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**Enhancing the Carbon Dioxide Sequestering Capacity of Louisiana Highway Right of Way Lands**

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# Enhancing the Carbon Dioxide Sequestering Capacity of Louisiana Highway Right of Way Lands

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Louisiana Department of Transportation and Development
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The contents do not necessarily reflect the views or policies of the Louisiana Department of Transportation and Development, the Federal Highway Administration or the Louisiana Transportation Research Center. This report does not constitute a standard, specification, or regulation.

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# Abstract

Executive Order No. 2020-18 initiated the Climate Initiatives Task Force for the State of Louisiana in charge of supporting the State’s effort to become greenhouse gas neutral by 2050. Aiming to provide a first assessment of the $CO_2$ sequestration potential of the large-scale afforestation of right of way lands in Louisiana as an alternative to increase $CO_2$ sinks in the State, this project simulated three scenarios of forest management that ranged from no-intervention to frequent thinning and replanting. The results indicate that planting in the 10,305 amenable acres of right of way (ROW) lands available on four major highways in Louisiana (I10, I20, I49, and a southern section of US 90), the $CO_2$ sequestration potential is estimated to be between 73,543 and as large as 653,987 US tons $CO_2$ annually by 2050 (7 to 63 US tons acre$^{-1}$ yr$^{-1}$), depending mainly on tree $CO_2$ uptake values used. These $CO_2$ sequestration potentials tend to increase when reduced, and less frequent thinning and replanting management scenarios are considered.

# Acknowledgments

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# Implementation Statement

This project assessed the potential $CO_2$ sequestration in selected ROW lands of Louisiana. Implementing large-scale reforestation projects of the magnitude and diverging site conditions require proper planning that must begin with inventory of available ROW lands amenable to afforestation. This approach can also be used as an assessment tool for evaluating similar uptake potential on other types of lands within Louisiana. Elucidating the actual soil conditions in ROW lands is instrumental to more accurate estimates of tree growth and $CO_2$ sequestration potential. Implementation should continue with the physical plant and logistics needed to secure the provision of saplings through the lifetime of the project. The estimates presented in this report include 25- and 60-years projections that correspond to the 2050-time target of the Governor's order and a later date after the peak $CO_2$ sequestration potential, respectively. These estimates include 3+ years to allow for the establishment of the mechanisms and procedures, and the development of studies needed to ensure that the initial phases described above are completed. The development of studies addressing tree growth under local conditions (soil and weather), planting design for highway safety, and economic viability of forestry and associated activities are the steppingstones towards a large-scale afforestation of ROW lands.

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# Introduction

On August 19, 2020, Governor John Bell Edwards of Louisiana, via Executive Order No. 2020-18, initiated a Climate Initiatives Task Force for the State of Louisiana. The Order focus on reducing and eliminating net greenhouse gas (GHG) emissions within the state on an incremental basis, using as a reference the 2005 emissions. It aims for a short-term reduction of approximately 27% by 2025, approximately~45% by 2030, and zero net emissions by 2050. This government initiative positions the State of Louisiana among the 20 or so US states with formal GHG net neutrality plans. It also places the state among other areas within US states developing GHG reduction/elimination plans (including New Orleans, LA, with a completed plan in place). Transportation is viewed as a significant avenue for GHG reduction by all of the ~10 GHG reduction plans reviewed from other US states (in-house research to support the Governor's initiative via a support request). However, if net-zero emissions are to be achieved in Louisiana, new $CO_2$ sinks will be needed. Natural, biotic sinks appear to be one of the most attractive alternatives since $CO_2$ is actually incorporated into biomass and not stored in other reservoirs where its potential release may easily occur. It also allows forest-based products like timber, pulp/paper, and resins to be generated, potentially adding to the state economy, particularly in rural regions where new economic development is badly needed.

The results of Louisiana's Climate Initiative Task Force were released in February 2022 [1]. The final Louisiana Climate Action Plan reported that in 2018, a total of 216 M metric tons of $CO_2$ equivalents ($CO_2$ e) were released in Louisiana through various source vectors. Of these vectors, industry-based facilities accounted for 66% of this annual tonnage which differs significantly from the overall US emissions distribution, as industry vectors generally account for about 25% of the total $CO_2$ e tonnage. It is also noteworthy that Louisiana's $CO_2$ equivalent commissions in 2017 represented about 5% of the total US emissions [2].

The Louisiana Climate Action Plan suggested 28 strategies and 84 actions that could be used to achieve carbon net neutrality in Louisiana by 2050. Three of the twenty-eight strategies focused on using natural (mainly flora-based) systems, such as forest and wetland carbon uptake, that could be used in Louisiana to meet the 2050 carbon neutrality goal. Hence, the present TIRE (Transportation Innovation for Research Exploration) study offers insights into land utilization oriented toward supporting forest-based carbon dioxide uptake via the reforestation of highway right-of-way (ROW) lands.

Additionally, the Louisiana Climate Action Plan evaluated, via a series of carbon dioxide equivalent mass balances, various scenarios that could be utilized to meet the carbon neutrality goal in 2050. The figure below was presented in the Louisiana Climate Action Plan.

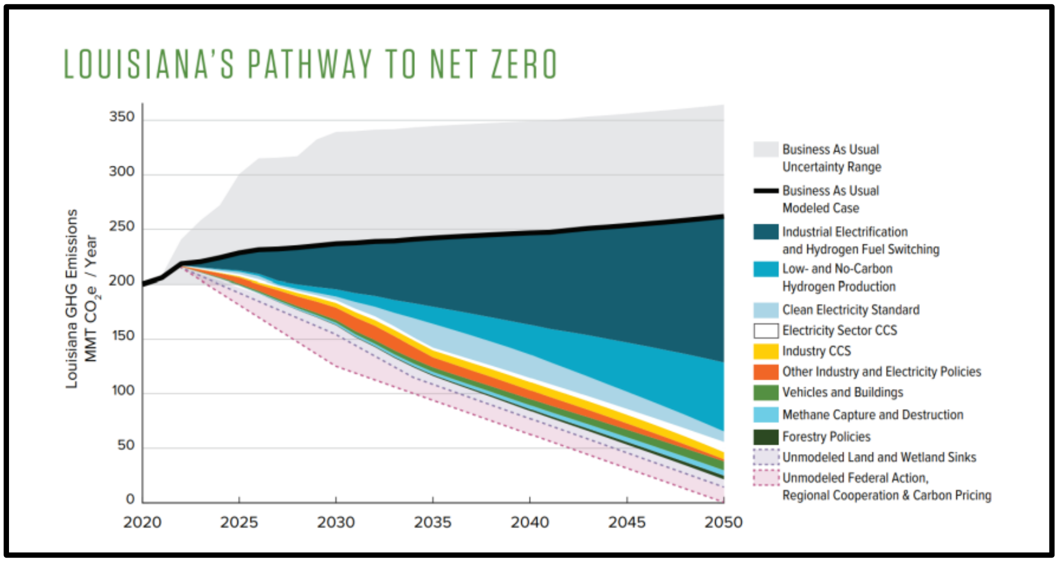


**Figure 1. Louisiana Climate Plan suggested $CO_2$ equivalent ($CO_2$ e) reduction vectors to meet the carbon neutrality 2050 goal (figure from [1])**

Based on Figure 1, the bulk of $CO_2$ e reduction achieved is planning to utilize non-carbon emitting production/manufacturing technologies, such as green and blue hydrogen-based processes. Albeit, these are very promising, their current state of development will need to be dramatically changed over the next 27 years if they are to be utilized at full-scale. Also, from this figure, note that forest and wetland-based $CO_2$ e reduction is held fairly constant, indicating, at this time, that there is little to no change in the acreage of forested lands and wetlands in Louisiana. Yet, this sequestration vector is easily implemented and does have potential direct and indirect economic returns.

In October 2021, the Center for Energy Studies at LSU released their 2021 greenhouse gas statewide inventory report, which detailed the sources of $CO_2$ equivalents released in Louisiana during 2019, along with a ranking of the top emitters [2]. Table 1 below presents a summary of findings by the amount of 2019 $CO_2$ e released by the top 10 industrial facilities (in terms of US tons of $CO_2$ released in 2019). Note that the report dealt with 2019 data, which was the latest complete dataset available during the drafting of the report.

**Table 1. Top 10 Louisiana-based industrial facility $CO_2$ emitters**

| Ranking | M-Tons $CO_2$ eq 2019 Emissions |
|---|---|
| 1 | 11.0 |
| 2 | 7.1 |
| 3 | 5.6 |
| 4 | 5.2 |
| 5 | 4.4 |
| 6 | 4.4 |
| 7 | 3.6 |
| 8 | 3.3 |
| 9 | 3.0 |
| 10 | 2.5 |

The actual sources of $CO_2$, i.e., facility names, for the case of this TIRE study are not of interest because our study premise is that the planted flora will be removing the $CO_2$ from the overall atmosphere and not from a stack(s). However, for the sake of understanding the potential magnitude of potential $CO_2$ uptake using proposed reforested ROWs, the calculated right of way forest removal levels will be compared to the level of the various top 10 industrial facility emitters in Louisiana. It was also encouraging to observe from the LSU report that $CO_2$ e releases in Louisiana appear to be declining over the past 10 years.

The US Department of Energy's Energy Information Agency regards Louisiana within the top 20 states for GHG emissions in the US, ranking the state first for industrial power usage and fourth for transportation energy consumption [3]. Moreover, Louisiana is home to the largest concentration of oil refineries and manufacturing facilities in the US. Meeting the total net GHG elimination goal will be challenging. Relying only on reductions from generating sources will likely make it difficult to meet the reduction targets. Hence, requiring the development of multiple new carbon dioxide sinks/sequestration sources becomes a top priority to help achieve reduction targets. Forest-based carbon dioxide sequestration stands out as the option with the single largest GHG reduction/mitigation potential in the US [4]. Land forestation/reforestation options are the most mature and viable compared to carbon capture technologies and low-carbon release technologies. Given its high biomass growth potential, Louisiana is a particularly attractive region for utilizing managed forest biomass as a carbon dioxide sink.

### Louisiana Highway Right of Ways

All publicly owned transportation roadways, including interstates, federal highways, state highways, county roads, and municipal roads, are constructed on ROW land areas. These areas encompass the constructed transportation infrastructure and the maintenance and safety buffer zones. Generally, ROW land areas associated with municipal and county roadways are mainly tied to drainage ditches (if present), sidewalks, or shoulder areas. Thus, these roadways have minimal land areas. Conversely, federal and state highways often have much larger land spaces tied to their ROW areas. Whitesides and Hanks [5] estimated the total available (or open) highway ROW land areas in the US at about 40 million acres. Other non-traditional public lands similar to highway ROWs that Whitesides and Hanks also assessed were municipal airports (2 million acres), railroad ROWs (1.2 million acres), and military base land areas (90 million acres).

# Literature Review

The practice of forestry in ROW lands gained traction in the 1970s when the budget of most transportation departments was drastically reduced [5]. A recent trend with highway ROW areas' management has been toward cultivating trees of regional relevance that require low maintenance, as mowing ROW lands represents a considerable cost to highway departments. ROW forestry as a concept is part of a group of alternatives for ROW management focused on reducing maintenance and adding market value to activities conducted in these "unconventional" agricultural lands. Such practices may include conventional harvesting crops like Hay [6] or biofuel crops [5].

Besides cost reductions, planting trees in the ROWs is associated with several additional benefits. Neale [7] argued that landscaping, including trees and flowers in ROWs, while essential for improving the aesthetics and overall driving experience, can also improve road safety by providing shade which helps prevent driver fatigue. Trees along the roadways have been demonstrated to influence wind speed and direction [8]. For example, they can provide cost-effective alternatives to conventional 4-foot fences to help control snowdrifts on roads in cold climates or other climates subject to harsh seasonal conditions [9]. Forthright, shrubs and small, medium-sized trees in medians can also provide safe physical barriers to accidental vehicle crossings from one side of the interstate highways [10] [11].

When used for landscaping, trees can be spaced with appropriate buffer allowances to safely serve as natural barriers and provide noise abatement, privacy and comfort to communities alongside roadways [12] [13]. In general, the presence of trees is associated with better air quality because plant leaves and branches intercept and retain dust particles [14] [15] [16] [17], with relevant implications for a safer living environment [18]. Further, communities can benefit economically when they are included in participatory management programs of the forest on ROWs [19]. The benefits of forested ROWs may expand to connecting natural systems. Trees and shrubs provide critical wildlife habitats for different animal groups [20] [21].

More recently, the interest in ROW forestry has been focused on capturing and sequestering $CO_2$ to abate emissions from the transportation sector, with particular developments in Asian countries [22] [19] [23] [24]. In the USA, developments have been comparatively tepid. In one of the most comprehensive assessments available to date, Ament et al. [25] estimated over 8 million metric tons of carbon sequestered per year on ROWs of eight federal land management agencies. This estimate is the equivalent of annual emissions from 6 million passenger vehicles. However, this was an estimate based upon physiographic vegetation classes (i.e., evergreen, deciduous, mixed, grassland, shrubland, and wetlands), and to our knowledge, there are no studies that discern tree genera or species which is the level of specificity needed for actual implementation.

# Objective

This project aimed to research the potential placement and supporting biomass management protocols for establishing Louisiana's highway ROW land areas as growth zones for high-carbon dioxide uptake forests. The objectives of the project were:

- Evaluate the available land areas for reforestation using GIS data from LDOTD and US Forest Service databases.
- Select candidate tree species with comparatively high carbon dioxide uptake and rapid and sustainable growth within Louisiana's climate.
- Evaluate candidate tree species regarding highway safety and carbon dioxide uptake.
- Develop an implementation protocol of reforestation for use by the LDOTD.
- Evaluate forest management techniques for potentially improving $CO_2$ uptake.
- Identify additional benefits and potential future efforts to implement the proposed concept within Louisiana.
- Interface with the Louisiana GHG Reduction Task Force for rapid transfer of data.

# Scope

This project constitutes the first assessment of the $CO_2$ sequestration potential in ROW lands along Highways in Louisiana. $CO_2$ sequestration potential was modeled with GIS parameters for I-10 and I-49 within Louisiana, I-20, and Hwy 90, from Lafayette to Houma, for three hypothetical scenarios of forest management that may be used in the decision-making processes for meeting the goal of carbon net neutrality by 2050. Besides providing an initial estimate of the ROW lands as $CO_2$ sinks actionable under the Governor's Order, this project also sheds light on existing knowledge gaps that must be addressed looking forward to implementing large-scale afforestation plans on these lands to assist with managing carbon dioxide levels. This study sets the stage for more R&D that needs to be done to refine carbon sequestration estimates and to best position land reforestation management for maximizing carbon dioxide uptake. It also sheds light on the vast carbon dioxide sequestration potential that managed natural sinks can offer in an attempt to reach carbon neutrality.

# Methodology

## Determining ROW lands on interstate highways

The right-of-way (ROW) vector files (shapefiles) for the Interstate 10 and Interstate 20 in the state of Louisiana were available as outputs from the previous LADOT-LTRC-funded project in the year 2018 [26] [27]. ROW vector files were created for Interstate 49 and Highway 90, from Lafayette to Houma, in the same way. The I-10, I-20, I-49, and Hwy 90 ROW shapefiles were projected with the coordinate reference system (CRS) of EPSG:4326. Hence, all geospatial analysis data (shapefiles and raster files) were projected in the same CRS EPSG:4326 (e.g., Figure 2). All geo-spatial processing and analyses were performed in the QGIS software.

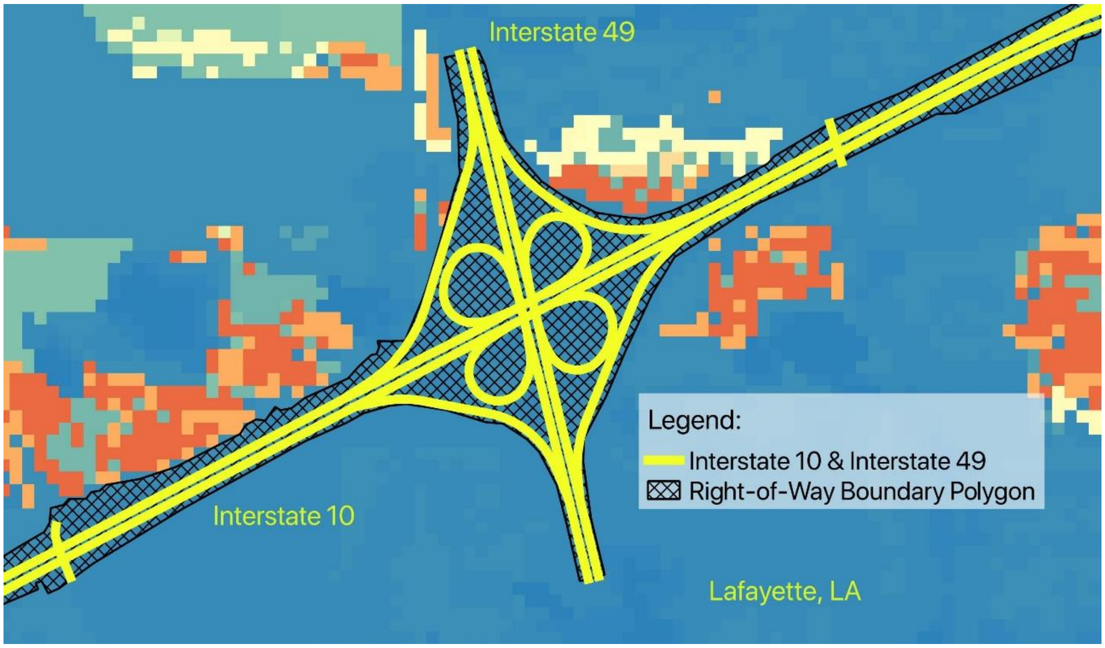


**Figure 2. A sample section of an intersection of Interstate 10 with Interstate 49 in Lafayette showing the highway lanes (yellow) and the ROW boundary polygon (black mesh)**

## Tree information and species selection

The main tree species growing in the four vegetation regions of continental Louisiana (i.e., upland hardwoods, pine forests, prairie, and bottomland hardwoods) were identified [28]. The MyTree web application from the iTree software suite was utilized to obtain potential $CO_2$ sequestered annually and over the plant's lifetime growing under optimal conditions [29] (https://www.itreetools.org/). This is the net $CO_2$ sequestration minus the decomposition [30]. Potential $CO_2$ sequestration was calculated for species growing in full sun conditions and with excellent health. The calculations were made for tree diameters (expressed as diameter at breast height, DBH) of one, five, ten, twenty, and thirty inches, which are the diameters available on the MyTree tool. Following, spatial $CO_2$ sequestration estimates were performed using assumed tree densities for each vegetation region. Also, $CO_2$ sequestration estimates from the literature were also used to provide additional insights as these values can be significantly different under the growth parameters defined in each respective study.

