon by increasing root mass and reducing tillage.[37] Energy grasses are predicted to be the largest contributor to future bioenergy supply, making up more than 50 percent of biomass supply in the US Mid-Century Strategy.[38] Although energy grasses can increase soil carbon, increased nitrogen application and resulting N_2O emissions could offset any soil carbon improvements.[39]

The larger challenge of managing impacts of energy grasses is direct and indirect land use change. To supply bioenergy and BECCS demand, energy grasses could cover upward of 40 million acres by 2050, similar in scale to projected forest area expansion.[40] Shifting nearly 100 million acres, an area the size of Montana, into energy crops and forestry could have substantial environmental and economic impacts, increasing competition for land use and driving up land, water, nutrient, and other input costs. Key strategies for minimizing these economic impacts include:

- **Developing rotational strategies for grazing, energy grass production, and forestry.** Using land more efficiently will be critical—for example, regions with long growing seasons can rotate summer grazing land with winter energy grass production. Energy grasses could be grown in the first 10 years of planted forest rotation. They could also be integrated into field edges and low-producing cropland areas. However, these approaches are at very early conceptual and demonstration stages at best. Much more research and demonstration support will be needed to verify whether they are economically and agronomically feasible at commercial scale.
- **Focusing on non-irrigated landscapes to minimize water impacts**. Biomass is not currently a valuable enough crop to make irrigation economical, but as carbon prices increase, this could change. Non-irrigated agriculture accounts for more than 60 percent of US farm sales, concentrated heavily in the East and South. This would likely limit biomass deployment in drier Western states.
- **Utilizing precision agriculture techniques to rightsize nutrient application and timing.** Farmers are increasingly using geospatial tracking technology to track agricultural inputs and yields within and across fields to optimize profits. These approaches reduce excess fertilizer application and also help farmers adjust the timing of nutrient application and harvests to minimize nitrogen loss.[41] Keeping fields

covered for as much of the year as possible, through cover crops and rotational planting, can also help reduce N_2O emissions.

None of these strategies can completely mitigate the potential impacts of energy crop production. Much further work remains if researchers are to better understand the effectiveness and scalability of each. Thus, although energy crops could contribute significantly to future biomass supply, significant challenges will need to be overcome, and investments in addressing those challenges need to be made as soon as possible if biomass production is needed at a multi-gigaton scale within the next several decades. Recall that IPCC scenarios point to the need for up to 2,000 Gt CO_2 of cumulative sequestration to 2100. Even if only half of this need were supported by BECCS, it would require the mobilization of hundreds of millions of acres around the world to grow biomass.

TABLE 3: SUMMARY OF US AGRICULTURAL CLIMATE MITIGATION OPTIONS

	US potential (Gt CO_2/y, 2050)	Research needs	Policy needs (+ carbon payments)
Agroforestry and silvopasture	0.24–1.98[xviii]	Economic incentives and barriers to deployment Carbon accounting protocols	Increased funding for large-scale demonstration Precision agriculture technology deployment
Soils	0.17–0.27[xix]	Research to reduce uncertainty regarding permanence, scale, trade-offs with bioenergy Carbon accounting protocols	
Bioenergy	See BECCS estimate in Table 4	RD&D for rotational strategies with grazing and forestry and low-productivity farmland Assess potential to minimize nitrogen and water impacts of energy crops	

Technological and Engineered Options

In addition to ecosystem-based carbon storage, landscapes can contribute to engineered and technology-based opportunities. These include BECCS, deep-rooted commodity crops, algae farming, global shifts in dietary preferences, and biomass gasification paired with biochar.

Bioenergy Plus Carbon Capture and Storage (BECCS)

Converting carbon-beneficial sources of biomass to energy and then sequestering the net CO_2 emissions in geologic storage creates a negative emission source of renewable energy. However, as discussed above, it is critical to limit biomass to “carbon-beneficial forms,” that is, forms that meet emissions-reduction standards as measured and verified under rigorous emissions accounting frameworks. The elements required in these accounting frameworks, discussed already in using wood products to offset fossil fuels, include carbon fluxes from land management and land use changes, indirect land use changes and other market effects, wood product decay rates, and transparent assumptions on time and spatial scales over which carbon fluxes are assessed. Bioenergy policy will also need to protect high-carbon landscapes (such as forests or natural grasslands) from conversion to bioenergy crops, protect natural and high-value conservation lands, and minimize consequences for nutrient runoff and water use. The US Mid-Century Strategy estimates up to 1 billion dry tons of carbon-beneficial biomass can be produced while also deploying substantial forest expansion. This

[xviii] Low based on riparian buffer and alley crop (10 percent of cropland) estimates, high represents low plus 10 percent of all pasture land managed under silvopasture, all based on Udawatta and Jose, 2011.

[xix] Low represents Murray et al., \$15/ton CO_2 (2005), high based on maximum estimate in Chambers et al., 2016.

would support 600 million tons of CO_2 sequestration via BECCS by 2050, contributing more than 10 percent of total projected US primary energy use. Note that BECCS is not limited to the electricity sector—it can be utilized across the power, industry, building, and transportation sectors. Carbon capture and storage can be paired with any facilities that convert biomass into gas, liquid, or electricity.

The cost of BECCS, depending on the sector and conversion technology, can range from $50 to $150 per ton of CO_2 reduced, and potentially go even higher, considering the ongoing uncertainty over the costs of carbon capture and storage.[42] BECCS will be more expensive than fossil fuels with carbon capture and storage (CCS), so models predict BECCS will not be deployed until virtually all fossil fuels emissions are paired with CCS. The total capital costs of BECCS deployment would be sizable—reaching multiple Gt of global BECCS could require nearly $2 trillion by 2050.[43]

The above biomass supply estimates assume food crop yield will increase robustly such that humans will not need additional land for food production from today's row crop acreage. This also assumes it is possible to integrate biomass into rotational strategies for more efficiently utilizing agriculture land, especially managed pasture. None of these assumptions are guaranteed—they require smart policy, research investment, and incentives for farmers and ranchers to launch innovative strategies for integrating biomass into food-producing operations. As discussed in the context of forest management and agriculture, research and development support is critical for verifying these assumptions.

