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RESEARCH ARTICLE

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A simple tree planting framework to improve climate, air pollution, health, and urban heat in vulnerable locations using non-traditional partners

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Societal Impact Statement

Planting trees is considered an effective method for climate change adaptation and mitigation. This framework provides a replicable blueprint to improve health, urban heat, flooding, and air pollution via a multisectoral, collaborative, environmental data-driven approach. Native tree species with targeted ecosystem services are selected, and sites are strategically identified based on environmental and health benefits, with the intent of engaging community involvement through education and large-scale tree plantings. Including non-traditional partners in the framework provides heightened awareness of the relationship between climate change and health, thus catalyzing decision-making regarding sustainable actions that reduce effects of climate change. This native tree planting framework is highly adaptable in other cities.

Summary

- A multidisciplinary framework is presented for a data-driven, climate change adaptation and climate change and air pollution mitigation project. This framework leverages heightened awareness of the connections between climate change, air pollution, and health to expand the cadre and societal impacts of those working to intervene in resilience planning and implementation.
- The framework, implemented in Houston, Texas, USA, beginning in 2019, consists of three parts: (1) identification of optimal native tree species for climate change adaptations and air pollution mitigation around variables important locally; (2) selection of large-scale native tree planting locations where populations are already disproportionately experiencing flooding, increased heat, and air pollution-related health effects that could be further exacerbated from climate change; and (3) engagement of multisectoral leadership broadened beyond those traditionally working on climate change resilience through heightening awareness of the link to human health.
- Native tree species were identified that had the highest combination of absorption of carbon dioxide, other air pollutants, and water absorption (aiding in flood adaptation and air pollution/heat mitigation). Thousands of the top tree species were planted in locations that experience substantial flooding during large rain events,

have high rates of health effects exacerbated by air pollution (e.g., cardiac arrest and asthma attacks), and experience multiple days of elevated heat and air pollution.

- This multidisciplinary framework addresses a critical need to provide interventions accessible to the community; educate on the connection between climate change adaptation, air pollution mitigation, and health; and foster multisectoral leadership to accelerate local resilience actions.

KEYWORDS
air pollution, carbon sequestration, climate change, ecosystem services, human health, population exposure, trees, urban heat island

1 | INTRODUCTION

Climate change has grave ramifications for the environment and human health. Imposing devastating impacts throughout the world, climate change is linked to unpredictable weather patterns, unbalanced growing seasons for agriculture, and destabilized ecosystems (U.S. Global Change Research Program, 2017). Climate change consequences—ranging from an increase in droughts and heat waves to sea level rise and flooding-related damages as well as diminished air quality—adversely impact human health morbidity and mortality, including the exacerbation of cardiovascular and respiratory conditions (e.g., cardiac arrest and asthma attacks) (Barreau et al., 2017; U.S. Global Change Research Program, 2016; U.S. Global Change Research Program, 2018; Rudolph et al., 2015). Further, disadvantaged populations are disproportionately exposed to, and at most risk from, the impacts of climate change, and poor air quality (Rudolph et al., 2015; White-Newsome et al., 2018; Younger et al., 2008).

Public health researchers have called for health professionals to focus attention on the complex intersection of climate change, health, and equity to heighten awareness and proactively address the problems at this important nexus (White-Newsome et al., 2018). Specifically, researchers have called for health professionals to engage with traditional environmental community partners as well as industries, other businesses, and health officials to develop multidisciplinary climate and health education tools that provide stakeholders with sufficient knowledge to take action (Esty & Bell, 2018; Kreslake et al., 2018; Shaman & Knowlton, 2018; White-Newsome et al., 2018; Younger et al., 2008). To date, climate action has largely fallen on environmental groups, government, and industry, often unilaterally. This call to action encourages the inclusion of non-traditional partners to respond to climate change based on recognition climate change effects everyone; the number of stakeholders needs to be broadened given the enormity of the problem and diversity in stakeholders offers differing perspectives and areas of expertise (Bello et al., 2016; Nasca et al., 2019).

In response, a non-traditional partner, the health department in Houston, Texas, joined with a leading environmental non-profit group to design and implement a straightforward framework aimed at mitigating and adapting to climate change and mitigating air pollution to reduce adverse health effects related to air quality and climate. These two partners—the health department and the environmental group—had not worked together and did not previously recognize their shared interest. The leadership was broadened beyond these two partners to include others not traditionally working on climate change through heightening awareness of the link to health. The key players included county and local governments, health professionals, and companies in the upstream and downstream oil industry, consumer electricity companies, and shipping industry players.

Though many climate and air quality interventions involve policy on a national or global scale, for this purpose, a smaller and simpler intervention accessible by the community and that can be applied locally was needed (Lin, 2020; Morani et al., 2011; Riondato et al., 2020; Younger et al., 2008). For these reasons, the mechanism chosen was to add native tree coverage using specifically selected species based on their unique ecosystem services (Bastin et al., 2019; Donovan et al., 2013; Nowak, Hirabayashi, et al., 2018). Strategic planting efforts offer an accessible and effective climate intervention at a smaller scale more suitable for specific communities. It is a highly attractive intervention because anyone can do it. There are a large number of native trees that provide ecological assets to the Greater Houston region, with growing research connecting large-scale tree plantings to the package of important climate change solutions and carbon reductions, urban heat reduction, removing many environmental pollutants from air, economic benefits, and improving physical and mental health (Donovan et al., 2013; Heo et al., 2021; Jones et al., 2019; Lovasi et al., 2008).

Regarding air pollution, researchers have found that pollution moves with atmospheric transport processes and, therefore, so does the benefit of lower pollutant concentrations as a result of pollution removal by vegetation (Jones et al., 2019). Recent studies offer insight into the scale of the benefit. Nemitz et al. (2020) concluded that urban tree planting is not the solution for reducing urban air pollution at the city scale but more beneficial on a wide scale and in conjunction with emissions reductions efforts. A separate study concluded that at the microscale, pollution hotspots created from tree and vegetation planting near high traffic areas may make it seem like vegetation planting increases pollution. However, the pollution that is being trapped reduces overall pollution at the neighborhood and city scale through limiting the atmospheric transport (Badach et al., 2020). As researchers continue to explore the degree and scale of the benefits of tree planting, the concept as a benefit in air pollution reduction is accepted (EPA, 2020).