All tree species (twenty-six total) selected for this report were pre-screened to meet Louisiana's diverse growing conditions. Other key variables were introduced in order to produce an evaluation matrix of tree species' relative capability of sequestering carbon and suitability for longevity within Louisiana ROW environments. The three variables evaluated for each tree species in order to rank each species for potential implementation into the Louisiana ROW system were:

1. Peak Annual $CO_2$ Sequestration (lb $CO_2$ acre$^{-1}$ yr$^{-1}$)
2. Lifetime $CO_2$ Sequestration (lb $CO_2$ acre$^{-1}$).
3. Storm Survivability.

The peak annual and lifetime carbon sequestration capacities were based on their respective values generated by the MyTree model under the assumed conditions previously outlined. In order to create a decision matrix ranking, the range of each of the two carbon sequestration values was divided by five to create a ranking scale of one through five. That quotient was then divided into the carbon sequestration values for each species and rounded up to the next integer, resulting in a matrix evaluation between 1 and 5 for each species for both the peak annual and lifetime carbon sequestration potential.

Storm survivability is an essential aspect of tree species selection for potential implementation into the Louisiana ROW system. Tree species planted within ROW systems outside of the Federal Highway Administration (FHWA) defined clear zone, as adopted by the LDOTD Policy for Roadside Vegetation Management [31] need to be able to withstand storms and high-wind events. Damage to tree trunks and large branches poses a significant maintenance issue for the LDOTD as well as the potential for limbs and tree debris causing safety concerns in travel lanes or shutting down evacuation routes. Storm survivability for Louisiana tree species was addressed by the LSU AgCenter [32] and includes an evaluation of three properties that characterize a tree's ability to withstand high-wind conditions as may be experienced during hurricane season in Louisiana. The three characteristics are:

1. Defoliation during storms - trees that lose their leaves easily in high winds exhibit less structural damage to trunks and larger branches.
2. The elasticity of the wood - tree species with wood that is flexible, with a higher breaking point, do better during high-wind storm events and exhibit lower incidents of branch loss and better post-storm recovery. While age and tree height also play a role in flexibility as older wood becomes more brittle, loss of large branches and fracturing of tree trunks represent significant maintenance along ROWs after storms and potential safety hazards within travel lanes.
3. Modulus of rupture - a high modulus of rupture is a measure of the ability of a tree species to resist breaking. Soil saturation, root depth and other factors also play a role in determining a tree's ability to resist high-wind events without uprooting or breaking.

Comparing the Louisiana-selected tree species to the data provided in the LSU AgCenter Report, tree species could be subjectively evaluated for storm survivability. Taking into account the three primary factors described above, each Louisiana tree species evaluated in the report was assigned a value of one through five for storm survivability. Five being the highest resistance (most favorable) and one being the lowest (most susceptible) to high-wind event damage. While the authors recognize this is a subjective evaluation of storm survivability, it is a means to quantify the varying abilities of tree species to withstand storm events with the intent of minimizing LDOTD storm-related maintenance and travel safety concerns during and after high-wind events. The respective storm survivability rankings for each species are provided in Table 2 as part of the overall decision matrix.

The normalized and scaled sum of peak annual carbon sequestration (scale of 1-5), lifetime carbon sequestration (scale of 1-5) along with storm survivability (scale of 1-5) comprises a total matrix score of 3-15. The higher the total score for a specific tree species, the better that species should perform with the blended objective of maximizing carbon sequestration coupled with minimizing ROW maintenance and travel lane safety.

Table 2 shows the summary matrix for all tree species considered. The mean ranking score was 7.7 ± 2.7 (SD). Of the twenty-six species, six species, including conifers and hardwood, scored above this range (i.e., score $\geq$ 10.6): Swamp Tupelo, Bald Cypress, American Elm, Willow Oak, Loblolly Pine, and Swamp Post Oak. The species that ranked lowest (i.e., score $\leq$ 5) were Eastern Hophornbeam, White Ash, Cow Oak, Southern Hackberry, Laurel Oak, and Spruce Pine (Table 2). Thus, subsequent carbon sequestration modeling within this report is generally represented by hardwood and conifer tree classifications.

## Table 2. Tree Summary Matrix

| Common name | Scientific name | Ranked Variables (1-5 scale) | | | Total |
|---|---|---|---|---|---|
| | | Storm survivability | Peak annual $CO_2$ sequestration | Lifetime $CO_2$ sequestration | |
| Swamp Tupelo | *Nyssa sylvatica var. biflora* | 4 | 4 | 5 | 13 |
| Bald Cypress* | *Taxodium distichum* | 5 | 4 | 3 | 12 |
| American Elm | *Ulmus americana* | 3 | 5 | 4 | 12 |
| Willow Oak | *Quercus phellos* | 4 | 4 | 4 | 12 |
| Loblolly Pine* | *Pinus taeda* | 3 | 5 | 4 | 12 |
| Swamp Post Oak | *Quercus similis* | 4 | 3 | 4 | 11 |
| Water Oak | *Quercus nigra* | 1 | 5 | 4 | 10 |
| American Sycamore | *Platanus occidentalis* | 3 | 4 | 3 | 10 |
| Cedar Elm | *Ulmus crassifolia* | 3 | 4 | 2 | 9 |
| Overcup Oak | *Quercus lyrata* | 4 | 2 | 2 | 8 |
| Water Tupelo | *Nyssa aquatica* | 4 | 2 | 2 | 8 |
| Southern Magnolia | *Magnolia grandiflora* | 5 | 1 | 1 | 7 |
| Swamp Red Maple | *Acer rubrum var. drummondii* | 3 | 3 | 1 | 7 |
| Green Ash | *Fraxinus pennsylvanica* | 3 | 2 | 1 | 6 |
| American Holly | *Ilex opaca* | 4 | 1 | 1 | 6 |
| Blackjack Oak | *Quercus marilandica* | 4 | 1 | 1 | 6 |
| White oak | *Quercus alba* | 4 | 1 | 1 | 6 |
| American Beech | *Fagus grandifolia* | 4 | 1 | 1 | 6 |
| Sweet Gum | *Liquidambar styraciflua* | 3 | 2 | 1 | 6 |
| Southern Red Oak | *Quercus falcata* | 2 | 2 | 2 | 6 |
| E. Hophornbeam | *Ostrya virginiana* | 3 | 1 | 1 | 5 |
| White Ash | *Fraxinus americana* | 3 | 1 | 1 | 5 |
| Cow Oak | *Quercus michauxii* | 3 | 1 | 1 | 5 |
| Southern Hackberry | *Celtis laevigata* | 3 | 1 | 1 | 5 |
| Laurel Oak | *Quercus laurifolia* | 1 | 3 | 1 | 5 |
| Spruce Pine* | *Pinus glabra* | 2 | 1 | 1 | 4 |

**Indicate conifer species. The rest are included in the hardwood group.*

## Geo-spatial datasets and $CO_2$ sequestration modeling approach

Geo-spatial datasets and analysis techniques were integrated with the conifer and hardwood carbon sequestration models to estimate the carbon sequestration potential of interstate ROW lands in Louisiana (Figure 3).

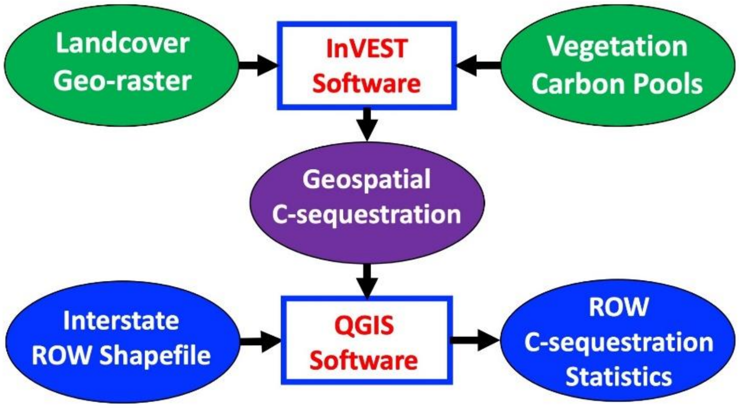


**Figure 3. Schematic of the workflow for the integration of geo-spatial data and techniques with carbon sequestration models of vegetation**

### Land cover Geo-raster

The landcover geo-raster files used were collected from the online landcover repository of USGS via the GAP/LANDFIRE database [33] [34]. The resolution of the landcover data used is 30 meters by 30 meters (30mx30m). Hence each landcover raster file has "per pixel area" of 30mx30m/pixel = 900m2/pixel = 0.222395 acre/pixel = 0.09 hectare/pixel. The landcover type is coded according to the set standard codes in National Land Cover Dataset (NLCD) [35]. These numeric codes were used as the '*lucode*' values in the carbon pools table within the InVEST software (see sub-section 'Carbon Sequestration Estimation Using InVEST').

### Tree $CO_2$ sequestration models

Tree age vs. diameter (DBH) empirical relationships found in the literature were used to derive $CO_2$ sequestration vs. age, using the annual $CO_2$ sequestration rates for the different diameters available in the My Tree tool (see subsection "Tree information and classification"). These types of relationships have seldom been reported for all species of interest that were identified, and in the cases that a relationship was not available, the assumed value reported from a taxonomically closer species was used. The spatial analysis of $CO_2$ sequestration potential on hardwoods and conifers as two contrasting groups of tree species was analyzed. The equations that were derived from this analysis are shown below. This set of sequestration equations and associated tree planting densities should be considered relatively high-yielding $CO_2$ sequestration rates for conifers and relatively low sequestration values for hardwoods. An additional $CO_2$ sequestration model was also derived from a Department of Energy (DOE) source considered to yield more moderate sequestration values for both conifers and hardwoods [36]. Scenarios from both sequestration models, high and low tree planting densities, and three different forestation management scenarios were used to yield a range of potential $CO_2$ sequestration values for Louisiana ROW lands. The following equations (1,2) are associated with the MyTree $CO_2$ sequestration data. Details on the approach based on DOE sequestration rates are provided in a later section.

$$\text{Conifers: Annual } CO_2 \text{ (lb-}CO_2\text{ yr}^{-1}\text{ tree}^{-1}) = -0.007t^3 + 0.5t^2 - 0.5t \qquad \text{(Equation 1)}$$

$$\text{Hardwood: Annual } CO_2 \text{ (lb-}CO_2\text{ yr}^{-1}\text{ tree}^{-1}) = -0.01t^2 + 2.8t \qquad \text{(Equation 2)}$$

where,

$t$ = time in years.

For conifers, the age-to-DBH relationships were for the Loblolly Pine [37]. For hardwoods, we use available relationships for the Overcup Oak [38].

## $CO_2$ sequestration estimation using InVEST

The landcover data and the time-series carbon sequestration model of pine and oak were integrated into the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software to project the carbon sequestration to a geospatial model. InVEST version 3.9.0 is a suite of models used to map and value the goods and services from nature that sustain and fulfill human life; hence, it helps explore how changes in ecosystems can lead to changes in the flows of many different benefits to people [39]. Within InVEST, the "Carbon Storage and Sequestration" modeling platform was implemented. The model maps carbon storage densities to land use/land cover (LULC) rasters which may include types such as forest, pasture, or agricultural land. The model summarizes results into raster outputs of storage, sequestration, and value, as well as aggregate totals. Following are the two input data types required:

**1 - Current land use/land cover** (required): Raster of LULC for each pixel, where each unique integer represents a different land use/land cover class. This was the landcover data from USGS (see sub-section on Landcover Data).

**2 - Carbon pools** (required): A CSV (comma-separated value) table of LULC classes containing data on carbon stored in each of the four fundamental pools for each LULC class. If the information on some carbon pools is not available, pools can be estimated from other pools or omitted by leaving all values for the pool equal to 0. The table must contain the following columns:

- *lucode*: Represents a unique integer for each LULC class (e.g., 1 for forests, 3 for grasslands, etc.) *Every value in the LULC map MUST have a corresponding lucode* value in the Carbon Pool table.
- *c_above***:** Represents the carbon density in aboveground biomass [units: megagrams/hectare]. This was the annual carbon sequestration potential of a tree, i.e., conifers, hardwoods, combination of conifer and hardwoods. To extrapolate from tree to areal carbon sequestration potential, an assumed tree planting density (TPA) of 600 for conifers [40] and 350 for hardwoods [41], which lies on the high end of possible species densities in plantations, was initially used.
- *c_below***:** Represents the carbon density in belowground biomass [units: megagrams/hectare]. This was set to zero in this work.
- *c_soil***:** Represents the carbon density in soil [units: megagrams/hectare]. A value of 50 megagrams C/hectare was used based on typical values in published works [42].
- *c_dead*: Represents the carbon density in dead matter [units: megagrams/hectare]. This was set to zero in this work.

### Carbon Sequestration in ROW Using QGIS

After geospatial projection of the carbon sequestration potential via InVEST, the resulting geo-raster files contain carbon sequestration per pixel information. These were then used as input raster layers in the QGIS software (version 3.16) [43] to extract the necessary information pertaining to the modeled areas within the ROW of each interstate. The ROW shapefiles were used to extract the carbon sequestration data from the geo-raster file from InVEST. Summary statistics were then applied to the extracted carbon geo-raster using the 'Raster Layer Statistics' function under the 'Raster Analysis' platform in QGIS. This procedure was implemented for each carbon sequestration geo-raster file produced from InVEST analysis. All GIS works were done with the CRS of EPSG:4326.

## $CO_2$ Sequestration Simulations

$CO_2$ sequestration rates attributed to individual trees can be estimated through several methods and from numerous sources in published literature. To account for the overall contribution from amenable ROW lands, $CO_2$ sequestration models were established for individual trees, then applied at various initial planting densities to the GIS-determined amenable ROW lands. This report utilized two different $CO_2$ sequestration data sets to derive sequestration rates over time for conifers and hardwoods. The resulting two mathematical models are considered exemplary of $CO_2$ sequestration values over time, but neither model is considered more or less accurate for application within Louisiana ROWs. Both models were utilized to yield a range of expected $CO_2$ sequestration values rather than reliance on a single model. The $CO_2$ sequestration models are described below and subsequently applied along with relatively high and low initial planting densities and three different forest management scenarios.

The MyTree-derived $CO_2$ sequestration data [29,30] was generated by estimating tree size (DBH) with age and then correlating tree size to $CO_2$ sequestration, resulting in a mathematical model of sequestration over time. This model was developed for both conifers and hardwoods. The resulting $CO_2$ sequestration rates are deemed relatively high for conifers and relatively low for hardwoods. These relationships were not deliberate but a result of the data from the MrTree resource. This model was applied to relatively high initial planting rates for conifers and hardwoods that may not be feasible in all field conditions.

The second source of $CO_2$ sequestration data was utilized as published by the Department of Energy (DOE) [36]. This set of empirical data was provided as $CO_2$ sequestration over time for both conifers and hardwoods and deemed applicable to growing conditions in Louisiana. The resulting $CO_2$ sequestration rates from the DOE data are deemed to be relatively moderate for both conifers and hardwoods. This $CO_2$ sequestration model was applied with both relatively high initial planting densities for direct comparison to the MyTree model and relatively low initial planting densities to create a range of potential $CO_2$ sequestration values.

Three ROW-based forest management scenarios were computationally investigated to estimate the resulting $CO_2$ sequestration within the estimated ROW land areas amenable to forestation within each interstate system. The simulations excluded the 35-ft buffer zones from the edge of the outer and inner lanes. These buffer zones (aka clear zone) are within the typical range for many highways and are allocated for road maintenance activities along with providing safety zones. The three management scenarios are described below.

**Scenario 1: No intervention**

Vary the fraction of pine and oak planted in the ROW and allow the forest to grow without any intervention (i.e., forest management, such as thinning and harvest). However, this scenario does represent an initial planting of the targeted tree type. This scenario was mathematically done by simply applying the fraction of the tree as the weighing fraction on the calculated $CO_2$ sequestration of each tree.

$$C_{total} = C_{pine} \times p_{pine} + C_{oak} \times p_{oak} \qquad \text{(Equation 3)}$$

where,

$C_{total}$ = the combined $CO_2$ sequestration of pine and oak

$C_{pine}$ = the $CO_2$ sequestration of pine only

$C_{oak}$ = the $CO_2$ sequestration of oak only

$p_{pine}$ = fraction of pine planted

$p_{oak}$ = fraction of oak planted = 1 - $p_{pine}$ (only pine and oak combined)

**Scenario 2: Implementing thinning**

This scenario evaluated the implementation of forest thinning at various time intervals for the pine and oak trees planted in the ROW. Several studies have documented the effect of thinning on the growth of pine and oak, and many of these studies found that forest thinning may have a significant improvement effect on the growth of the remaining trees in the forest [44] [45]. Carbon sequestration is proportionally impacted by tree rate growth, whereas a fast-growing maturing tree uses more carbon than a mature tree or a sapling (building biomass needs carbon via photosynthesis). Also, the weight of the biomass present on a land area also impacts the sequestration rate (the more biomass, the higher rate). Even though the current literature does not contain a definite model describing these improvements in tree growth via thinning, the available empirical data may be used to calibrate models that represent forest growth. This work proposes the following development of the effect of forest thinning for pine and oak.

The general model used in this effort for evaluating the effect of thinning is as follows:

$$C_{thinned} = C_{unthinned}\,[1 - f][1 + r_i] \qquad \text{(Equation 4)}$$

where,

$C_{unthinned}$ = the $CO_2$ sequestration if no thinning at time, $t$

$f$ = the fraction of thinning implemented at time $t_{thin}$. The empirical data used in the calibration of the $r_i$ model is within 30% to 50% forest thinning, so this work limited the explored thinning range to thinning levels of 30-50%.

$r_i$ = the improvement in the forest growth after thinning; this is a function of the time that elapsed from time $t_{thin}$ when a thinning of f-fraction is implemented. This is a dimensionless ratio that compares the improvement from a baseline of 1. The improvement ratio can be less than one, but cannot be negative in this context.

The effect of thinning model (Equation 4) is similar to a simple interest model on investment, which is a common framework for developing return on investment for ecological systems like forests [46] [47].

*Thinned forest growth improvement rate for pine,* $r_i = r_{pine}$:

The improvement in the forest growth after thinning was modeled as a function of the time that elapsed after implementing a thinning level. This time-dependent model was developed as follows. For pine, take the $CO_2$ sequestration model Equation 1 but generalize the constant parameters, where $t$ is time in years after a thinning at time $t_{thin}$

$$r_{pine} = -at^3 + bt^2 - ct \qquad \text{(Equation 5)}$$

The model constants a, b, and c are positive numbers, and the sign of the terms must be maintained to restrict the dynamical behavior of the model to be similar to $CO_2$ sequestration. Calibrating this model form with empirical data to the 3rd order (Equation 5) shown essentially emulates the time-series dynamical behavior of the proportional relation of the $CO_2$ sequestration pine and the growth (by mass or by volume) of pine. Using similar logic, the tree's growth is proportional to the improvement of growth due to thinning. That is (note: "~" means proportional),

[$CO_2$ sequestered] ~ [mass of tree or volume of tree]

[mass of tree or volume of tree] ~ [$r_i$]

[$CO_2$ sequestered] ~ [$r_i$]

Hence *Equation 5* formed maybe an acceptable model for the $r_i = r_{pine}$. The empirical data used to calibrate *Equation 4* was the published by Stewart and Dawson [44] on the improvement of pine tree diameter after thinning.