Biomass Gasification and Biochar

One bioenergy technology that is especially well suited to CCS, but can also be deployed without CCS, is gasification. Gasification is a thermochemical conversion process that heats biomass (or any solid fuel) to very high temperatures and creates clean gas streams of carbon monoxide, hydrogen, and carbon dioxide. The carbon monoxide and hydrogen (or syngas) can be combusted for energy use while the pure CO_2 stream can be captured and geologically stored through the conventional CCS process. Yet there is even more opportunity for carbon storage through another gasification byproduct, biochar. This is the blackened charcoal that remains after the biomass is processed, which makes the remaining carbon inert. When applied to soils as an amendment, it is capable of storing carbon for hundreds of years.

Fargione et al. indicate that by 2025, biochar has the potential to sequester 95 million tons of CO_2 annually in the United States at costs of up to $100 per ton of CO_2.[44] However, this estimate overlaps with the top-line mitigation estimates for BECCS, given that all biomass use depends on sustainable, carbon-beneficial biomass supply. As a biomass utilization option, biochar should be assessed using the same carbon accounting frameworks applied to bioenergy, BECCS, wood products, and other strategies.

There are even further agronomic and economic benefits to biochar soil application, including restoration of degraded soils. A number of studies have shown potential for biochar application to increase crop yields, while other studies have shown no or negative effects.[45] Further research into the co-benefits of biochar and demonstrations of integrated biomass gasification and biochar projects will be needed. Such co-benefits may be able to offset costs of carbon storage.

Deep-rooted Commodity Crops

The US Department of Energy (DOE) has initiated research on the potential to increase the root mass and depth of major commodity crops, thereby increasing carbon inputs to the soil. Deeper roots can also ensure that more carbon is stored permanently. Although this research is in its early stages, if successful it could represent a scalable opportunity for carbon sequestration and increasing resilience for 400 million acres of corn, wheat, and soy produced in the United States. DOE estimates such an approach could sequester up to 8 Gt CO_2 cumulatively by 2050 if implemented across all US cropland.[46]

Micro- and Macroalgae

Algae resources have a particularly high biomass yield per unit of area per unit of time, and algae can be grown in non-arable landscapes with non-potable water, making it a highly attractive and flexible resource. Current constraints are very high technology costs and limited scale of demonstration. The US DOE's "Billion-Ton Report" on US biomass supply dynamics posits that in the near term, algae facilities will need to be co-located with concentrated CO_2 sources such as coal, natural gas, and ethanol facilities. This creates a significant economic and logistical constraint in the deployment of algae. DOE projects 46 million tons of algae could be made available by 2040, although at costs significantly higher ($719 to $2,030/dry ton) than other biomass types (which are in the range of $100/dry ton or less). Additional research is ongoing to unlock algae supply.

Macroalgae, or seaweed, shows particular promise as a major source of biomass on a longer time horizon. Macroalgae has a high growth rate relative to other sources of biomass, does not face the same spatial competition and constraints as land-based biomass, has higher photosynthetic activity (6–8 percent) than terrestrial biomass (1.8–2.2 percent), is distributed around the world, and is a versatile product that can be used for food, food additives, animal feed, fertilizer, medicine, fiber, biofuels, and cosmetics. Key challenges to commercial scalability must be addressed: the biggest cost drivers include capital costs, labor, and energy consumption (harvesting, processing, and transportation), soft costs (regulations and permitting), and sustainable nutrient supply (whether through applying fertilizer, using nitrogen runoff from terrestrial farms, using fish effluent from aquaculture, or drawing nutrients from deep water). Additional tasks include breeding for improved yield, developing systems to manage macroalgae "fields" in the open ocean, and managing currents, temperatures, nutrient flows, and losses to deeper depths, and interactions with the broader marine ecosystem.

There are many opportunities to bring down the costs of macroalgae production and promote this growing industry, which has the potential to reach $23 billion by 2024. Ecosystem improvement co-benefits such as shoreline protection, denitrification, and water conservation could help finance these systems, especially if located in strategic sites such as the Gulf of Mexico's dead zone. Macroalgae has potential to support bioremediation of industrial, agricultural, and septage waste streams, as well as the cleaning of polluted natural waterways, through the removal of CO_2, nitrogen, phosphorus, and heavy metals.[47] Advances in automation, the use of marine renewable energy technologies, and co-location with infrastructure such as offshore wind and oil rigs can bring down labor and capital expenses. Advances in algal breeding can increase macroalgae yield, increase the concentration of high value extracts, decrease risk of disease, and improve structural integrity. Due to the significant advancements in research and demonstration that must be made to enable large-scale biomass production through macroalgae, it is not included in any estimates of future biomass supply or carbon storage potential. However, it does represent an interesting and potentially scalable future opportunity that should receive research support in the near term.

There have also been discussions about how to utilize marine algae to sequester carbon, though this topic is controversial. This approach would involve upwelling deep-water nutrients to fertilize surface waters (where sunlight allows for plant growth) and stimulate algae blooms, potentially using anthropogenic iron fertilization. However, there are concerns about how this approach could affect marine ecosystems and the time line and permanence of sequestration. As a result, this option has been largely sidelined in academic discussion.[48] However, many of these concerns are related to the behavior of microalgae. Macroalgae may provide valuable carbon sinks relative to microalgae thanks to its higher carbon-to-phosphorus ratios and larger carbon retention time (weeks compared with hours).[49] Because of its high productivity per unit area, marine algae offers potential for scalable carbon sequestration.[50] One organization, the Climate Foundation, has developed an integrated approach for mariculture and carbon fixation called marine permaculture. The Climate Foundation has been working over the past decade to validate and scale marine permaculture arrays that can achieve both objectives sustainably.

Dietary Changes

Pasture and rangeland for livestock grazing are the largest agricultural land uses in the world and the US, covering more than 500 million acres in the lower 48 states.[51] Pasture and rangeland are generally less productive than row cropland, though some areas are irrigated and fertilized to enhance productivity. Given the large area covered by pasture and rangeland, there is substantial interest in incorporating mitigation strategies, including agroforestry, biomass production, forest expansion, and other opportunities. However, the growing global meat demand may limit this potential, increasing grazing intensity and expanding grazing lands.