Trees act as a sink for carbon through photosynthesis and carbon fixation of absorbed carbon dioxide (CO_2), storing carbon as biomass in a process known as carbon sequestration (Bastin et al., 2019). Other Air Pollutants (OAP) absorbed by trees include nitrogen oxides (NO_x), ozone (O_3), particulate matter that is 2.5 microns and smaller ($PM_{2.5}$), sulfur dioxide (SO_2), and carbon monoxide (CO), with larger leaves and canopies leading to more absorption (Arshad et al., 2019; Lovasi et al., 2008). The trees remove gaseous air pollution primarily by uptake via leaf stomata and particle pollution on the plant surface (Lovasi et al., 2008). Trees also play an important role in water absorption, tempering the impacts of climate change by regulating water flow and mitigating floods through Rainfall Interception and Avoided Runoff (RI + AR). Finally, dense tree canopy cover provides erosion control by intercepting rainfall, allowing more time for infiltration via root uptake as well as shade, providing urban heat island reductions (UHIR) (Chen et al., 2020; Heaviside et al., 2017; Loughner et al., 2012; NOAA Heat Watch, 2020; Tan et al., 2016).

A framework was created to develop native tree planting programs that capitalize on three key components. First, tree species were selected among all native tree species in the region according to the different capabilities of specific native trees in carbon sequestration, air pollutant reduction, flood mitigation through water absorption, and urban heat reduction. The unique properties between individual native tree species can be prioritized to optimize response to the program goals and educate the community about their benefits. For example, in Houston, the Live Oak ranks high in annual carbon sequestration, OAP absorption, and water absorption but lower in tree canopy size, whereas the American Sycamore ranks high in canopy size and annual OAP absorption and water absorption but lower in carbon sequestration. Tree species with the highest combined capacity for carbon sequestration, other air pollution reduction, flood mitigation, and shade were selected for this program.

Second, although there are many locations where native tree plantings could occur to enhance tree coverage, sites were strategically selected to catalyze awareness of the connection between climate change, air pollution, and health. Site selection can be based on historical knowledge of local climate-related issues such as drought, flooding, heat island effects, and health conditions exacerbated by air pollution and climate change (e.g., cardiac arrest and asthma attacks).

For example, Houston health researchers from the health department, the medical school, and academia found air pollution in Houston poses an increased risk of cardiac arrest and asthma attacks and that these adverse health events were found to be higher in certain parts of the city than others. This research can be used in selection of locations for the planting.

In the third and final part, educating partners in non-traditional sectors, such as health professionals, on the connection between climate change and health can expand those working to mitigate climate change. In the example above, educating the health researchers that found the link between air pollution and adverse health effects in Houston regarding the potential that climate change could increase pollution and thus further exacerbate the health effects of concern (Ensor et al., 2013; Raun et al., 2013, 2019) provides the catalyst for the health researchers to actively join in climate change mitigation.

Researchers have presented a variety of other frameworks that differ in scope than the framework presented here. An earlier influential framework evaluating the role of green infrastructure in climate change mitigation and adaptation examined the services, benefits, and trade-offs that come with greenspace projects (Demuzere et al., 2014). For example, planting more trees leads to enhanced CO_2 removal and carbon sequestration (service), and the additional greenspace improves mood for people in the neighborhood (benefit); however, there is a limit to how much can be planted as additional tree cover may increase pollution levels at the local level (trade-off). Evaluations such as these play an integral role in frameworks that consider pursuing planting efforts (Demuzere et al., 2014). Some more recent frameworks seek to combine ecological, structural, and visual landscape indicators to identify optimal planting locations that support biodiversity and ecosystem sustainability, while others utilize political ecology to provide international, sustainable solutions (Badach & Raszeja, 2019; Osborne et al., 2021). These solutions tend to prioritize conservation and sustainability, with limited if any focus on the environmental or human health aspects. In addition, there are frameworks designed for specific needs, such as using GIS mapping in order to prioritize planting to maximize water source volume; using the i-Tree calculator to select approved trees to prioritize a reduction in heat; or using optimization algorithms utilizing environmental factors to determine suitability of trees in neighborhoods (Nisbet et al., 2011; Nyelele & Kroll, 2021; Werbin et al., 2020).

The framework presented here complements and builds on the existing frameworks in the following ways: A simple method is presented to select native trees with the area's specific needed ecosystem services other than a predesignated purpose; the locations are selected based on adverse environmental conditions as well as existing health effects that could be exacerbated by climate change; and implementation is sought through multisectoral leadership with the intent of heightening awareness of the connections between climate change, air pollution, and health to expand the cadre and societal impacts of those working to intervene in resilience planning and implementation.

The application of the framework is demonstrated for projects in Houston, Texas. The specific climate and health concerns developed for Houston's program can be adapted in other cities to take similar action based on regionally specific climate, health, and pollution mitigation goals.

2 | METHODS

The framework created and applied in Houston, Texas, consists of three parts: (1) the identification of ecosystem services of native tree species ranked on their respective climate and environmental benefits; (2) identification of large-scale native tree mixture planting

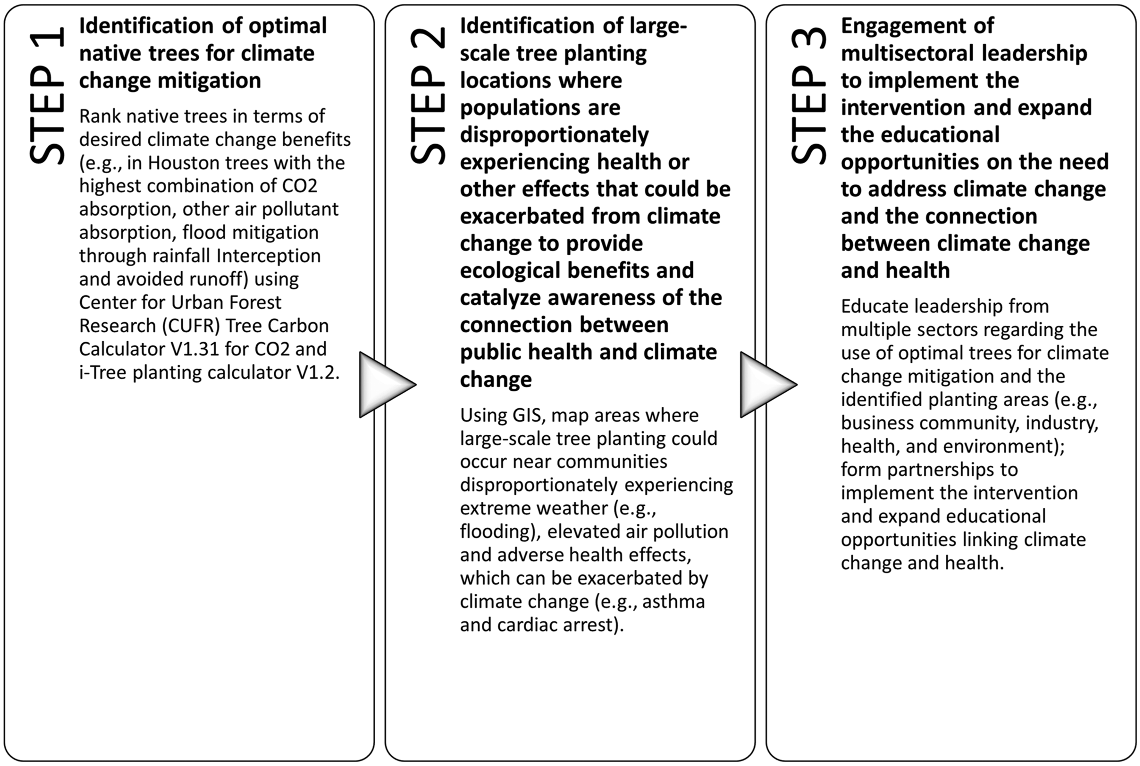

FIGURE 1 Three-part framework to implement large scale tree planting to address climate change and health and promote multisectoral leadership

