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Nature-Based Solutions Can Compete with Technology for Mitigating Air Emissions Across the United States

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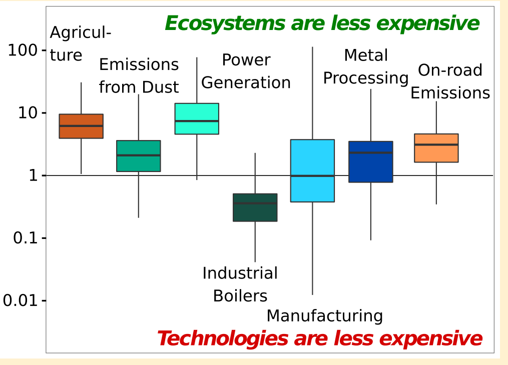
Supporting Information

ABSTRACT: Despite the proliferation of control technologies, air pollution remains a major concern across the United States, suggesting the need for a paradigm shift in methods for mitigating emissions. Based on data about annual emissions in U.S. counties and current land cover, we show that existing forest, grassland, and shrubland vegetation take up a significant portion of current U.S. emissions. Restoring land cover, where possible, to county-level average canopy cover can further remove pollution of SO_2, PM_{10}, $PM_{2.5}$, and NO_2 by an average of 27% through interception of particulate matter and absorption of gaseous pollutants. We find such nature-based solutions to be cheaper than technology for several National Emission Inventory sectors. Our results with and without monetary valuation of ecological cobenefits identify sectors and counties that are most economically attractive for nature-based solutions as compared to the use of pollution control technologies. We also estimate the sizes of urban and rural populations that would benefit from this novel ecosystem-based approach. This suggests that even though vegetation cannot fully negate the impact of emissions at all times, policies encouraging ecosystems as control measures in addition to technological solutions may promote large investments in ecological restoration and provide several societal benefits.



1. INTRODUCTION

Control and removal of criteria air pollutants is essential for maintaining air quality and preventing human and ecological harm.[1] Air quality across the U.S. has improved drastically since the Clean Air Act of 1970 due to technological and policy advances. Still, an estimated 166 million individuals representing more than half the population live in regions that have either high levels of ground level ozone (O_3) or particulate matter (PM) pollution and fail to comply with the maximum allowable limits.[2]

With increasing realization of the importance of ecosystems for sustaining human well-being,[3,4] there is growing interest in understanding how "Nature-Based Solutions" (NBS) such as "green infrastructure" can meet human needs by providing services like air quality regulation,[5] climate regulation,[6] and preventing soil erosion.[7] The International Union for Conservation of Nature (IUCN) defines nature-based solutions as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Previous studies have quantified the capacity of urban trees to remove air pollutants,[8−10] often in a more cost-effective manner than conventional control measures.[8,11,12] However, the focus of such studies is mainly on the role of nature in supplying ecosystem services, whereas the demand created for these services by emissions from human activities and the ecological capacity are not always considered. Ecological capacity is the ability of an ecosystem to provide goods and services while maintaining current conditions. Comparison of the demand and supply of ecosystem services can provide unique information about a "safe operating space" analogous to planetary boundaries.[13] This can help quantify "absolute sustainability" metrics and identify innovative opportunities for reducing ecological overshoot to ensure environmental sustainability.

In previous work,[14] we considered emissions from about 20,000 point sources across the U.S. and the capacity of restored vegetation (trees) on land available within 500 m of the source to capture emissions equivalent to emissions occurring at each source. We showed that the uptake capacity after such restoration is comparable to the emissions from point sources at many locations. However, that work only considered about 2% of U.S. emissions, and it did not consider other vegetation classes such as grasslands and shrublands

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which are predominant in many regions of the Great Plains and Great Basin. In this work, we consider all sources of emissions including point and nonpoint sources aggregated at the county scale and the capacity of current (trees, grasslands, and shrublands) and restored vegetation to mitigate emissions of sulfur dioxide (SO_2), PM_{10}, $PM_{2.5}$, and nitrogen dioxide (NO_2). These vegetation classes are considered as nature-based solutions to provide air quality regulation ecosystem service. O_3 is not considered in this work due to the lack of data on its formation and emissions data from different sectors. For the scenario of restored vegetation, we consider a case where grasslands and shrublands are restored to the average current canopy cover within each county making it analogous to restoring native vegetation. We consider nine climatic regions across the lower 48 states and an active restoration scenario to a hybrid ecosystem with the goal of maintaining native canopy composition while providing multiple ecosystem services.[15] Active restoration is an approach where management techniques such as planting, weeding, and a range of other human interventions take place to accelerate and influence the recovery of ecosystems.[16] In addition to this biophysical analysis, we also analyze the cost and societal impact of ecological restoration. For various economic sectors, we compare the costs of technological versus nature-based solutions to improve air quality. We also assess the benefits of adopting such an approach to populations across the country. We demonstrate the many benefits of relying on vegetation for mitigating selected criteria air pollutants in terms of net emissions, cost of conventional technological alternatives, and human health benefits. In the rest of this paper, the next section describes our approach and sources of data. This is followed by a description of the results, and finally, a discussion of the findings and opportunities for future work.