*Thinned forest growth improvement rate for oak,* $r_i = r_{oak}$:

For oak, the same logic and procedure was applied in developing the model for the improvement in the forest growth after thinning. The only difference is the model form, which is similar to *Equation 2*, and the empirical data used for model calibration. The rate of improvement for $r_{oak}$ is expressed as follows, where $t$ is time in years after a thinning at time $t_{thin}$:

$$r_{oak} = -\mathrm{d}t^2 + \mathrm{e}t \qquad \text{(Equation 6)}$$

The model constants d and e are positive numbers, and the sign of the terms must be maintained to restrict the dynamical behavior of the model to be similar to $CO_2$ sequestration. The empirical data used to calibrate *Equation 6* was from the published data by [45] on the improvement of oak tree volume (mass) after thinning.

**Scenario 3: Implementing thinning and replanting**

The effect of replanting available or portions of available spaces in the growing forest was also implemented, along with thinning, to simulate the performance of a ROW forest in the long run. Though the following narrative uses Interstate 10, conifer-only, 15-year thinning, the same workflow of calculations can be done to other interstates and forest thinning and replanting scenarios. An assumption of the calculations done is that no tree seedlings grow out of the existing forest and that young trees are introduced by deliberate replanting at a specific time and fraction of the available forest land. The model starts with 2,171,154 pine trees (to achieve 600 TPA initially) in the Interstate 10 ROW land area amenable to forestation. The 15-year thinning is implemented throughout the ROW land area. The first replanting is done 45 years into the forestation period, and this replanting uses all the available land and brings back the tree density to 600 TPA. The second replanting is done at Year 75 when all the remaining old trees originally planted are cut, and their space is replanted with young trees. The numbers used for the timing of these replanting and the number of trees replanted are arbitrarily set within a typical range to illustrate the effects of such timings and replanting on the long-term dynamics of the ROW forest.

In addition to the three forestation management scenarios described, the contribution of soil within the same ROW lands to sequester $CO_2$ was also estimated within each of the three modeling applications. Under Scenario 1, no implementation. While soil is already typically present within the ROW systems, this analysis was included to show the accounting potential for $CO_2$ sequestration as carbon offsets within Louisiana ROWs.

In summary, two different $CO_2$ sequestration models, applied with high and/or low initial planting densities, each with three different forest management scenarios, were applied to GIS-identified amenable ROW areas to yield a range of $CO_2$ sequestration values potentially applicable to Louisiana ROW lands. The following is a summary of the $CO_2$ sequestration models, tree planting densities, and forest management scenarios that are documented within this report. While this matrix of sequestration models, planting densities, and management variables potentially represent approximately 12 different sequestration scenarios, the authors are comfortable that the following three modeling scenarios are representative of the larger matrix and suitable for the purposes of this report.

Model 1: MyTree $CO_2$ sequestration rates with relatively high tree planting densities subject to Scenario 1 - No management other than the original planting; Scenario 2 – Scenario 1 plus implement thinning); and Scenario 3 - Scenario 2 plus implement replanting.

Model 2: DOE available sequestration rates with relatively high tree planting densities subject to the same scenario approaches detailed above in Model 1.

Model 3: DOE published sequestration rates with relatively low tree planting densities subject to the same scenario approaches detailed above for Models 1 and 2.

## The land area of ROWs on Louisiana's major highways

10,305 acres of ROWs along the Interstates 10, 20, and 49 and Lafayette to Houmas-Highway 90 corridors were identified as being potentially available to plant trees. This section of US Highway 90 has been constructed to US Interstate Highway standards and will eventually become the future extended length of I-49). The estimate can be as high as 12,325 acres if 35-ft buffer zones are included (see Figure 3).

**Figure 4. The four major highways in the state of Louisiana: Interstate 10 (blue), Interstate (blue) 20, Interstate 49 (orange), and Highway 90 Section (green)**

**Table 3. Estimated land area in Louisiana's major highways amenable to forestation**

| Highway | ROW (acre) |
|---|---|
| | Available * |
| I-10 | 3,620 |
| I-20 | 2,195 |
| I-49 | 3,203 |
| Highway 90 ** | 1,288 |

**This is the area from the edge of the 35-ft buffer zone to the outside boundary of the ROW.*

***The length of Highway 90 used is from its intersection with I-49 down to Houma, LA. It was assumed that only this stretch contains the land area suitable for forest management within the ROW.*

## Model 1: $CO_2$ sequestration in Louisiana's ROW lands from MyTree with relatively high planting densities

### Model 1, Scenario 1: Initial Planting With No Intervention

The $CO_2$ sequestration potential is a direct function of the group of trees to be planted, with faster-growing conifers outpacing the sequestration potential of hardwoods with slower growth. The sequestration is also dynamic in response to tree development with peaking rates after several decades of planting. This peak is to be expected at or after the four decades, with important implications for $CO_2$ budgets, well beyond the 2050 mark for the net carbon neutrality targeted in the Governor's Order. The general dynamics of annual $CO_2$ sequestration potentials are illustrated for I-10, I-20, I-49, and Hwy 90 in Figures 5-8 for different mixtures of conifer and hardwood trees and the inclusion of carbon in the soils.

With no forest management intervention after planting, the potential annual $CO_2$ sequestration rate in Louisiana's ROW lands by 2050 can range from 115,200 to 653,987 US tons $CO_2$ $yr^{-1}$ (Table 4). This range is based on the numerical levels of the input parameters – mainly individual tree $CO_2$ uptake (species dependent) and planting/growth density. After 60 years, the annual $CO_2$ sequestration rate can be as high as 1,211,356 US tons $CO_2$ $yr^{-1}$ if the planted forest achieves a very high rate of carbon intake. From Table 4, it can be seen that a conifer-only forest will offer the highest sequestration rate. With Louisiana targeting a Year 2050 Net Zero Carbon Emission goal, the total $CO_2$ sequestration potential using the proposed concept could be removing as much as 650,000 US tons and 1,211,356 US tons per year for Year 2050 (28 years from today) and Year 2085 (58 years from today), respectively. At Year 2050, this amount of $CO_2$ sequestration from all of the Louisiana interstate ROWs combined would net out about 25% of the No. 10 manufacturing plant in the top ten list of highest GHG emitters in Louisiana (see Table 1). By Year 2085, the amount of total ROW sequestration would net out about 50% of the No. 10 top $CO_2$ emitting industrial plant in Louisiana.

**Table 4. Model 1, Scenario 1: Annual $CO_2$ sequestration potentials in ROW lands [US ton $CO_2$ $yr^{-1}$] MyTree data with relatively high tree planting density.**

| **BY 2050*** | | | | | | |
|---|---|---|---|---|---|---|
| Highway | 10% C - 90% H | 25% C - 75% H | 50% C - 50% H | 75% C - 25% H | Only C | Only H |
| I-10 | 63,766 | 91,450 | 137590 | 183,730 | 229,870 | 45,309 |
| I-20 | 34,572 | 52,015 | 81,087 | 110,158 | 139,230 | 22,944 |
| I-49 | 50,453 | 75,908 | 118,333 | 160,758 | 203,183 | 33,483 |
| HW-90 | 20,288 | 30,524 | 47,584 | 64,644 | 81,704 | 13,464 |
| **TOTAL** | **169,079** | **249,897** | **384,594** | **519,290** | **653,987** | **115,200** |
| **BY 2085*** | | | | | | |
| Highway | 10% C - 90% H | 25% C - 75% H | 50% C - 50% H | 75% C - 25% H | Only C | Only H |
| I-10 | 119,647 | 170,669 | 255,704 | 340,739 | 425,775 | 85,633 |
| I-20 | 64,816 | 96,995 | 150,627 | 204,260 | 257,892 | 43,363 |
| I-49 | 94,588 | 141,548 | 219,816 | 298,083 | 376,351 | 63,281 |
| HW-90 | 38,036 | 56,919 | 88,392 | 119865 | 151,338 | 25,446 |
| **TOTAL** | **317,087** | **466,131** | **714,539** | **962,947** | **1,211,356** | **217,723** |

*C: conifer*

*H: hardwood*

** The sequestration potentials are calculated starting in 2025.*

The time dynamics of the forest in terms of $CO_2$ sequestration must also be considered in addition to sequestration values at specific time points. Figures 5 to 8 show that the $CO_2$ sequestration of highway forests changes depending on the age of the forest and the type of trees in the forest. Conifers have higher $CO_2$ sequestration per acre compared to hardwood trees, but the conifers attain their peak performance at around 50 years, while the hardwoods are still improving in their growth rates (see Figure 9 for a growth rate of hardwood) and peaking at 100 years. At Year 50, conifers planted along I-10 can have a total sequestration rate of 450,000 US tons $CO_2$ $yr^{-1}$ (see Figure 5e). At Year 60, hardwood along I-10 can achieve a sequestration rate of around 85,000 US tons $CO_2$ $yr^{-1}$ (Figure 5f). What this means for a highway forest is that there is a period of lag in terms of $CO_2$ sequestration before having trees that are mature enough to sequester $CO_2$ at high rates. The ratio of tree types must also be considered in highway ROW forest design because it is believed that having species diversity within the ROWs may offer several benefits, including (a) a healthier and more sustainable forest, (b) a richer ecological system, and (c) the presence of the more storm resilient hardwoods would prop the weaker conifers (reduce wind sway) and thus potentially reduce storm impacts. It can be observed from Figures 5 through 8 that the higher the percentage of conifers making up the forest species distribution, the higher the maximum sequestration achieved. Therefore, the value of forest species diversity should be further analyzed in future works.

It is also noted that the contribution of soil-based carbon sequestration can be a significant portion of the $CO_2$ sequestration achieved by a highway forest (see Figures 6 and 8). These can be seen visually as the baseline levels (constant levels) at the bottom of the graphs in Figures 6 and 8. Depending on the age of the forest and the type of tree planted, soil carbon sequestration can be a significant contributor to the sequestration levels of the highway forest. For a hardwood-only forest (or hardwood-dominant forest), the soil carbon sequestration is higher than the carbon sequestration by the hardwood trees. On the other hand, the carbon sequestration of conifers is significantly higher than the soil carbon sequestration. The role of soil carbon sequestration must be emphasized when considering the benefit of the 35-ft buffer zone along the highway in addition to its role in highway safety and maintenance. Even though that 35-ft buffer zone may contain only grass as vegetation, the processes happening within that topsoil can favor significant levels of $CO_2$ sequestration. However, it also must be pointed out that the soil within the ROW lands is constant, and therefore, only planting additional trees will achieve significant new amounts of sequestration. This is an important point if only new additional carbon sequestration is the goal and not the accounting for all carbon sinks.

It is also realized that there are already some trees growing in the ROWs. Hence the predicted carbon sequestration reflects the envisioned maximum forest growth in the ROW areas evaluated, but since there are trees already present, this level of actual additional sequestration will be smaller. At this time, the research team has no way to properly calculate the current tree population/density within the ROWs. Also, even with some trees present, this study points out the benefits of selective speciation and maximizing growth density.

The similar behavior of the $CO_2$ sequestration curves for I-10 (Figures 5 and 6) and I-20 (Figures 7 and 8) manifests visually the linear nature of the modeling implemented in this work. That is, only the area available for forest growth changes from one highway to another, while other modeling aspects, such as the tree growth equations, were the same (Equations 1 to 6). Hence, a linear scaling of the levels of $CO_2$ sequestration can be applied to other highways such as I-49 and Highway 90 (or any additional land areas for that matter).

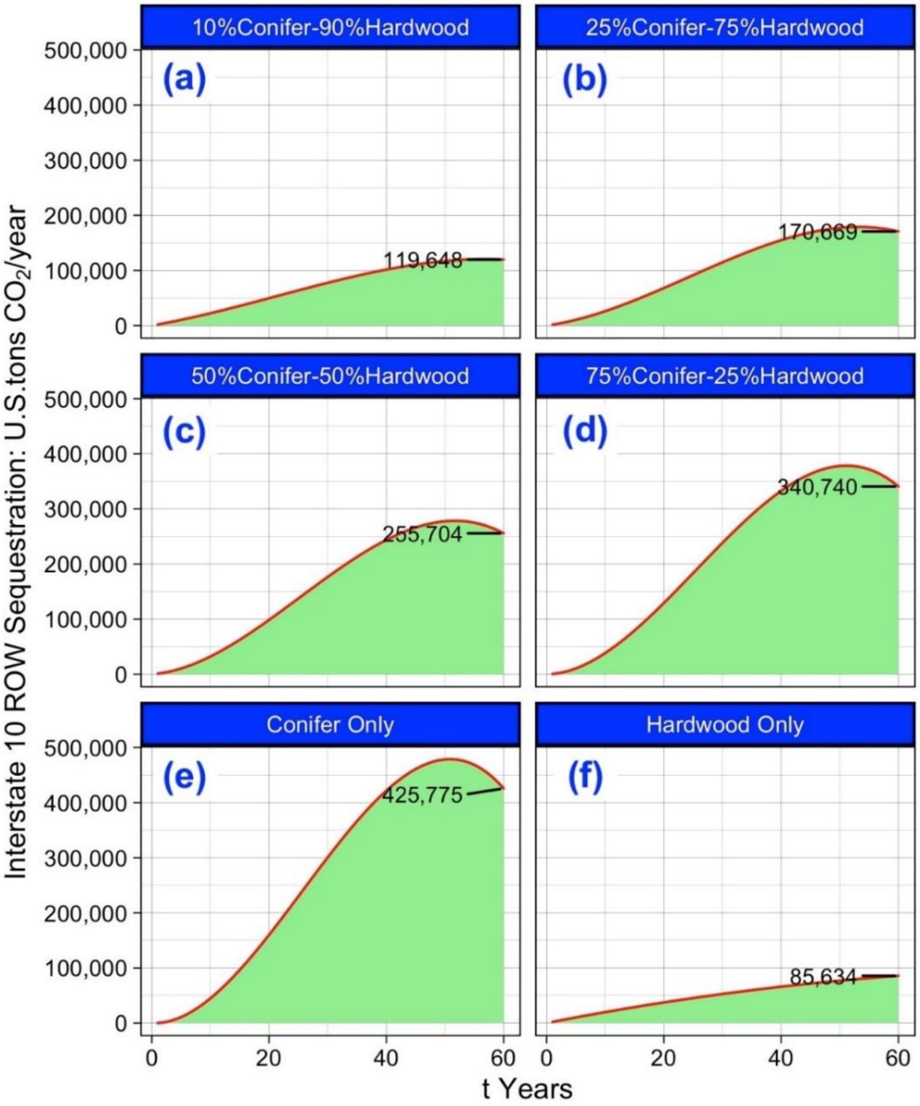


**Figure 5. Estimated $CO_2$ sequestration per year along the entire Interstate 10 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates do not include the carbon sequestration potential of the soil – thus a tree-only carbon uptake**

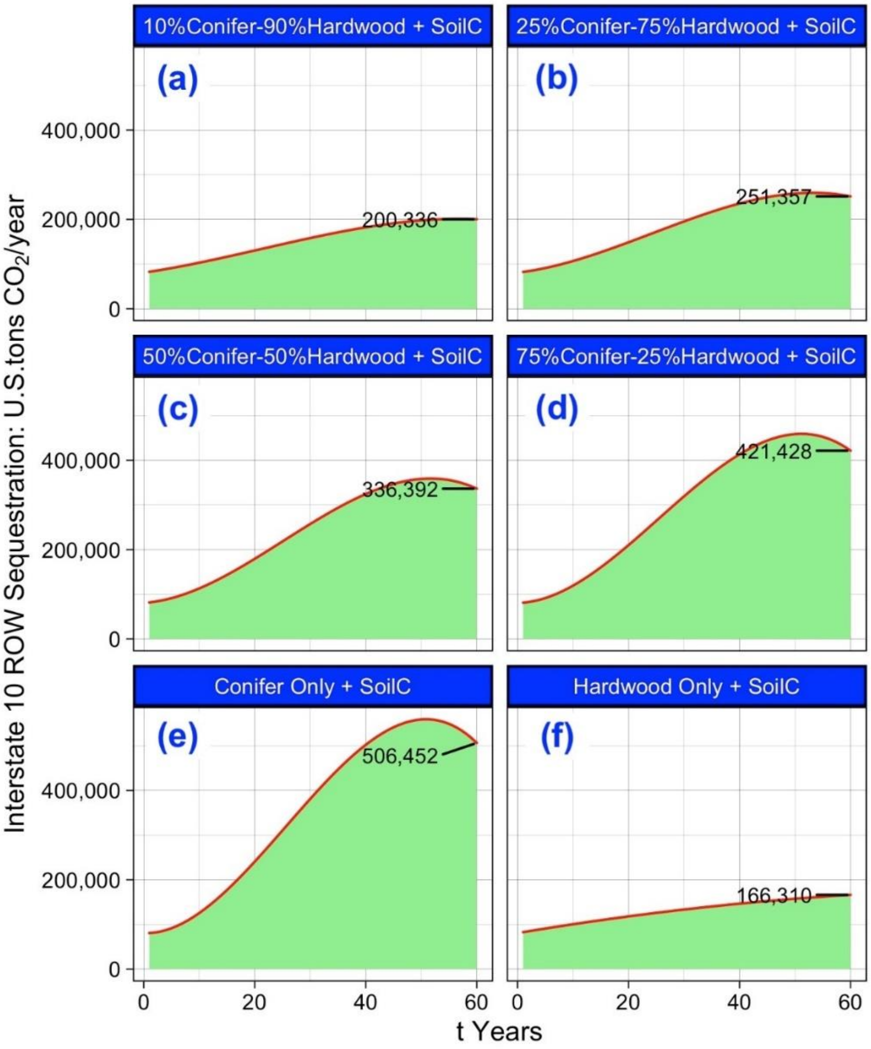


**Figure 6. Estimated CO₂ sequestration per year along the entire Interstate 10 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the CO₂ sequestration rate at the end of the simulated period of 60 years. These estimates do include the carbon sequestration potential of the soil**

