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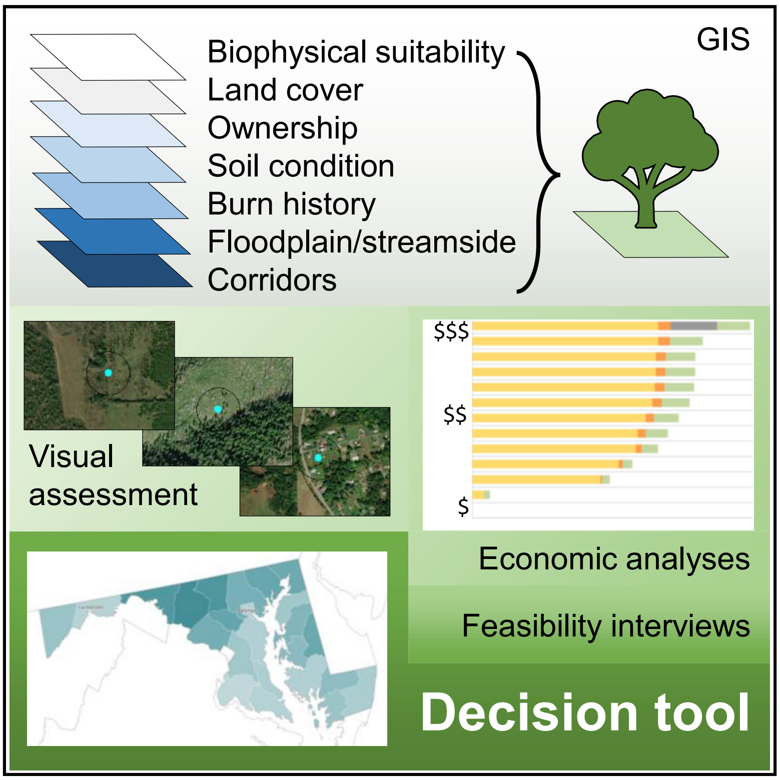
Lower cost and more feasible options to restore forest cover in the contiguous United States for climate mitigation

Graphical Abstract



Highlights

- Restoring forest cover in the US can be a cost-effective climate solution
- New forest across 51.6 Mha could capture 314 $MtCO_2$ $year^{-1}$
- We provide critical information to guide decisions about where to restore forests

Authors

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In Brief

To inform decisions about where to deploy restoration of forest cover as a climate solution, we produced maps of opportunities across the contiguous United States. We found up to 51.6 Mha of opportunity for new forest, which we divided into 10 different classes to compare their carbon capture, costs, co-benefits, and feasibility. We found that the opportunity class with the strongest potential differed by state but that many opportunities fall in lower-cost and more feasible locations.

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Lower cost and more feasible options to restore forest cover in the contiguous United States for climate mitigation

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SCIENCE FOR SOCIETY Restoring forest cover can help tackle climate change, so we created maps of opportunities to deploy this natural climate solution. We found up to 51.6 Mha of area in the US to restore forest cover, which is about double the size of Oregon. These new forests could capture 314 $MtCO_2$ $year^{-1}$, equivalent to the annual emissions from 67 million cars, but not all areas are equally suitable for new forest. We divided overall area of opportunity into 10 classes to compare their carbon capture potential, cost, co-benefits, and feasibility. Pastures hold the most carbon capture potential at lowest cost, which could be realized via increased efficiencies in livestock production, reductions in meat consumption, or incorporation of trees among grasses. Non-stocked forest patches and federal lands also hold substantial low-cost opportunity, whereas watersheds and urban areas hold high potential to capture carbon, and provide water and human health benefits, but are more costly.

SUMMARY

Restoring forest cover is a prominent option for climate mitigation. Effective deployment requires knowing where opportunities are and how they vary in carbon capture, costs, co-benefits, and feasibility. Here, we combined spatial, economic, and feasibility analyses to examine 10 different opportunity classes for restoration of forest cover across the contiguous United States. These include non-stocked forests, shrublands, protected areas, post-burn landscapes, pasture lands, croplands with challenging soils, urban areas, floodplains, streamsides, and biodiversity corridors. We found 51.6 Mha of total opportunity, which could capture 314.2 million tons of carbon dioxide each year, equivalent to 15% of the United States' 2016 commitment to the Paris Agreement. Half of this mitigation is possible at \$20 tCO_2^{-1}. However, the highest-ranked opportunity class with respect to carbon capture, costs, co-benefits, and feasibility changed depending on location. Our maps are publicly available to guide policy and implementation efforts at local, state, and national levels.

INTRODUCTION

Reductions in fossil fuel emissions are necessary but insufficient to constrain global warming—we must also remove carbon dioxide from the atmosphere.[1] Restoration of forest cover, defined here as planting or using natural regeneration to transition tree cover on historically forested lands from less than 25% to more than 25%,[2] is prioritized in many national and global initiatives,[3,4] and is a promising option for capturing additional carbon from the atmosphere.[2] For example, a recent study estimated that restoring forest cover across 63 Mha in the contiguous United States (US) would capture 307 million metric tons of carbon dioxide per year ($MtCO_2$ $year^{-1}$), equal to 15% of the 2016 US nationally determined contribution to the Paris Agreement.[5] Restoration of forest cover is also low-tech, scalable, enhances ecosystem services, and can create habitat for biodiversity.[6]

However, the overall climate mitigation potential from restoration of forest cover depends heavily on the extent and location of new forest (“area of opportunity”). Many previous studies have focused on documenting areas that are biophysically suitable for restoration of forest cover (see, e.g., Griscom et al.[2] and Fargione et al.[5]), but there are multiple factors beyond biophysical suitability that influence whether restoration of forest cover is practical and/or socially desirable in a given area.[7] Places that are more likely candidates for restoration of forest cover may include areas that are already allocated to a natural land use, have limited value as a non-forest land use, or provide additional co-benefits beyond carbon capture that further incentivize investments in restoration of forest cover. However, in the US, there is no national map of opportunities to restore forest cover that accounts for these factors that influence feasibility.

Areas allocated to a natural land use include areas with a forest land use, but no forest cover. While the US currently has 270 Mha of land with forest cover,[8] there are actually 310 Mha classified as forest land use.[9] The latter includes lands temporarily cleared or just beginning to regrow after harvest, fire, or other disturbances. Under business-as-usual conditions, many of these lands will recover without intervention and thus do not represent opportunities for additional climate mitigation. However, other disturbed areas are not recovering. For example, Sample[10] identified substantial understocked forest land across the US, primarily resulting from fire disturbance. Similarly, the US Forest Service (USFS) estimated that it is only able to restore forest cover to 20% of the total area in need of restoration on national forest lands due to resource constraints.[11] Furthermore, others document an increasing need to restore forest cover after disturbance.[12]

Outside of areas with a natural land use, restoration of forest cover may be more challenging because land must be converted out of its current use. However, in some locations the current use may offer limited value. For example, marginal crop and pasture lands could be good candidates for restoration of forest cover, especially with expansion of incentive mechanisms, such as the Conservation Reserve Program (CRP).[13]

Even areas with higher land values for a non-forest use could be candidates for restoration if the added trees deliver valuable co-benefits. For example, restoring tree cover within urban landscapes can capture carbon, improve air quality, and reduce urban heat effects.[14] One study in California found, for example, that every $1 spent on urban tree planting and maintenance delivers $5.82 in benefits.[15] Restoration of forest cover can also provide habitat for biodiversity, as well as improved water quality and quantity. For example, Barnett et al.[16] found that restoration of bottomland forests in the Mississippi Alluvial Valley could increase bird breeding habitat, improve connectivity of black bear habitat, capture carbon, and decrease sediment and nitrogen export. Similarly, Keller and Fox[17] estimated that restoring forests in marginal cropland in the Ohio River basin could substantially reduce nitrogen and phosphorus losses.

Beyond land use, land value, and co-benefits there are additional feasibility factors to consider when evaluating where and how to restore forest cover to mitigate climate change. Knowing who owns and/or manages the land will especially influence the options available for scaling restoration of forest cover. For example, increasing restoration on national forest lands requires shifts in federal budget allocation,[11] whereas urban restoration requires coordination among local government entities and multiple private landowners in addition to financial resources.[18] Costs will also clearly influence feasibility. While restoration of forest cover can be less expensive than technological approaches to removing carbon, such as direct air capture,[19] it can be more expensive than other natural climate solutions.[2,5,20] Depending on location and land use, costs can include tree planting and management, as well as opportunity costs (i.e., the loss of future economic returns from crops, livestock, or development).