Technological advances in plant-based meat alternatives could disrupt these projections. RMI's *Positive Disruption* report indicates that the plant-based meat industry is projected to grow at 6.6 percent annually in the next decade. Veganism in the US has risen by 500 percent since 2014.[52] Should these trends continue, the world could see an unprecedented shift away from livestock production and associated land use, freeing up billions of acres of land for alternative uses. This would be a true game changer in creating additional potential for negative emissions solutions—if the global community were to phase out red meat or all meat consumption, 2.7 billion hectares of grazing lands would be freed to sequester an estimated 4.3–7.8 Gt CO_2 annually by 2050.[53] Furthermore, mitigation costs for stabilizing at 450 ppm atmospheric CO_2 levels would decrease by 70 percent from a business-as-usual scenario. Although these scenarios are extreme, they indicate the scale of impact of animal product consumption, and signal that the potential for harnessing even a fraction of this opportunity would be significant. The private sector has been leading the way in developing commercial alternatives to meat and animal products, and nongovernmental groups can continue to play an important role in advocacy and awareness of plant-based alternatives.

TABLE 4: SUMMARY OF NEGATIVE EMISSIONS ENGINEERED AND TECHNOLOGICAL CLIMATE MITIGATION OPTIONS

	US potential (Gt CO_2/y, 2050)	Research needs	Policy needs (+ carbon payments)
BECCS	0.1–0.6[xx]	• See Tables 1 and 2 for bioenergy research needs	• Funding to deploy a first-generation BECCS fleet
Biomass gasification/biochar	.01–0.1[xxi]	• Economic/agronomic co-benefits of biochar • Increasing efficiency and cost of gasification	• Funding for gasification + biochar demonstrations
Deep-rooted crops	.25–1.2[xxii]	• RD&D support for first-of-kind demonstration • Identify and quantify ecological, economic co-benefits	• Farmer outreach to socialize new seed varieties
Algae	Uncertain		• Legal, regulatory frameworks for marine algae facilities • Risk-sharing, legal frameworks for algal CO_2 utilization
Dietary changes	0.26–0.48[xxiii]	• Improved, low-cost plant-based alternatives	• Social awareness of plant-based alternatives to animal products

Synthesis

The negative emissions climate solutions discussed above have the potential to contribute multiple Gt of carbon sequestration in the coming decades. The numbers laid out in Tables 1 through 4 range from 2.6 to 7.6 Gt CO_2/year in total technical potential in the US alone. Some of this potential could be overlapping, for example, between dietary change (Table 4) and agroforestry (Table 3) or deep-rooted crops (Table 4) and agricultural soils (Table 3). Much of this potential would require breakthroughs in soil carbon potential, crop varieties, and dietary shifts. However, more mature technologies (forest expansion, enhanced forest management, avoided

[xx] Range based on Limited Sink (low) and Benchmark (high) scenarios in US Mid-Century Strategy for Deep Decarbonization (White House, 2016).

[xxi] Range based on Fargione et al. (in prep), with low based on $50/ton carbon price and high based on $100/ton carbon price. Assumes only crop residues are used for biochar production.

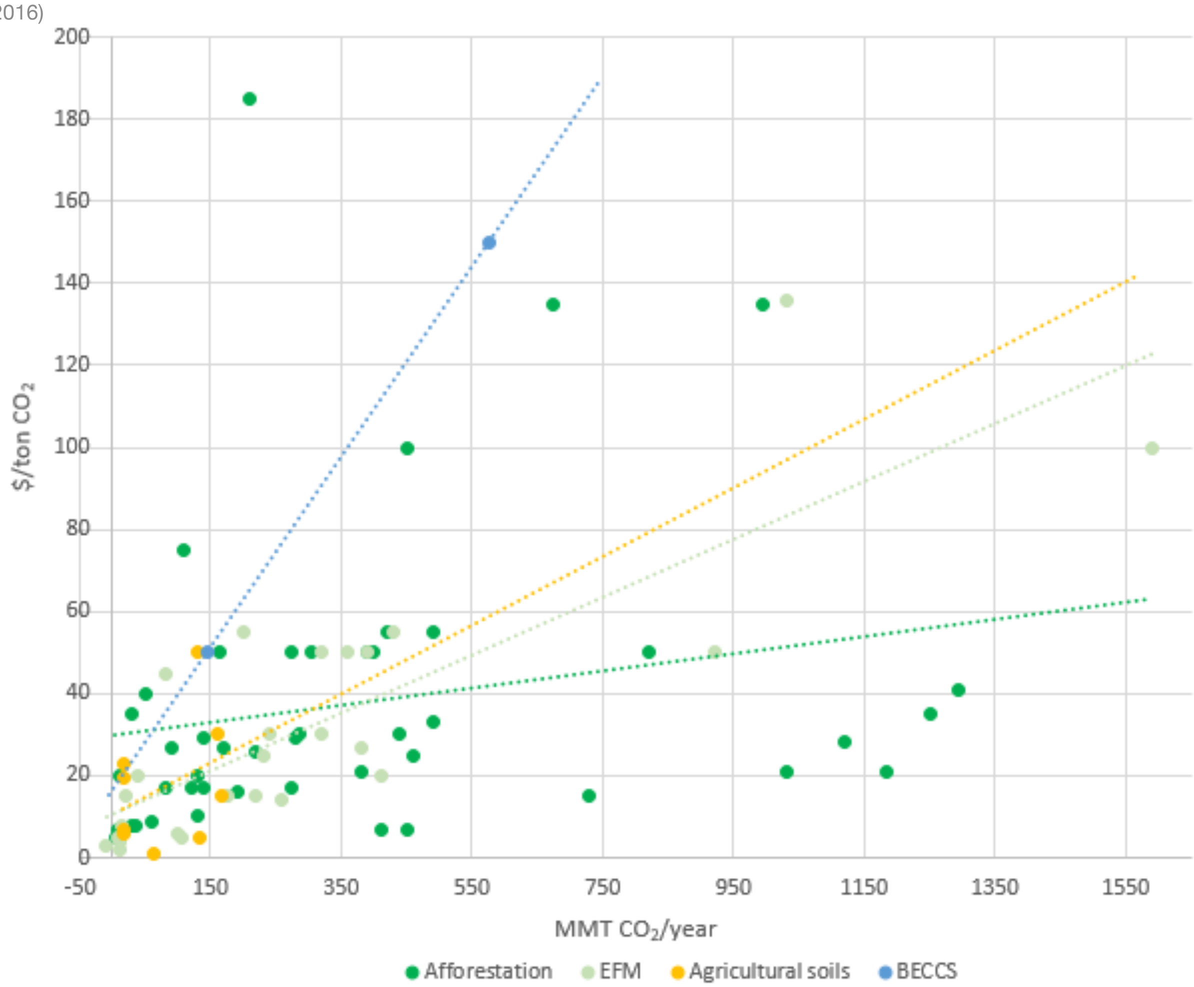
[xxii] Range based on US Mid-Century Strategy for Deep Decarbonization (White House, 2016), p. 78.