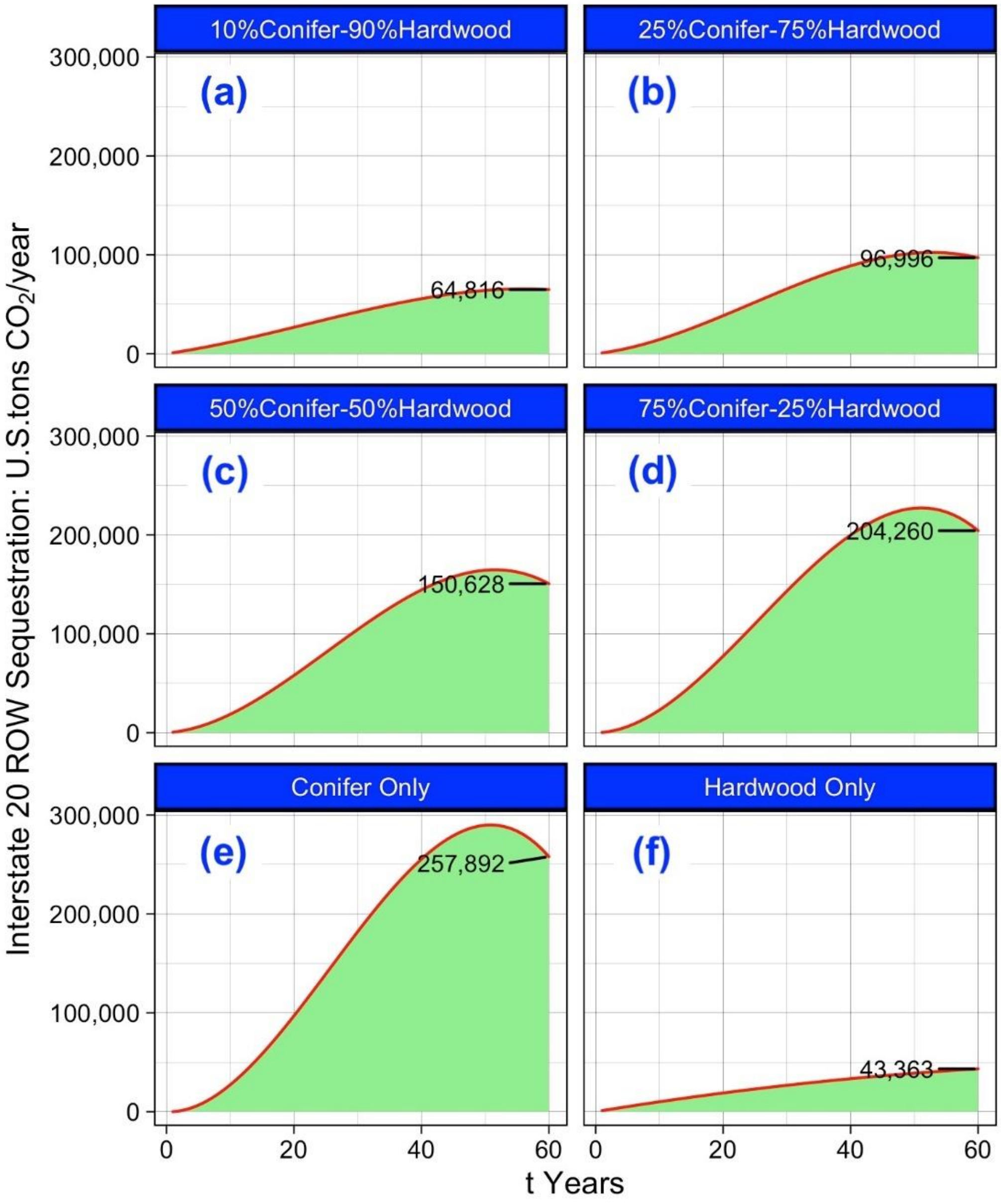


**Figure 7. Estimated $CO_2$ sequestration per year along the entire Interstate 20 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood m mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates do not include the carbon sequestration potential of the soil – thus a tree-only carbon uptake**

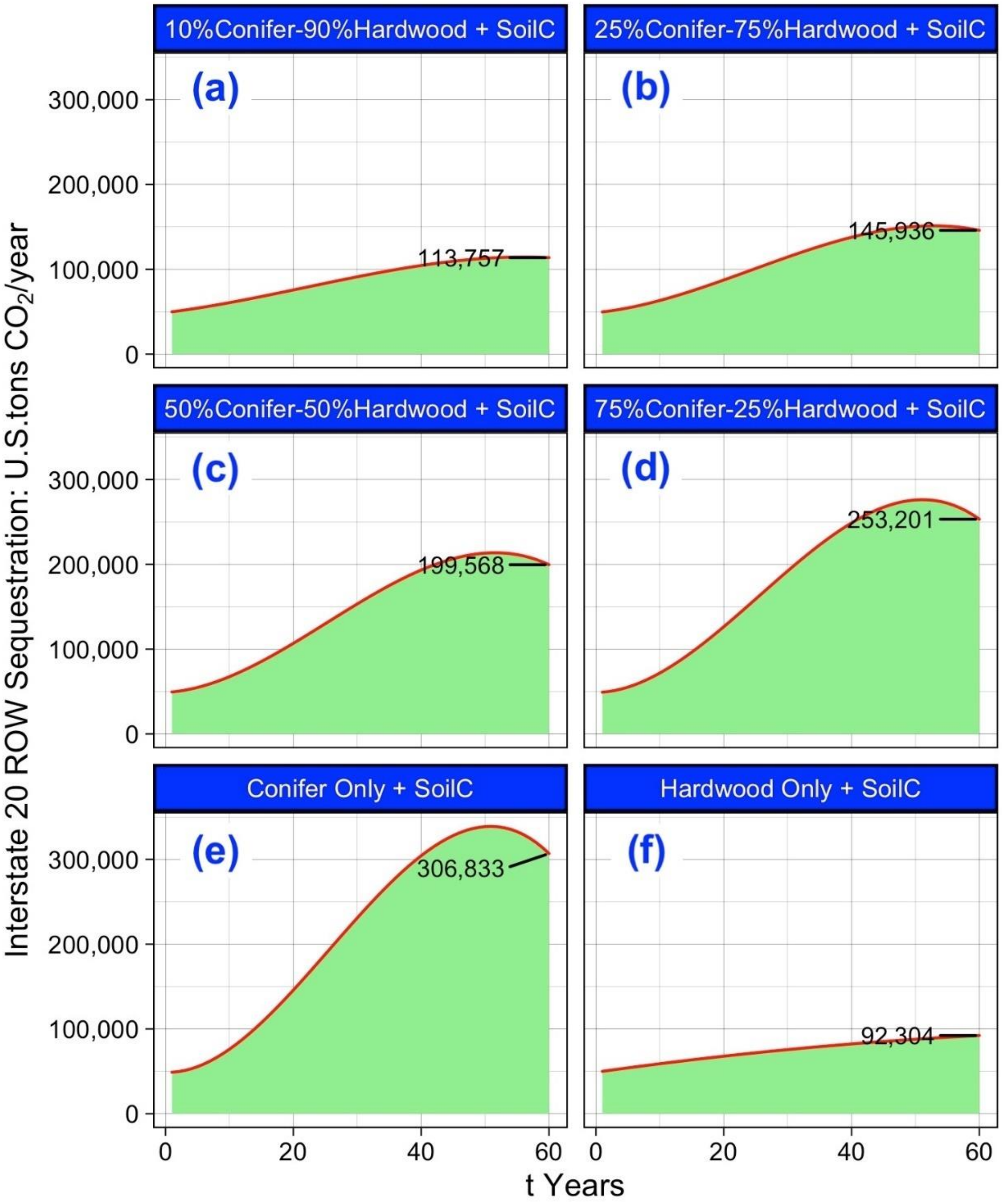


**Figure 8. Estimated $CO_2$ sequestration per year along the entire Interstate 20 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates do include the carbon sequestration potential of the soil**

### Model 1, Scenario 2: Implementing thinning

Forest thinning is a crucial part of maintaining a well-managed forest, and some research works in the past collected data on the effects of thinning on forest growth which in turn impacts $CO_2$ uptake [48, 49]. Improvements in forest growth due to thinning were observed with these past works in terms of the mass and volume of trees harvested over decades. Those reported results were used in this work to develop mathematical models on the effect of thinning on the improvement of tree growth, hence forest growth. The model equations for the rate of improvement in forest growth after thinning are summarized in Table 5. Note that the applicability of these models is within fraction thinning $30\% < f < 50\%$ since this was the range of thinning from which the empirical data were collected. The behavior of these $r_i$ models can be visualized over time $t$, as shown in Figure 9. The data shown in Figure 9 represents the fitting of the actual data (solid line) followed by the projected benefit as a rate (dashed line) over time using the performance projection of the developed model. Thus, these models can computationally project times beyond (dash lines) the reported time frame used in the actual data. Note that for the stated validity of $t$, the runs must be strictly used within their valid $t$ periods. Also, take note that the $r_i$ values cannot be negative, but can be less than one. Table 4 presents the mathematical expressions used in the models from Figure 9.

It is interesting to note that thinning shows improvements to sequestration which is due to the provision of conditions within the forest conducive to maximum carbon uptake, such as improved light penetration into the inner-growth area trees (reduces shading), thereby maximizing photosynthesis (and in turn $CO_2$ uptake). However, as shown with the conifers, these trees reach their maximum uptake (and thus maturation) at Year 50, then uptake begins to drop off. This supports the use of more advanced management methods such as thinning and harvest (discussed later in this report). The hardwoods, being much slower growing species, indicate a steady increase in benefit of thinning well into 100 years, where this begins to show reducing benefit.

**Table 5. Equations for the rate of improvement in forest growth after thinning.**

| **Tree** | **“$r_i$“ expression in the thinning model: $C_{thinned} = C_{unthinned} [1 - f] [1 + r_i]$** |
|---|---|
| Conifer | $r_i = r_{pine} = -7x10^{-5}t^3 + 0.005t^2 - 0.0046t$; for $t$ up to 25 years, $0.3 < f < 0.5$ |

| | |
|---|---|
| Hardwood | $r_i = r_{oak} = -0.0001t^2 + 0.0221t$; for $t$ up to 80 years, $0.3 < f < 0.5$ |

The effect of thinning at different intervals on $CO_2$ sequestration potential is illustrated for a hypothetical planting of conifers and hardwood trees along I-10 in Figures 10 and 11, respectively. It must be noted that lower and upper-bound levels of thinning were taken based on the sources of empirical data used to develop the model for thinning (Table 5). Hence, 30% thinning is the lower bound, and 50% thinning is the upper bound for forest thinning used in the succeeding model simulations. Consequently, interpolation of performance must be done only within the shaded area between the 30% and 50% thinning model lines and including the 30% and 50% thinning lines. The sequestration potential tends to increase at low thinning levels and is less frequent. It can even lead to increased sequestrations compared to the no thinning (i.e., no intervention) management alternative. Thus, it appears that implementing a thinning strategy for conifers at growth years of above 15 years shows the most improvement in terms of carbon sequestration. This practice could lead to improvements in the rate of carbon dioxide uptake by over twofold. This observation made into practice requires less access to the ROW for thinning since the periods between thinning (and likely replanting – discuss more in the next section) are further apart.  If the forest is being thinned too quickly, such as every 5 to 10 years for conifer and 10 to 20 years for hardwood, then the thinning does not improve the $CO_2$ sequestration compared to the baseline of no-thinning.

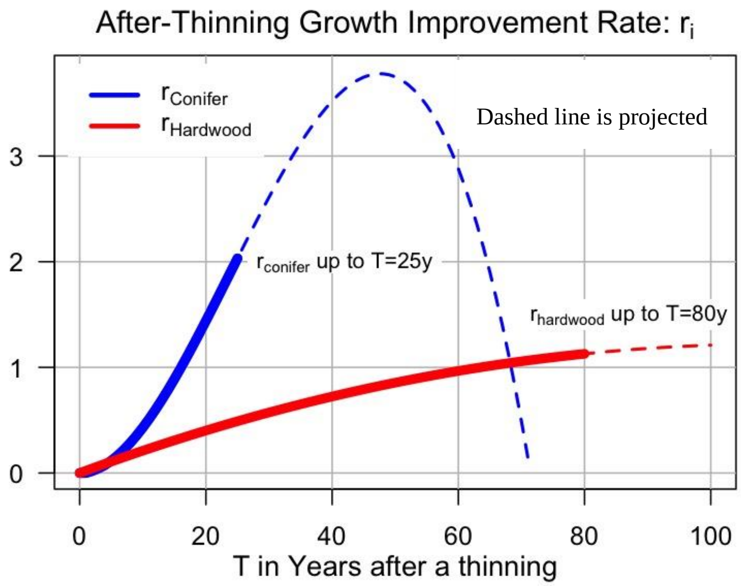


**Figure 9. Graphical rendering of the changes in the growth improvement over time after a thinning is implemented for pine and oak tree forest**

The hardwood results are not presenting as much benefit for sequestration compared to no thinning (Figure 11). This is not surprising given hardwoods' slower biomass growth rates over conifers. It is also notable that the extent of $CO_2$ sequestration for hardwoods is generally about 10% of the rates achievable for conifers.

If implemented properly, the $CO_2$ sequestration of conifers along I-10 can double compared to no-thinning by implementing a 30% thinning every 20 years resulting in a peak of around 1,200,000 U.S.tons $CO_2$/year at Year 60 (Figure 10d). That is more than double the peak performance at 500,000 U.S.tons $CO_2$/year at Year 50 for no-thinning (Figure 10d). The sequestration performance of hardwood trees can also be improved by the right combination of %-thinning and interval of thinning compared to no-thinning, but the level of performance improvement is not as good as the improvement for the conifer. For example, the 30% thinning of hardwood every 40 years peaked at around 130,000 U.S.tons $CO_2$/year at Year 120 compared to the no-thinning performance of 100,000 U.S.tons $CO_2$/year at Year 100 (Figure 11d). Even though these sequestration values are specific to I-10, the trends can also be expected in the other highways after applying a scaling of areas available for forest growth (see Table 3).

It is important also to point out that thinning will produce biomass that can be used for producing forest products and/or used as renewable fuels. Markets for woody residuals are expanding as manufacturing is moving toward more sustainable practices. This benefit is further discussed later in this document. Noteworthy is that hardwood chips generally are more valuable than softwoods (conifers).

### Model 1, Scenario 3: Implementing thinning and replanting

Implementing thinning followed by replanting increases $CO_2$ sequestration considerably while it maintains the suitability of the ROW lands forests in the long term as potential $CO_2$ sinks (Figure 12). The simulation results show the long-term effect of forest management on the proposed ROW forest, which is represented by I-10 in this case for demonstration (Figure 12a). The trajectory of 30% thinning follows an improved performance in the long term compared to the no-thinning model (baseline for 30% thinning). On the other hand, 50% thinning cannot perform better than no-thinning even for a long-term cycle (baseline for 50% thinning). This shows that thinning levels may dictate the long-term dynamics in terms of $CO_2$ sequestration of the highway forest.

Looking at the number of trees harvested/cut (Figure 12b and 12c), the 30% thinning leaves more trees by count while at the same time still achieving cumulative trees harvested close to 50% thinning close to 4 million trees by 120 years. These trees, which are conifers in the example dynamics, have a market value that can offset some costs in maintaining the highway.

The replanting strategy can be varied and can be the subject matter of modeling investigation on its own, but the results of this work (Figure 12) show that the replanting strategy significantly alters the $CO_2$ sequestration dynamics. Take, for example, the 30% thinning replanting at t = 75 years. Since the remaining older trees, which are planted at the beginning of the first cycle, are all cut and replaced by young trees, the estimated performance of the 30% thinning is lower than the baseline of no thinning. This is a period that is similar to the first thinning in cycle 1, when the removal of trees suddenly decreases a period of forest growth improvement. This period, however, is followed by a higher growth rate due to improvement from the benefits of thinning. Also evident in this 2-cycle model is the need for continuous cycling of the thinning and replanting strategy to sustain high $CO_2$ sequestration rates. As the forest time gets close to the t = 120 years, when no additional cycling is implemented, the $CO_2$ sequestration performance can suddenly drop and approach the no-thinning baseline performance.

The thinning-only options yielded maximum annual CO2 sequestration rates of around 1,100,000 tons per year (enough to offset about 50% of the carbon released annually from the No. 10 facility on the top ten producer list shown earlier in this report). Conversely, the benefits with regard to replanting do not seem to be significant as the resulting sequestration rates are at about the same level (see Figure 12) as the 1,100,000 tons per year level observed with the thinning-only data. This amount of annual CO2 sequestration (~1,100,000 M-T/yr) will net out Louisiana industrial complexes within the upper 25 of overall top producers.

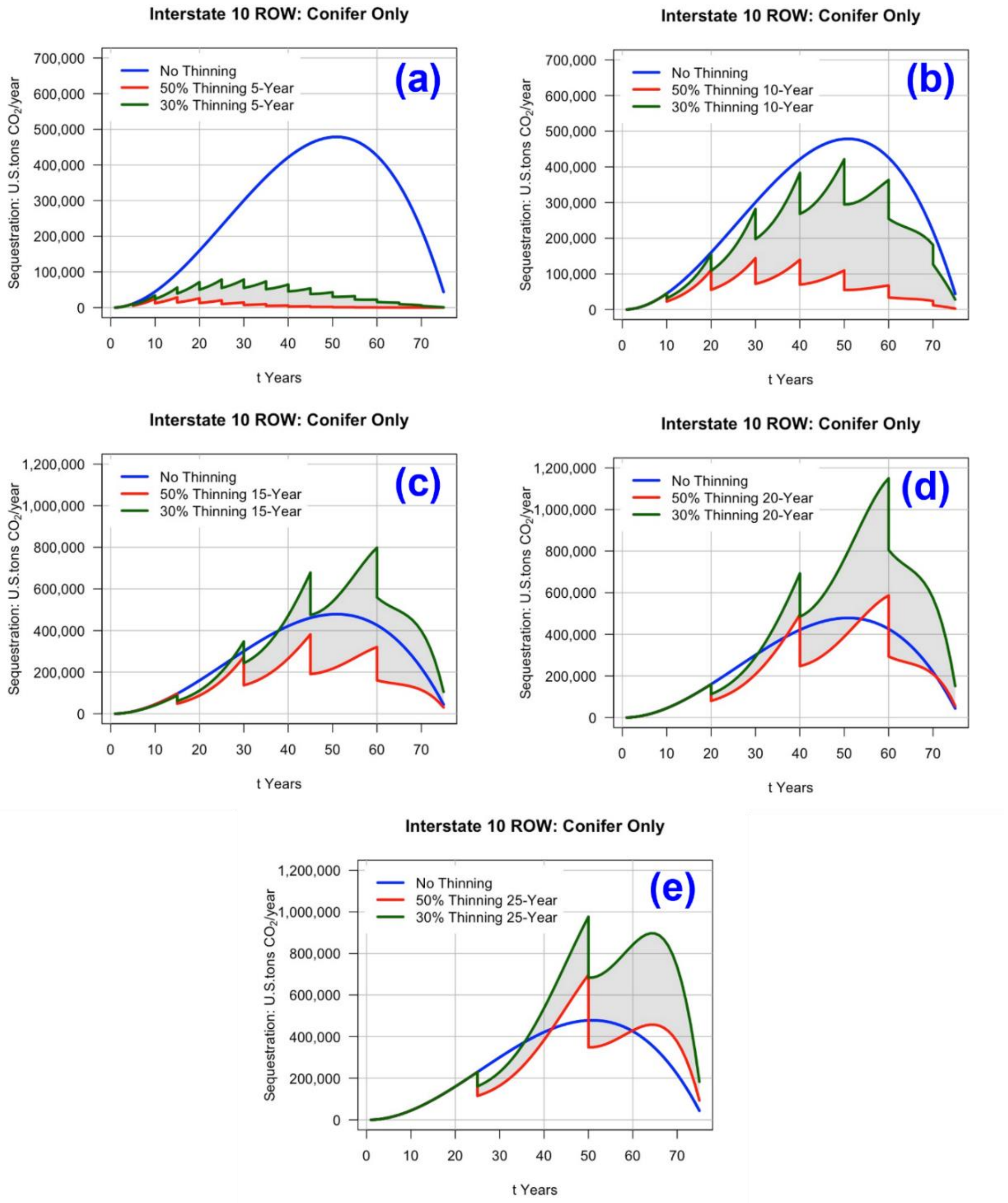


**Figure 10. Estimated $CO_2$ sequestration when applying forest thinning to hypothetical planting of conifer trees on the ROW lands of I-10 in Louisiana. Interpolation of thinning performance must be done within the shaded region between30% and 50% thinning and including the lines of 30% and 50% thinning.**