Here, we combined spatial analyses, forest growth and yield curves, economic analyses, and interviews with conservation practitioners to map more promising options for restoration of forest cover across the contiguous US as a potential climate change mitigation strategy. Specifically, we combined multiple publicly available spatial layers to create 30-m resolution maps of 10 different opportunity classes to restore forest cover (Figure S1). We focused on classes with potentially lower barriers to restoration (Table 1). These include (1) non-stocked forest patches, (2) shrublands, (3) lands with a protected status (e.g., federal public lands), (4) post-burn landscapes, (5) pasture lands, including those with “challenging” soil conditions that impose severe limitations on production), (6) croplands with challenging soil conditions, (7) urban open space, (8) floodplains with 5-year flood return intervals, (9) areas within 30 m of a stream, and (10) “biodiversity corridors” that can facilitate species movement in response to climate change. We then evaluated how these classes differ in location and extent of opportunity, mitigation potential, co-benefits, marginal abatement costs, and feasibility. We also identified how the lands are currently used and who owns them (Figure S1). For accounting purposes, we used a 10-year time horizon, since this decade is critical for stabilizing global warming to below 1.5°C,[29] but also examined how results change with a mid-century time horizon.

RESULTS

Our opportunity classes cover 51.6 Mha across the contiguous US, which could capture up to 314.2 $MtCO_2$ $year^{-1}$. Mitigation potential varies across the country (see Figure 1, as well as the *Reforestation Hub* tool described in Resource Availability). Total potential is greatest in the Southeast and Midwest with five states (Tennessee, Kentucky, Pennsylvania, Virginia, and Arkansas) containing 26% of total mitigation potential (Table S1). Mitigation potential is a function of both extent (Mha) and rate of carbon accumulation (tC ha^{-1} $year^{-1}$), so states with large areas of opportunity do not necessarily have high mitigation potential if their forests have lower carbon accumulation rates. For example, Idaho ranks 9th in total area of opportunity but 31st in total mitigation potential due to slower carbon accumulation in the drier forests there.

Table 1. Focal opportunity classes in the contiguous US

Opportunity classes	Description	Area (Mha)	Mitigation ($MtCO_2$ $year^{-1}$)
Non-stocked forest patches	Proportional area identified as having forest cover[21] but estimated to lack forest cover based on our visual assessment.	4.0	17.9
Shrub	Opportunities in areas dominated by shrubs and/or young trees in an early successional stage or trees stunted from environmental conditions.[21]	5.0	19.3
Protected areas	Opportunities in lands with protected status. The majority are public lands owned in fee, but long-term easements, leases, agreements, and areas with special designations (e.g., national monuments or areas of critical environmental concern) are included.[22]	8.5	34.4
Post-burn landscapes	Opportunities in lands that burned between 1984 and 2015 classified by the most recent year they burned.[23]	1.7	6.1
Pasture	Areas of grasses, legumes, or grass-legume mixtures planted for grazing, seed production, or hay crops.[21] Opportunities that fall within pasture with soil types that constrain production.[24]	28 4.9	194.1 33.3
Crop lands with challenging soil conditions	Opportunities that fall within croplands[21] with soil types that constrain production.[24]	2.8	14.3
Urban open space	Opportunities with some human construction (<20% of cover), but mostly vegetative cover typically in the form of lawn grasses.[21]	7.6	52.5
Frequently flooded areas	Opportunities with a 1 in 5 year average frequency of pluvial or fluvial flooding of any depth after accounting for existing flood defense structures.[25,26]	9.9	56.1
Streamside corridors	Opportunities within 30 m of a stream.[27]	3.9	20.1
Biodiversity corridors	Opportunities within easier migration pathways for species to track their climate envelopes, based on temperature and avoidance of areas with high human impacts.[28]	6.2	36.0

Note that these opportunity classes are not mutually exclusive and overlap in many locations. See also state-level and regional summaries in Table S1.

Opportunity in natural areas

Opportunity classes in natural areas include non-stocked forest patches, shrublands, protected areas, and post-burn landscapes. In the non-stocked forest class, we found 4.0 Mha (17.9 $MtCO_2$ $year^{-1}$) of opportunity (Figure 2; Table 1), with the Rocky Mountains (primarily Colorado and Utah) and Midwest (primarily Missouri and Kentucky) holding 59% of mitigation potential (Figure 1; Table S1). In shrublands that historically held forests, we found 5.0 Mha (19.3 $MtCO_2$ $year^{-1}$) of opportunity (Figure 2; Table 1). Although the area of opportunity is 25% greater in shrublands than non-stocked forest, shrubland mitigation potential is only 8% higher because the opportunity occurs in slower-growing forest types. The Rocky Mountains (primarily Utah and Colorado) and Southwest (primarily New Mexico and Arizona) hold 71% of shrubland mitigation potential and 78% of the area of opportunity (Figure 1; Table S1). The Southeast holds the next largest fraction of shrubland mitigation potential (12%), but only 6% of the area opportunity, reflecting the higher carbon accumulation rates there.

We observed 8.5 Mha (34.4 $MtCO_2$ $year^{-1}$) of opportunity in the protected lands class (Figure 2; Table 1). Almost half (48%) of protected lands mitigation potential is on federal lands, with the greatest potential on USFS (3.1 Mha, 9.1 $MtCO_2$ $year^{-1}$) and Bureau of Land Management (BLM) lands (1.6 Mha, 6.6 $MtCO_2$ $year^{-1}$) (Table S2). Unsurprisingly, states with extensive public lands contain most of this opportunity class, with five states (Utah, Colorado, New Mexico, Idaho, and Arizona) encompassing 41% of mitigation potential (Figure 1; Table S1). In contrast, the Northeast holds only 3% of the mitigation potential in the protected lands class, given that most land there is privately owned. Protected land opportunities span multiple National Land Cover Dataset (NLCD) classes (Figure 2) and therefore partially overlap with non-stocked forest and shrubland classes. Thus, the combined opportunity across the first three opportunity classes spans 12.1 Mha (51.7 $MtCO_2$ $year^{-1}$), which is a quarter of the total area of opportunity and 17% of total mitigation potential.

A substantial portion of the area of opportunity in natural areas occurs in post-burn landscapes (17%). More broadly, we observed 1.7 Mha (6.1 $MtCO_2$ $year^{-1}$) in the post-burn opportunity class (Table 1; Figure 2). Half of the post-burn area is on federal lands (0.9 Mha, 3.0 $MtCO_2$ $year^{-1}$), predominantly on USFS lands (0.7 Mha, 2.0 $MtCO_2$ $year^{-1}$). This class includes 0.8 Mha (2.3 $MtCO_2$ $year^{-1}$) that has not regenerated despite enough time post-fire (see Experimental Procedures for details). These latter are primarily in the West, with 68% of the stalled area in seven states (Montana, Idaho, California, Colorado, Wyoming, Arizona, and Nevada).