2. METHODS AND DATA

2.1. Techno-Ecological Synergy (TES) Framework. In this work, we calculate local sustainability of the *i*-th ecosystem service by the following formula based on the fraction of emissions sequestered in each county,[17]

$$V_i = \frac{S_i - D_i}{D_i} \tag{1}$$

Here D_i represents the emitted quantity of the pollutant, which is the ecosystem service demand created by technological systems for pollutant *i*. Variable S_i represents the supply of ecosystem service for pollutant *i*. This is the capacity of the ecosystem to take up the relevant pollutant. A negative value of V_i indicates that the current level of emission overshoots the carrying capacity of ecosystems at the county level, while a positive value indicates that current level of emissions is within the carrying capacity for the region in the selected time period. Values of V_i calculated based on the current vegetation cover indicate the extent of overshoot of emissions over the current and future sequestration capacities, S_i^* and S_i^{**}, respectively. While determining the potential sequestration and sustainability index, we assume that the demand (emissions) density during and after the restoration period is the same as the current demand density. This metric is analogous to metrics for absolute sustainability in life cycle assessment.[18,19]

2.2. Ecosystem Service Demand. The 2011 National Emissions Inventory[20] contains data on emissions of hazardous and criteria air pollutants from 60 emissions inventory system (EIS) sectors for each county in the U.S. We consider four primary criteria air pollutants, SO_2, PM_{10}-primary, $PM_{2.5}$-primary, and NO_2. Emissions sources from these sectors include point sources like industrial processes, fuel combustion units; mobile emission sources like on-road and nonroad vehicles, aircraft and marine vehicles; nonpoint sources like agricultural activities, biogenic soil emissions, waste disposal, etc. Columns 1 and 2 in Supporting Information (SI) Table S1 list the different sources of emissions along with the EIS sector numbers. 3,109 counties located in the conterminous U.S. are considered in this analysis. SI Figure S1 shows the nine regions based on the homogeneity of climatic conditions within the states and the climatological map developed by the National Oceanic Atmospheric Association (NOAA).

SI Figure S2 depicts the current demand density for all the four pollutants calculated based on the emissions and land area of each county. The figures were prepared in ArcGIS using a county-level boundary map from ESRI.[21] To enable easier access to the visualization, we have created interactive maps that contain county level values.[22] Currently, PM_{10} and NO_2 are emitted in the highest quantity (mass units), followed by SO_2 and $PM_{2.5}$. Contribution to NO_2 emissions in most regions except counties in the West North Central is primarily from on-road combustion of gasoline in light duty vehicles and from electricity generating units using coal-based fuels. In the West North Central, highest contribution to emissions is from soil and vegetation. Combustion of diesel used in nonroad heavy equipment and coal used in electricity generating units also contribute to NO_2. Highest contribution to PM_{10} emissions in all regions except East North Central is from dust stirred up from unpaved roads caused by dust blown off the surface during windy conditions. PM emissions in the East North Central region are from agricultural crops and livestock dust. Another major contributor to PM emissions, especially finer particles like $PM_{2.5}$ is wildfire and prescribed burning. This contribution is more common in the West, South West, and South East regions including states like California, Nevada, Georgia, Texas, Kansas, and Arkansas. Contribution to SO_2 emissions is primarily from coal burning sectors including electricity generating units and from other stationary sources like petroleum refineries, and oil and gas production units. Note that intercounty transport of pollutant molecules due to flow of air mass across county borders and hence the variation in ecosystem service demand is not considered in this work. The demand is thus based on sector-level emissions of different pollutant molecules.

2.3. Geographic Land Cover Analysis. Information about current canopy, grassland, and shrubland cover and the availability of land for restoration was estimated from the 2011 National Land Cover Database (NLCD).[23] Land types classified as "scrub/shrub" (category 52) and as "grassland/herbaceous" (category 71) were considered as areas that can be restored with vegetation species native to that region. These land categories are dominated by shrubs, short trees, and grasslands that are not subject to any intense tilling or management practices.[23] Land classified as "pasture/hay" (category 81) which includes legumes planted for livestock grazing and "cultivated crops" (category 82) which includes land for production of annual crops were not considered in this work to avoid interference with land allocated for food and grain production.

Changes in the precipitation pattern across the country and within each county can cause major changes in land type,

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development patterns, tree growth, and productivity. To control for this effect, only land areas within each county that receive more than 500 mm of precipitation annually were considered to be available for restoration.[24] Precipitation data for each county were obtained from the PRISM database based on the 30 year normal annual precipitation from years 1981 to 2010.[25]

A rural and urban parameter index was assigned to the available land within each county based on the geographical distribution of population. The 2010 urban census data was used to assign these indices in each county. According to the census classification, areas with at least 2,500 people with at least 1,500 residing outside institutional group quarters are classified as urban areas.[26] The reason behind assigning a rural or urban index to counties was to account for the differences in sequestration rates of air pollutants by vegetation. Rural areas tend to have higher sequestration rates for certain pollutants than urban regions. Thus, restoration benefits also vary depending on rural or urban areas.

To estimate the current benefits provided by vegetation cover, we used land areas classified as “evergreen forests”, “deciduous forests”, and “mixed forests” under categories 41, 42, and 43, respectively, and land classified as “grasslands/herbaceous”, and “shrublands” under categories 71 and 52, respectively. A 30 × 30 m resolution was used to calculate the number of pixels within each county for estimating current vegetation cover (canopy, grasslands, and shrublands) and land that can be restored.