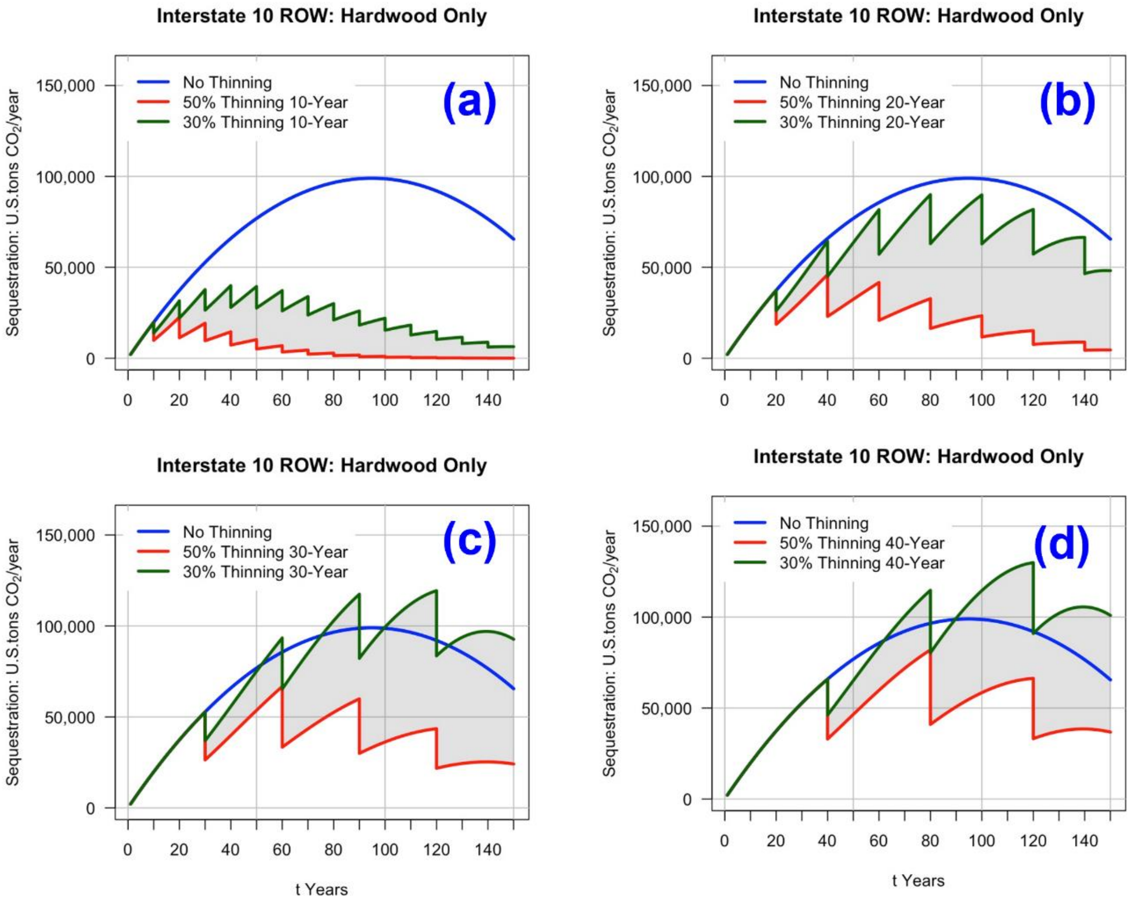


Figure 11. Estimated $CO_2$ sequestration when applying forest thinning to a hypothetical planting of hardwood trees on the ROW lands of I-10 in Louisiana. Interpolation of thinning performance must be done within the shaded region between30% and 50% thinning and including the lines of 30% and 50% thinning.

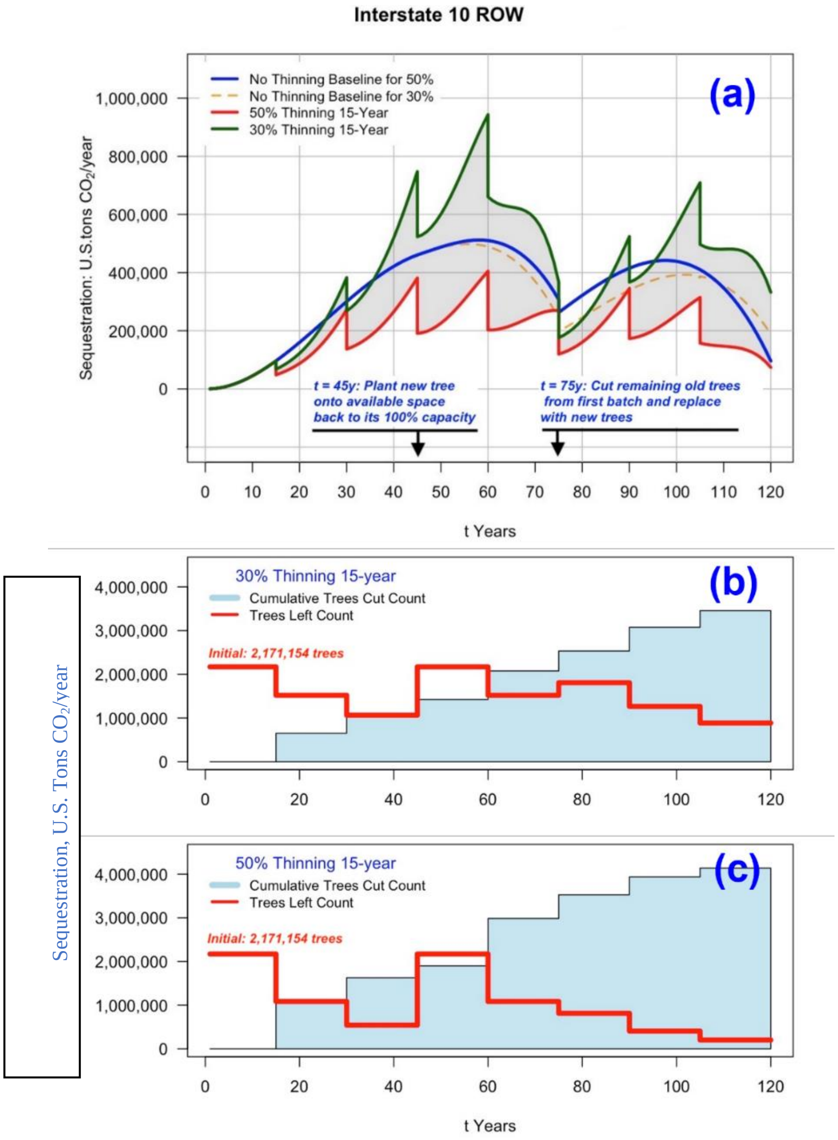


**Figure 12. Estimated $CO_2$ sequestration and count of trees when thinning and planting strategies are implemented to achieve continuous cycling of the ROW forest. This example uses Interstate 10 with conifers-only at 15-year intervals of thinning as the base model augmented by the replanting effect. The maximum tree density was set to 600 trees per acre. Two cycles are shown to illustrate trends, but this can be extended to longer projections, and the trends will be almost similar. An assumption is that no tree seedlings grow out of the existing forest and that young trees are introduced by deliberate replanting at a specific time and fraction of the available forest land**

## Model 2: $CO_2$ sequestration in Louisiana's ROW lands from DOE with relatively high planting densities

Another set of empirical data representing $CO_2$ sequestration values for conifers and hardwoods over time [36] was used to generate regression equations of the same order as previously generated in Equations 1 and 2. This set of sequestration equations and associated tree planting densities should be considered relatively moderate with respect to $CO_2$ sequestration values and relatively high with respect to tree planting density (conifers 600 TPA; hardwoods 350 TPA). Additional simulations for more moderate sequestration yields and lower tree planting densities are also presented in the following sections (Model 3) to give a range of $CO_2$ sequestration values depending on forestry management options that may be implemented.

Conifers: Annual $CO_2$ (lb-$CO_2$ $yr^{-1}$ $tree^{-1}$) $= -0.0026t^3 + 0.20t^2 - 0.18t$ (Equation 7)

Hardwood: Annual $CO_2$ (lb-$CO_2$ $yr^{-1}$ $tree^{-1}$) $= -0.0265t^2 + 5.034t$ (Equation 8)

where, $t$ = time in years.

A new set of estimated $CO_2$ sequestration rates were produced using the more conservative tree uptake rates. The same modeling processes incorporated for producing Table 4 were used to produce another dataset, as shown in Table 6, using the more conservative datasets that were based on the moderate $CO_2$ sequestration models [Equations 7 and 8]).

### Model 2, Scenario 1: No Intervention

With no intervention after planting (such as thinning and/or replanting) and excluding soil C sequestration, the potential annual $CO_2$ sequestration rate in Louisiana's ROW lands by 2050 can range from 227,795 to 251,205 US tons $CO_2$/year (see Table 6). After 60 years, annual $CO_2$ sequestration rate can be as high as 465,294 US tons $CO_2$/year. The impact of using the lesser, more conservative sequestration rates for the tree types are clear upon comparing Tables 4 and 5. The more conservative rates generally reduced the predicted sequestration rates by about half. Where the more optimistic uptake rates in Table 5 for conifers only in 2050 was 653,987 US tons/year, the same conditions for the more conservative rates only yielded 251,205 US tons/year. This difference highlights the value of future research to increase $CO_2$ uptake by trees. Most of the past forest management/planting methods focused on biomass yields, not carbon sequestration. Yet, this new, more conservative rate still shows the potential to reduce enough carbon dioxide to net out a significant portion of the released $CO_2$ from Louisiana manufacturers.

**Table 6. Model 2, Scenario 1: Annual $CO_2$ sequestration potentials in ROW lands [US ton $CO_2$ $yr^{-1}$] DOE data, relatively high tree planting density**

| **Year 2050*** | | | | | | |
|---|---|---|---|---|---|---|
| Highway | 10% C - 90% H | 25% C - 75% H | 50% C - 50% H | 75% C - 25% H | Only C | Only H |
| I-10 | 83,459 | 84,258 | 85,590 | 86,921 | 88,253 | 82,926 |
| I-20 | 43,128 | 44,849 | 47,717 | 50,585 | 53,454 | 41,980 |
| I-49 | 73,852 | 74,559 | 75,738 | 76,916 | 78,095 | 73,381 |
| HW-90 | 29,697 | 29,982 | 30,456 | 30,929 | 31,403 | 29,508 |
| **TOTAL** | **230,136** | **233,648** | **239,501** | **245,351** | **251,205** | **227,795** |
| **Year 2085*** | | | | | | |
| Highway | 10% C - 90% H | 25% C - 75% H | 50% C - 50% H | 75% C - 25% H | Only C | Only H |
| I-10 | 157,401 | 158,412 | 160,097 | 161,781 | 163,466 | 156,728 |
| I-20 | 81,308 | 84,258 | 89,176 | 94,094 | 99,011 | 79,341 |
| I-49 | 73,852 | 140,178 | 141,669 | 76,916 | 144,650 | 138,688 |
| HW-90 | 56,009 | 56,368 | 56,968 | 57,567 | 58,167 | 55,769 |
| **TOTAL** | **368,570** | **439,216** | **447,910** | **390,358** | **465,294** | **430,526** |

*C: conifer*

*H: hardwood*

** The sequestration potentials are calculated in Years 2025 and 2085. No soil C sequestration.*

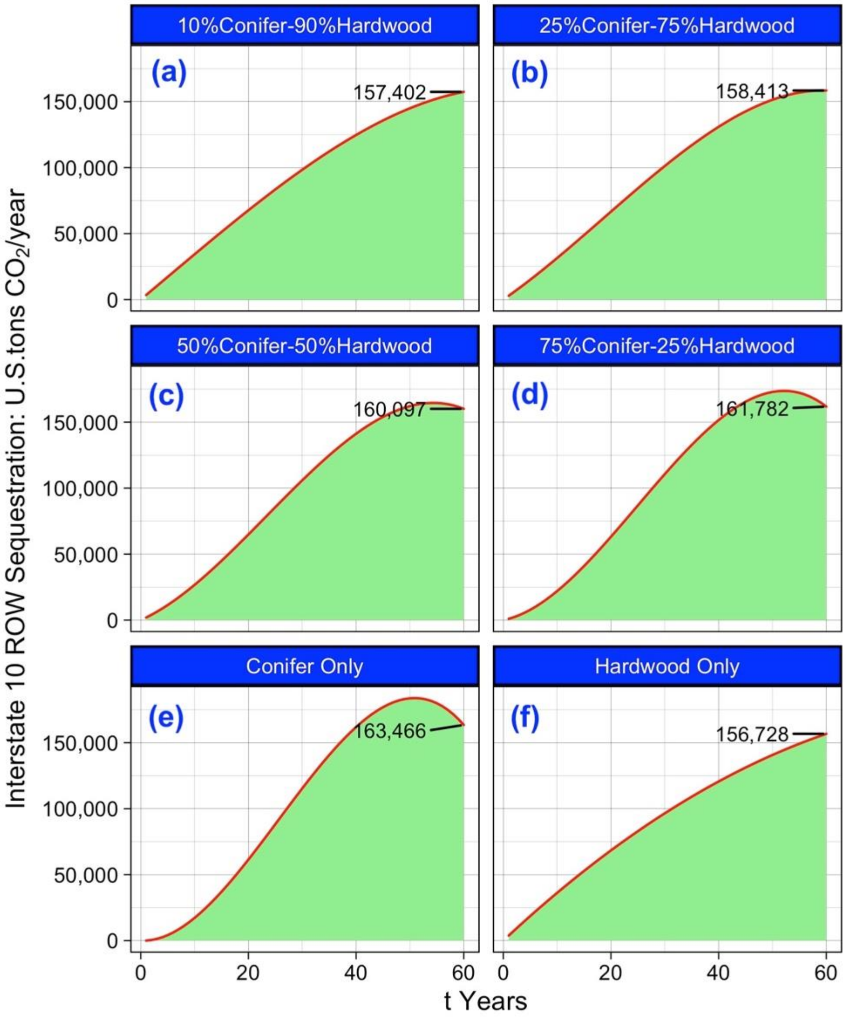


**Figure 13. Estimated $CO_2$ sequestration per year along the entire Interstate 10 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the CO2 sequestration rate at the end of the simulated period of 60 years. These estimates do not include the carbon sequestration potential of the soil.**

The data in the figures (Figures 13 through 16) generally follow the same trending as observed with the more optimistic per tree $CO_2$ uptake rates shown in Figures 10 and 11. However, in terms of magnitude, these new estimates are about half those from the previous datasets. Still, these new data using the DOE estimates still shown substantial capacity to remove large amounts of $CO_2$. In the case using the DOE database, the best case of 100% conifers is able to sequester about 17% of the emitted CO2 from the No. 10

industrial facility as listed in Table 1. The difference in performance between conifers and hardwoods is much less pronounced using the new database (DOE) as both tree types remove about the same tons per year by Year 2085 – 465,294 versus 430,526 for conifers and hardwoods, respectively (see Table 6).

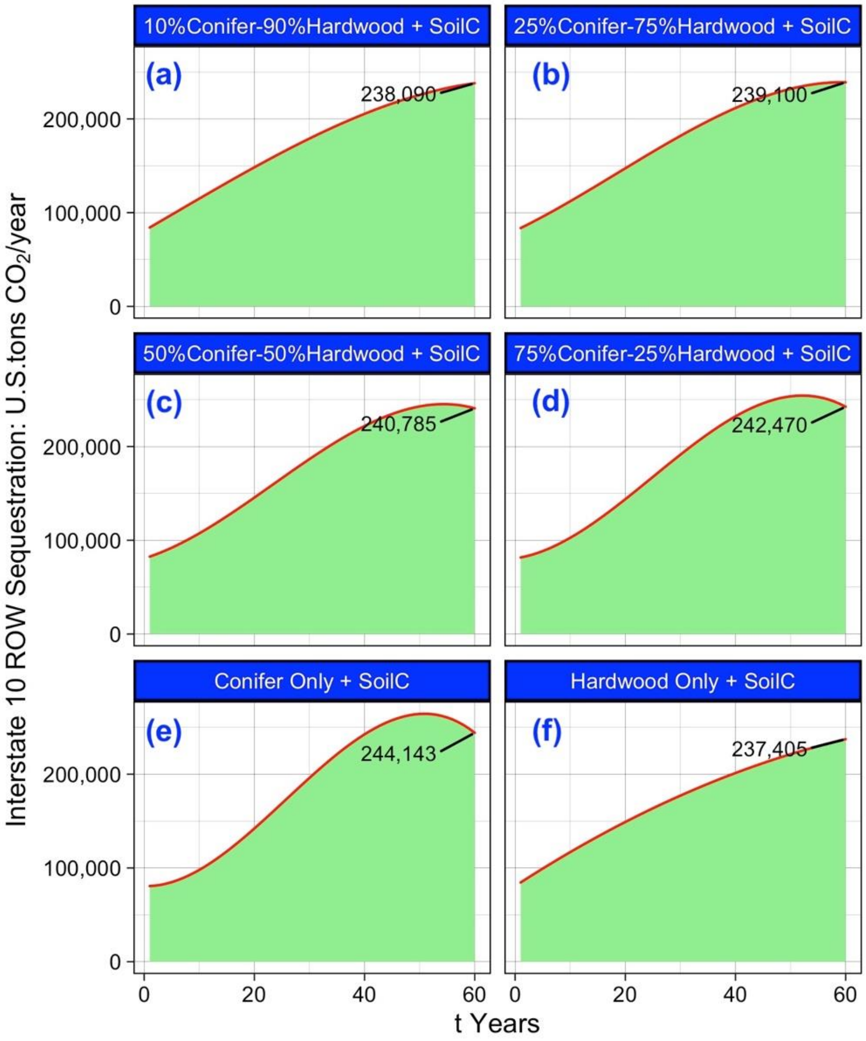


**Figure 14. Estimated $CO_2$ sequestration per year along the entire Interstate 10 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimated include the carbon sequestration potential of the soil**