Opportunity in agricultural lands

Beyond natural areas, we observed a large proportion of opportunity in agricultural lands. Pasture represents the single largest class, spanning 28.0 Mha (194.1 $MtCO_2$ $year^{-1}$; Figure 2). The Southeast (primarily Tennessee, Arkansas, Texas, and Alabama)

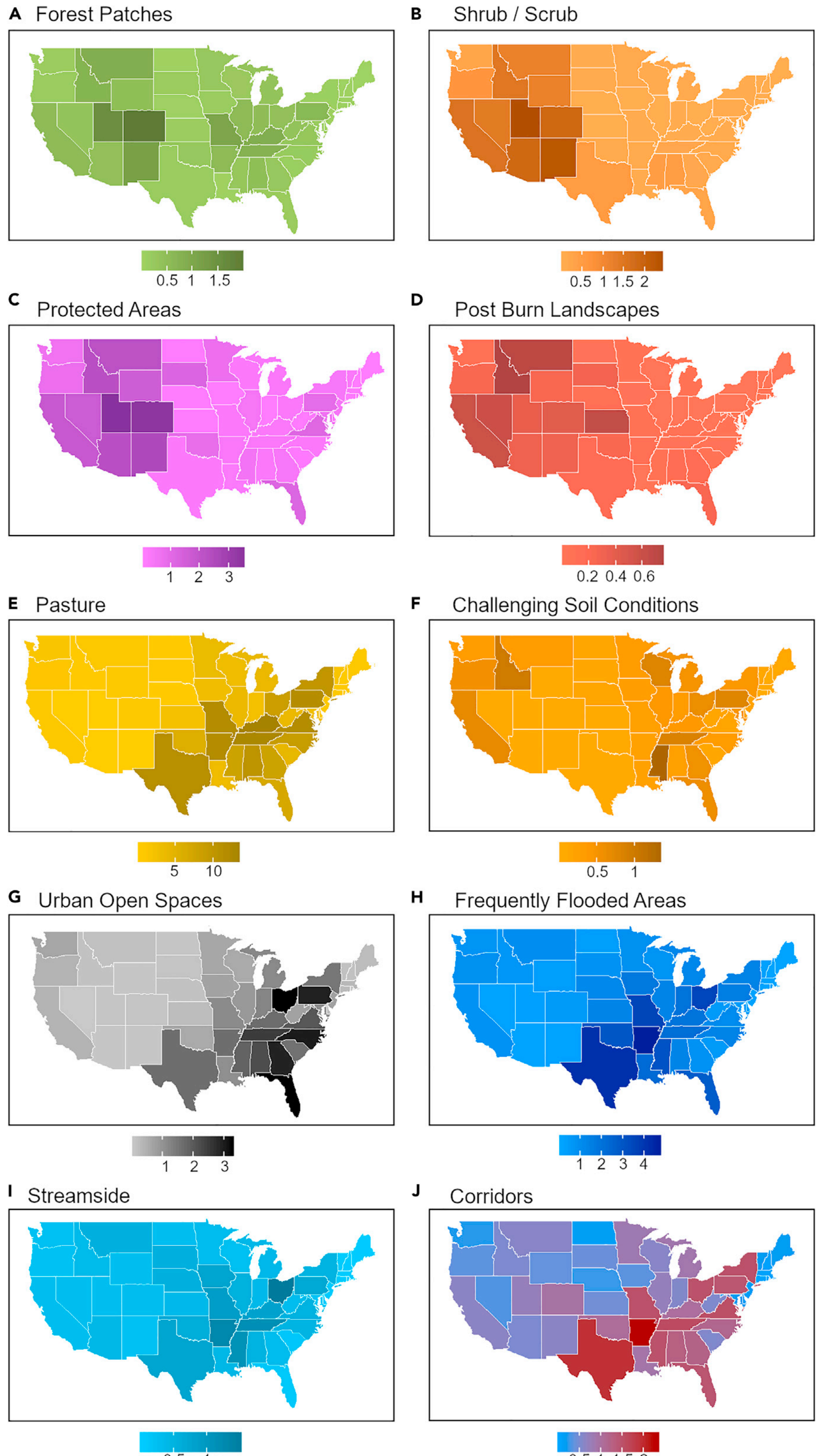

Figure 1nnkh. State-level mitigation potential ($MtCO_2$ $year^{-1}$)

(A–J) Each of the ten opportunity classes. Darker colors indicate states with higher mitigation potential. Note that the pasture class (E) includes all pasture, whereas the challenging soil class (F) only includes cropland. Corridors (J) refers to biodiversity corridors. See also Table S1.

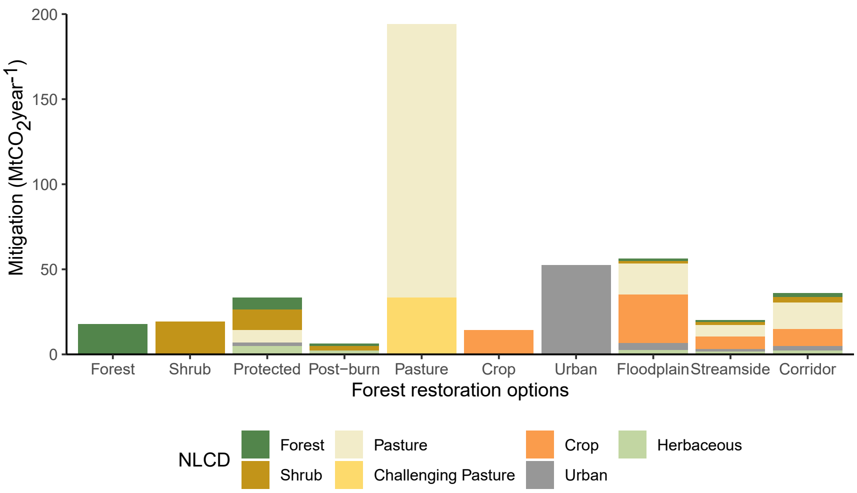

Figure 2. Total mitigation potential ($MtCO_2$ $year^{-1}$) within each of the ten opportunity classes

The colors indicate NLCD land cover type, so opportunity classes that span multiple land cover types are shown as a stacked bar. Note that the pasture class includes all pasture areas (ivory color) with the portion on challenging soils denoted as a brighter yellow. The floodplain, streamside, and biodiversity corridor classes shown here include pasture and cropland with both productive and challenging soil conditions, but we did not include productive cropland in our estimates of total opportunity. See also Table 1.

and Midwest (primarily Kentucky and Missouri) hold 72% of the pasture mitigation opportunity (Figure 1, Table S1). Almost a fifth of the total pasture area of opportunity (4.9 Mha, 33.3 $MtCO_2$ $year^{-1}$; Figure 2) falls on challenging soils, which are soil types that impose severe limitations on agricultural production.[24] While these challenging soils may be more appropriate for native forests than agricultural production, the soil constraints could lead to lower mitigation potential than what we estimated based on regional averages for each forest type.[30] In contrast, the opportunity on croplands with challenging soils is more limited (2.8 Mha, 14.3 $MtCO_2$ $year^{-1}$; Figure 2). As with pasture, most of the cropland opportunity is in the Midwest and Southeast (Figure 1; Table S1). In all, agricultural lands represent 63% of the total area of opportunity and 69% of total mitigation potential.

Opportunity with high potential co-benefits

We observed high potential in urban open spaces (7.6 Mha, 52.5 $MtCO_2$ $year^{-1}$, Figure 2; Table 1), with areas of opportunity more evenly distributed across regions (Table S1). Our visual assessments of individual pixels of opportunity (see Experimental Procedures for more detail) suggested that areas along roads represent over half of the area of opportunity in the urban opportunity class (53%), followed by residential areas (26%), municipal infrastructure, such as government buildings and schools (6%), agricultural infrastructure (5%), recreational lands (4%), commercial business (3%), and finally a mix of other land uses.

We also estimated that there are 9.9 Mha (56.1 $MtCO_2$ $year^{-1}$) of opportunity in frequently flooded landscapes, 3.9 Mha (20.1 $MtCO_2$ $year^{-1}$) within 30 m of a stream, and 6.2 Mha (36.0 $MtCO_2$ $year^{-1}$) in biodiversity corridors (Table 1; Figure 2). These opportunity classes usually occur in different locations, but there are 0.2 Mha across the contiguous US where the three opportunity classes overlap, and 2.8 Mha where two of the three overlap. Thus, there is some potential to restore forest cover in places that can simultaneously provide multiple co-benefits. The Midwest and Southeast hold most of the opportunity to mitigate climate change while providing strong co-benefits (Figure 1; Table S1), with 76% of floodplain mitigation potential, 69% of streamside mitigation potential, and 64% of the mitigation potential in biodiversity corridors. Notably, Arkansas has the highest mitigation potential in floodplains and biodiversity corridors and the second highest mitigation potential along streamsides (after Ohio).

Most of the floodplain area of opportunity falls in agricultural landscapes, with 51% in croplands and 29% in pasture lands. Similarly, streamside areas of opportunity fall primarily in croplands (35%) and pasture lands (28%), as do biodiversity corridors, with 27% in croplands and 36% in pasture lands (Figure 2). These areas of cropland opportunity span both productive and challenging soil conditions, but we only included the latter in our estimates of total opportunity (i.e., 51.6 Mha, 314.2 $MtCO_2$ $year^{-1}$) to safeguard food production.