[xxiii] Range based on Stehfest et al., 2009, assuming US can account for 6 percent (202 million hectares of 3.3 billion hectares global grazing lands, FAO, 2017) of global mitigation from phasing out global red meat consumption (low) to all meat consumption (high).

conversion, agricultural soils, and agroforestry) could still contribute more than 2 Gt annually of negative emissions by 2050 on the lower end of each estimated potential.

Figure 2 synthesizes mitigation and carbon costs across forestry, agriculture, and BECCS opportunities, which have the most quantitative cost and mitigation data available. This provides an indication of the important role carbon pricing plays in driving higher levels of mitigation and the range of mitigation estimates across studies. The linear fits across mitigation options show how quickly costs increase with scale, indicating that forestry options will likely deliver the largest mitigation outcomes at lowest cost, though all can contribute meaningfully.

FIGURE 2: ESTIMATES OF US ANNUAL CO_2 MILLION METRIC TONS (MMT) SEQUESTRATION THROUGH AFFORESTATION, ENHANCED FOREST MANAGEMENT (EFM), IMPROVED AGRICULTURAL SOIL MANAGEMENT, AND BIOENERGY PLUS CARBON CAPTURE AND STORAGE (BECCS). BASED ON 13 STUDIES (SYNTHESIZED IN VAN WINKLE ET AL., 2017; MURRAY ET AL., 2005; CHAMBERS ET AL., 2016)



3. POLICY CONSIDERATIONS FOR DEPLOYING NATURAL CARBON SEQUESTRATION

Negative emissions opportunities are not a free lunch—policymakers and society at large cannot expect to depend entirely on negative emissions and land carbon sequestration to resolve climate change.[54] These mitigation tools must be used responsibly and in a way that is consistent with long-term climate goals. Furthermore, responsibly increasing land carbon sequestration requires balancing competing land uses and optimizing limited land resources across many societal goods and services. This section tackles these trade-offs and ways to optimize land use across food, feed, fiber, recreation, housing, and commercial development, as well as climate change.

Prioritizing Basic Societal Needs and Economic Justice

Creating demand for biomass and carbon storage on landscapes can drive up prices of other land-based goods by increasing prices of land; increasing prices of inputs such as nutrients, water, labor, and logistics; and, in more extreme scenarios, limiting the amount of production of other land-based goods and making them scarcer. Successful climate policy will avoid increasing pressures on food insecurity, housing insecurity, and other challenges, especially for those already at risk in these areas.

Minimizing Social Impacts

Global food demand could double by 2050, yet improving crop yields in line with historical growth rates would deliver only a 38–67 percent increase in crop production.[55] To double food output by 2050 without any additional land conversion to agriculture, global annual yield growth rates need to reach 2.4 percent, significantly higher than the 1.6 (corn), 1.0 (rice), 0.9 (wheat), and 1.3 (soy) historical average rates (1961–2008). Assuming the US contribution of these four major crops (which provide nearly two-thirds of global calories) stays proportional to global production, and US yield growth stays constant in accordance with historical rates calculated in Ray et al., US cropland area could increase by 52 million acres.[56] Note that more recent studies question the need for "doubling" future food supply, indicating that more recent yield improvements show that an increase of 25–70 percent in food production by 2050 from current levels may be more accurate.[57]

Furthermore, land will be needed to support housing, transportation, commercial, and recreational needs for a growing US population. The US Census projects a US population of 398 million in 2050, growth of 23 percent from today's levels. Depending on how much urban density can be increased, such growth could require between 15 million and 45 million acres of urban settlement growth; the lower range is achievable if urban density increases consistently with trends from 2000 to 2010, and the higher range if current urban density holds into the future. This does not account for non-urban development that would also likely occur, for transportation, industrial, and commercial expansion. It is possible to achieve denser urban development, but it could come at the cost of increasing real estate prices, especially in areas closest to commercial centers and jobs. Ensuring equal access to cities of the future through affordable housing development and mixed-use neighborhoods will be critical in any case, but will be especially useful for reducing competitive effects of climate mitigation strategies on lower-income individuals.

Addressing these aspects of land use policy will require action outside climate policy alone. Policies and programs that can help optimize land use include:

- Research supporting increasing crop yields and innovative rotational strategies
- Policies that promote affordable housing and livable neighborhoods with access to food, commercial needs, and transportation
- Policies that promote wise urban planning and revitalization versus expansion

- Conservation easements for farmland and forests at the margins of urban areas, which can help reduce urban sprawl and preserve natural and open lands for the future

Land use considerations also need to be integrated into climate policy, such as:

- Including potential impacts to food production and land use change in carbon accounting protocols.
- Undertaking national and international tracking to understand impacts of climate policies on land use over time, and modifying policies if negative consequences occur, such as large-scale land conversions away from food production. Setting boundaries on what is “acceptable” in this arena is a critical issue for policy discussion. Such policy modification should be programmatically simple, such as reducing funding for future negative emissions and land carbon activities.

Life-cycle Accounting Issues

The need for robust carbon accounting has been raised often in this report, to ensure climate policy is driving incentives toward the “biggest bang for the buck” mitigation options. It also allows us to incorporate potential direct and indirect impacts that can affect net carbon emissions over time and over geographic areas.