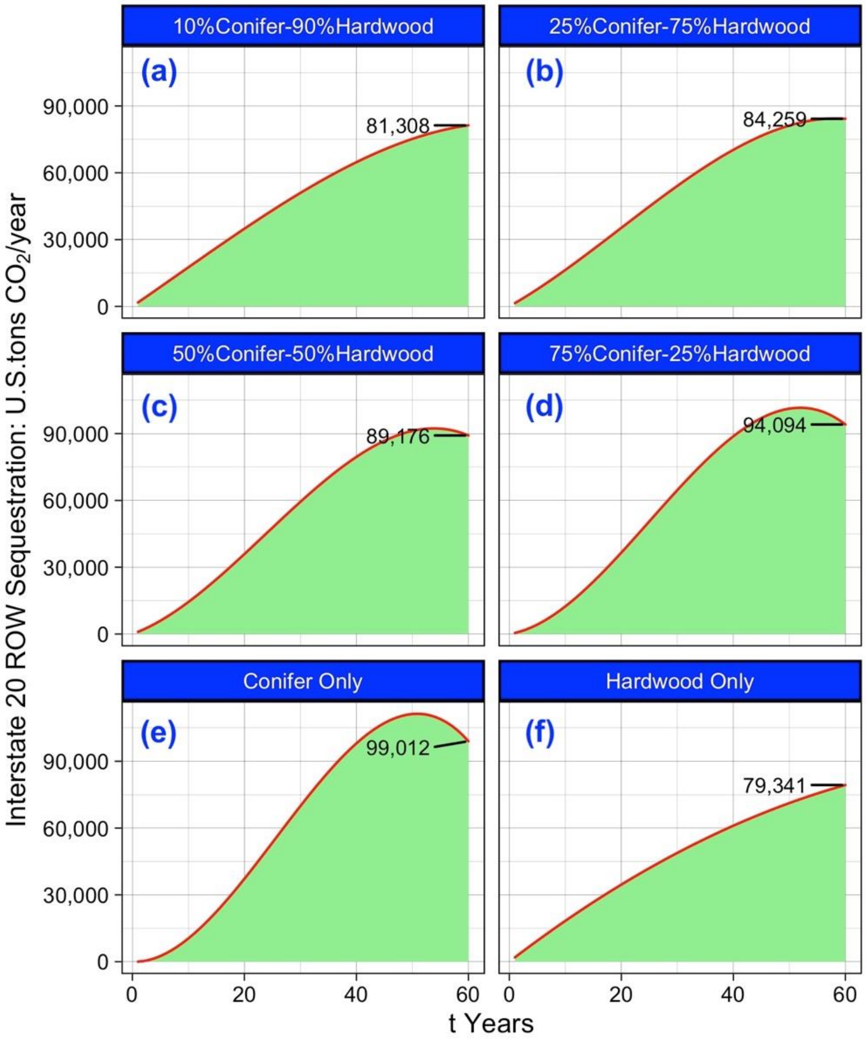


**Figure 15. Estimated CO2 sequestration per year along the entire Interstate 20 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates do not include the carbon sequestration potential of the soil**

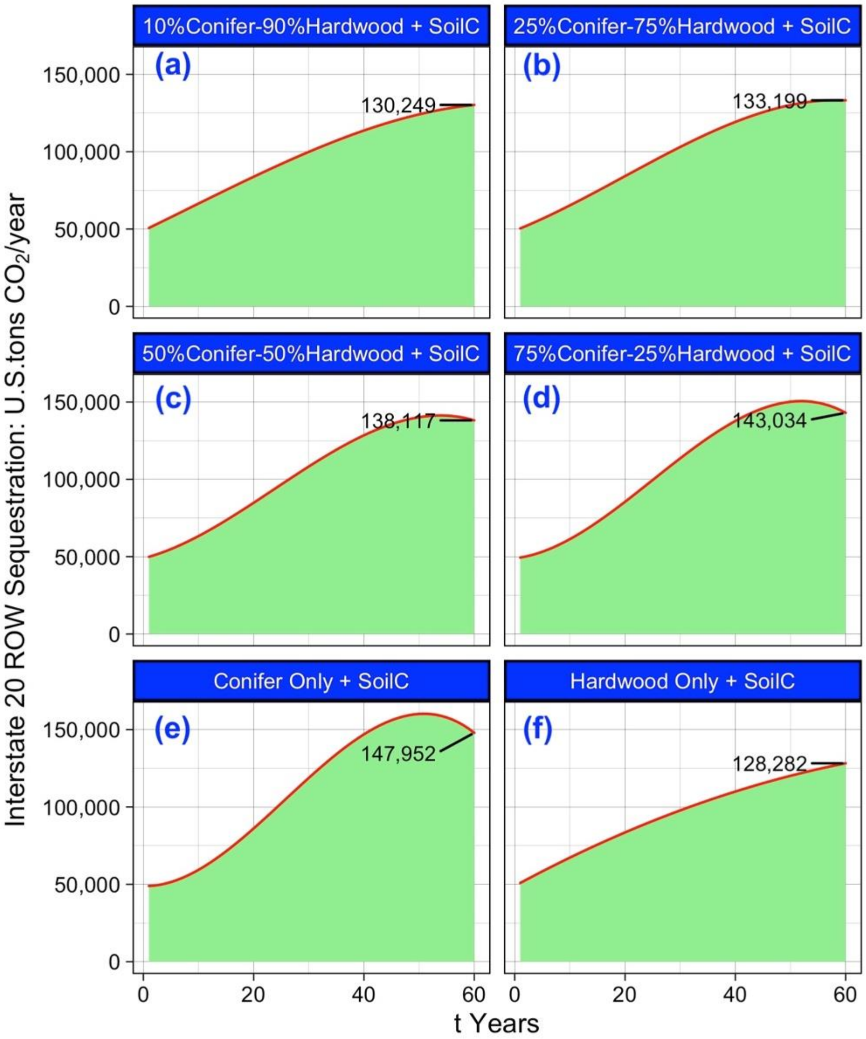


**Figure 16. Estimated CO2 sequestration per year along the entire Interstate 20 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates include the carbon sequestration potential of the soil**

### Model 2, Scenario 2: Implement thinning

When properly managed, the $CO_2$ sequestration of conifers along I-10 can double compared to no-thinning by implementing a 30% thinning every 20 years resulting in a peak of around 450,000 US tons of $CO_2$ $yr^{-1}$ at Year 60 (Figure 17d). That is more than double the peak performance at 190,000 U.S. tons of $CO_2$ $yr^{-1}$ at Year 50 for no-thinning (Figure 17d). The sequestration performance of hardwood trees can also be improved by the right combination of percent thinning and interval of thinning compared to no thinning, but the level of performance improvement is not as good as the improvement for the conifer. For example, the 30% thinning of hardwood every 40 years peaked at around 225,000 US tons $CO_2$ $yr^{-1}$ at Year 120 compared to the no-thinning performance of 175,000 US tons $CO_2$ $yr^{-1}$ at Year 100 (Figure 18d). Even though these sequestration values are specific to I-10, the trends can also be expected in the other highways after applying a scaling of areas available for forest growth (see Table 2).

### Model 2, Scenario 3: Implement thinning and replanting

Implementing thinning followed by replanting increases $CO_2$ sequestration considerably compared to just thinning while it maintains the suitability of the ROW lands forests in the long term as potential $CO_2$ sinks (Figure 19). The simulation results show the long-term effect of forest management on the proposed interstate forest via two thinning cycles: 30% cut versus 50% cut. In this case, I-10, was selected for demonstration (see Figure 19a). The trajectory of 30% thinning follows an improved performance in the long term compared to the no-thinning model (baseline for 30% thinning). On the other hand, 50% thinning cannot perform better than no thinning, even for a long-term cycle (baseline for 50% thinning). This shows that thinning levels may dictate the long-term dynamics in terms of $CO_2$ sequestration of the highway forest. Yet, thinning does appear to have a positive benefit in terms of $CO_2$ sequestration if done correctly.

Looking at the number of trees harvested/cut (Figure 19b and 19c), the 30% thinning leaves more trees by count while at the same time still achieving cumulative trees harvested close to 50% thinning close to 4 million trees by 120 years. These trees, which are conifers in the example dynamics, have a market value that can offset some costs in maintaining the highway.

The replanting strategy can be varied and can be a subject matter of modeling investigation on its own, but the results of this work (Figure 19) show that the replanting strategy significantly alters the $CO_2$ sequestration dynamics. Take, for example, the 30% thinning replanting at t = 75 years. Since the remaining older trees, which are planted at the beginning of the first cycle, are all cut and replaced by young trees, the estimated performance of the 30% thinning is lower than the baseline of no thinning. This is a period that is similar to the first thinning in cycle 1, when a period f forest growth improvement is suddenly decreased by the removal of trees. This period, however, is followed by a higher growth rate due to improvement from the benefits of thinning. Also evident in this 2-cycle model is the need for continuous cycling of the thinning and replanting strategy to sustain high $CO_2$ sequestration rates. As the forest time gets close to the t = 120 years, when no additional cycling is implemented, the $CO_2$ sequestration performance can suddenly drop and approach the no-thinning baseline performance.

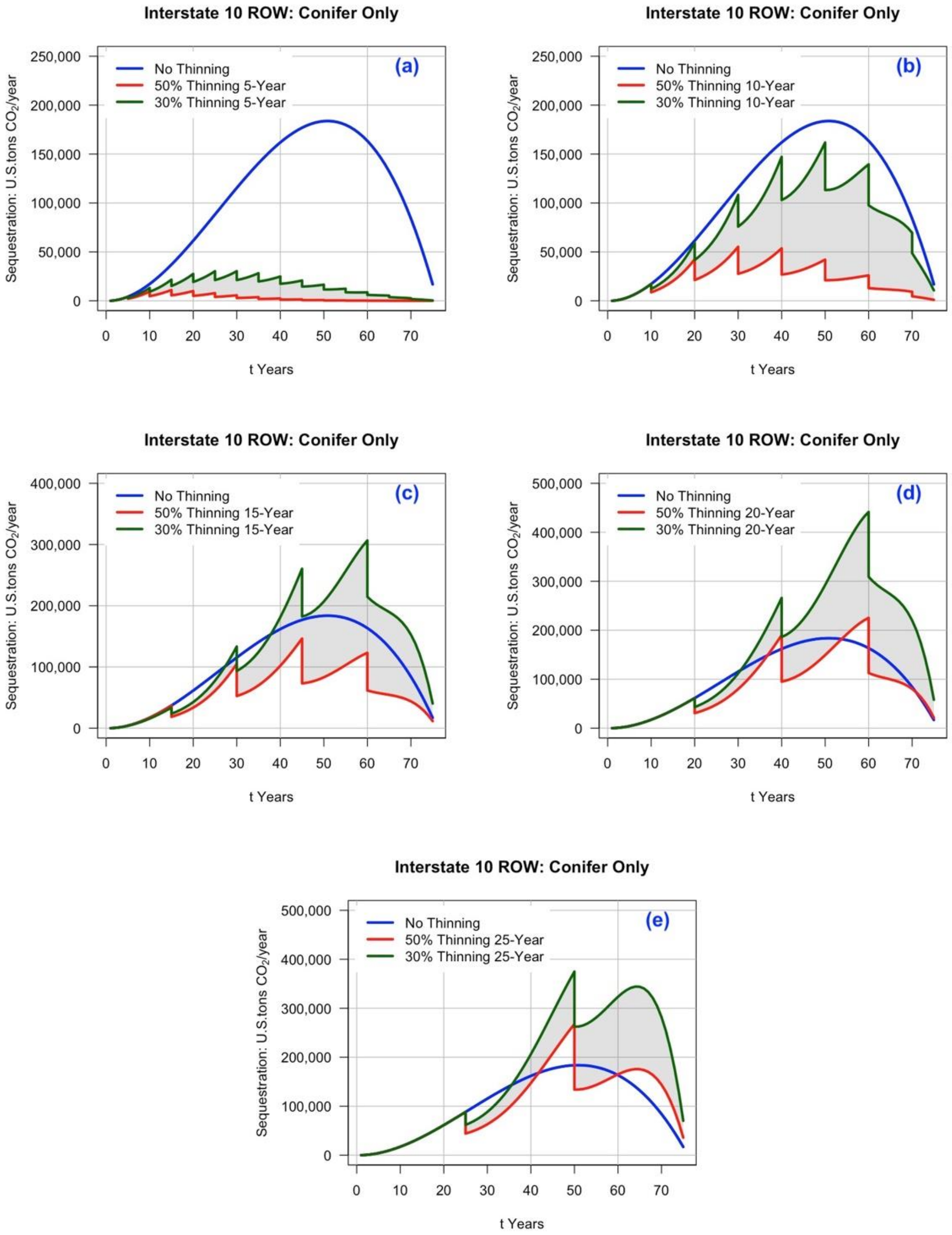


**Figure 17. Estimated $CO_2$ sequestration when applying forest thinning to hypothetical planting of conifer trees on the ROW lands of I-10 in Louisiana. Interpolation of thinning performance must be done within the shaded region between 30% and 50% thinning and including the lines of 30% and 50% thinning.**

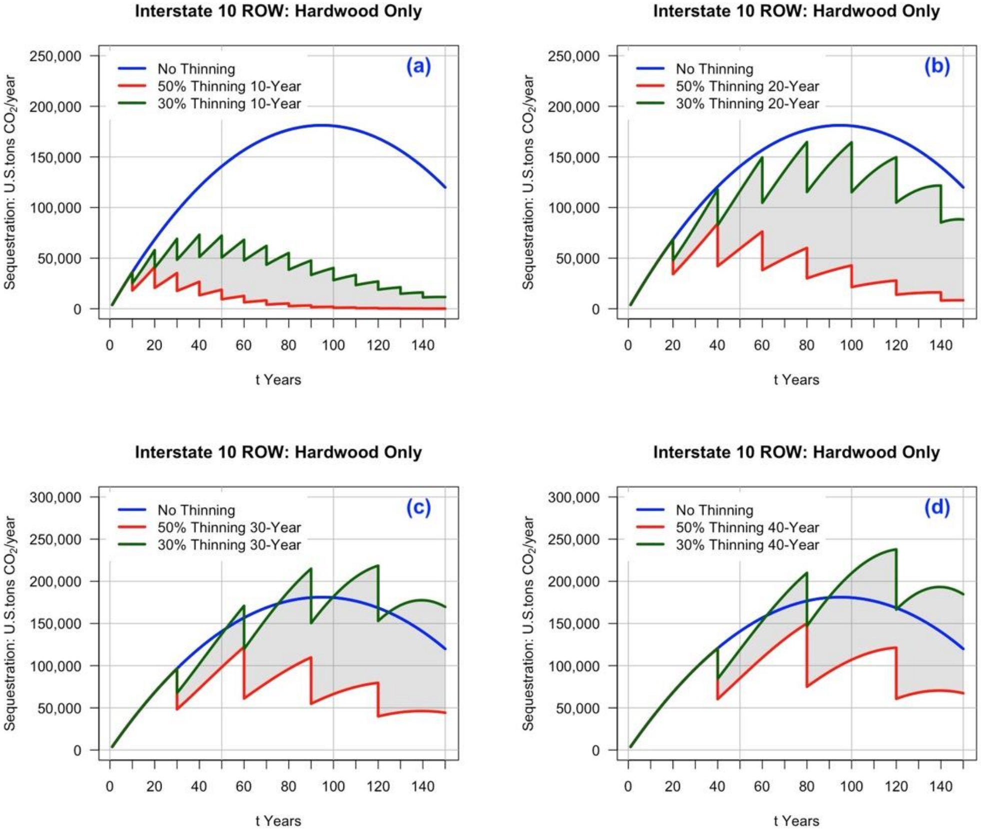


**Figure 18. Estimated $CO_2$ sequestration when applying forest thinning to a hypothetical planting of hardwood trees on the ROW lands of I-10 in Louisiana. Interpolation of thinning performance must be done within the shaded region between30% and 50% thinning and including the lines of 30% and 50% thinning.**

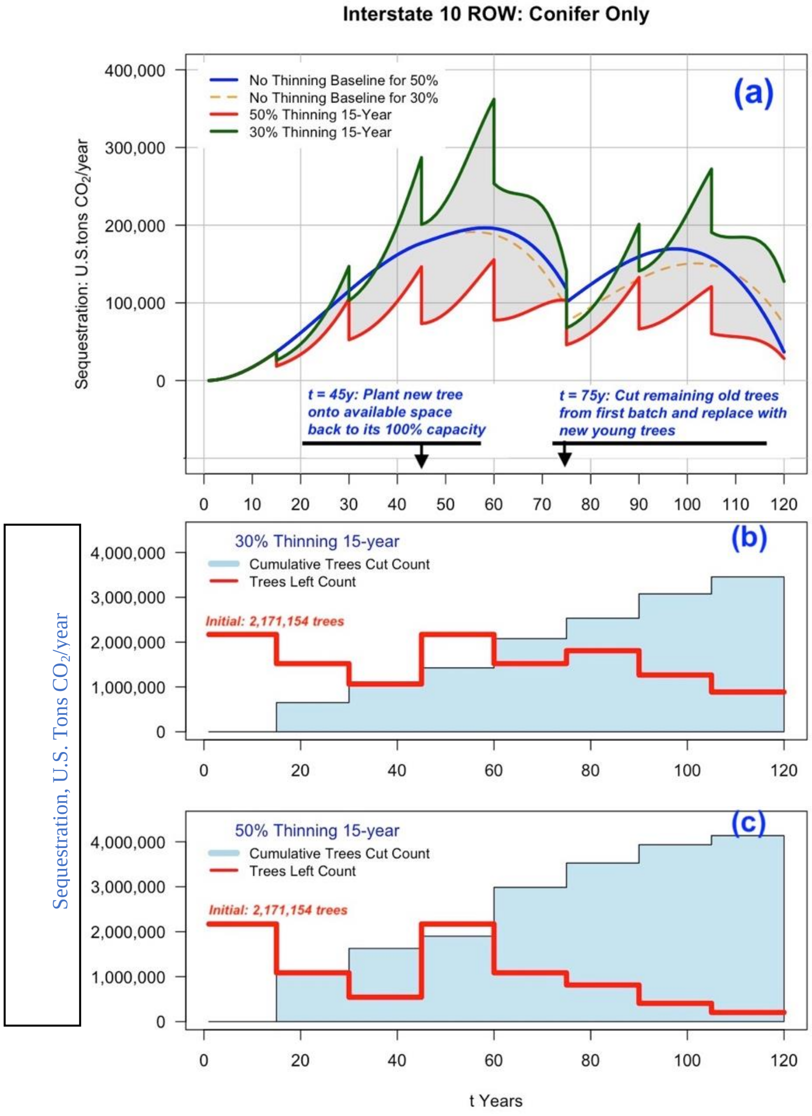


**Figure 19. Estimated $CO_2$ sequestration and count of trees when thinning and planting strategies are implemented to achieve continuous cycling of the ROW forest. This example uses Interstate 10 with conifers-only at 15-year intervals of thinning as the base model augmented by the replanting effect. The maximum tree density was set to 600 trees per acre. Two cycles are shown to illustrate trends, but this can be extended to longer projections, and the trends will be almost similar. An assumption is that no tree seedlings grow out of the existing forest and that young trees are introduced by deliberate replanting at a specific time and fraction of the available forest land**

## Model 3: $CO_2$ sequestration in Louisiana's ROW lands Using the DOE Database with Relatively Low Planting Densities

Equations 7 and 8 from the DOE empirical relationships were used to generate $CO_2$ sequestration values for conifers and hardwoods [36]. This set of sequestration equations and associated tree planting densities should be considered relatively moderate for $CO_2$ sequestration values and relatively low regarding tree planting density; conifers 325 TPA [40]; hardwoods 113 TPA) [41].