Economic costs of restoration of forest cover

Most of these opportunities to restore forest cover could be achieved at reasonable costs (Figure 3; Table S3). We estimated that 19.1 Mha, or 37% of our total area of opportunity could be restored at or below \$20 tCO_2^{-1}, resulting in about half of the potential climate mitigation (156 $MtCO_2$ $year^{-1}$). We further estimated that about two-thirds of the mitigation potential (210 $MtCO_2$ $year^{-1}$) is available at or below \$40 tCO_2^{-1}. Increasing the price threshold to \$50 tCO_2^{-1} could restore about 32 Mha (221 $MtCO_2$ $year^{-1}$), whereas \$80 tCO_2^{-1} could restore 41 Mha (251 $MtCO_2$ $year^{-1}$). Higher price thresholds resulted in minor additional gains, so we estimated that 80% of the total area of opportunity would be economically viable at or below \$100 tCO_2^{-1}, which could capture approximately 80% of total mitigation potential (252 $MtCO_2$ $year^{-1}$).

Most of the opportunity to restore forest cover to natural opportunity classes is economically feasible at \$50 tCO_2^{-1} or below (Figure S2) because these areas typically only face implementation costs. In contrast, restoring forest cover to agricultural lands imposes both opportunity and implementation costs. Compared with croplands, a larger portion of the pasture opportunity class is available at lower carbon prices (Figure 3), because pasture typically has lower opportunity costs, while planting costs for pasture versus croplands remain more constant within a region. In contrast, for urban areas, we found no potential to restore forest cover below \$200 tCO_2^{-1} due to high opportunity costs (Figure 3).

Restoration costs also vary across the US (Table S3). Most of the low-cost restoration opportunity occurs in the Southeast, followed by the Midwest and Mid-Atlantic, and this pattern generally persisted as we increased the cost threshold. Lower costs in the Southeast are due to relatively low annualized

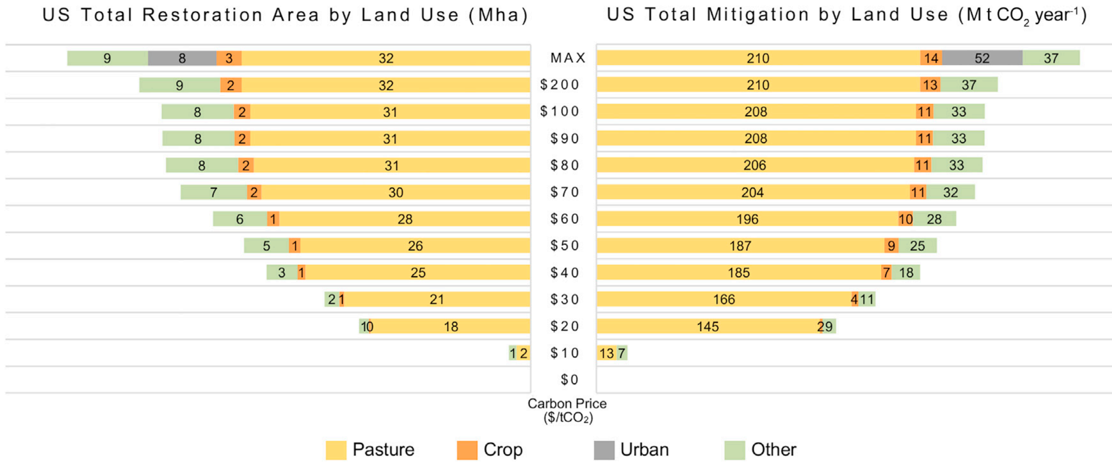

Figure 3. Restoration area (Mha) and mitigation potential ($MtCO_2$ $year^{-1}$) by land use and at different carbon price points ($ tCO_2^{-1})
Horizontal bars indicate the potential area (left) and mitigation (right) available at or below each price point. Note that the pasture class includes all pasture areas, whereas the cropland class only includes those on challenging soils. See also Table S3.

costs of site prep ($136 ha^{-1} $year^{-1}$) and the lower opportunity costs in pasture. Average annualized planting costs in the Northeast states are also relatively low ($171 ha^{-1} $year^{-1}$) because forests are typically established through natural regeneration, although opportunity costs are higher. Concurrently, in the Midwest the low to medium costs are due to lower opportunity costs. We estimated that most of the potential area of opportunity could be restored in the Northeast and Midwest regions at $40 $tCO2^{-1}$ and $70 $tCO2^{-1}$, respectively, and that the Southeast could restore 76% of its total area of opportunity at a price of $20 $tCO2^{-1}$.

Feasibility of restoration

We asked conservation practitioners and scientists to rate the feasibility of different opportunity classes (see Experimental Procedures for details; Table S4). These experts demonstrated a regional split based on their geographic-specific knowledge (Figure 4). Most participants from the Southeast, Southwest, Pacific, and Rocky Mountain regions said that post-burn landscapes had medium or high feasibility (50% and 43%, respectively, of respondents to an online survey) and 64% of the respondents from these regions attributed the higher feasibility to the co-benefits that post-fire restoration provides. In contrast, respondents from regions with less frequent fire did not highlight post-fire locations. Instead, 86% of the respondents from the Mid-Atlantic, Midwest, and Northeast regions most frequently cited ‘‘marginal’’ or low-value land as having the greatest opportunity, describing these lands as abandoned, degraded, frequently flooded agricultural lands or former mine lands. While only 30% of respondents indicated that restoring forest to current cropland would be possible given the right economic incentives, in the eastern US 70% of respondents believed there could be opportunities on pasture given the right economic incentives.

There was little regional differentiation, however, around other opportunity classes. Half of all respondents said that water benefits provide a strong motivation for restoration of forest cover, and these responses were distributed evenly across regions. In contrast, participants described restoration of forest cover in wetlands as entirely infeasible, citing regulatory constraints and/or negative environmental impacts that preclude further disruption of wetlands. Respondents also generally scored biodiversity corridors as having low (42%) to medium (45%) feasibility. Those that scored this option as low primarily cited economic (36%) and cultural barriers (36%), whereas 62% of those that scored this option as having medium feasibility cited co-benefits as the principal motivator for restoration.

When asked to score potential co-benefits from most (5) to least (1) important, the survey respondents ranked water quality as the highest (a score of 4.2 on average), followed by water regulation/flood control (3.8), habitat for biodiversity (3.6), recreational/cultural values (3.6), economic opportunity (3.2), climate change mitigation (3.2), climate change adaptation (3.0), and air quality (3.0). The high ranking of water co-benefits was consistent across regions, with six of seven regions scoring water quality the highest, except for the Southeast where flood regulation scored the highest.

When asked to score different potential obstacles, respondents most often cited insufficient funding, with an average score of 4.0 where 1 is no obstacle and 5 represents a major obstacle. Lack of public awareness, a lack of value attributed to ecosystem services, and lack of coordination among funders/implementers all rated moderately, with average scores between 3.0 and 3.2. Participants also frequently mentioned implementation constraints, such as limited coordination and information sharing, long-term maintenance of plantings, insufficient planting stock, management of invasive species, and deer browse. We observed some regional variation in obstacles. Although lack of funding remained the primary obstacle in both the eastern (scores of 3.8) and western US (score of 3.9), lack of coordination among funders/implementers, land availability, and science gaps (e.g., how and where to restore forests) were ranked more heavily in the West. In the East, lack of value attributed to ecosystem services and lack of public awareness were emphasized more (3.0).