locations to provide these important benefits where populations are disproportionately experiencing health or other effects that are exacerbated by increased air and water pollution, flooding, and climate change; and (3) engagement of multisectoral leadership to implement the mitigation and adaptation interventions and to expand the educational opportunities at the nexus of climate change, public health, and the environment (Figure 1). Specific factors considered in the Houston Region were organic soil carbon sequestration, broadly, and geographically varied parameters: air pollution and related health disparity history, flood history, and urban heat island effects. Method details of each part are discussed below.

2.1 | Identification of optimal native trees

First, regional native tree species were selected from the existing City of Houston Tree and Shrub Ordinance developed by an expert panel of landscape architects, the state forester, local tree planting nonprofits, and tree enthusiasts (Tree and Shrub Ordinance, 2015). Research was conducted on 54 of these native tree species to characterize their ecosystem functions associated with carbon sequestration, air pollution absorption, water absorption, and heat island via canopy size. From this ranking of native tree species, optimal trees for climate change mitigation and adaptation effects in Houston were identified as native trees with the highest combination of CO_2 absorption and sequestration, *Other Air Pollutant* absorption (OAP), flood mitigation through *Rainfall Interception and Avoided Runoff* (RI + AR), and Urban Heat Island Reduction effects (UHIR) (Table 1).

The air-related absorption component consists of two variables, CO_2 and a combination of OAP. CO_2 was evaluated separately because it is the largest contributor to global warming (National Atmospheric Emissions Inventory, 2019). The OAP absorption variable considers absorption of the indirect greenhouse gasses and air pollutants that are most associated with adverse health effects: nitrogen dioxide (NO_2) as a proxy for NO_x compounds, O_3, $PM_{2.5}$, and SO_2 (National Atmospheric Emissions Inventory, 2019). The ranking of the native trees by tree canopy size of individual tree species was performed to evaluate the RI + AR and the potential for UHIR (Chen et al., 2020; Loughner et al., 2012; NOAA Heat Watch, 2020; Tan et al., 2016). Climate change mitigation and adaptation and air pollution variable values were calculated using the diameter at breast height (DBH) equivalent to 10-year-old trees, which varies by species (CUFR Tree Carbon Calculator).

2.1.1 | Climate change mitigation

The potential of each climate change *mitigation* variable (CO_2 and OAP) was calculated separately for each of the 54 native tree species using two widely recognized ecosystem services calculation tools: the Center for Urban Forest Research (CUFR) Tree Carbon Calculator V1.31 for CO_2 and the i-Tree planting calculator V1.2.0 (a routinely

TABLE 1 Super trees identified in project

Native tree	Carbon emission score	Other air pollutant absorption (OAP)	Flood mitigation score (IR + AR)	Urban Heat Island reduction score (UHIR)	Mitigation/adaptation score	Rank	Thrive under future climate conditions: 40 years? (Y/N[a];Y/N[b])
Live oak	100%	100%	88%	76%	91%	1	Y/Y
American sycamore	41%	100%	91%	100%	83%	2	N/Y
River birch	80%	68%	88%	88%	81%	3	N/Y
Slippery elm	74%	79%	73%	94%	78%	4	Y/Y
Tuliptree	30%	100%	100%	82%	78%	5	N/Y
Water oak	65%	74%	96%	76%	78%	6	Y/Y
Red maple	52%	84%	86%	82%	76%	7	Y/Y
Sweetgum	56%	79%	80%	82%	74%	8	Y/Y
Black walnut	28%	100%	84%	82%	74%	9	N/Y
Laurel oak	72%	68%	84%	65%	72%	10	Y/Y
American elm	43%	74%	79%	94%	72%	11	Y/Y
Boxelder	59%	68%	68%	82%	70%	12	N/Y
Green ash	75%	68%	66%	65%	68%	13	N/Y
Willow oak	53%	58%	77%	82%	63%	14	Y/Y
White ash	44%	68%	61%	82%	64%	15	N/Y
Black cherry	38%	58%	70%	65%	57%	16	N/N
Loblolly pine	40%	58%	49%	65%	53%	17	Y/Y

[a]UF askifas (2021).
[b]NC State Gardener Toolbox (2021).

used, peer-reviewed software created by the U. S. Department of Agriculture [USDA] Forest Service; i-Tree, 2021) for OAP (CUFR Tree Carbon Calculator; Hilde & Paterson, 2014; Lin, 2020; McPherson, 2010; Russo et al., 2014). The individual air pollutants in the OAP absorption variable cannot be separated out when using the calculation tool available under the i-Tree software system.

Both the CURF and i-Tree calculators provide estimates for CO_2 sequestration. However, the CUFR calculator was used to calculate the CO_2 sequestration values because base references in the tool were more regionally specific compared to those from i-Tree. The CUFR calculator models CO_2 sequestration based on the specific climate zone inputs the user selects, allowing for less benefit transfer of ecosystem services data and stronger correlation with regional climate characteristics and soil content. In addition, the CUFR is the only tool approved by the Climate Action Reserves Urban Forest Project Protocol for estimating CO_2 sequestration (Beller et al., 2020; Nowak, Maco, et al., 2018).

The OAP absorption rate was calculated in pounds of NO_2, O_3, $PM_{2.5}$, and SO_2, removed by native trees using i-Tree. NO_2 was used as a proxy for the greenhouse gas NO_x family because NO_x absorption rates are not available in these tools. The individual air pollutant absorption rates were summed to create an overall rate for this variable.