In general, it was observed that counties in the South East, North East, North West, and some parts of the West North Central regions have more canopy cover than most counties in the Central and Western regions that are dominated by croplands, as shown in SI Figure S3a. Grassland cover was found to be highest in the West North Central and Southern regions, as shown in SI Figure S3b. Shrubland cover was highest in the Western and South Western regions including states like Colorado, Nevada, and California, as shown in SI Figure S3c. SI Figure S3d is a map of counties where conversion of grasslands and shrublands to county-average canopy cover is feasible based on the total county area. Land areas marked in white represent counties where restoration is not feasible due to the precipitation constraint. Shrublands and grasslands were considered to be available for restoration since studies on land conversion from 1973 to 2000 in the eastern U.S. have shown that canopy cover gain has been highest from these land covers.[27] While restoration of canopy cover on agricultural land and development of agroforestry systems can contribute significantly to improvement of some ecosystem services, primarily carbon sequestration,[28] we considered only land areas that do not interfere with food and grain production or urban development, and have an annual precipitation greater than 500 mm. The total restorable area ranges from 0 to 1.14 million hectares (0−74% of county area) across U.S. counties with a median value of 7,368 ha (SI Figure S3d). We considered active restoration to county-average vegetation based on species that are native to a region. We are also not assuming the creation of forests in regions where they do not grow naturally.

2.4. Supply of Ecosystem Services.

2.4.1. Forest, Shrubland, and Grassland Ecosystems. To estimate the air quality regulation ecosystem service provided by current vegetation cover and from areas where restoration of land is feasible, sequestration of pollutants by canopy, grasslands, and shrublands were estimated individually. The i-Tree canopy database[29−31] contains comprehensive estimates of air pollution sequestration by forest, shrubland, and grassland cover in rural and urban regions in the lower 48 states. Gaseous pollutants enter leaves via the leaf stomata, while PM is deposited on the leaf surface. Uptake of pollutants (pollutant flux to vegetation) on the vegetative surface is estimated as a function of the deposition velocity of each air pollutant on the leaf surface, local ambient air concentration and local meteorological conditions. The daily Leaf Area Index (LAI) throughout a year estimated from the maximum (midsummer) LAI with local leaf-on/off dates within each county was used to determine the sequestration rate of pollutants. County-level median LAI for each land class was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) database.[32] Using the i-Tree Eco model,[33] we quantified the annual dry deposition rates by grasslands (SI Figures S4−S7), shrublands (SI Figures S8−S11), and forestland (SI Figures S12−S15) in $g/m^2/yr$ in both rural and urban areas. We used these values to map the current and potential supplies of the air quality regulation service for the four emissions (SI Figures S16 and S17) in 3,109 counties. We considered only removal of pollutants by dry deposition on vegetative surfaces similar to i-Tree Eco. Removal of pollutants from the atmosphere via wet deposition (e.g., precipitation scavenging) plays a dominant role in removal of certain pollutants such as nitrates and sulfates,[34] but is not a focus of this study. Other effects of increasing canopy cover such as changes in atmospheric recycling pattern, changes in wet deposition, and dynamics of ecological systems are beyond the scope of this study.

Flux for each pollutant was estimated as,

$$F = U_d \cdot c \tag{2}$$

where U_d is the deposition velocity of the pollutant (ms^{-1}) and c is the pollutant concentration in (gm^{-3}). Hourly pollution concentration data were obtained from the U.S. EPA’s Air Quality System national database for the year 2010[35] from the monitor closest to the rural or urban area for a county. For missing PM concentration data, daily and 6-day measurements were used to represent hourly concentration values through the day. The deposition velocity is calculated as an inverse sum of the aerodynamic (R_a), quasilaminar boundary layer (R_b), and canopy resistances (R_c) as,

$$U_d = (R_a + R_b + R_c)^{-1} \tag{3}$$

Hourly weather information including parameters like ambient temperature, dew point temperature, pressure, wind speed, sky cover, and ceiling height obtained from the National Climate Data Center (NCDC)[36] for the year 2010 were used to determine R_a and R_b in units of s/m. Canopy resistances (R_c) were estimated as a function of soil resistance, cuticular resistance, and mesophyll resistance in s/m. More information on the calculation of deposition velocity and the resuspension rate for PM can be found in refs 5, 29, 37, and 38.

2.4.2. Current and Potential Ecosystem Service Supply. Based on the pollutant flux for canopy, grasses, and shrubs, the current supply of air quality regulation ecosystem service for pollutant i was estimated as the product of pollutant flux per unit of vegetation cover F ($gm^{-2}s^{-1}$) and the area of vegetation cover in each county Λ_j (m^2). For brevity, we do not explicitly include a county index; however, all calculations were done for rural ($m = 1$) and urban ($m = 2$) areas at the

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county level. For each vegetation type, the current supply (in kg) of an ecosystem service is calculated as

$$S_i^* = 0.001 \sum_{m=1}^{2} \sum_{j=1}^{3} (\Lambda_{j,m} \cdot F_{j,i,m});\ i = 1,2,3,4 \quad (4)$$

where j represents canopy, grassland and shrubland cover, and i represents SO_2, PM_{10}, $PM_{2.5}$, and NO_2.

To determine the maximum restoration potential for each county, first the maximum land area Λ_m^{max} (in m^2) that has to be restored (maximum land footprint) to capture all emissions was calculated. This footprint was calculated as a function of total emissions of a pollutant within each county and the sequestration rate of each pollutant by woody vegetation cover as,

$$\Lambda_m^{max} = \max_i \left(1000 \frac{D_{i,m}}{F_{1,i,m}} \right);\ i = 1,2,3,4;\ m = 1,2 \quad (5)$$

For some counties, the maximum land footprint exceeds the land available for restoration and hence the minimum land that can be restored Λ_m^{total} (in m^2) to mitigate pollutants from the atmosphere equivalent to emissions was estimated as

$$\Lambda_m^{total} = \min(\Lambda_m^{max}, \Lambda_m^{avail}) \quad (6)$$

where Λ_m^{avail} is the maximum rural or urban land available for restoration (in m^2) within each county. This is calculated as the total area of grasslands and shrublands that can be restored,

$$\Lambda_m^{avail} = \sum_{j=2}^{3} \Lambda_{j,m} \quad (7)$$

Potential pollutant removal benefits due to conversion to county-average canopy cover was then calculated as the sum of product of minimum land area that can be restored in each county and the sequestration potential of each pollutant in rural and urban areas and added to the total current sequestration by forests.