Conifers: Annual $CO_2$ ($\text{lb-}CO_2\ \text{yr}^{-1}\ \text{tree}^{-1}$) $= -0.0026t^3 + 0.20t^2 - 0.18t$ (Equation 7)

Hardwood: Annual $CO_2$ ($\text{lb-}CO_2\ \text{yr}^{-1}\ \text{tree}^{-1}$) $= -0.0265t^2 + 5.034t$ (Equation 8)

where $t$ = time in years.

The same modeling processes were incorporated under the same GIS conditions and forest management scenarios (tree thinning) to yield the following summary table with associated $CO_2$ sequestration graphics and thinning graphics specific to these moderate $CO_2$ sequestration equations.

### Model 3, Scenario 1: No Intervention

With no intervention after planting and excluding soil C sequestration, the potential annual $CO_2$ sequestration rate in Louisiana's ROW lands by 2050 can range from 73,543 to 136,068 US tons $CO_2\ \text{yr}^{-1}$ (Table 7). After 60 years, the annual $CO_2$ sequestration rate can be as high as 252,034 US tons $CO_2\ \text{yr}^{-1}$.

With these simulations, the difference between conifers and hardwoods, in terms of $CO_2$ sequestration, becomes very small. Thus, other selection factors such as wood value, highway fall hazard potential, and planting costs could be factored more into the decision. With any tree species composition, an appreciable amount of sequestration is observed.

**Table 7. Model 3, Scenario 1; Annual CO2 sequestration potentials in ROW lands [US tons CO2 yr-1] DOE data, relatively low tree planting density**

| Year 2050* | | | | | | |
|---|---|---|---|---|---|---|
| Highway | 10% C - 90% H | 25% C - 75% H | 50% C - 50% H | 75% C - 25% H | Only C | Only H |
| I-10 | 28,876 | 32,031 | 37,288 | 42,546 | 47,803 | 26,773 |
| I-20 | 15,093 | 17,403 | 21,254 | 25,104 | 28,954 | 13,553 |
| I-49 | 25,552 | 28,344 | 32,996 | 37,649 | 42,301 | 23,691 |
| HW-90 | 10,275 | 11,397 | 13,268 | 15,139 | 17,010 | 9,526 |
| **TOTAL** | **79,796** | **89,175** | **104,806** | **120,438** | **136,068** | **73,543** |
| **Year 2085*** | | | | | | |
| Highway | 10% C - 90% H | 25% C - 75% H | 50% C - 50% H | 75% C - 25% H | Only C | Only H |
| I-10 | 54,395 | 60,086 | 69,572 | 79,058 | 88,544 | 50,600 |
| I-20 | 28,417 | 32,619 | 39,623 | 46,627 | 53,631 | 25,615 |
| I-49 | 48,134 | 53,170 | 61,564 | 69,958 | 78,352 | 44,776 |
| HW-90 | 19,355 | 21,380 | 24,756 | 28,131 | 31,507 | 18,005 |
| **TOTAL** | **150,301** | **167,255** | **195,515** | **223,774** | **252,034** | **138,996** |

*C: conifer*

*H: hardwood*

** The sequestration potentials are calculated starting in 2025. No soil $CO_2$ sequestration.*

The time dynamics of the forest in terms of $CO_2$ sequestration must also be considered in addition to sequestration values at specific time points. Figures 20 to 23 show that the $CO_2$ sequestration of highway forests changes depending on the age of the forest and the type of trees in the forest. Conifers have higher $CO_2$ sequestration per acre compared to hardwood trees, but the conifers attain their peak performance at around 50 years, while the hardwoods are still improving in their growth rates (see Figure 9 for the growth rate of hardwood) and peaking at 100 years. At year 50, conifer planted along I-10 can have a total sequestration rate of 100,000 US tons $CO_2$ $yr^{-1}$ (Figure 20e). At Year 60, hardwood along I-10 can achieve a sequestration rate of around 50,601 US tons $CO_2$ $yr^{-1}$ (Figure 20f). What this means for a highway forest is that there is a period of lag in terms of $CO_2$ sequestration before having trees that are mature enough to sequester $CO_2$ at high rates. The ratio of tree types must also be considered in the forest highway design.

It also is noted that the contribution of soil-based carbon sequestration can be a very significant portion of the highway forest (see Figures 21 and 23). These can be seen visually as the baseline levels (constant levels) at the bottom of the graphs in Figures 21 and 23. Depending on the age of the forest and the type of tree planted, soil carbon sequestration can be a significant contributor to the sequestration levels of the highway forest. For a hardwood-only forest (or hardwood-dominant forest), the soil carbon sequestration is higher than the carbon sequestration by the hardwood trees. On the other hand, the carbon sequestration of conifers is significantly higher than the soil carbon sequestration. The role of soil carbon sequestration must be emphasized when considering the benefit of the 35-ft buffer zones along the highway in addition to its role in highway safety and maintenance. Even though the 35-ft buffer zones may contain only grass as vegetation, the processes within that topsoil can favor significant levels of $CO_2$ sequestration.

The similar behavior of the $CO_2$ sequestration curves for I-10 (Figure 20 and 21) and I-20 (Figure 22 and 23) graphically manifest the linear nature of the modeling implemented in this project. That is, only the area available for forest growth changes from one highway to another (see Table 3), while other modeling aspects, such as the tree growth equations, were the same (Equations 1 to 8) for each modeling scenario. Hence, linear scaling of the levels of $CO_2$ sequestration can be applied to other highways, such as I-49 and Highway 90.

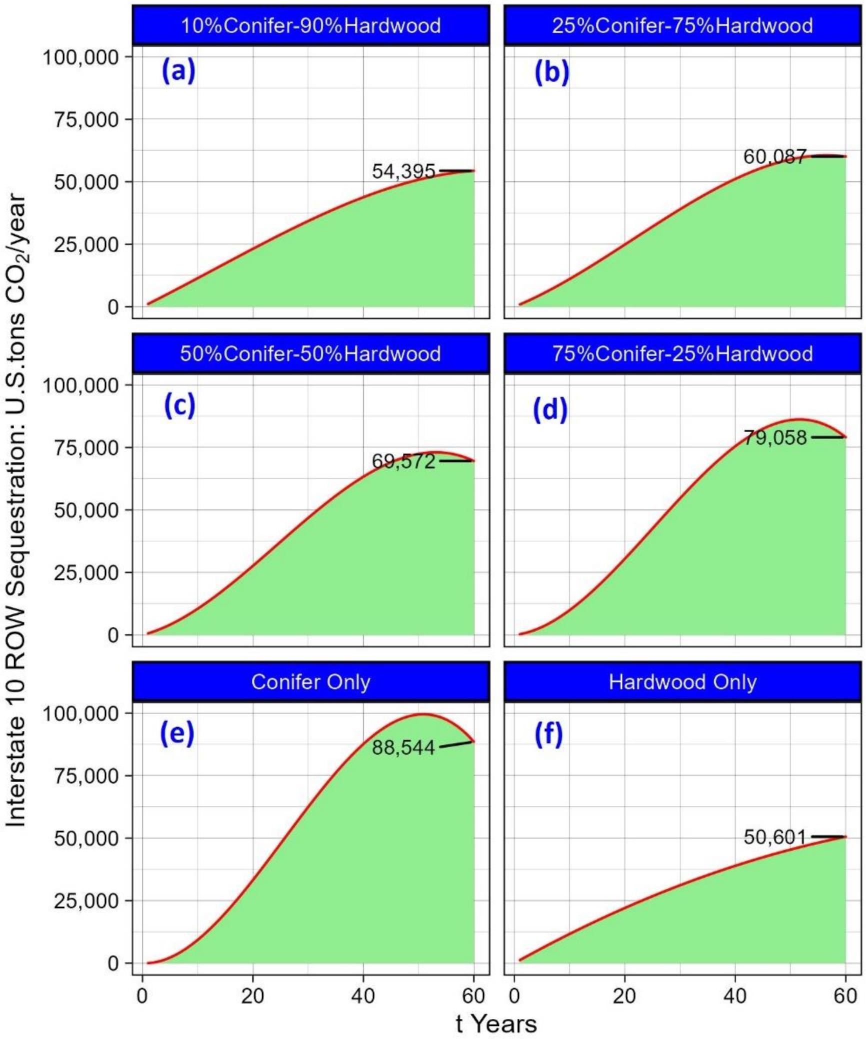


**Figure 20. Estimated $CO_2$ sequestration per year along the entire Interstate 10 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates do not include the carbon sequestration potential of the soil**

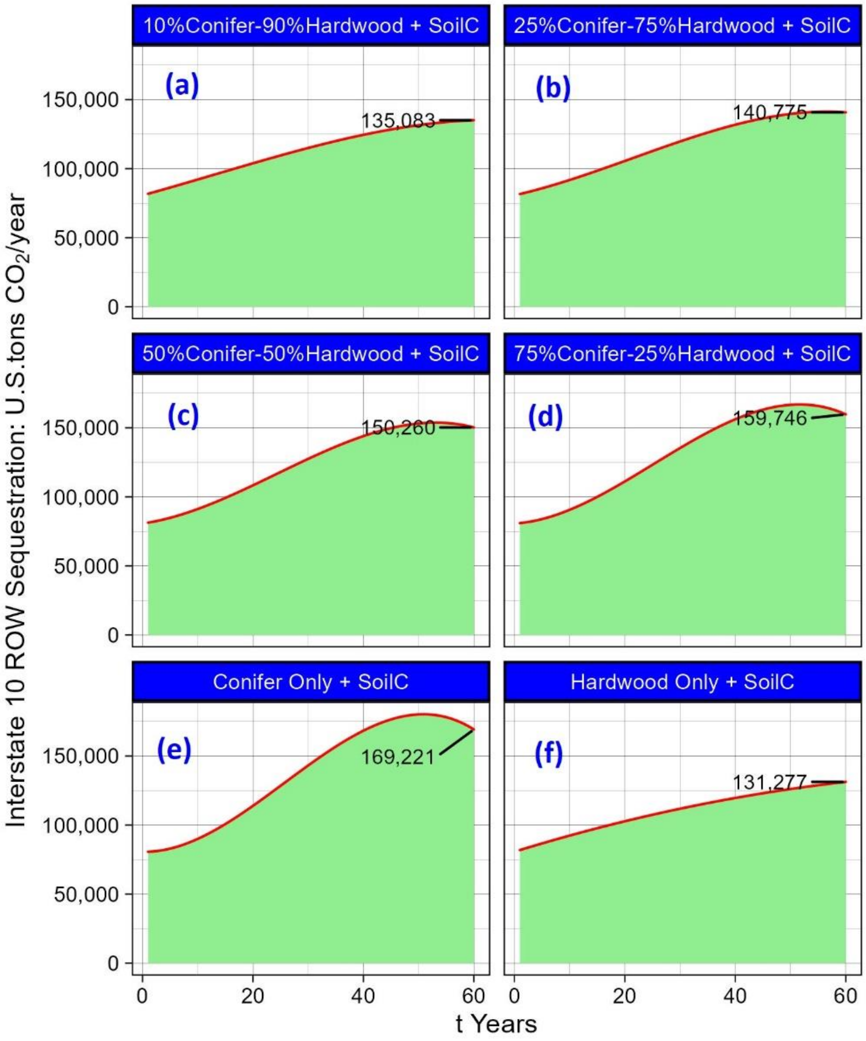


**Figure 21. Estimated $CO_2$ sequestration per year along the entire Interstate 10 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimated include the carbon sequestration potential of the soil**

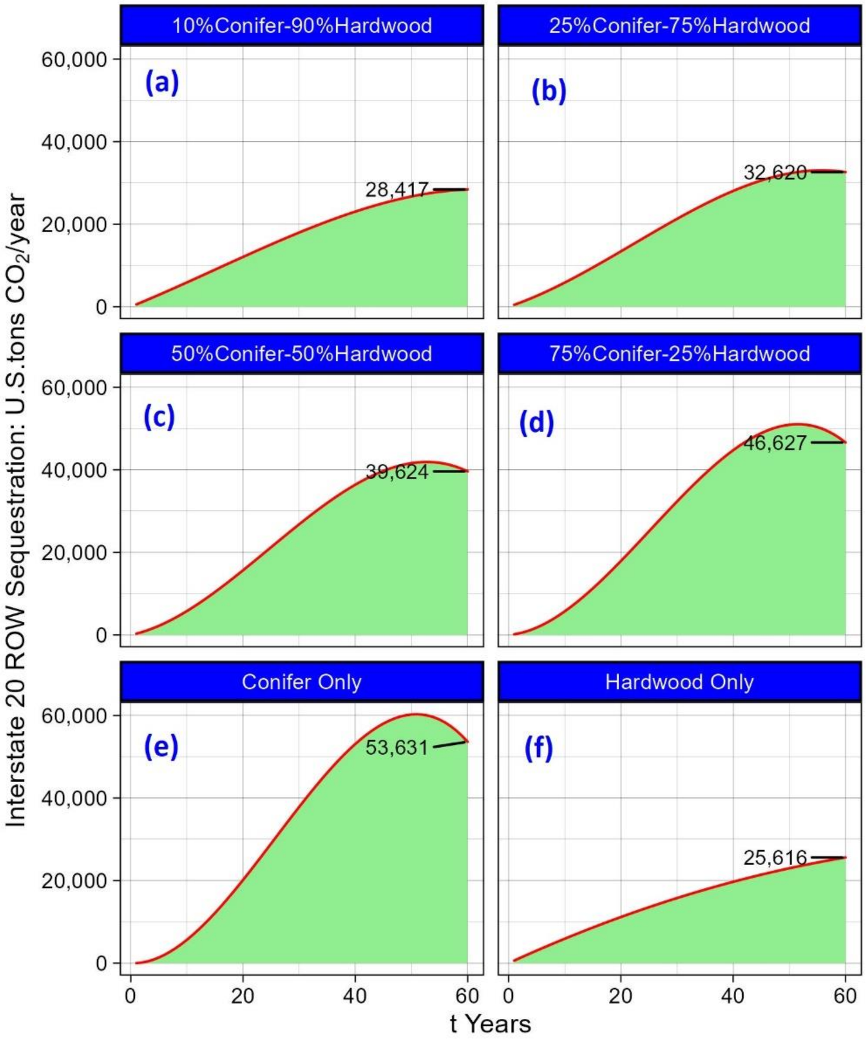


**Figure 22. Estimated $CO_2$ sequestration per year along the entire Interstate 20 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates do not include the carbon sequestration potential of the soil**

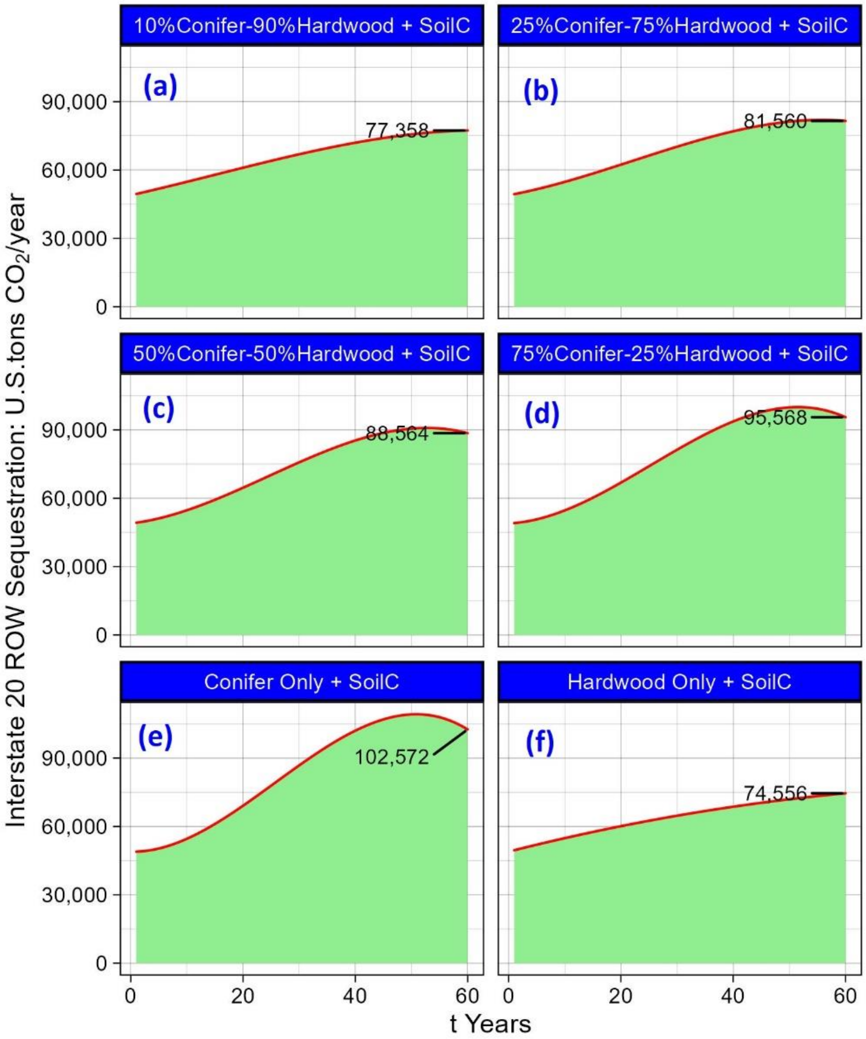


**Figure 23. Estimated $CO_2$ sequestration per year along the entire Interstate 20 highway ROW lands in Louisiana. (a) 10% conifer – 90% hardwood mixture, (b) 25% conifer – 75% hardwood mixture, (c) 50% conifer – 50% hardwood mixture, (d) 75% conifer – 25% hardwood mixture, (e) conifer only and (f) hardwood only. The number indicated in the plots is the $CO_2$ sequestration rate at the end of the simulated period of 60 years. These estimates include the carbon sequestration potential of the soil**

### Model 3, Scenario 2: Implementing Thinning

$CO_2$ sequestration of conifers along I-10 can double compared to no-thinning by properly implementing a 30% thinning every 20 years, resulting in a peak of around 240,000 US tons $CO_2$ $yr^{-1}$ at year 60 (Figure 24d). That is more than double the peak performance at 100,000 US tons $CO_2$ $yr^{-1}$ at year 50 for no-thinning (Figure 24d). The sequestration performance of hardwood trees can also be improved by the right combination of percent thinning and interval of thinning compared to no-thinning, but the level of performance improvement is not as good as the improvement for the conifer. For example, the 30% thinning of hardwood every 40 years peaked at around 75,000 US tons $CO_2$ $yr^{-1}$ at year 120 compared to the no-thinning performance of 60,000 US tons $CO_2$ $yr^{-1}$ at year 100 (Figure 25d). Even though these sequestration values are specific to I-10, the trends can also be expected in the other highways after applying a scaling of areas available for forest growth (see Table 3).