Critical components of any greenhouse gas emissions (GHG) accounting protocol for land carbon activities:

- **Permanence**—To provide effective climate mitigation, any carbon incentives for negative emissions need to demonstrate that carbon will be sequestered “permanently.” This word can take on different meanings depending on policy or program design. For example, the land use, land use change, and forestry (LULUCF) sequestration recorded in the annual US GHG Inventory is not assumed to be permanent, which is justified because net emissions from LULUCF are also accounted for on an annual basis. Thus total annual fluxes are consistently reflected in total US emissions. For an individual carbon-sequestering project that receives incentive funding, there would need to be higher bars for proof of permanence, especially if the emissions reduction is meant to offset a unit of fossil fuels, which are permanently emitted into the atmosphere. Thus the degree of “permanence” required should be assessed on an individual policy basis.
- **Additionality**—If payments are being made for carbon sequestering activity, it should be limited to activities that would not have happened otherwise. Verifying “additionality” often takes the form of market analysis designed to understand the feasibility of undertaking a certain action in the absence of any carbon incentive funding.
- **Double counting**—Similar to additionality, climate policies should avoid double counting for potential emissions reductions vis-à-vis land carbon programs. For example, a wood products incentive program might not receive credit for carbon avoided from fossil fuel–based products if those same products are already facing their own carbon price.
- **Indirect market effects and leakage**—As noted above, land-based commodities are highly prone to “leakage” effects due to interconnected regional and global agricultural and forestry markets. Market effects can have both positive and negative impacts on net carbon emissions—for example, expanding US forest area could drive up the price of pasture land and therefore the global price of beef, causing greater deforestation in other regions to provide more pasture land. Conversely, putting in place carbon incentives for forests can result in more competition with timber and pulpwood, potentially driving additional expansion of forest area to support more competitive markets. Tracking the econometric effects of climate policies over time can help decision makers better tailor carbon accounting protocol calculations of indirect market effects.

Relevant Policy Structures

In the United States, there already exist a variety of incentives that play some role (almost always an indirect one) in promoting carbon sequestration. These include conservation easements, sustainable practice incentives (such as the federal Environmental Quality Incentives Program), and tax incentives for forest owners.

Going forward, policymakers should make negative emissions strategies a key pillar of national climate policy. Two of the main policy structures that can be used to achieve this are offsets and direct payments.

Offsets

Land carbon offsets are used already in a number of climate policies, including the California cap and trade program, RGGI, as part of the proposed International Civil Aviation Organization's (ICAO's) emissions trading program, market-based mechanisms under the Paris Agreement, EU emissions trading program, and the Kyoto Protocol Clean Development Mechanism. To qualify as an offset, a unit of emissions reduction from land carbon activities must meet a high bar of demonstrating permanence and additionality, because it must act as a near perfect countermeasure to a unit of fossil fuels that is emitted under a carbon cap. Offsets are an effective mechanism for encouraging land carbon mitigation and have been successful in scaling up these activities. For example, the California offset program has registered 173 forestry projects and awarded more than 60 million tons of CO_2 reductions, and the Australian Carbon Farming Initiative (now the Emissions Reduction Fund) has registered 500 projects with nearly 40 million tons of CO_2 credits issued.[58] However, the technical complexity of meeting rigorous offset standards, paired with low carbon prices in many programs, has limited broader deployment. Stakeholders have further raised concerns that land carbon is inherently not well matched to counteracting fossil fuel emissions because permanence cannot be guaranteed and fossil fuels should not be given undue flexibility.

Direct Payments

Another option is to use revenues raised by carbon tax or carbon credit auctions to issue carbon incentives for negative emissions activities. Such a program can utilize many of the aspects of an offset program, including accounting measures and certain standards for permanence and additionality, and the use of competitive auctions or markets to ensure incentives are competitively determined. However, because these units of mitigation are no longer assumed to be offsetting fossil fuels, standards for accounting, permanence, and additionality might be less stringent. The objective would be to enhance economy-wide emissions that are otherwise falling under a carbon tax or cap and trade system with negative emissions activities that can help lower overall costs of meeting economy-wide climate targets.

Policy Needs Summary

A common theme across these policy options is that, at least in the near term, revenues for negative emissions incentives need to be integrated into climate policy frameworks if this approach is envisioned as a substantial component of US climate mitigation. Note the distinction for the energy, building, transport, and industrial sectors, where carbon emissions will be priced, but revenue outflows will not be required (other than for research and development support and early market incentive programs before carbon pricing has matured).

Note in particular that land-based mitigation options offer less opportunity for technology advancement and learning-by-doing to bring down the cost of mitigation, compared with the experience with renewable energy technologies and electric cars. RMI's *Positive Disruption* report highlights the immense potential for driving down clean technology costs through innovation and existing market forces. However, the majority of land carbon opportunities are based on mature agriculture and forestry practices where costs are generally well known and opportunities for innovation are real but constrained by many decades of productivity improvements. To be sure, increases in efficiency and innovation along the lines discussed for each of the mitigation categories above will be critical for meeting a meaningful scale of mitigation. However, whether those innovations can bring costs down by, for example, 400 percent, as was the experience with solar panels over the last 10 years, seems unlikely. The innovations described above are more likely to allow land carbon practices to scale readily than to bring costs down substantially per unit of mitigation. For those opportunities that require technology advancement, such as BECCS, algae, and deep-rooted crop varieties, further research and demonstration could have tremendous impacts on mitigation potential. However, great uncertainty remains as to whether these technologies will ultimately be feasible.

In summary, if negative emissions are to constitute a meaningful contribution to US climate mitigation, incentive programs and robust policy, in addition to robust research and innovation, will be critical.

4. ENDNOTES

[1] Marshall Abramczyk, Martha Campbell, Aman Chitkara, Mia Diawara, Aileen Lerch, and James Newcomb, *Positive Disruption: Limiting Global Temperature Rise to Well Below 2 Cº* (Basalt, CO: Rocky Mountain Institute, 2017). http://www.rmi.org/insights/reports/positive_disruption_limiting_global_temperature_rise

[2] P. Smith, M. Bustamante, H. Ahammad, H. Clark, H. Dong, et al., "Agriculture, Forestry and Other Land Use (AFOLU)," in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (O. Edenhofer et al., eds.) (Cambridge, United Kingdom, and New York: Cambridge University Press, 2014); P. Smith, S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, et al., "Biophysical and Economic Limits to Negative CO2 Emissions," Nature Climate Change, 6 (2015): 42-50; Keith Paustian, Johannes Lehmann, Stephen Ogle, David Reay, G. Philip Robertson, and Pete Smith, "Climate Smart Soils," Nature 532 (2017): 49-57, doi:10.1038/nature17174.