$$S_i^{**} = 0.001 \sum_{m=1}^{2} (F_{1,i,m}(\Lambda_m^{total} + \Lambda_{1,m}));\ i = 1,2,3,4 \quad (8)$$

where S_i^{**} (in kg) represents the total potential ecosystem service supply after restoration. SI Figure S17 depicts the supply density graph of air pollutants calculated based on the land area within each county after restoration. Notice that the scale in SI Figure S2 is different from the scale in SI Figures S16 and S17.

For some pollutants such as PM_{10} occurring from ground-level sources (road-dust and livestock dust), sequestration potential of grasslands and shrublands will be higher since these emissions occur at a lower height than forest canopy. With restoration to county-average vegetation, this study would be underestimating sequestration of PM_{10} occurring from all sources (including ground-level and elevated sources) since shorter vegetation would receive a bulk of the PM_{10} emissions occurring from ground-level sources compared to canopy. Given the spatial extent of this study, we do not have enough details to capture dispersion of pollutants from each type of source in order to determine the effectiveness of canopy vs grasslands or shrublands.

The sequestration capacity of different vegetation classes is based on the county-level rural or urban sequestration rates, and these values are considered to be constant across each area of consideration. Typically, sequestration rates are highly variable and depend on multiple factors. Considering sequestration capacity in near real-time is beyond the scope of this study, and is a potential limitation of this work.

2.5. Cost Calculations. Cost estimates of nature-based solutions and technological options were obtained at the sector and county levels. Cost-effectiveness of nature-based solutions at the sector level was estimated based on the ratio of annualized equipment cost by annualized restoration cost for the same amount of emissions taken up by restoring 1 ha of land in each county. Cost-effectiveness at the county level was based on the total annualized cost of equipment and total annualized restoration cost for mitigating pollutants based on either the maximum amount of emissions within a county or the maximum sequestration potential, depending on the smaller quantity among the two. For both the cost-effectiveness calculations, sectors that had no equipment for pollution control, sectors with no information on costs, and counties where restoration is not feasible were ignored.

2.5.1. Technology Costs. Technological costs for conventional air pollution control equipment as an add-on device were based on the Control Strategy Tool (CoST) database[39] developed as a part of the Emissions Modeling Framework (EMF). This database provides detailed engineering costs associated with the Best Available Control Technology (BACT) to mitigate area, point, and mobile emission sources primarily for criteria air pollutants. Cost estimates for BACTs were based on technological design variables for each emission source or on cost factors in terms of mass of pollutant mitigated on an annual basis depending on data availability. Since detailed design parameters for emission sources were not available, the latter approach based on cost factors for each control technology was used.

Control equipment for each sector was chosen based on the BACT that had the least cost and highest control efficiency (maximum emission reduction) of each pollutant for different sectors. Cost factors for mitigating $PM_{2.5}$ are included in the cost of control for PM_{10}. However, for sectors where only $PM_{2.5}$ emissions exist, cost of control for PM_{10} was used. An equipment lifetime of 20 years with zero salvage value at the end-of-life and interest rate of 7% was used in the cost calculations. Equipment cost from the CoST database for the years between 1990−1999 was used. Producer Price Index (PPI) for air purification equipment sector (WPU1147)[40] was used to convert the cost values from the base year to 2011. SI Table S1 provides more details on the cost factors used for different sectors.

Total cost associated with control equipment (α_i^{eq}) at the county-level was calculated by accumulating individual equipment costs for each sector starting with the sector that had the lowest annual equipment cost per unit mass of pollutant. Individual equipment cost for each pollutant and sector was calculated for mitigating all the air emissions for that sector (total demand) or the same quantity of emissions based on the maximum possible restoration area, whichever is least. Algorithm 1 in the SI was used for calculating the total cost of equipment for each county.

Thus, the total equipment cost (in $) in each county was based on the sector that had the lowest or cheapest cost, and equipment costs were accumulated based on individual sector costs and total sectoral emissions, until the limit on total available supply or total demand was reached.

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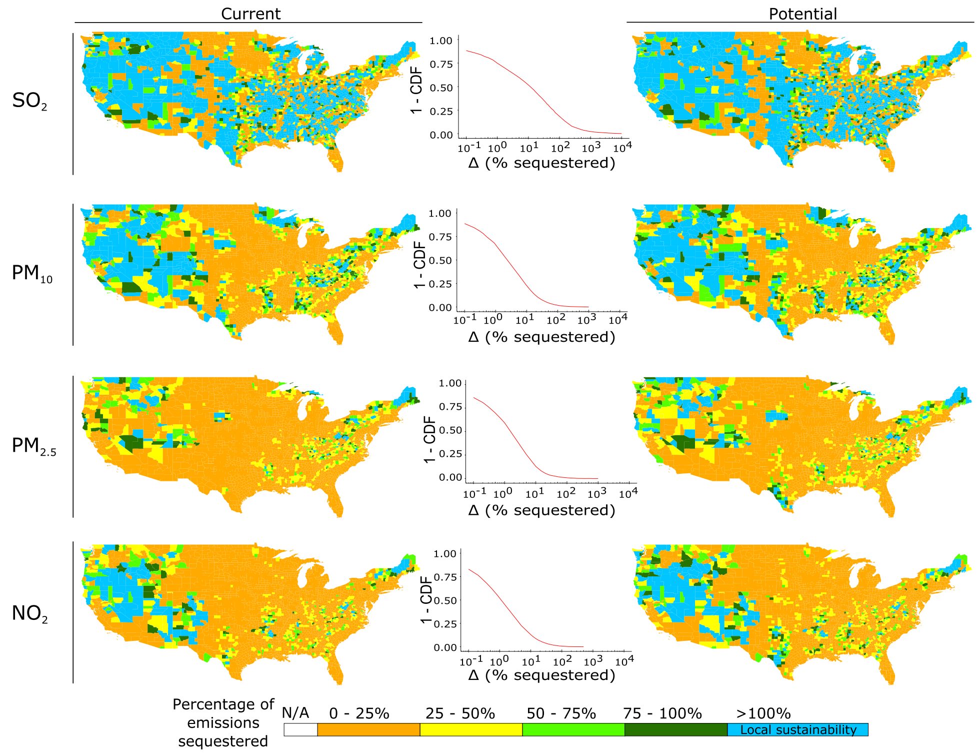