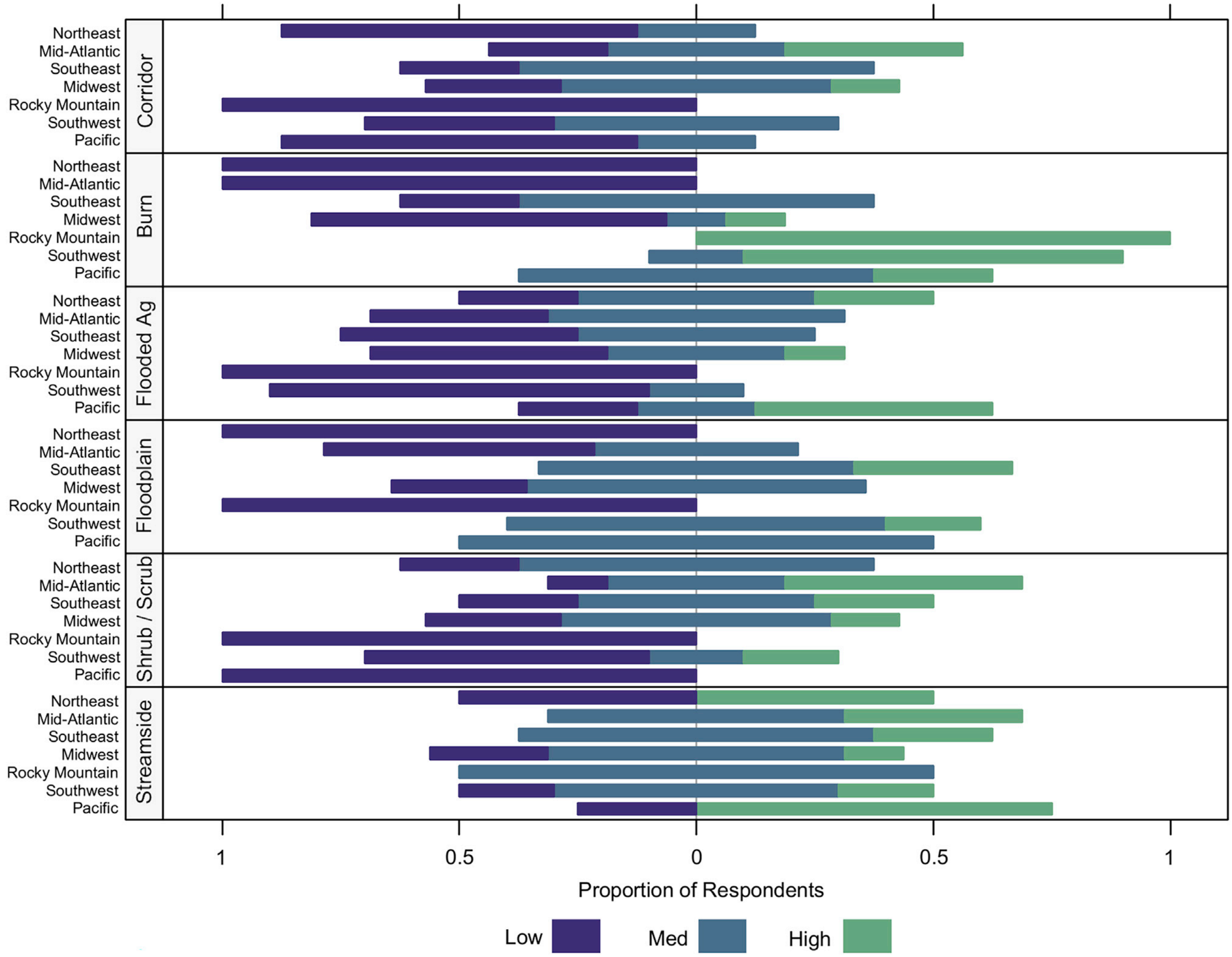

Figure 4. Perceived feasibility for a subset of opportunity classes

Results derived from responses to an anonymous, online survey. Opportunity classes are ranked as having high (green), medium (blue), or low (purple) feasibility. If all respondents deemed an opportunity class to be highly feasible, the bar reaches the "1" value on the right (e.g., post-burn opportunities in the Rocky Mountain region). If all respondents deemed an opportunity class to have low feasibility, the bar reaches the 1 value on the left (e.g., shrub/scrub in the Rocky Mountain and Pacific regions). Medium feasibility responses are centered on the "0" point of the x axis.

DISCUSSION

There is no panacea to climate change. A stable future climate will require strong reductions in emissions, protection of our intact landscapes, improved management of our working lands, and restoration of ecosystems.[31] Our analysis confirms the large climate mitigation potential from restoration of forest cover, with an additional 314.2 $MtCO_2$ $year^{-1}$ possible across 51.6 Mha compared with baseline conditions. This area represents less than 7% of the contiguous US and the carbon capture potential is equivalent to removing 67 million cars from the road each year,[32] 5% of US emissions (circa 2017) or 15% of the original US nationally determined contribution to the Paris Agreement. However, 51.6 Mha is a maximum that, unlike other studies, we disaggregated by factors such as cost and broader feasibility. To facilitate implementation at more local levels, we spatially partitioned this opportunity into 10 opportunity classes and show how these differ in location, carbon capture potential, costs, feasibility, and co-benefits.

Comparisons with previous analyses

Our total area estimates fall at or below previous assessments. For example, Sample[10] used USDA Forest Inventory and Analysis data to identify approximately 8 Mha of non-stocked forestland within the contiguous US. We found a roughly comparable 9.0 Mha of opportunity within non-stocked forest and shrublands. Both our analysis and Sample's showed that most of the public land opportunity is on USFS lands, estimating that there are 3.1 and 2.2 Mha of opportunity, respectively. Compared with our estimate of total opportunity, Fargione et al.[5] estimated a larger area (63 Mha), but only a slightly lower mitigation potential (307 $MtCO_2$ $year^{-1}$). Although we used similar methods, we updated the latter analysis to (1) remove wilderness areas, (2) remove a proportion of erroneous pixels based on a visual assessment, (3) remove all opportunity with wetland covers, (4) include all pasture lands that used to be forest, (5) apply the background regrowth deduction to a smaller area (i.e., not in urban or agricultural landscapes), and (6) remove an albedo deduction (see Experimental Procedures for details).

The cost estimates from our analysis are within the high range of previous studies[5,33] (Figure S3). Economists have been estimating the cost of forest carbon capture in the US for more than three decades using a range of methods.[33] Early studies estimated average costs,[34,35] while subsequent studies used a marginal cost approach to estimate how additional areas could be returned to forest at increasing prices.[36] Many of the next phase of studies also accounted for the potential effect of large projects on commodity prices[37–39] and used a range of statistical and modeling methods to quantify costs at various scales.[5,40–42] Most of these studies estimated that restoration of US forest cover can often cost less than \$50 tCO_2^{-1}. However, implementation costs can be highly variable by practice and region,[33–43] and scaling up results can lead to a wide range of estimates that depend on the method used. For example, bottom-up methods often result in higher costs at the low end of the forest carbon accumulation spectrum (and lower costs at the high end), compared with econometric or optimization approaches that account for market adjustments in response to the change in forest area and management.[33,43]

Our higher cost estimates are likely due to several factors. First, findings from earlier studies were not always adjusted for inflation, so earlier studies can appear cheaper than our estimates in 2018 US dollars (Figure S3). We also focused on the first decade of forest growth, when carbon accumulation rates are lower and there has been limited time to annualize costs. Lengthening the analysis time frame from 10 to 30 years increased the total mitigation potential by 8% to 339.1 $MtCO_2^{-1}$ $year^{-1}$ and provided a longer time to annualize costs, which increased mitigation potential available at or below \$50 tCO_2^{-1} (273 $MtCO_2^{-1}$ $year^{-1}$) by 23% (Figure S4). Our core analysis also did not include potential timber or carbon revenue. However, if we modeled annualized revenue from periodic timber harvests, which reduced opportunity costs, mitigation potential at or below \$50 tCO_2^{-1} only increased by 4.0% and 0.4% over 10- and 30-year time horizons, respectively. Thus, the results were most sensitive to the time frame over which costs were amortized (Figure S4). Despite our more conservative estimates, our economic analysis implies that there is potential for large-scale expansion of forest cover if the price on carbon continues to rise.[44]

Opportunity classes with high potential

We found that restoring forests to pasture lands represented the single largest opportunity to mitigate climate change. This opportunity class contains over half of the area of opportunity (56%) and two-thirds (66%) of the mitigation potential. The area of opportunity we identified represents 13% of total range and pasture within the contiguous US.[45] Returning these lands to forest would likely require a shift toward plant-based diets in line with current diet recommendations[46] and recommendations for climate change mitigation.[29] Alternatively, establishing silvopasture (adding trees to pasture) rather than forests could provide a portion of the carbon benefit while maintaining livestock production.[47] The pasture class also contains some of the lowest cost opportunities. In particular, opportunities on challenging soils (4.7 Mha in pasture and 2.8 Mha in croplands) may cost even less and have lower impacts on food production, since these soils severely limit production and require additional management.[24] In sum, agricultural lands with challenging soil conditions could provide 15% of the total mitigation potential (46.2 $MtCO_2$ $year^{-1}$). Furthermore, eastern conservation practitioners tended to view these potentially marginal lands, especially pasture lands, as a more feasible opportunity class.