2.1.2 | Climate change adaptation

The potential of each climate change *adaptation* variable (RI + AR and UHIR) was calculated separately for each of the 54 native tree species using a widely recognized ecosystem services calculation tool and a reference paper on tree canopy. The flood mitigation effects (RI + AR) were calculated using i-Tree by adding both rainfall (canopy) and storm water (runoff) interception. These were then summed to provide a total amount of gallons of water that can be absorbed per year. The urban heat island reduction (UHIR) effects were determined by using tree canopy estimates from a study out of the City of Harrisonburg, in cooperation with Virginia Nursery and Landscape Association and the Virginia Tech Urban Forestry Department (City of Harrisonburg, Virginia, 2015). These estimates were used to determine the UHIR because many studies have shown that increasing tree canopies in urban areas can greatly reduce Urban Heat Island (Chen et al., 2020; Loughner et al., 2012; NOAA Heath Watch, 2020; Tan et al., 2016).

The list of native tree species was sorted by each of the four variables, the two climate change mitigation variables (CO_2 and OAP) and the two climate change adaptation variables (RI + AR and UHIR). The maximum value for each variable was identified and used to scale the values for each tree species. For example, each native tree species' value for CO_2 sequestered was divided by the maximum CO_2 sequestered in the list, which was the Live Oak in our study example. A total climate change benefit score was created by combining all four scaled variables with a weight of 1/4 per variable. If there were a tree that ranked highest in all four variables, the total climate change benefit score would be 100 (Table 1).

The formula for the total Mitigation/Adaptation Score for each individual native tree species is below, where *N* is the total number of ecosystem services (ES) of interest the native tree provides, ES_N is the native tree species' value for that particular ecosystem service, and ESM_N is the maximum observed value by any native tree species for that particular ecosystem service.

$$\text{Total Mitigation/Adaptation Score} = \frac{1}{N} * \sum \left(\frac{ES_1}{ESM_1}, \frac{ES_2}{ESM_2}, \dots \frac{ES_N}{ESM_N} \right) * 100\%$$

Tree species with the highest combined climate change benefit score for CO_2 absorption, OAP, RI + AR, and UHIR were considered trees which optimize the program goals for improving climate, environmental, and public health. In this case, the leadership assigned climate change mitigation and adaptation variables equal weights, as the Greater Houston region is routinely, negatively impacted by the effects of air and water pollution, flooding, increased heat, and other extreme weather events on a comparatively equal basis. Also, many of the same targeted high-risk locations are negatively affected by all four variables at once. Alternatively, ranking by individual ecosystem service (i.e., only CO_2), instead of weighted sums, could be used if the effects of climate change impacts are not comparatively equal. While the trees are ranked individually, the intent is to plant a mixture of the recommended native trees, and ages, if possible, to provide a range of services, enhance biodiversity, and resilience (Brockerhoff et al., 2017). Of these tree species, other factors such as availability and cost were considered in discretionary final selection of which trees to select in tree plantings.

Additional discretionary factors to consider are indicators that the recommended trees will survive with climate change, and if any disbenefits of a selected tree species outweigh the benefit provided. For example, does a specific tree species release volatile organic compounds (VOCs) or pollen to an extent to cause a worsening of air pollution or severe allergic reactions, respectively, are any known to have disease vector hosting concerns for the area, and/or is there evidence that the recommended trees would fare poorly with climate change?

To evaluate the discretionary variables considering VOCs, pollen, and disease vector hosting, the literature was reviewed, and the list was discussed with the local forester/parks department. To support the discretionary assessment of how the recommended trees would fare with climate change, the percentage of the recommended trees listed in their anticipated future climate and hardiness zone (i.e., the zone where the tree is mostly likely to thrive) was calculated. Because climate and hardiness zones are shifting upwards as global warming continues (Lanza & Stone, 2016), knowing if a recommended tree is listed in the future hardiness zones provides an indicator (yes/no) of how a tree and, taken together the mixture of trees, will fare with climate change. Houston, which is currently in hardiness zone 9a, may transition to hardiness zone 9b in an estimated 40 years, given that research indicates a full zone shift to zone 10 by the year 2100 (Lanza & Stone, 2016). Tools are available online for this assessment (UF askifas, 2021; NC State Gardener Toolbox, 2021). This approach was selected because it can be easily implemented by the community.

2.2 | Identification of location for framework

To highlight the connection between public health, climate change, and air pollution, sites were identified for tree planting near communities disproportionately experiencing adverse health effects which can be exacerbated by increased air pollution and climate change (e.g., cardiac arrest and asthma attacks) and consequences of extreme weather (e.g., flooding and heat). Potential sites were considered based upon mapping of these factors using ArcGIS Version 10.5.1 (ESRI, 2011).

Specifically, areas with high rates of cardiac arrest and asthma attacks (upper quartile) or that flooded during hurricane Harvey were mapped (Blake & Zelinsky, 2018; Chakraborty et al., 2019; Facts and Figures, 2019). The areas with increased rates of cardiac arrests and asthma attacks occur in disadvantaged neighborhoods where more factors than air pollution are at play. However, other research in Houston has linked increased risk of cardiac arrests and asthma attacks to increased air pollution (Ensor et al., 2013; Raun et al., 2014). Reducing air pollution will reduce the risk of these health effects.

The annual average concentrations of NO_2 (in proxy for NO_x), O_3, $PM_{2.5}$, and SO_2 in 2018 were obtained from the Texas Commission on Environmental Quality fixed site air pollution monitoring locations and mapped using inverse distance weighting (TCEQ, 2019). Areas with concentrations of any of these pollutants in the upper quartile were denoted on the map. As more granular information becomes available of the spatial variation of pollutants and/or the contributions of long-range transport on O_3 and $PM_{2.5}$ concentrations, the mapping will be modified.

The data used to assess Urban Heat Islands were collected during a 1-day urban heat island mapping effort as part of the 2020 Heat Watch Program (NOAA Heat Watch, 2020). The high temperature areas (upper quartile) were mapped.

Finally, riparian-based open areas of land where the tree planting intervention could occur near the communities experiencing elevated levels (upper quartile), these variables as indicated by the GIS mapping were identified using satellite images.

2.3 | Engagement of multisectoral leadership to implement the intervention

A leading environmental non-profit group ranked the native tree species in the region, as discussed in Section 2.1 above, according to capabilities in carbon sequestration, air pollutant reduction, flood mitigation through water absorption, and urban heat reduction. This group educated the Houston Health Department about the services of the trees and benefits to public health, introducing the concept of working together given the link between each sector's goals of improving the environment and improving health. The health department conducted the mapping (discussed in Section 2.2 above) and worked with the environmental group to select locations to heighten awareness of the link to health.

Next, other partners were engaged to expand leadership to multiple sectors, broaden education, and implement the intervention. The health department facilitated engagement of the environmental group with other city departments, council members, county officials, and outside medical/health partners incorporating the framework in area-wide plans and policies. The health department promoted the message that this work was not just for the environment but vital to the city's health.