Figure 1. Current and potential sequestration of air emissions. The left and right panels represent the current and potential percentage of emissions sequestered by current canopy, grasslands, and shrublands for four pollutants, respectively. The potential sequestration (right) considers conversion of land classified as grasslands and shrublands, not allocated for food-production, to county-level average canopy cover where annual precipitation is more than 500 mm per year. The middle panel shows the percentage change in sequestered emissions due to restoration. (Survival Function = 1 − Cumulative Distribution Function). Interactive maps are also available.[21,22]

2.5.2. Restoration Costs. Costs for converting grasslands and shrublands to county-average canopy cover by active restoration were estimated based on county-wide site preparation cost and decadal management cost on an annual basis. These costs were also based on regional cost estimates for land conversion to timberland.[41] Even though the objective of our study is not to restore grasslands and shrublands to timber land, restoration costs available from this study[41] provided the best cost estimates for conversion to county-average canopy cover. This study accounted for the spatial variation of the dominant tree species in each region and accounted for different management intensities depending on land use and land management options at the national level. Dominant canopy types in different regions were based on the forest inventory data for reforested land obtained from Forest and Agricultural Section Optimization Model (FASOM).[42] Even though these species appear to be the dominant canopy types in the FASOM model, the study assumes cost estimates of these dominant categories to be representative of restoration costs in that region. Only cost of conversion to county-average canopy cover is included in these calculations and the current canopy cover is assumed to have no maintenance cost associated with it. All the 48 states were split into nine different timber producing regions, and site preparation and management costs were based on planted management practices without intensive intermediate treatment as listed in SI Table S2. Cost estimates for planting and management reported in this study are for early 2000s, and hence there is a potential for these costs to be higher in recent years, making restoration costs higher than what is reported in this study.

Since restoration activities were considered over a 20 year period, we assumed that the land value is recovered at the end of year 20. In other words, since land cost does not depreciate over the years, we assumed that the land value after restoration is equal to the initial purchase cost of land thus canceling out the land costs during the restoration period.

Restoration cost for each county was calculated as,

$$\alpha^{R} = 2.47 \times 10^{-4}((\alpha^{SP})(\Lambda^{total})a_{f} + (\alpha^{M}\Lambda^{total})) \tag{9}$$

where, α^{R} represents the restoration cost (in \$), α^{SP} is the site preparation cost per acre (in \$/*acre*), a_f represents the annualization factor with a 20 year lifetime and 7% interest rate and α^{M} represents the annual management costs per acre (in \$/acre). Total restorable land is converted from units of m^2 to acre.

2.5.3. Cost Ratios. To determine cost ratios at the sectoral-level, we aggregated the 60 sectors into a total of 16 sectors based on the primary EIS. These include Agricultural Sector (Sector 1); Emissions from Dust (Sector 2); Commercial Boilers (Sector 3); Electricity Generating Units (Sector 4); Industrial Boilers (Sector 5); Residential Sector (Sector 6); Manufacturing (Sector 7); Metal Processing (Sector 8); Mining, Oil, and Gas (Sector 9); Industrial NEC and Storage & Transfer (Sector 10); Non-Industrial NEC (Sector 11); Non-Road Emissions (Sector 12); On-Road Emissions (Sector 13); Other Mobile Emissions (Sector 14); Solvent (Sector 15); and Miscellaneous Emissions (Sector 16).

Cost ratio of technological to ecological solutions for each sector (disaggregated) in each county was calculated as,

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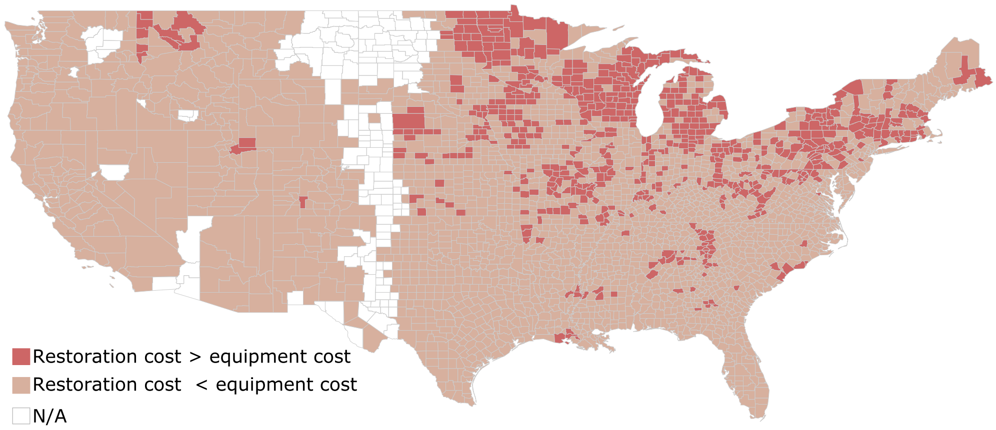