[3] White House. United States Mid-Century Strategy for Deep Decarbonization (2016). http://unfccc.int/files/focus/longterm_strategies/application/pdf/mid_century_strategy_report-final_red.pdf

[4] United Nations Framework Convention on Climate Change, Adoption of the Paris Agreement (2015). 21st Conference of the Parties, Paris: United Nations.

[5] Marshall Abramczyk et al., *Positive Disruption*, 2017.

[6] G. Peters and O. Geden, "Catalysing a Political Shift from Low to Negative Carbon," Nature Climate Change 7 (2017): 619–621.

[7] Smith et al., 2014.

[8] Smith et al., 2015.

[9] White House, 2016.

[10] Bronson W. Griscom, Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, David Shoch, Juha V. Siikamäki, Pete Smith, Peter Woodbury, Chris Zganjar, Allen Blackman, João Campari, Richard T. Conant, Christopher Delgado, Patricia Elias, Trisha Gopalakrishna, Marisa R. Hamsik, Mario Herrero, Joseph Kiesecker, Emily Landis, Lars Laestadius, Sara M. Leavitt, Susan Minnemeyer, Stephen Polasky, Peter Potapov, Francis E. Putz, Jonathan Sanderman, Marcel Silvius, Eva Wollenberg, and Joseph Fargione, "Natural Climate Solutions," *PNAS*, 114 (44) 11645-11650 (October 16, 2017); doi:10.1073/pnas.1710465114.

[11] Smith et al., 2014.

[12] B. C. Murray, B. L. Sohngen, A. J. Sommer, B. M. Depro, K. M. Jones, B.A. McCarl, et al., *Greenhouse Gas Mitigation Potential in US Forestry and Agriculture* (Washington, D.C.: US Environmental Protection Agency, 2005).

[13] Climate Leadership Council, 2017. A Winning Trade: https://www.clcouncil.org/wp-content/uploads/2017/02/A_Winning_Trade.pdf

[14] "US EPA's Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2015," https://www3.epa.gov/climatechange/ghgemissions/inventoryexplorer/ - iallsectors/allgas/inventsect/all

[15] Murray et al., 2005; A. Eagle, L. Olander, H. Henry, K. Haugen-Kozyra, N. Miller, and G. P. Robertson. *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*. Technical Working Group on Agricultural Greenhouse Gases Report (2012); A. Chambers, R. Lal, and K. Paustian, “Soil Carbon Sequestration Potential of US Croplands and Grasslands: Implementing the 4 per Thousand Initiative,” *Journal of Soil and Water Conservation*, 71(3) (2016): 68A-74A; J. W. Coulston, D. N. Wear, and J. M. Vose, *Complex Forest Dynamics Indicate Potential for Slowing Carbon Accumulation in the Southeastern United States*, Scientific Reports 5, Article no. 8002 (2015): doi:10.1038/srep08002. Retrieved from http://www.nature.com/articles/srep08002; C. Van Winkle, J. S. Baker, D. Lapidus, S. Ohrel, J. Steller, G. Latta, and D. Birur, *US Forest Sector Greenhouse Gas Mitigation Potential and Implications for Intended Nationally Determined Contributions* (2017).

[16] US EPA, 2017.

[17] G. Nabuurs, M. Lindner, P. J. Verkerk, K. Gunia, P. Deda, R. Michalak, and G. Grassi, National Interagency Fire Center, *Statistics, National Fire News Year-to-date Fires and Acres* (2013/2016): https://www.nifc.gov/fireInfo/nfn.htm; R. Valentini, G. Matteucci, A. J. Dolman, E. D. Schulze, C. Rebmann, E. J. Moors, A. Granier, et al., “Respiration as the Main Determinant of Carbon Balance in European Forests,” *Nature* 404 (2000): 861–865; J. G. Canadell, D. E. Pataki, R. Gifford, R. A. Houghton, Y. Luo, M. R. Raupach, et al., “Chapter 6: Saturation of the Terrestrial Carbon Sink,” in J. G. Canadell, D. E. Pataki, and L. Pitelka (eds), *Terrestrial Ecosystems in a Changing World*. The IGBP Series (Berlin Heidelberg: Springer-Verlag, 2007). http://www.globalcarbonproject.org/global/pdf/Canadell.2007.SinkSaturation.Springer.pdf

[18] White House, 2016.

[19] Sonja N. Oswalt, W. Brad Smith, Patrick D. Miles, and Scott A. Pugh, *Forest Resources of the United States, 2012: A Technical Document Supporting the Forest Service 2015 Update of the RPA Assessment*, Gen. Tech. Rep. WO-91. Washington, DC: US Department of Agriculture, Forest Service, Washington Office (2014).

[20] B. C. Murray, B. A. McCarl, and H. C. Lee. “Estimating Leakage from Forest Carbon Sequestration Programs,” *Land Economics*, 80(1) (2004): 109-124.

[21] Coulston et al., 2015.

[22] X. Tian, B. Sohngen, J. Baker, S. Ohrel, and A. Fawcett, “Will US Forests Continue to Be a Carbon Sink?” Working Paper (2016); J. S. Baker, B. L. Sohngen, S. Ohrel, and A. Fawcett, “Economic Analysis of Greenhouse Gas Mitigation Potential in the US Forest Sector,” RTI Press Policy Brief (2017). https://www.rti.org/sites/default/files/resources/18132216_Greenhouse_Gas_Mitigation_Potential.pdf

[23] Nabuurs et al., 2016.

[24] Oswalt et al., 2014.