Floodplains represented the second largest opportunity class. We also observed substantial opportunity within 30 m of a stream, which partially overlapped with the floodplain opportunity. Conservation practitioners across the country scored these lands highly for feasibility and co-benefits. This aligns with the economic importance of hydrological ecosystems services,[48] emphasizing that the benefits from restoration of forest cover extend beyond climate change mitigation. Although floodplains often represent valuable agricultural lands, we identified locations already impacted by frequent flooding (approximately every 5 years). Flood events are becoming even more frequent as the climate warms.[49] Increased future flooding could further reduce the value of this land for crop production and increase the benefit of floodplain restoration to help store and convey floodwaters. Restoration of forest cover in riparian zones also improves freshwater habitat for biodiversity,[50] and a 30-m forest buffer can improve water quality by capturing pollutants and sediments, stabilizing streambanks, providing habitat for species, attenuating floods by intercepting overland flow, and providing important detrital inputs.[51]

Urban open spaces represented the third largest opportunity. From a strictly economic lens, the high values of these lands could preclude restoration of forest cover. However, trees within urban areas offer many additional co-benefits, such as mitigation of heat islands, pollution reduction, and improved human health outcomes,[18] which could foster momentum for forest restoration within urban areas despite the relatively high cost. Moreover, the economic analysis conservatively assumed that land would be converted out of its current land use, but we estimated that more than half of the urban opportunity falls along roadsides where planting additional trees may be possible without changing current land use. Although we removed areas around primary and secondary highways, including medians, we retained the area around slower roads. Roadside trees do represent a potential crash hazard, but research suggests that most tree-related crashes occur where a street intersects a faster road,[52] implying that trees could be incorporated along some stretches of slower roads without increasing safety risks. Roadside vegetation may also reduce driving speeds,[53] and accidents along more vegetated roads tend to result in less injury or death than accidents along more open roadways.[54]

Post-fire landscapes represented another promising opportunity class, which conservation practitioners from western states viewed as most feasible to restore compared with other opportunity classes. We estimated that at least 47% of the post-burn area had failed to recover for at least 5 years, which did not include lands burned recently. There is a growing need for post-fire restoration. On national forest lands, for example, post-fire restoration represented 15% of all reforestation needs in 2007, but 81% in 2017 due to an increase in burn frequency and severity.[11]

Finally, restoration of forest cover within biodiversity corridors represents an important strategy for biodiversity conservation. Currently only 41% of natural areas are connected enough to allow plants and animals to track their thermal envelopes as the climate warms, whereas restoration of key corridors may help preserve biodiversity by connecting an additional 25% of natural areas.[28] Corridor restoration can reduce annual extirpation rates in forests and increase the likelihood of patch colonization, with the effect accumulating over time.[55]

Regional variation in results

We observed strong regional variation in the magnitude and costs of opportunities to restore forest cover (Figure 1; Tables S1 and S3). Natural lands opportunities occurred most frequently in the West, whereas opportunities within agricultural lands occurred primarily in the Southeast and Midwest. Similarly, we observed that opportunities on publicly owned lands occurred primarily in the West, whereas opportunities on presumably privately owned lands (i.e., those without a known protected status) occurred predominantly in the East. The percentage of the area of opportunity under public ownership ranged from 1% in Kentucky, Missouri, Tennessee, and Texas to 87% in Arizona. This is important information because it indicates whether implementation will require engaging a large number of private landowners versus a handful of public entities, with implications for costs. Floodplains, streamsides, and biodiversity corridors also occurred more often in the Southeast and Midwest, whereas urban open space opportunities were more evenly distributed across regions.

There was also regional variation in costs, where four regions held about 80% of the total mitigation opportunity at or below \$40 tCO_2^{-1}: the Southeast (96 $MtCO_2$ $year^{-1}$), the Mid-Atlantic (43 $MtCO_2$ $year^{-1}$), the Northeast (17 $MtCO_2$ $year^{-1}$), and the Southwest (14 $MtCO_2$ $year^{-1}$). The majority (85%) of this low-cost potential occurs in pasture. However, even lower cost options exist. The region with the largest percentage of its potential available at \$20 tCO_2^{-1} is the Northeast (82%), with 14 $MtCO_2$ $year^{-1}$ available, followed by the Southeast (77%, 93 $MtCO_2$ $year^{-1}$), and the Southwest (47%, 7 $MtCO_2$ $year^{-1}$). These low-cost opportunities stem from lower implementation costs due to reliance on natural regeneration and/or low to no opportunity costs (see Experimental Procedures).

Finally, we observed regional differentiation in assessments of feasibility and potential obstacles. Western conservation practitioners emphasized post-fire restoration as most feasible and highlighted lack of coordination among funders/implementers, land availability, and science gaps as the largest obstacles. Eastern conservation practitioners focused more on pasture with challenging soils and more heavily emphasized the lack of public awareness around the value of ecosystem services. We hypothesize that this variation hints at the large scale of land ownership and management by state and federal government in the western US, and the need for science and a high degree of coordination to inform land management. In the more urban and densely populated eastern US, our findings may indicate an opportunity to raise awareness regarding human needs for ecosystem services provided by forests and thus build demand for increasing forest cover.

While there were often trade-offs among opportunity classes with respect to extent, location, magnitude of mitigation potential, costs, feasibility, and co-benefits, a few locations possess a greater density of opportunity. The Southeast had relatively high opportunity within shrublands, pasture, and challenging croplands. The Southeast, especially Arkansas, also had a high density of opportunity that could provide key co-benefits, such as floodplain and streamside restoration.

Considerations for implementation

In fire-prone landscapes, climate change is expected to further increase burn severity and the patch size of area burned,[56] which can limit natural regeneration due to soil erosion and/or a lack of nearby seed sources.[57,58] Early on-the-ground assessments can determine where intervention is necessary. Another important consideration is whether post-fire landscapes should be restored. With climate change, many low-elevation western forests may permanently convert to open shrublands after a stand-clearing wildfire.[59,60] Indeed, up to 30% of all low-elevation forests in the intermountain western US may be at risk for this type of conversion.[59] Investments in restoring forest cover in these areas would be wasted if the area converts to shrubland after the next fire, and repeated interventions would be cost-prohibitive. Instead, opportunities in these fire-prone landscapes may be restricted to higher elevations and/or riparian corridors where fire risks are lower.

A critical next analysis is to incorporate future climate modeling to identify areas that are likely to become less amenable for forests—across the US and not just fire-prone landscapes—and those that are likely to become more amenable. Even locations that continue to be suitable for forests may no longer be suitable for the species and/or populations that historically grew there. The climatic envelopes for many tree species are shifting and expected to shift further.[61,62] Research and site-level planning to identify the best planting material for future climate conditions are critical for the long-term persistence of forest cover.[63]

Climate change may also influence the effectiveness of natural regeneration. Most restoration of forest cover in the US occurs due to natural regeneration, with, for example, two-thirds of Forest Service needs met through natural regeneration, although potentially with some site preparation.[11] Natural regeneration can maintain a high level of diversity and costs less than tree planting,[11] but may only establish forest communities adapted to current, rather than future conditions.[64] Moreover, natural regeneration is only suitable when seed sources are spatially near (and, in the case of masting species, temporally aligned with) the area in need of restoration.[12] For example, wind-dispersed conifer seeds typically travel only 200 m from a seed source.[65] Thus, tree planting will be necessary in some locations, and indeed it may be possible to achieve higher rates of carbon accumulation with tree planting rather than natural regeneration.[66] Factors such as species or population choice, tree density, and/or spatial distribution of trees will also influence the success of restoration efforts and are increasingly important as the climate warms.[12,67] However, planting the entire area of opportunity with a regionally appropriate number of trees

(T. Schuler, personal communication) would require over 68 billion trees, which would outstrip budgets and available planting stock, highlighting the value of first prioritizing natural regeneration where possible and then planting where necessary. Post-planting management will also influence success, such as early prescribed burns to remove ground fuels in fire-prone landscapes[12] or controlling browse by white-tailed deer (*Odocoileus virginianus*), especially in the eastern US.[68]

Conclusion

To inform land-use decisions made at local and regional levels, we identified how different opportunities to restore forest cover vary across the contiguous US. While land use and management decisions should be made based on local priorities, there are a few particularly promising options that merit additional attention. These include the very large opportunity within pasture lands that would naturally support forest, which could either be planted with trees for silvopasture, which maintains or increases livestock production, or restored to forest if livestock production efficiency increases or human diets shift. We also observed substantial opportunities within floodplains and alongside streams, which offer an opportunity to improve water quality while reducing flood damages. Similarly, increasing forest cover along slower roads may cause safer driving and would provide many direct benefits to people, such as improved air quality. Finally, restoration of non-stocked forest and shrublands within natural areas may represent opportunities with particularly low barriers to implementation if those forests can be restored without increasing fire risk.