Figure 2. Map representing the counties where cost of conversion to canopy is lower than cost of installing control equipment for the equivalent ecosystem service supply provided by trees in each county.[21,22]

$$C_1 = \frac{\sum_{i=1}^{4} 10\alpha_{i,1}^{S} F_{1,i}}{0.4046(\alpha^{SP} a_f + \alpha^{M})} \quad (10)$$

where $F_{1,i}$ represents the county-level average canopy sequestration from rural and urban areas and $\alpha_{i,l}^{S}$ is the equipment cost for sector l and pollutant *i*. The equipment cost is converted to units of \$/ha, whereas the restoration cost is converted from a per acre to per hectare basis. The cost ratio for each sector is based on the equipment cost for sequestering emissions equivalent to the quantity of supply from restoring a hectare of land in each county and the restoration costs for the same.

2.5.4. Subsidies from Ecosystem Services after Restoration. Due to the multifunctional behavior of vegetation to provide multiple ecosystem service benefits, we included additional benefits of air quality regulation ecosystem service as monetary subsidies in the cost calculations. Subsidies were calculated for the additional pollutants sequestered for sectors where no equipment for pollution control are available or sectors that do not have cost values associated with pollution control ($\overline{F}_{1,i}$). Thus, sequestration of emissions by nature-based solutions from sectors that do not have a technological counterpart or from sectors with no cost information for technological systems provide additional benefits, and are included as subsidies. These include sectors that were eliminated from the cost ratio calculations in eq 10. These subsidies or ecosystem service benefits for sequestering excess pollutants were obtained from the U.S. Environmental Protection Agency's BenMAP program. This program provides an estimate of monetary benefits associated with a reduction in concentration of criteria air pollutants in the atmosphere calculated based on the reduction in incidences of adverse health effects. County-level BenMAP estimates from the i-Tree Eco tool was used to calculate the monetary benefits.[43,44] The cost ratio was calculated as the ratio of annualized equipment cost to annualized restoration cost less subsidies as,

$$C_l^S = \frac{\sum_{i=1}^{4} 10\alpha_{i,l}^{S} F_{1,i}}{\max\left(0, \left[(0.4046(\alpha^{SP} a_f + \alpha^{M})) - \sum_{i=1}^{4} (10\overline{F}_{1,i} B_i)\right]\right)} \quad (11)$$

Here B_i represents the BenMAP benefits associated with additional pollutant sequestration. BenMAP numbers were highest for $PM_{2.5}$ followed by PM_{10} mainly due to health benefits from reduction of incidences like respiratory illness and lower mortality rates with improvement in air quality.

3. RESULTS AND DISCUSSION

3.1. Biophysical Estimates. We combine the annual supply and demand of air quality regulation service to determine the current and potential (post-restoration) fraction of emissions sequestered in each county. As shown in Figure 1, we find that forest, grassland, and shrubland vegetation take up 14%, 30%, 10%, and 11% of current SO_2, PM_{10}, $PM_{2.5}$, and NO_2 emissions, respectively. Furthermore, restoring land cover where possible to the county-level average canopy cover increases dry deposition sequestration of SO_2, PM_{10}, $PM_{2.5}$, and NO_2 by 24%, 23%, 37%, and 24%, respectively. As can be seen from the left panel of this figure, the Western U.S. shows greater potential to mitigate emissions than the Southern or Northern regions, and that current percentage of sequestered emissions is higher for SO_2 and lower for PM_{10}, $PM_{2.5}$, and NO_2 progressively. Overall, ecosystem service supply after restoration exceeds the demand for 49% of counties for SO_2, 13% for PM_{10}, 4% for $PM_{2.5}$, and 5% of the counties for NO_2 as marked in cyan in the right panel in Figure 1. Furthermore, after restoration the ecosystem service supply can meet more than 50% of the county-level demand for about 60% of counties for SO_2, 26% for PM_{10}, 12% for $PM_{2.5}$, and 13% for NO_2 as marked in cyan, light, and dark green in the right panel of Figure 1. All these maps are also available online.[22] Insets in the middle panel of Figure 1 indicate that the change in percentage of emissions sequestered in relation to current demand increases by up to 10% for at least 51% of the counties for SO_2, 23% for PM_{10}, 13% for $PM_{2.5}$, and 13% for NO_2. Thus, even though the current demand for air quality regulation ecosystem service is significantly higher than the supply, the capacity of vegetation to offset air emissions is still substantial in some areas, and could be adopted as a nature-based solution to mitigate pollution.