[25] US EPA, 2017

[26] S. L. Stephens, R. E. Boerner, J. J. Moghaddas, E. E. Moghaddas, B. M. Collins, and C. B. Dow, “Fuel Treatment Impacts on Estimated Wildfire Carbon Loss from Forests in Montana, Oregon, California, and Arizona,” *Ecosphere*, 3(5) (2012): 38; E. L. Loudermilk, R. M. Scheller, P. J. Weisberg, J. Yang, T. E. Dilts, S. L. Karam, and C. Skinner, “Carbon Dynamics in the Future Forest: The Importance of Long-Term Successional Legacy and Climate-Fire Interactions,” *Global Change Biology*, 19(11) (2013): 3502-3515; M. D. Hurteau, S. Liang, K. Martin, M. P. North, G. W. Koch, and B. A. Hungate, “Restoring Forest Structure and Process Stabilizes Forest Carbon in Wildfire-Prone Southwestern Ponderosa Pine Forests,” *Ecological Applications*, 26(2) (2016): 382-391; B. E. Law, T. Hudiburg, and S. Luyssaert, “Thinning Effects on Forest Productivity: Consequences of Preserving Old Forests and Mitigating Impacts of Fire and Drought,” *Plant Ecology and Diversity*, 6 (2013): 73-85; S. Mitchell, “Carbon Dynamics of Mixed- and High-Severity Wildfires: Pyrogenic CO_2 Emissions, Postfire Carbon Balance, and Succession,” in D. A. DellaSala and C. T. Hanson (eds.), *Nature’s Phoenix: The Ecological Importance of Mixed-Severity Fires* (Amsterdam, Netherlands: Elsevier, 2015): pp. 290-309.

[27] R. N. Lubowski, A. J. Plantinga, and R. N. Stavins, “Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function,” *Journal of Environmental Economics and Management*, 51(2) (2006): 135-152.

[28] R. Sathre and J. O’Connor, *A synthesis of research on wood products and greenhouse gas impacts* (Vancouver, B.C.: FPInnovations, 2010).

[29] D. C. McKinley, M. G. Ryan, R. A. Birdsey, C. P. Giardina, M. E. Harmon, L. S. Heath, R. A. Houghton, R. B. Jackson, J. F. Morrison, B. C. Murray, D. E. Pataki, and K. E. Skog, “A synthesis of current knowledge on forests and carbon storage in the United States,” *Ecological Applications*, 21(6) (2011): 1902-1924.

[30] R. H. Beach, S. K. Pattanayak, J. Yang, B. C. Murray, and R. C. Abt, *Empirical studies of non-industrial private forest management: A review and synthesis* (Research Triangle Institute International, 2002); R. J. Alig, G. Latta, D. Adams, and B. McCarl, “Mitigation greenhouse gases: The importance of land based interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices,” *Forest Policy and Economics*, 12 (2010): 67-75; R. A. Miner, R. C. Abt, J. L. Bowyer, M. A. Buford, R. W. Malmsheimer, J. O’Laughlin, J., E. E. Oneil, R. A. Sedjo, and K. E. Skog, “Forest carbon accounting considerations in US bioenergy policy,” *Journal of Forestry*, 112(6) (2014): 591-606; K. L. Abt, R. C. Abt, C. S. Galik, and K. E. Skog, *Effect of policies on pellet production and forests in the US South: A technical document supporting the Forest Service update of the 2010 RPA Assessment* (Asheville, N.C.: US Department of Agriculture Forest Service, Southern Research Station, 2014).

[31] US EPA, 2017.

[32] R. P. Udawatta and S. Jose, “Carbon sequestration potential of agroforestry practices in temperate North America,” in B. M. Kumar and P. K. Nair (eds.), *Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges* (Dordrecht, Netherlands: Springer, 2011).

[33] Eagle et al., 2012.

[34] D. S. Powlson, C. M. Stirling, and M. L. Jat, “Limited potential of no-till agriculture for climate change mitigation,” *Nat. Clim. Chang.* 4 (2014): 678–683; J. M. Baker, T. E. Ochsner, R. T. Venterea, and T. J. Griffis, “Tillage and soil carbon sequestration—What do we really know?” *Agric. Ecosyst. Environ.* 118 (2007): 1–5.

[35] Chambers et al., 2016, Murray et al., 2005.

[36] V. L. Jin, J. M. Baker, J. M. Johnson, D. L. Karlen, R. M. Lehman, S. L. Osborne, T. J. Sauer, D. E. Stott, G .E. Varvel, R. T. Venterea, M. R. Schmer, and B. J. Wienhold, “Soil greenhouse gas emissions in response to corn stover removal and tillage management across the US corn belt,” *BioEnergy Research*. 7(2) (2014): 517-527. DOI: 10.1007/S12155-014-9421-0; J. M. Johnson, J. S. Strock, J. E. Tallaksen, and M. Reese, “Soil responses to stover management in the Northern Corn Belt [abstract],” *ASA-CSSA-SSSA Annual Meeting Abstracts*. ASA-CSSA-SSSA Annual Meeting. Nov. 2–5, 2014, Long Beach, CA; Adam Liska, Haishun Yang, Maribeth Milner, Steve Goddard, Humberto Blanco-Canqui, Matthew Pelton, Xiao Fang, Haitao Zhu, and Andrew Suyker, “Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions,” *Nature Climate Change* 4 (2014): 398-401, doi:10.1038/nclimate2187.

[37] Samuel McLaughlin and Lynn Adams Kszos, “Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States,” *Biomass & Bioenergy* 28(6) (2005): 515-535; Kristina Anderson-Teixeira, Sarah Davis, Michael Masters, and Evan Delucia, “Changes in soil organic carbon under biofuel crops,” *Global Change Biology: Bioenergy*, 1(1) (2009): 75-96, doi:10.1111/j.1757-1707.2008.01001.x; L. Lai, S. Kumar, S. M. Folle, and V. N. Owens, “Predicting soils and environmental impacts associated with switchgrass for bioenergy production: a DAYCENT modeling approach,” *GCB Bioenergy* (2017). doi:10.1111/gcbb.12490; Eagle et al., 2012.

[38] White House, 2016.

[39] J. M. Johnson and N.W. Barbour, “Impacts of managing perennial grasses in the northern Midwest United States for bioenergy on soil organic C and nitrous oxide emission” [abstract]. *Proceedings of the 6th International Symposium on Soil Organic Matter* (2017): 436.