The environmental group facilitated engagement of the health department with environmental groups, businesses, and industry and promoted the same messaging. Together, the health department and the environmental group partners emphasized the data driven nature of the framework with education on trees with the desired ecosystem services and areas of the city suffering in multiple aspects that could be ameliorated with this intervention.

The environmental group, including the health department as possible, conducted a series of meetings, a luncheon, lectures, webinars, video and in-person forums, on-site tree species demonstrations, examples of targeted large-scale native tree plantings, and ecosystem services metrics and emphasized the health benefits of this framework. They shared the GIS mapping of areas suffering from health effects which could be exacerbated from climate change, poor air quality, flooding, and heat.

3 | RESULTS

3.1 | Identification of optimal native trees

Through this program, 54 tree species native to the Houston area were evaluated for optimal climate change mitigation and adaptation capacity (CO_2, OAP, RI + AR, and UHIR). Each climate change mitigation variable was calculated for a 10-year-old tree DBH. The CO_2 sequestration values from the CUFR tool ranged from 81 pounds per year (Tuliptree) to 268 pounds per year (Live Oak). OAP absorption values from i-Tree (the summation of NO_2 as a proxy for NOx, O_3, $PM_{2.5}$, and SO_2) ranged from 1.1 pounds per year (Loblolly Pine) to 1.9 pounds per year (Live Oak, Tuliptree, American Sycamore, and Black Walnut). Flood mitigation values from i-Tree (RI + AR) ranged from 1,839 gallons per year (White Ash) to 3,006 gallons per year (Tuliptree). Finally, UHIR values ranged from canopy widths of 11 feet (Laurel Oak, Green Ash, Willow Oak, Black Cherry, and Loblolly Pine) to 17 feet (American Sycamore). Figure 2 shows the eight species with the highest weighted total climate change mitigation score including an example calculation for the Red Maple.

The project leadership ultimately chose a mixture of 17 native tree species from the top 21 ranked trees after consideration of discretionary variables (Table 1). These resulting trees were named Houston "Super Trees" for ease in communicating.

No species were identified with specific dis-benefit concerns regarding release of VOCs, pollen, host for disease vector, or poor ability to adjust to climate change. With respect to VOCs, the highest

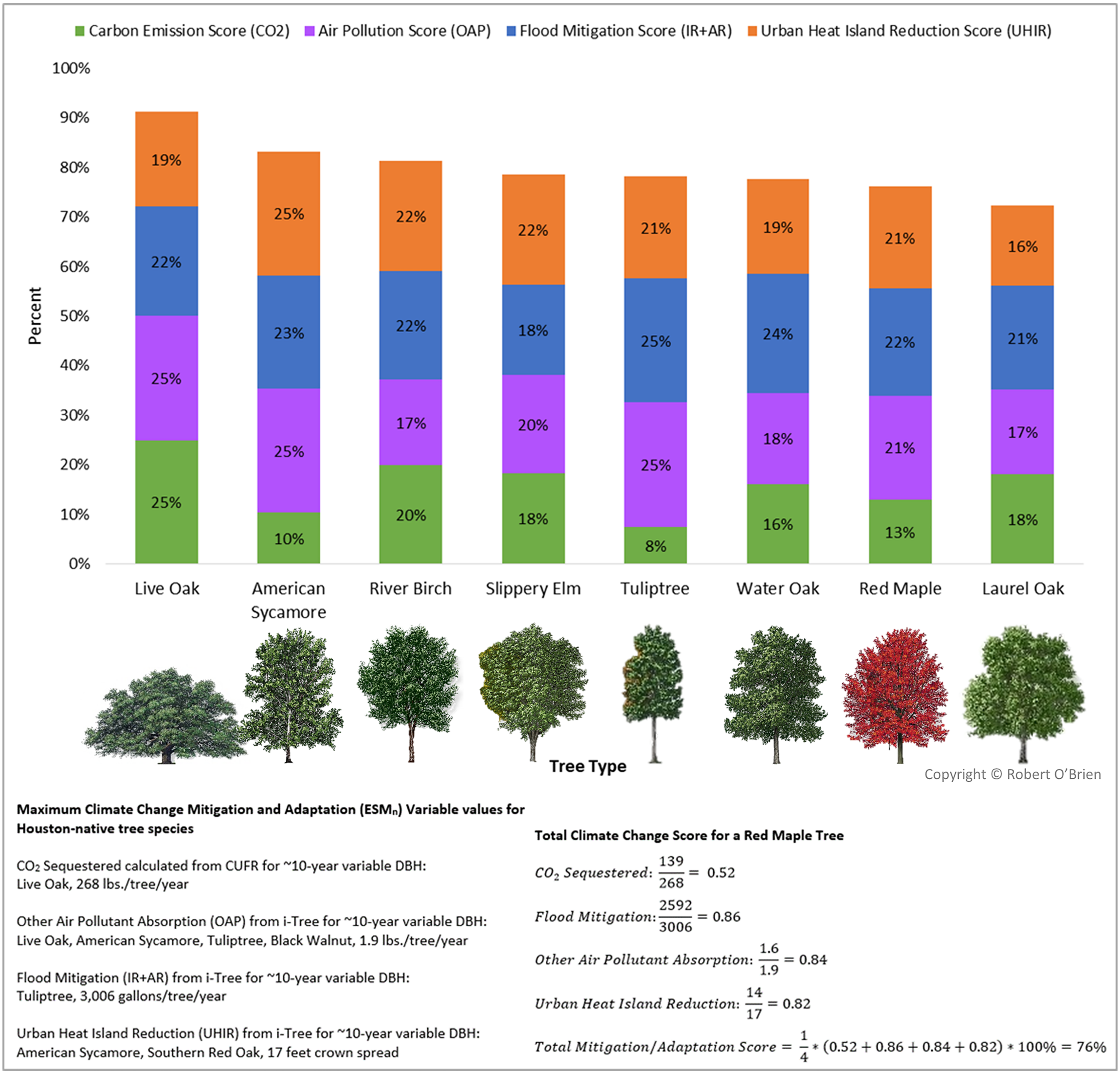

FIGURE 2 Top eight mitigation/adaptation for score native trees in Houston

emitters in Houston of those selected are sweetgum and oak (Nowak et al., 2017). These trees were not eliminated for two reasons: Planting will occur in a multi-species approach, thus diluting their impact, and this dis-benefit is mediated by the research indicating that, in Houston, increased tree cover works to decrease ozone (Nowak et al., 2017). The multi-species approach will also support biodiversity (Brockerhoff et al., 2017).

This group of selected trees was found to fare well with climate change. Houston, which is currently in hardiness zone 9a, will transition to hardiness zone 9b. From the list of Super Trees, 53% to 94% of species are also listed in hardiness zone 9b (NC State Gardener Toolbox, 2021; UF askifas, 2021). The range reflects two sources indicated by *Y* or *N* in Table 1. For these reasons, no changes were made to the Super Trees list based on this discretionary variable.