3.2. Cost Estimates. Figure 2 represents a map of counties where restoration is more cost-effective than control equipment to meet ecosystem service demand. County-level cost values for the total equipment cost were calculated using algorithm 1 in the SI, and county-level restoration costs were calculated using eq 9. The regions marked in white are the counties where restoration is not feasible, whereas the regions in brown are the counties where restoration is more cost-effective than control equipment. From this map, it can be seen

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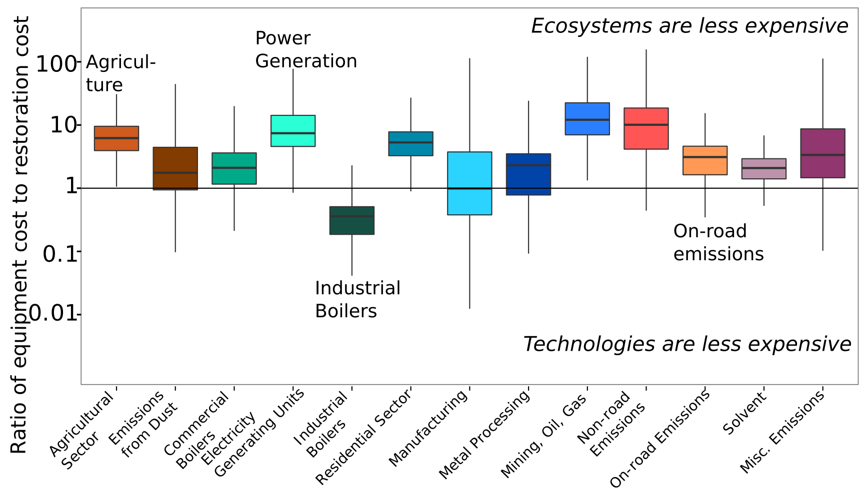

Figure 3. Ratio of annualized equipment cost per sector to annualized restoration cost per hectare of land in each county to take up equal quantities of emissions. Equipment costs are calculated based on the Best Available Control Technology for each sector. Restoration costs include site preparation and annual maintenance costs. Cost ratio of more than one indicates that restoration is more economical than control technology to improve air quality. Sectors 10 and 11 (Storage and Transfer and Nonclassified Industrial sectors) are not included since these sectors do not have any associated control equipment, making ecosystems the default option for sequestering emissions.

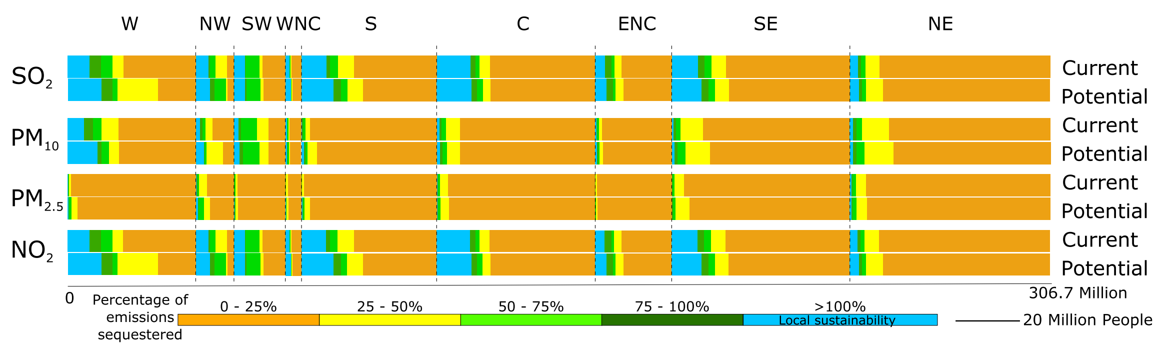

Figure 4. Number of people in each region who benefit from sequestration of pollutants by vegetation based on the current land cover and total potential land cover after restoration. The color of each bar represents the extent of mitigation corresponding to Figure 1.

that for more than 75% of the counties, restoration is more cost-effective to reach average net zero emissions. Counties in the North East, Central, and East North Central marked in red represents counties where restoration is not cost-effective. These represent counties where cost of equipment is much cheaper than restoration costs or regions where land available for restoration is very low.

Counties where restoration is infeasible and sectors with no equipment available for either pollutants were eliminated while calculating the cost ratios. These include Biogenic Emissions (Sector 4); Bulk Gasoline Terminals (Sector 5); Fires, Prescribed Burning (Sector 11); Fires, Wild Fire (Sector 12); Residential Sector, Natural Gas (Sector 28); Residential Sector, Other (Sector 30); Industrial Processes, Mining (Sector 36); Industrial Processes, NEC (Sector 37); Industrial Processes, Nonferrous Metal (Sector 38); Industrial Processes, Oil & Gas Production (Sector 39); Industrial Processes, Storage & Transfer (Sector 42); Industrial Processes, Non-NEC (Sector 43); Mobile Emissions, Aircraft (Sector 44); Mobile Emissions, Marine Vessels (Sector 45); and Mobile Emissions, Locomotives (Sector 46). For sectors where no control equipment exists, nature-based solutions were considered to be the default option for reducing emissions.

For each county, we identified individual sectors that are most suited for adopting NBS. We used eq 10 to calculate the ratio of the lowest cost of equipment from appropriate sectors to remove the same quantity of pollutants as can be taken up by one hectare of restored land. These ratios are plotted on a log scale in Figure 3. In some counties even though restoration is possible we observe that nature based solutions are not cost-effective for sectors. This includes sectors like industrial boilers, some manufacturing activities, some activities that emit dust, and some metal processing activities that contribute 0.49%, 0.12%, 7.91%, and 0.13%, of total U.S. emissions, respectively. While these represent the top few sectors for which nature-based solutions are not cost-effective at the national scale, we also observe regional variation in cost-effectiveness across different sectors. In general, we find that nature-based solutions are more expensive than conventional equipment for sectors that have primarily PM emissions (SI Figure S18). For these sectors, the low rate of sequestration of pollutants like $PM_{2.5}$ by vegetation results in lower cost for technological solutions. However, by considering the monetary value of sequestration of additional pollutants by vegetation compared to its technological counterpart, the cost ratio of these sectors becomes closer to 1 (SI Figure S19). Variations in cost ratios also arise from differences in dry deposition rates across counties, and the cost of BACT for different sectors.