[40] White House, 2016.

[41] E. Brandes, G. McNunn, L. A. Schulte, I. J. Bonner, D. J. Muth, B. A. Babcock, and E. A. Heaton, "Subfield profitability analysis reveals an economic case for cropland diversification," *Environmental Research Letters*, 11(1) (2016).

[42] Smith et al., 2015; White House, 2016.

[43] D. L. Sanchez, D. M. Kammen, "A commercialization strategy for carbon-negative energy," *Nature Energy*, 1 (2016). doi: 10.1038/ nenergy.2015.2.

[44] Fargione JE, Bassett S, Boucher T, Bridgham S, Conant RT, Cook-Patton S, Ellis PW, Falcucci A, Forqurean J, Gopalakrishna T, Gu H, Henderson B, Hurteau MD, Kroeger KD, Kroeger T, Lark TJ, Leavitt SM, Lomax G, McDonald R, Megonigal JP, Miteva DA, Richardson C, Sanderman S, Shoch D, Spawn SA, Veldman JW, Williams CA, Woodbury P, Zganjar C, Baranski M, Elias P, Houghton RA, Landis E, Mcglynn E, Ohler S, Schlesinger WH, Siikamaki JV, Sutton-Grier AE, Griscom BW. *Natural Climate Solutions for the United States*, in press.

[45] K. A. Spokas, K. B. Cantrell, J. M. Novak, D. W. Archer, J. A. Ippolito, H. P. Collins, A. A. Boateng, I. M. Lima, M. C. Lamb, A. J. McAloon, R. D. Lentz, and K. A. Nichols, "Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration," *Journal of Environmental Quality*, 41 (2012). Doi:10.2134/jeq2011.0069

[46] White House, 2016.

[47] Y. S. Al-Hafedh, A. Alam, and A. H. Buschmann, *Bioremediation potential, growth and biomass yield of the green seaweed, Ulva lactuca in an integrated marine aquaculture system at the Red Sea coast of Saudi Arabia at different stocking densities and effluent flow rates* (2015); S. Sode, A. Bruhn, T. J. S. Balsby, M. M. Larsen, A. Gotfredsen, and M. B. Rasmussen, "Bioremediation of reject water from anaerobically digested waste water sludge with macroalgae (ulva lactuca, chlorophyta)," *Bioresource Technology*, 146 (2013): 426-435; J. T. Kidgell, R. de Nys, Y. Hu, N. A. Paul, and D. A. Roberts, "Bioremediation of a complex industrial effluent by biosorbents derived from freshwater macroalgae" (2014); A. J. Cole, L. Mata, N. A. Paul, and R. Nys, "Using CO2 to enhance carbon capture and biomass applications of freshwater macroalgae," *GCB Bioenergy*, 6(6) (2014): 637-645.

[48] Mike Packer, "Algal capture of carbon dioxide; biomass generation as a tool for greenhouse gas mitigation with reference to New Zealand energy strategy and policy," *Energy Policy* 37(9) (2009): 3428-3437.

[49] A. C. Redfield, B. H. Ketchum, and F. A. Richards, "The influence of organisms on the composition of seawater," in M. N. Hill, ed., *The Sea*. Interscience. (1963): 26–77; K. C. Rao and V. K Indusekhar, "Carbon, Nitrogen & Phosphorus Ratios in Seawater & Seaweeds of Saurashtra, North West Coast of India," *Indian Journal of Marine Science*s, 16 (1987): 117–121; M. Atkinson and S. Smith, "C: N: P ratios of benthic marine plants," *Limnology and Oceanography* (1983): 568–574; D. Krause-Jensen and C. M. Duarte, "Substantial role of macroalgae in marine carbon sequestration," *Nature Geoscience*, 9(10) (2016): 737-742.

[50] F. Arenas and F. Vaz-Pinto, "Marine Algae as Carbon Sinks and Allies to Combat Global Warming," in L. Pereira and J. M. Neto (eds.), *Marine Algae: Biodiversity, Taxonomy, Environmental Assessment, and Biotechnology* (2014): 398.

[51] US Natural Resources Conservation Service, 2017.
https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/landuse/rangepasture/

[52] Top Trends, June 2017. https://www.reportbuyer.com/product/4959853/top-trends-in-prepared-foods-2017-exploring-trends-in-meat-fish-and-seafood-pasta-noodles-and-rice-prepared-meals-savory-deli-food-soup-and-meat-substitutes.html

[53] Elke Stehfest, Lex Bouwman, Detlef van Vuuren, Michel den Elzen, Bas Eickhout, and Pavel Kabat, "Climate benefits of changing diet," *Climatic Change* 95(1-2) (2009): 83-102. https://doi.org/10.1007/s10584-008-9534-6

[54] L. R. Boysen, W. Lucht, D. Gerten, V. Heck, T. M. Lenton, H. J. Schellnhuber, “The limits to global-warming mitigation by terrestrial carbon removal,” *Earth’s Future*, 5 (2017): 463-474.

[55] David Tilman, Christian Balzer, Jason Hill, and Belinda Belfort, “Global food demand and the sustainable intensification of agriculture,” *PNAS* 108 (50) (2011): 20260-20264. Doi:10.1073/pnas.1116437108; Deepak Ray, Nathaniel Mueller, Paul West, and Jonathan Foley, “Yield Trends Are Insufficient to Double Global Crop Production by 2050,” PLOS, (2013). https://doi.org/10.1371/journal.pone.0066428

[56] Ray et al., 2013.

[57] M. C. Hunter, R. G. Smith, M. E. Schipanski, L. W. Atwood, and D. A. Mortensen, “Agriculture in 2050: Recalibrating Targets for Sustainable Intensification,” BioScience, 67(4) (2017): 386-391.

[58] California Air Resources Board (2017). Compliance Offset Program. https://www.arb.ca.gov/cc/capandtrade/offsets/offsets.htm; Clean Energy Regulator (Australia) (2017). ACCUs issued in financial year 2016–17. http://www.cleanenergyregulator.gov.au/ERF/Pages/Emissions Reduction Fund project and contract registers/Project register/Historical ACCU data/ACCUs-issued-in-financial-year-2016-17.aspx

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