3.2 | Identification of locations

The health department created the maps indicating areas of the city which are, compared to the rest of the city, in the upper quartile for rate of cardiac arrest and asthma attacks, the upper quartile of the proportion of census tract that flooded during hurricane Harvey, upper quartile for NO_2 (in proxy for NO_x), O_3, $PM_{2.5}$ or SO_2 air

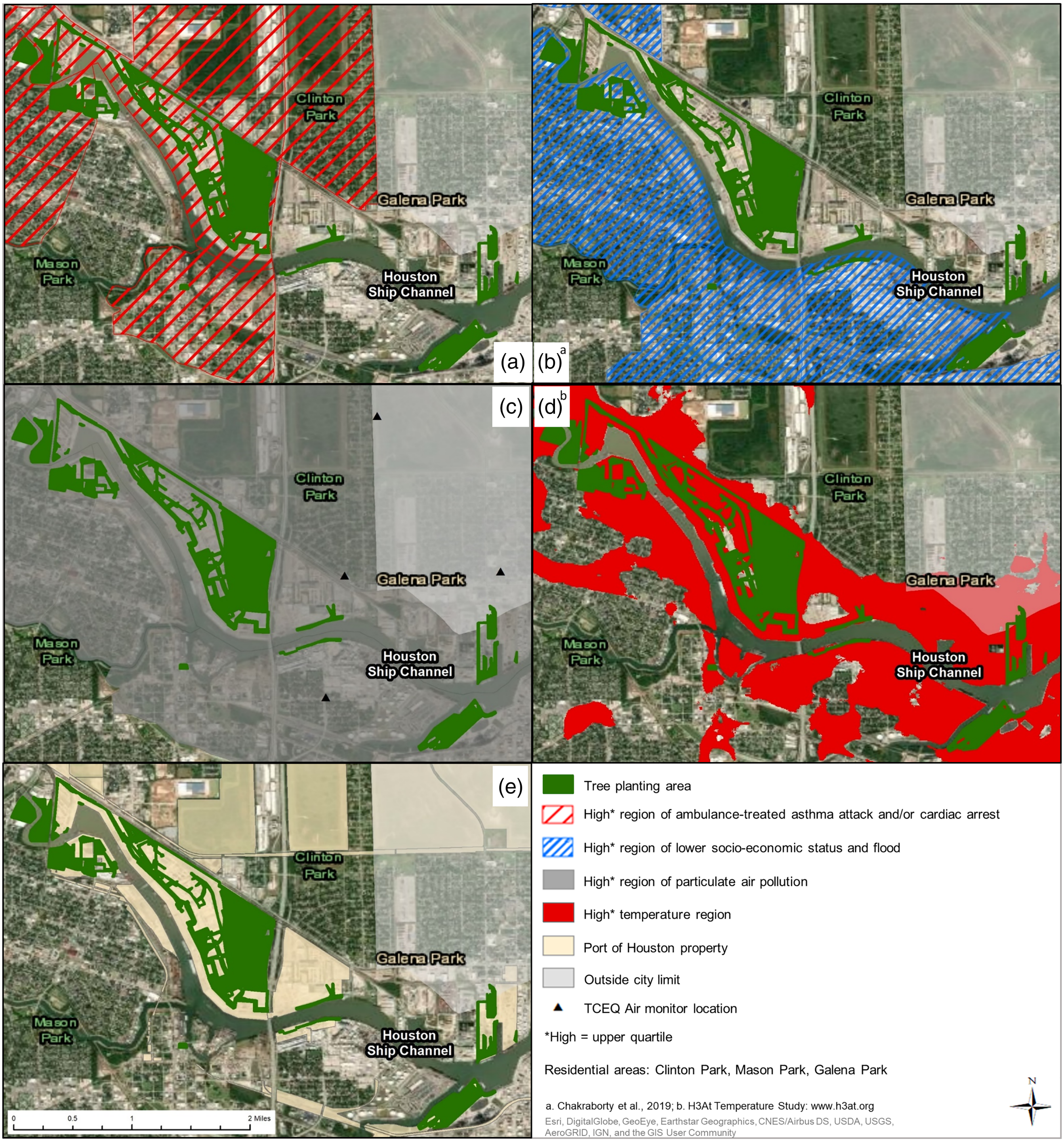

FIGURE 3 Location in Houston with (a) PM2.5 concentrations in the upper quartile of Houston (OAP); (b) high rate of cardiac arrest and ambulance-treated asthma attacks; (c) flooded by Hurricane Harvey (IR + AR); (d) high temperature areas (UHIR) in the upper quartile; and (e) residences in proximity with Port of Houston property for large-scale planting

pollutants, and upper quartile for temperature. Also mapped was the riparian-based open land available for tree planting. The maps were compared to select tree planting areas near residences where multiple of these variables related to climate change, poor air quality, and health effects that could be exacerbated by climate change were found at disproportionate levels.

The results of mapping identified multiple locations throughout the city. The maps for the locations selected as the first program site are shown in Figure 3. The locations are on either side of the Houston Ship Channel in close proximity to the Mason Park and Clinton Park communities inside of Houston city limits, as well as Galena Park, just outside of the city limits. The gray-shaded area indicates locations in the city where the average concentration of $PM_{2.5}$ pollution are in the upper quartile of $PM_{2.5}$ compared with the rest of the city (Figure 3a) (TCEQ, 2019) (none of the other pollutants assessed [NO_2, O_3, SO_2] had average concentrations in the upper quartile compared to the rest of the city). The red hatched area indicates locations in the city in the high rate region (upper quartile compared with the rest of the city) for cardiac arrest and asthma attack (Figure 3b) (Ensor et al., 2013; Raun et al., 2013, 2019). The blue hatched area indicates locations in the city in the upper quartile of the proportion of a census block that flooded during Hurricane Harvey (Figure 3c). The red shaded area indicates temperatures in the upper quartile (Figure 3d) (NOAA Heat Watch, 2020). The potential tree planting target locations in the same area are shaded dark green (Figure 3e). In this case, the green areas are within or surrounded by a large industrial complex associated with the Port of Houston.

3.3 | Engagement of multisectoral leadership and timeline of collaboration

First, the leading environmental group, Houston Wilderness, approached the Houston Health Department, speaking directly with the researchers which uncovered the spatial health disparities in cardiac arrest and asthma attacks and the link between pollution and health in Houston, and educated them on the related benefits of Super Trees. Upon recognizing the use of these trees as an intervention, coupled with knowledge of air pollution and spatial health disparities in Houston as a platform to inform and catalyze action for change, the Houston Health Department joined Houston Wilderness in educating and engaging other partners to implement the intervention.