While there is no best single location or approach to forest restoration, our analysis confirmed its large climate mitigation potential. Unlike more expensive carbon removal technology, these forest restoration opportunities could be rapidly unlocked this decade as part of post-covid government stimulus for job creation and rural household income, in particular if mechanisms are in place for stakeholders to benefit from the increasing value of carbon storage.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Dr. Susan Cook-Patton (susan.cook-patton@tnc.org).

Materials availability

The *Reforestation Hub* tool provides county-level results after all non-spatial deductions have been applied and can be accessed at https://www.reforestationhub.org/. The 30 m resolution GIS data can also be downloaded from this site. Raster data show opportunity before the semi-spatial deductions but are attributed with area and mitigation potential after deductions. State-level tabular summaries are also available on the *Reforestation Hub*, as well as linked to this publication (Data S1).

Data and code availability

All spatial and carbon datasets used in this study are publicly available and can be found by accessing the referenced studies, except for the floodplain layer which we accessed via a memorandum of understanding with the authors. To enable recreation of our methods (details below), we also include the LANDFIRE Biophysical Setting (BPS) groups used in this study (Data S2) and the semi-spatial deductions per NLCD cover type based on our visual assessment and background gain calculations (Table S5). The Python and R code supporting the current study are in a distributed format across multiple coauthors. However, code is available from the Lead Contact on request.

Mapping restoration opportunity in the contiguous US

We constrained our analysis to only locations where forests with ≥25% tree cover historically occurred, using LANDFIRE BPS data.[69] These data denote dominant vegetation types before Euro-American settlement, based on current biophysical conditions and historical disturbance regimes. We included all BPS groups classified as "Forest and Woodland" or "Woody Wetland,"[70] although ultimately excluded areas that currently have wetland cover (details below). To avoid perverse biodiversity consequences of trees in grassy biomes,[71] we further excluded any grass-dominated ecosystems with potentially <25% tree cover (see Data S2 for BPS types that remained). Although we initially included areas appropriate for the restoration of sparser (10%–25%) forest cover, our feasibility interviews with experts (details below) showed that this approach erroneously identified opportunities in intact woodlands (e.g., current Pinyon-Juniper forests) and where future disturbance regimes are not likely to support forest cover.[72] To avoid including locations that do not need additional cover, we conservatively opted to only include in our final analysis those areas where ≥25% forest cover is appropriate based on historical conditions. However, there are forest and woodland types that would benefit from additional cover, which are not captured in our analyses, such as Tamaulipan thornforest.[73]

We then excluded areas that currently have forest cover using the 2010 North American Forest Dynamics (NAFD) data.[74] We excluded areas with open water, perennial ice and snow, and barren rock/sand/clay land covers using the 2011 NLCD.[21] We further removed areas with NLCD wetland land covers based on our feasibility interviews with experts (details below). The NLCD also contains four developed categories (high intensity, medium intensity, low intensity, and open space) and we removed all but the latter, since densely developed areas do not typically have room for the large patches of trees considered here. To protect food security, we removed most cropland identified in NLCD, except those areas with soil conditions that place severe to very severe constraints on production (termed "challenging" soils here) or that overlap with floodplain, streamsides, and/or biodiversity corridors (details below). We further excluded areas with a wilderness designation using the Protected Areas Database (PAD-US)[22] since regulations curtail interventions such as tree planting within wilderness.[75] Finally, we excluded all primary and secondary roads and areas within the highway median by converting polyline vector data[76] to a 30 m raster using a 2 × 2 pixel rectangular neighbor window and a "majority" rule. We excluded primary and secondary roads because these higher-speed roads often require substantial tree clearance for visibility and safety,[77] but did not exclude smaller roads since trees adjacent to these roads can improve safety by visually cuing drivers to slow down.[52]

The resulting state-level maps are publicly available (see Resource Availability). These represent all areas where restoration of forest cover is theoretically possible after ensuring safeguards for grassland biodiversity and food production. However, we also included several semi-spatial deductions to proportionally discount areas of opportunity. The first deduction removed areas erroneously identified as opportunities by the GIS analysis. We developed this deduction by visually assessing satellite imagery[78] within a 90-m radius window around a stratified random set of pixels (n = 5,000). We distributed these random pixels proportionally by NLCD class within each state. For each NLCD cover class type, we determined what proportion of the windows already had >50% forest cover. We then deducted this proportion from the area of opportunity within the respective NLCD classes. For natural NLCD classes (Evergreen, Deciduous and Mixed forests, and Shrub/Scrub), we further determined the proportion of random pixels that represented small patches within a forest mosaic. For example, many western forests with frequent fire naturally consist of individual conifers scattered throughout a matrix of shrubs, hardwoods, and openings.[12] We assumed that any patches less than six contiguous pixels (~0.5 ha) represented a natural opening and excluded an equal proportion from the respective NLCD classes. The combination of these two deductions are in Table S5.

Finally, some areas of opportunity are only temporarily cleared due to recent harvest, fire, or other disturbance and will regrow in the absence of intervention. These are locations with a forest land use, but temporarily without forest cover and represent baseline forest cycling rather than additional opportunities for climate mitigation. To remove these areas, we estimated annual average increases in forest cover from 1986 to 2010 per USFS forest type and region using the NAFD data.[74] Assuming historical rates of forest gain would continue, we deducted an area proportional to the amount expected to regrow over 10 years (i.e., until 2030) from the area within each USFS forest type and region. We only applied this deduction to natural NLCD cover classes, and did not assume that pasture, cropland, or urban areas would regrow. After this final deduction, the remaining area represented the total area of opportunity for restoration of forest cover.

We conducted all spatial analyses using ArcMap v10.3.1, Python v2.7, and R v3.5.1 (2018). We used 30 m resolution rasters projected to USA Contiguous Albers Equal Area Conic (USGS version) projection system (NAD, 1983 datum), spanning the contiguous US.

Partitioning maps into opportunity classes

We partitioned the overall area of opportunity into our 10 opportunity classes (Table 1), which are not mutually exclusive and overlap in some locations. To facilitate implementation and policy development, we further partitioned these by US state, NLCD class, BPS, and ownership (Figure S1). For ownership, we used the PAD-US[22] and identified areas of opportunity in (1) land managed by each federal agency (BLM, Department of Defense, National Park Service, National Oceanic and Atmospheric Administration, US Fish and Wildlife Service, and USFS), (2) other public lands (e.g., state and local lands), (3) private protected lands, (4) tribal lands, (5) other lands identified as protected but with limited details on ownership, and (6) lands without a known protected status, which we presumed are predominantly privately owned.