SI Figure S18 represents the regional cost ratio for different sectors. Similar to Figure 3, cost ratios are represented on a log

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scale in this figure. From the figure, nature-based solutions are more expensive than control equipment for sectors 5 (Industrial Boilers) and 7 (Manufacturing) in all the regions except the South for sector 7 (Manufacturing). This same trend was observed at the national level, as represented in Figure 3. Emissions primarily include $PM_{2.5}$ and PM_{10} from all Industrial Boiler EIS sectors and the Paper and Pulp Manufacturing sectors. Sectors 3 (Commercial Boilers), 4 (Electricity Generating Units), 8 (Metal Processing), and 15 (Solvent) show a significant variability in results with respect to the cost ratio. This variation is primarily due to differences in restoration costs, the total quantity of emissions sequestered within each county as well as difference in equipment costs for each individual EIS sector. These cost ratios, however, do not consider the supply of additional ecosystem services besides air quality regulation provided by vegetation.

Cost ratios with subsidies included were calculated as described in Section 2.5.4 by eq 11. SI Figure S19 depicts the regional cost ratio (log scale) with subsidies subtracted from restoration costs. Inclusion of subsidies in restoration cost impacts sectors that primarily emit only PM_{10} and $PM_{2.5}$. This includes sectors like Manufacturing, Industrial Boilers, Electricity Generating Units, and Metal Processing. For these sectors, benefits from subsidies exceed the restoration cost and sometimes results in a restoration cost of zero.

3.3. Population Benefits. Population benefits from restoration in terms of number of people were estimated based on the 2010 census[26] for rural and urban areas. Figure 4 depicts the number of people in each region who benefit from sequestration of pollutants by vegetation based on current land cover and based on the land cover after restoration. The length of each block is proportional to the total population in each region, and the bars are classified according to different extents of mitigation. An increase in the length of each bar indicates an increase in the number of people who live in areas that have a smaller net impact of air pollution. These results indicate that between 74 and 98% of individuals live in counties where vegetation takes up less than 50% of air emissions. Also, most of the population that resides in counties where mitigation capacity after restoration is more than emissions are in regions in the South and West, including states like California, Texas, Kansas, Louisiana, Colorado, and Arkansas. At the national scale, about 19% of the population in rural areas and about 74% of the population in urban areas benefit from an increase in ecosystem service supply with restoration. Even though availability of land for restoration is higher in rural areas, people living in urban areas would benefit more from the presence of trees. We also calculated the total population that would benefit from up to 50% of pollution sequestration in each county after restoration. Based on these calculations, a median value of 7.8 million people in rural areas and a median value of 6.8 million people in urban areas benefit from restoration. In general, benefits from SO_2 and PM_{10} sequestration were higher in urban areas than in rural parts of the country.

While the numbers reported here only account for the population benefits, improvement in air quality in most regions provides significant other benefits to the population including reduction in respiratory related health incidences (as quantified in the BenMAP numbers and SI Figure S19), improvement in visibility, and other recreational benefits which are currently underestimated in this study.

3.4. Discussion. Despite the important role in improving air quality by the conversion of grasslands and shrublands to the current average canopy cover, such change in land use can also have some negative effects. For example, it may compromise the availability of other ecosystem services due to reduced habitat for grassland species,[45] decreased streamflow, and changes in soil and water quality.[46] In addition, even if vegetation can take up all pollutants emitted over a year, it does not imply that there will be zero impact due to the emissions. This is because the dynamics of emissions and their environmental and societal impact are different from the dynamics of mitigation by vegetation. Such interaction is not considered in this work due to the static nature of the calculations. It is also important to note that technological systems achieve maximum removal capacity after they are implemented, while the removal capacity of vegetation increases slowly. Thus, the effectiveness of reforestation increases with time and should be considered as a long-term solution for pollution removal. This work does not consider the variable gas uptake capacity with time across each county since uptake capacity depends on many factors including seasonal changes, species composition, canopy structure, and height of the emissions source. Instead the study is static in nature and relies on the county level rural or urban sequestration rates. Nevertheless, our results clearly indicate that increasing awareness about NBS and ecological restoration can encourage greater use of these solutions for mitigating air pollution and increase provisioning of other ecosystem services.[47] Exploiting the synergy between ecological and technological systems[17] as demonstrated in this study is an innovative solution for both developing and developed countries to improve air quality in an economically feasible, societally beneficial, and environmentally sound way.

Realizing the benefits of NBS presents many challenges and opportunities. Setting up schemes that incentivize reforestation by providing income and other socio-economic benefits to land owners is important for such a large scale restoration to take place. One such scheme that could be adopted by local and state agencies is the Payment for Ecosystem Services (PES) scheme where financial incentives are provided to small and large-scale land owners for land conservation and restoration. Government agencies should also introduce more bills and policies that incentivize restoration options. Currently, the state of California has adopted Assembly Bill 1492 known as the Timber Regulation and Forest Restoration Program. The bill has established forest restoration grant programs and funding via a one-percent assessment on lumber and wood products sold at retail level. Expanding such schemes to several other states is an important step toward large scale restoration. Another opportunity is available due to the efforts of many university campuses, corporations, cities, and countries toward achieving carbon neutrality within the next few decades. Including reforestation or rewilding of available land in their climate action plans can be another way of achieving the benefits identified in this work.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b01445.

Tables S1−S3, Figures S1−S19, and Algorithm 1 (PDF)

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Notes

The authors declare no competing financial interest.

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