Houston Wilderness secured permission and support to plant in the areas identified in Figure 3 (482 acres) from the land owners, largely the Port of Houston Authority, but also a portion belonging to Harris County Precinct 2 and the Buffalo Bayou Partnership. They then worked with owners and operators along the Houston Ship Channel to engage project partners from major oil companies and businesses such as Shell Oil, ConocoPhillips, Dow Chemical, NRG, and Port of Houston Authority. They also brought in local government and other environmental groups as partners. Through development of and shared use of a spreadsheet that listed all collaborative partners, the role of each partner, the dates and locations of the large-scale native tree plantings, and the goals to be achieved over a 10-year period, Houston Wilderness was able to magnify the stakeholders' recognition of their role as part of the process. Stakeholders could clearly see where they and their organization fit into the roadmap towards the solution, increasing stakeholder belief, investment, and participation in the program. Further, Houston Wilderness educated the new project partners regarding the ecosystem services of the trees; the link between climate change, air pollution, and health; and that the planting areas were in communities suffering from flooding, heat, air pollution, and high rates of cardiac arrest and asthma attacks (Houston Wilderness, 2017). For example, a pre-planting gathering included explanation of the Super Trees and speakers from the health department regarding the health effects the surrounding community were suffering. Table 2 provides an example of the organization used in the project summarizing the leadership, partner, and community inputs; the actions taken by each of these stakeholders that revolve around tree planting, education on climate change and health; and tracking of outputs and outcomes.

Houston Wilderness and partners not only planted native trees but also conducted a tree inventory, removed invasive species, and prepared the sites for planting. This program has successfully planted over 7,500 targeted native Super Trees in the locations identified.

As hoped, the engagement of the broader partners provided the catalyst for other climate/pollution and health intervention decision-making. For example, a county commissioner that partnered in the tree planting has initiated environmental youth councils in four high schools in his precinct, incorporating climate/pollution and the link to health education with a Super Tree project in the curriculum as well as funding placement of air and meteorology monitors near the schools.

The educational outreach on these climate change actions and health benefits continues on several levels (e.g., corporate leaders and their volunteers, community groups, and local government officials) and through multiple outlets (e.g., presentations/conferences, public and private meetings, video and in-person forums, media coverage, websites, and urban/resilience planning, and goal implementation) beyond those related specifically to this tree planting.

For example, the Houston Wilderness award luncheon presentation has incorporated the importance of the Super Trees, tree planting and the multiple benefits air pollution/climate change, and the connection to health in the last 2 years with the most recent award luncheon recognizing the Port Houston Authority for its environmental stewardship. The event provides an opportunity to educate the 450 community leaders (e.g., national, state, and local elected officials, Port Houston executives, regional philanthropists, academics, engineers, architects, land developers, media outlets, and energy companies) in attendance that this work was not just for the environment but vital to the city's health.

Houston Wilderness' engagement, with support from the health department promoting internally, resulted in the adoption of significant policy changes in the city aimed at mitigating/adapting to climate change and mitigating air pollution. For example, the city's *Resilient Houston Strategy* includes the goal to plant 4.6 million trees by 2030 and has incorporated this three-part framework to determine where to plant native trees and which Super Tree species to plant in targeted high-health-risk locations (City of Houston, Mayor's Office Press Release, 2020a). A Tree Strategy Implementation Group was created, facilitated by Houston Wilderness to provide key strategies to reach this goal within 10 years by adopting this three-part framework as part of that effort. The kick-off for the implementation group's key strategies occurred during a City of Houston Press Conference on November 6, 2020, as part of a large-scale native Super Tree planting along the Houston Ship Channel (City of Houston, Mayor's Office Press Release, 2020b).

TABLE 2 Example logic model for a multisectoral collaborative leadership approach

INPUTS Resources that will be used to support the program →	ACTIVITIES The main activities that the project will involve. →	OUTPUTS Size + scope of tangible products/services that will be delivered. →	OUTCOMES Results/metrics Short-term: 12 months	OUTCOMES Results/metrics Long-term: 18 months
• Inventory (baseline and during plantings) • Houston wilderness (HW) staff time • Other City of Houston partners time • Port Houston Authority (PHA) partner staff time • Public health officials, providers, insurers, state, and local elected officials, regional philanthropists, academics, engineers, architects, land developers, media outlets and energy companies • Research w/Houston Health Department (HHD) staff and academic staff • Sufficient supply of targeted native super trees (ST) • Ecosystem services (ES) tools and techniques • Tree planting materials- mulch, organic compost, topsoil, fungi packets • Air quality, water absorption, carbon seq., erosion analysis • GIS database maps and updates based on health effects from climate change • Meeting space, presentations, media	• Retain/refer to existing tree inventory analysis • HW: Coordinate between all partners • Work with PHA on access and approval of planting sites as identified according to adverse health effects that could be exacerbated due to climate change • HW, HHD create climate change/health benefit/ ecosystem service/ST educational sheets • Planting dates/forms for volunteer plantings • Continue updating GIS maps of PHA TREES targeted and specific planting areas based on health effects arising from climate change • Collect data on the scope of the program and ways partners are improving methods to make implementation and management more effective and efficient • Provide annual analysis of impacts of targeted native tree planting planting - ES • Set up strategies so that ST species are available every year • Provide funders, organizational/ partners, and public updates on metrics and ES associated with targeted native tree plantings • HW: Facilitation of the TREES program	• Determine the location, type and # of ST species • Add volunteer groups and new partners within the PHA TREES implementation phase • Published media coverage, slide presentations/posters for conferences • Provide metrics on native ST plantings, ecosystem services data, and interested parties • Provide GIS-based maps of planting locations, # and types of ST species • Add volunteer groups and new partners within the PHA TREES implementation phase	• Inventory of current trees (baseline and annually added to baseline) • # of native ST species planted • Large-scale targeted ST species plantings (based on air, water and carbon absorption rates) • Inventory of the native tree species planted - identification and # of tree species- collaboration between multiple partners • # of acres restored with native tree plantings • ES analysis (air quality, water absorption, carbon seq.) • #of riparian miles restored with native tree plantings • Benefits of large-scale native ST plantings in high risk • Measurement of air quality • Measurement of carbon seq. in soils • Comparative data on management approaches before, during and after program implementation • # of acres under improved management • # of ES enhanced and maintained due to large-scale native tree plantings • # of organizations contributing to the native trees planted • # of jobs created through large-scale tree plantings • # of volunteers • # of people reached	• Analysis of the amount of change in ES after restoration. • # of acres of additional forested land • Enhancement and restoration of natural habitat • % more detention and erosion control • Awareness of the benefits of targeted large-scale tree planting throughout the region • More shade trees to reduce urban heat • Provide information on the vegetative composition and function • Use of this policy process/ implementation in other parts of region and in other cities • % and # of tons of soil carbon sequestration in planting areas • % increase in coastal surge protection • % and tons in reduction of ambient air pollution in planting areas • % and tons of water absorption in planting areas • Create/implement innovative tools, techniques and methods that can be scaled to use nationally or globally in large-scale tree plantings.
IMPACTS Long-term changes in systems/ conditions/environment	•Regional stakeholders make informed decisions and take action to create more and better connected wildlife habitat and increase ES based on targeted large-scale ST plantings •Increase air quality •Increase in esthetics •Decrease in invasive species •Increase in water absorption •Increase in carbon sequestration in soils •Increase in erosion control •Improve the function of existing habitat •Increase in environmental awareness, education, and links to health •Decrease in urban heat			