The first opportunity class was non-stocked forest, which we identified as the area of opportunity with a NLCD forest class designation after our proportional deductions. Visual inspection of these locations showed large open patches within forest areas. The second opportunity class was shrubland, which we identified as the area of opportunity with a NLCD "Shrub/Scrub" designation but that could be forest given historical conditions. The third opportunity class included protected lands, which we defined as the area opportunity that overlapped with areas within the PAD-US database. The fourth opportunity class included post-burn landscapes, which we identified using the Landsat Burned Area Essential Climate Variable data.[23] These data delineate areas that burned between 1984 and 2015 and record when the fire occurred. We quantified the time between the last burn and the vintage of our current forest layer (i.e., 2010 NAFD) to estimate whether sufficient time had passed for those areas to regenerate. If a post-burn pixel lacked forest cover for 5 or more years after burning and was not used for crop, pasture, or urban open space, then we scored it as failing to regenerate. However, some ecosystem types take longer than 5 years to regenerate. In these cases, we used typical regeneration times from LANDFIRE national vegetation dynamic models.[79]

The fifth opportunity class included the area of opportunity designated as "Pasture/Hay" in the NLCD, with a further subset to identify those with soil conditions that impose severe to very severe limitations on production,[80] which we called "challenging soils." The sixth opportunity class included all areas of opportunity designated as "Crop" in NLCD, but only included croplands with challenging soil conditions. We identified areas with challenging soil conditions using land capability classes 4e, 5w, 6, 7, or 8 in the Gridded Soil Survey Geographic Database.[80] Land capability class 4 soils have severe limitations on production, whereas classes 5 through 8 soils are typically only suited for native ecosystems, such as the forests described here.[24] These soil classes are also partitioned by specific limitations and hazards including high likelihood of erosion (e) and excess water (w).

Our remaining four opportunity classes included areas of opportunity with the potential to provide important co-benefits beyond carbon capture, including human health benefits in urban areas, watershed benefits in floodplains and streamsides, and biodiversity benefits. The seventh class thus included urban open space opportunities defined as areas designated as "Developed, Open Space" within the NLCD,[21] which we further partitioned into sub-classes based on the visual assessment of stratified random pixels (n = 313 specific to this class). These sub-classes included (1) agricultural infrastructure (e.g., crop, pasture, and forest plantations), (2) commercial lands (e.g., parking lot around a commercial center), (3) military infrastructure (e.g., military bases), (4) municipal infrastructure (e.g., landfill, areas around a government building, school yards, cemeteries), (5) recreational facilities (e.g., polo field, campgrounds), (6) residential areas, (7) roadsides, and (8) general vegetated areas without a discernible land use.

The eighth opportunity class included areas of opportunity within floodplains that experienced 1 in 5 year pluvial or fluvial floods of any height after accounting for current flood defense structures.[25,26] The ninth opportunity class included areas within a 30 m riparian buffer[51] around streams or rivers, found by buffering either side of "StreamRiver" polylines within the National Hydrography Dataset Plus Version 2[27] and converting to raster format. The final opportunity class, biodiversity corridors, were areas that fall within "least-cost" migration paths for species to track their climate envelopes.[28] These biodiversity corridors follow temperature gradients and avoid areas with high human impacts. We used a 1 km resolution map to delineate the top 20th percentile of climate corridors (i.e., the easiest to traverse) and resampled this to 30 m using the "nearest" resampling algorithm.

Calculating climate mitigation potential

We used USFS yield tables to estimate carbon accumulation rates ("live tree" data in Tables B1–B51 in Smith et al.[30]), which provide growth curves specific to both USFS forest type and region. These curves reflect standard stand establishment practices for a given USFS region and forest type, which can include natural regeneration and/or active planting depending on location. We used these curves to calculate an average rate of carbon accumulation (tC ha^{-1} $year^{-1}$) in above- and belowground plant biomass in the first decade of growth, as well as for the first 30 years (i.e., to 2050) to use in our sensitivity analysis. We included a further 0.23 tC ha^{-1} $year^{-1}$ for soil carbon accumulation rate, based on the midpoint observed from Nave et al.[81] for soil organic carbon recovery after clearance and cropping. We did not adjust mitigation estimates for albedo, but flag that albedo-driven warming can offset the cooling benefits of carbon storage in coniferous forests with high snow cover.[82] Final rates ranged from 0.50 tC ha^{-1} $year^{-1}$ in Ponderosa Pine (*Pinus ponderosa*) forests in the Rocky Mountains to 2.73 tC ha^{-1} $year^{-1}$ in Oak (*Quercus*)-Hickory (*Carya*) forests in the Northeast. We then cross-walked USFS forest types to the BPS groups used in the GIS analysis based on spatial overlap, name similarity, and environmental similarity (e.g., riparian species).[5]

Estimating costs

We estimated the economic cost of restoring forest cover using a standard bottom-up methodology to examine variation in costs across opportunity classes and among regions. We first quantified the cost of forest site establishment (e.g., clearing, planting) based on county-level costs estimated from the USDA's CRP and reported in Nielsen et al[42] These costs varied by location, original land use (e.g., crop, pasture), existing mix of tree species, and mode of forest establishment (e.g., natural regeneration and/or planting). Second, we estimated the opportunity costs from lost revenues due to restoring land to forest. Crop and pasture land costs were estimated using grassland and CRP land rental payments,[83] while urban open space opportunity costs were based on Davis et al.[84] All other opportunity classes (e.g., forest, shrub/scrub) only included site establishment costs. Site establishment costs only accrue in the first year, while land opportunity costs accrue on an annual basis. Thus, we annualized the establishment costs over the same period as carbon capture (2020–2030) using a discount rate (r) of 5%. Finally, we did not assume any harvest in the restored area because (1) we used a 10-year time horizon, (2) carbon accumulation rates were based on natural forests rather than plantations, and (3) many of the areas of opportunity are not suitable for harvest (e.g., adjacent to riparian corridors or within urban open spaces). Thus, we conservatively assumed that the landowner does not receive any revenue from timber products. However, we conducted a sensitivity analysis to assess how including the net present value of timber revenues ($r = 5\%$) from harvesting based on region-specific harvest cycles would alter our results (Figure S4). We then used the sum of these annual costs coupled with the annual carbon accumulation rates to quantify the break-even carbon price that landowners would be willing to accept to restore their land to forest. All monetary figures were measured in constant 2018 US dollars.

Assessing feasibility

To examine how our opportunity classes differed in feasibility and how this varied by region, we conducted interviews with 60 scientists and land managers within The Nature Conservancy and the USFS. We selected these individuals based on their knowledge of forests, forest restoration, and/or climate change mitigation, using snowball sampling.[85] We identified experts with knowledge of forests in each region (n = 11 Mid-Atlantic, 7 Midwest, 9 Northeast, 8 Pacific, 4 Rocky Mountains, 6 Southeast, 8 Southwest) or across the entire contiguous US (n = 7). Their knowledge spanned 20 states (AZ, CA, CO, KY, MA, MD, ME, MI, MN, ND, NM, NY, OR, PA, SD, TN, TX, VA, WI, and WV). We conducted semi-structured group interviews over video conference with experts from the same area (e.g., a state or multi-state area). During these interviews we shared our initial results and solicited group feedback on how they perceived the accuracy, feasibility, desirability of co-benefits, and potential barriers (e.g., costs, cultural constraints) of our different opportunity classes. A consistent refrain across geographies was that restoration of forest cover in wetlands was infeasible, for example, because those areas resulted from beaver damming that would not be removed or because the permits required would be very difficult to acquire. We therefore removed the NLCD wetland classes from our final areas of opportunity.

We followed up on the group interview with an online survey (questions in Table S4), which we sent to individuals and that collected answers anonymously. We constructed the survey questions to collect targeted information related to feasibility. For example, we only asked about the feasibility of a subset of opportunity classes, for which additional information was needed to better understand enablers and constraints. Of the 60 participants, 37 followed up by answering the more structured online survey. The online survey was sent to individuals and responses were anonymized. When numbers are reported in results, they stem from the online survey, but we also used qualitative information from the group interview to contextualize the results.

The Nature Conservancy has rules ("standard operating procedures") in place to ensure that all research involving human subjects is conducted ethically and with respect for those being asked to participate in the research. We followed all procedures and determined that, because we were not collecting data on the individuals themselves, our research did not need additional review to proceed. Documentation is available from the Lead Contact upon request.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.11.013.

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AUTHOR CONTRIBUTIONS

S.C.C.-P., T.G., S.M.L., P.W.E., B.W.G., and J.E.F. conceived and designed the research. T.G., O.A., and J.P. conducted GIS analyses. S.M.S. and S.C.C.-P. conducted the visual assessment. S.C.C.-P., T.G., and S.M.L. conducted feasibility analyses. A.D. conducted the economic analyses. J.L.McG. provided corridor data and advised on the analysis. S.C.C.-P. and T.G. conducted all remaining analyses. S.C.C.-P., T.G., A.D., S.M.Y., and J.E.F. analyzed the results. S.C.C.-P., T.G., and A.D. wrote the first draft of the manuscript and all authors contributed to revisions.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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