While engaging in multisectoral collaborative provided a necessary catalyst for planting thousands of native trees in high health risk areas, and the value of pursuing collaborations far outweighed any risks of the program dissolving or goals not being met, there are three potential pitfalls with engaging in multisectoral leadership including (1) disinterest in the program as time progresses due to changes in leadership or other competing goals; (2) promises by critical leadership to accomplish goals that are then not kept or met, causing other partners to take up the additional work load to keep the program progressing; and (3) disagreements between partners involved in the program. There must be urgency to act quickly, in order to avoid these pitfalls and take advantage of the limited time with partners. As indicated above, the key to avoiding these pitfalls is to provide the three-part framework approach with multiple partners and to provide one key partner who serves as the lead facilitator of the entire program.

The Houston Health Department, Houston Resilience Office, Houston Wilderness, and other program partners maintain webpages on their respective websites to highlight health and climate change mitigation benefits related to tree species. Finally, the multisectoral leadership on this program has worked closely with local and regional governments to integrate climate and health benefits of large-scale tree plantings around resilience plans in other regions (CUFR Tree Carbon Calculator, 2019).

4 | CONCLUSION

This framework was successfully applied in Houston, Texas. A local ranking of 54 native trees was created to optimize climate, health, and environmental risk factors, as selected for Greater Houston, with 17 optimal Super Trees chosen from the ranking. Communities were targeted for large-scale native tree plantings based upon disproportionately high adverse health effects and environmental concerns which will be further exacerbated by climate change. Entities from different sectors who do not typically coordinate at a framework level—such as public health officials, environmental leaders, and major industrial companies—came together in leadership roles to address climate and health issues. Leaders were able to conceptualize the data-driven complexity of the framework, catalyzing the marketing, commitment, and dedication that allowed the framework concept to inform real-life decisions. This partnership found common purpose, recognizing that targeted, large-scale planting of native trees can improve human health and the environment, allowing for continued economic well-being for individuals, communities, and businesses.

The resulting rank of a native tree species provides guidance and education on which trees have the maximum climate and health benefits based on the specific needs in Houston. The top trees were named, Super Trees to facilitate easier communication across future planting efforts and city-wide projects.

For the first time, mapping was conducted by the Houston Health Department of areas where communities are experiencing the joint effects of disproportionately poor air quality, flooding, elevated heat, and high rates of adverse health concerns which could be further exacerbated by climate change. These maps highlighted the intimate connection between climate and adverse pollution-based health effects and are continuing to be used to inform locations for future large-scale native Super Tree plantings.

Of the many locations identified by the Houston Health Department based on disproportionately high adverse health effects, the site of the first several projects to provide large-scale planting of native Super Trees was on property along the highly industrial Port of Houston. The success of this planting was a key indicator of the importance of engaging diverse leadership for long-term benefits. The lead environmental group, Houston Wilderness, worked with the health department and local government officials as well as owners/operators along the Port of Houston Ship Channel to bring major oil companies and business partners, such as Shell Oil, ConocoPhillips, Dow Chemical, and NRG and Port Houston Authority, together for this program.

The data-driven nature of this framework was instrumental in bringing the relationship between climate and health to the meaningful attention of health, government, and industrial and business partners, who began to see the critical connections between targeted re/afforestation and enhancement of ecosystem services for community health (Bello et al., 2016; Ismail et al., 2019; Nasca et al., 2019; Rizzi & Porębska, 2020).

Two key outcomes highlight the success of the implementation of the framework. First, participation in the initial tree planting acted as a catalyst for other environmental projects within the same community. Second, the City of Houston's Resilient Houston Plan's goal to plant 4.6 million trees by 2030 is using this three-part framework to determine where to plant these native trees and which tree species to plant. Other neighboring communities and corporate complexes are reviewing the framework to adopt large-scale tree planting goals in targeted locations.

Use of this three-part framework optimizes climate change actions, and helps protect vulnerable health populations by encouraging diverse leadership and cooperation that empowers community stakeholders with sufficient knowledge, tools and collective effort to implement a combination of adaptation and mitigation interventions through large-scale re/afforestation. The bridges formed between the community groups and other sectors, and the heightened awareness of shared goals, provide a catalyst for engaging in the planting of millions of targeted native trees to combat climate change, often filling an important government void and accomplishing large-scale native tree planting at a scale that is unattainable without multisector collaboration.

Other cities can adapt this three-part framework, adjusting for variables important for their area for both tree species and at-risk planting locations. For example, in the city of Houston, it was important to give equal priority and weighting to the climate change mitigation and adaptation variables associated with carbon sequestration, air pollution, flood and erosion control, and urban heat island reduction (City of Houston, Mayor's Office Press Release, 2020b; Lin, 2020). Houston is a unique urban metropolitan that suffers from frequent flood and erosion damages, poor air and water quality, and urban heat island effects.

Another city may specifically prioritize shade, drought resistance, fire prevention, or other parameters rather than deciding to prioritize the ecosystem services benefit variables chosen for Greater Houston.

Likewise, cities with differing climate change related health effects could identify planting areas according to their specific needs. These differences in targeted ecosystem services can be highlighted through the use of GIS-based mapping of areas with high risks of environmental and societal stressors leading to reduced health effects.

The framework adopted by the city of Houston provides a meaningful layout to address climate change and air-pollution-related public health outcomes that involve direct support from multisectoral leadership and can be extended to suit the needs of any local or regional government.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

AUTHOR CONTRIBUTIONS

Loren P. Hopkins: Writing, Health impacts Research, Investigation, Methodology. **Deborah January-Bevers:** Conceptualization, Tree Functions and Rankings Research, Writing, Investigation, Program Facilitation and Logic Model. **Erin Kelsey Caton:** Review & Editing. **Laura Campos:** Formal analysis, Visualization, Editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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