### Model 3, Scenario 3: Implementing thinning and replanting

Implementing thinning followed by replanting increases $CO_2$ sequestration considerably while it maintains the suitability of the ROW lands forests in the long term as potential $CO_2$ sinks (Figure 26). The simulation results show the long-term effect of forest management on the proposed interstate forest, which is represented by I-10 in this case for demonstration (Figure 26a). The trajectory of 30% thinning follows an improved performance in the long term compared to the no-thinning model (baseline for 30% thinning). On the other hand, 50% thinning did not perform better than no-thinning, even over the long-term cycle (baseline for 50% thinning). This shows that thinning levels may dictate the long-term dynamics in terms of $CO_2$ sequestration of the highway forest.

Looking at the number of trees harvested/cut (Figure 26b and 26c), the 30% thinning leaves more trees by count while at the same time still achieving cumulative trees harvested close to 50% thinning close to 4 million trees by 120 years. These trees, which are conifers in the example dynamics, have a market value that can offset some costs in maintaining the highway.

The replanting strategy can be varied and can be a subject matter of modeling investigation on its own, but the results of this work (Figure 26) show that the replanting strategy significantly alters the $CO_2$ sequestration dynamics. Take, for example, the 30% thinning replanting at t = 75 years. Since the remaining older trees, which are planted at the beginning of the first cycle, are all cut and replaced by young trees, the estimated performance of the 30% thinning is lower than the baseline of no thinning. This is a period that is similar to the first thinning in cycle 1, when a period f forest growth improvement is suddenly decreased by the removal of trees. This period, however, is followed by a higher growth rate due to improvement from the benefits of thinning. Also evident in this 2-cycle model is the need for continuous cycling of the thinning and replanting strategy to sustain high $CO_2$ sequestration rates. As the forest time gets close to the $t = 120$ years, when no additional cycling is implemented, the $CO_2$ sequestration performance can suddenly drop and approach the no-thinning baseline performance.

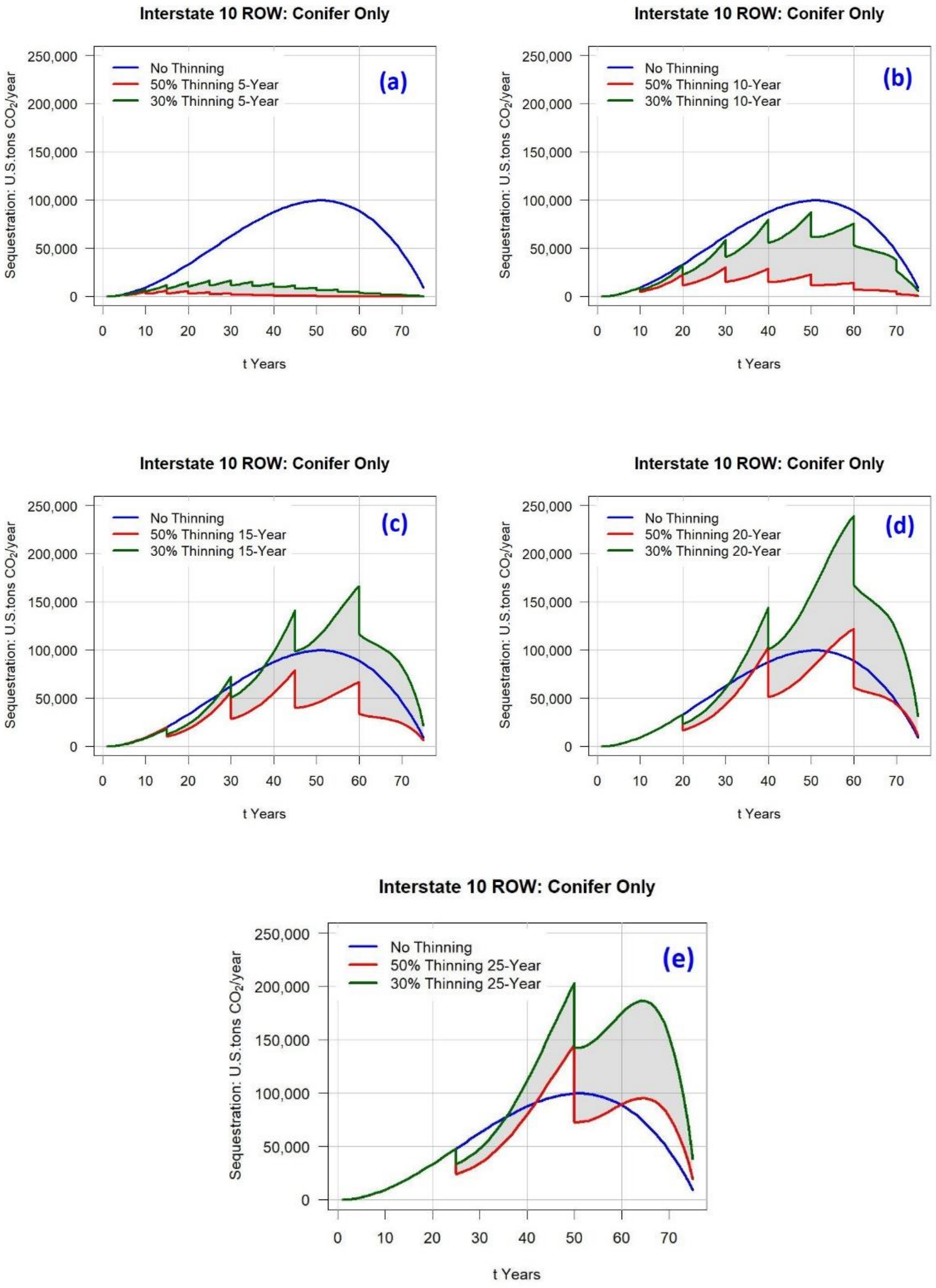


**Figure 24. Estimated $CO_2$ sequestration when applying forest thinning to hypothetical planting of conifer trees on the ROW lands of I-10 in Louisiana. Interpolation of thinning performance must be done within the shaded region between30% and 50% thinning and including the lines of 30% and 50% thinning.**

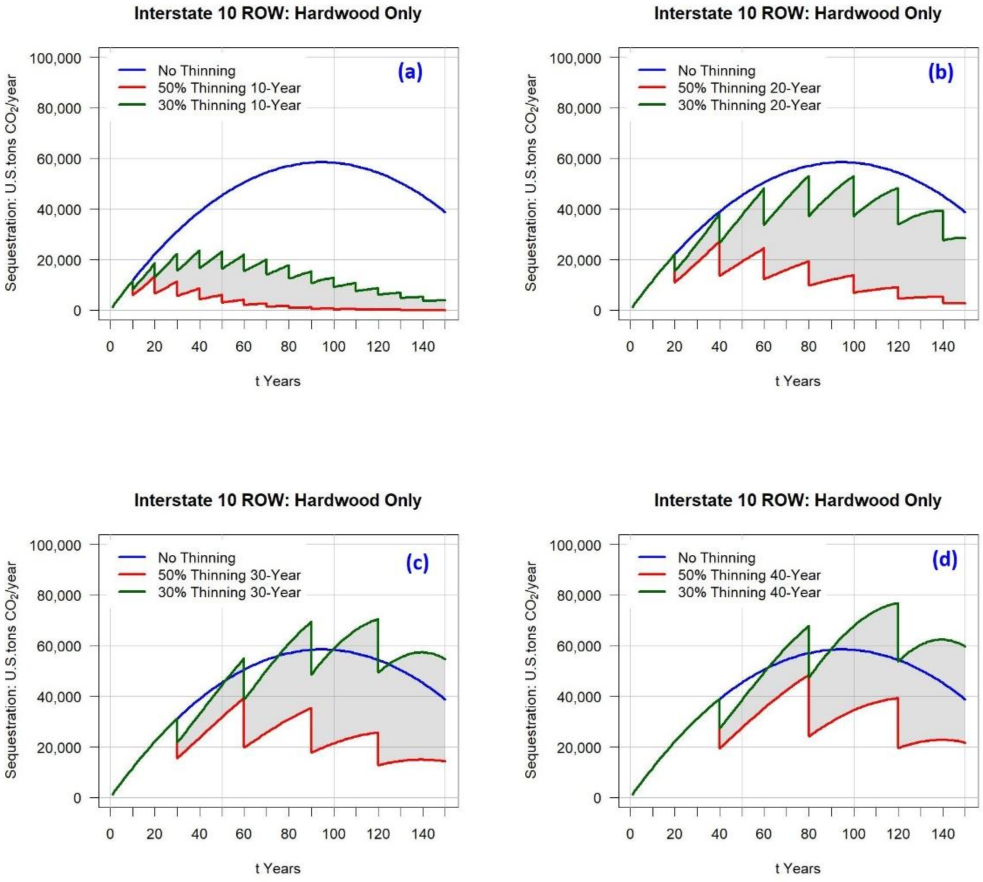


**Figure 25. Estimated $CO_2$ sequestration when applying forest thinning to a hypothetical planting of hardwood trees on the ROW lands of I-10 in Louisiana. Interpolation of thinning performance must be done within the shaded region between 30% and 50% thinning and including the lines of 30% and 50% thinning.**

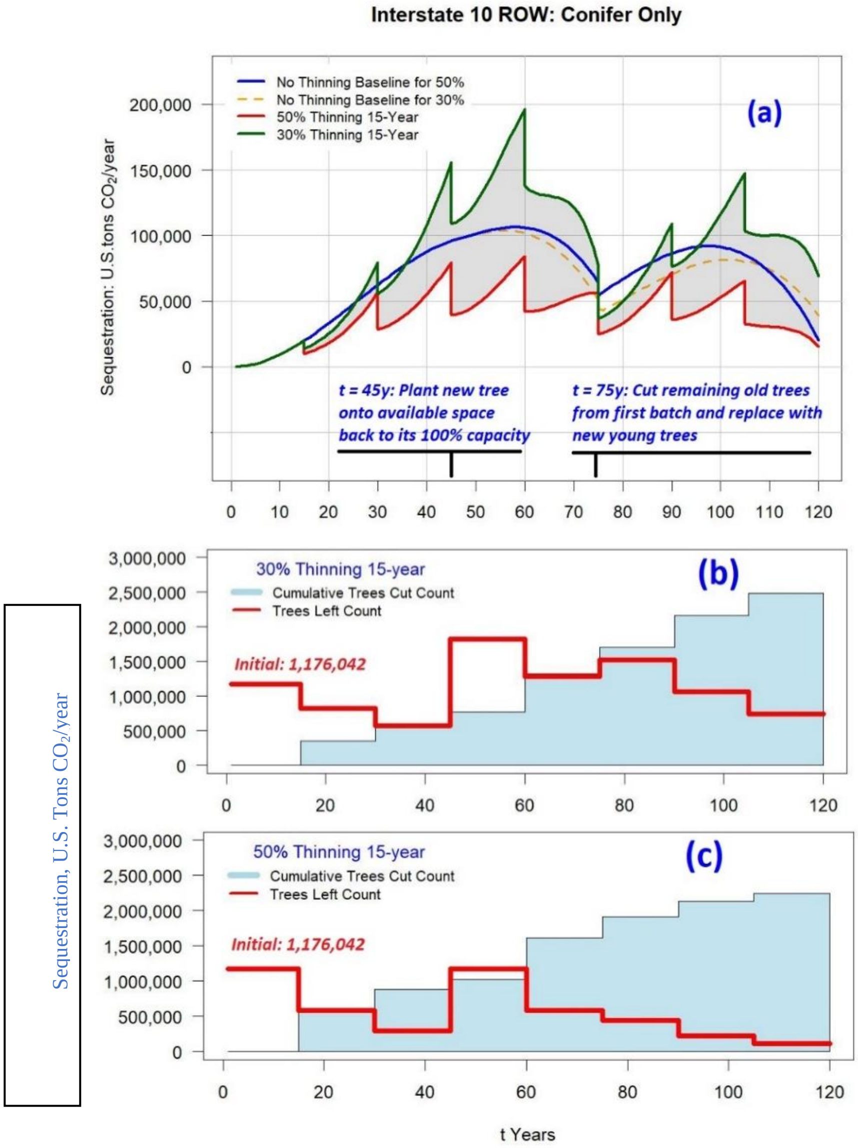


**Figure 26. Estimated $CO_2$ sequestration and tree count when thinning and planting strategies are implemented to achieve continuous cycling of the ROW forest. This example uses Interstate 10 with conifers-only at 15-year intervals of thinning as the base model augmented by the replanting effect. The maximum tree density was set to 325 trees per acre. Two cycles are shown to illustrate trends, but this can be extended to longer projections, and the trends will be almost similar. An assumption is that no tree seedlings grow out of the existing forest and that young trees are introduced by deliberate replanting at a specific time and fraction of the available forest land.**

## Timber Commercialization Preliminary Assessment

Sawtimber prices in Louisiana over the past ten years have been relatively stable, while pulpwood prices have seen a drop in the past two years, as seen in Figure 27 [50]. The overall southern US market over the past 20 years has seen growth even with the recent downturn in the market over the first and second quarters of 2022.

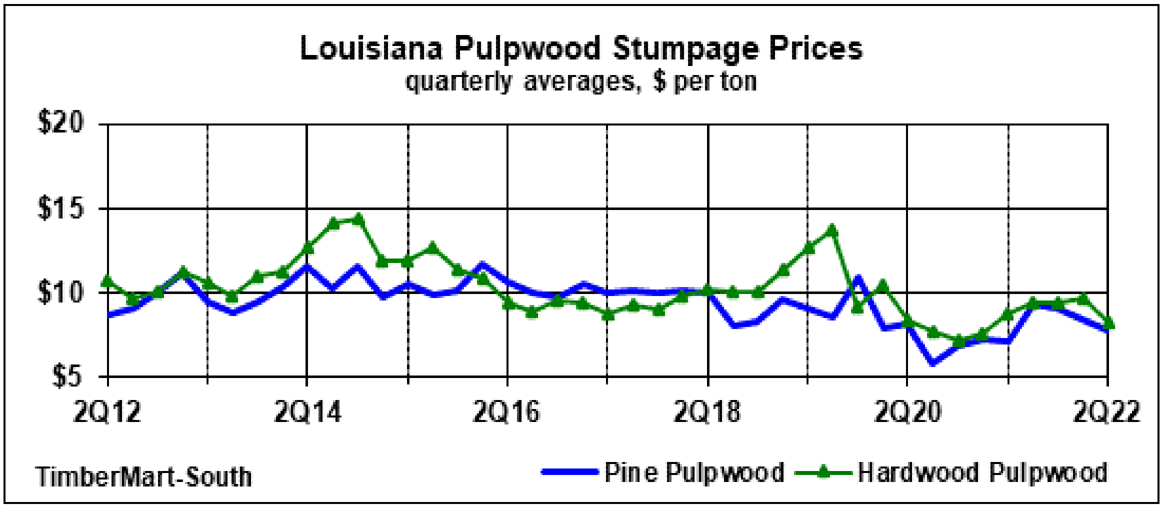
Looking into current prices of hardwood vs pinewood, sawtimber is carrying a premium price in both Louisiana and Mississippi. Mississippi hardwood sawtimber prices show a 42% higher stumpage return for growers than Louisiana hardwood, as shown in Figure 28 [50]. Louisiana has been hit the hardest by the loss of the number of mills creating a market problem. For example, Georgia-Pacific drastically scaled back operations at its Zachary, Louisiana plant. This has caused the remaining mills to have increased wood stock on hand. Current commodity pricing of timber has dropped over the past four months to a current price of $650 per 1000 board feet. This price drop reflects the impact of several factors. Higher gas prices and the overall drop in the housing market have led to this downturn. The overall estimate of demand for building products did not materialize, and the overall economy with rising inflation rate has led some builders who have permits to build to tap the breaks on starting new construction. Mills have wood yards at full capacity, thus reducing the rate of harvest, which holds prices down.

Supply of finished sawtimber at large supply stores such as Lowes and Home Depot has increased due to this reduced demand, thus forcing prices to be held down. These prices are reflected in Figure 29 plotting the past year trend with a moving average trendline [51]. Prices of hardwood sawtimber show a wide price differential of various species shown in Table 8. Timber used in cabinet and fine furniture carries a price premium, such as Black walnut at $725, White oak at $515 compared to White Pine at $70, and Red Maple at $125 [52]. Planting higher-value trees could yield a better valve for small tracts of land such as rite-of-ways. This will have to be offset with growth rate and $CO_2$ uptake to support the higher valve trees.

Yields of timber in tons per acre of land range from 25-40 tons for thinning harvests and 80-105 tons for clearcutting. These yields, combined with the price per cut of timber, generate a stumpage price for the state in addition to $CO_2$ reduction. Thinning method of harvesting wood can be achieved on a 15-year rotation for pinewood and 30 years for hardwood with a clearcut performed at 60 years end of the life cycle. From this report, the total land available for planting on rite-of-ways is 10,306 acres. Based on the Louisiana prices in Figure 28, the state (LDOTD ROW lands along the test areas of this study) could generate thinning pine timber revenue of \$12,882,500 for 25 tons acre$^{-1}$ to \$20,612,000 for 40 tons acre$^{-1}$ every 15 years, with thinning hardwood revenue of \$9,146,575 for 25 tons acre$^{-1}$ to \$14,634,520 for 40 tons acre$^{-1}$ at 30-year thinning practices. The end-of-life cycle revenue for pine could be \$41,224,000 for 80 tons acre$^{-1}$ and \$54,106,500 for 105 tons acre$^{-1}$, with hardwood at \$29,269,040 for 80 tons acre$^{-1}$ and \$38,415,615 for 105 tons acre$^{-1}$ using clearcut harvest. Given the 60 years life of the timber on the rite-of-way, the total projected revenue for the low range at 25 tons acre$^{-1}$ range could produce \$79,872,500 for pine and \$38,415,615 for hardwood. At the upper range level of 40 tons acre$^{-1}$, the total projected revenue could produce \$115,942,500 for pine and \$53,050135 for hardwood in the same 60-year span. These revenue streams could help offset the timber management cost for maximum $CO_2$ reduction and timber harvesting [53].

## Potential Additional $CO_2$ Sequestration

Albeit outside the scope of this study, a review of some of the literature indicated that large shrubs might be added along with the proposed tree plantings detailed above. The addition of shrubs into the ROW system, specifically located within the clear zone at a width of approximately ten feet on both exterior ROWs and the median (30' width total) over the modeled length of I10, I20, I49 and Hwy 90 presented in this report can potentially add 975 total acres to the amenable ROW planting area. At an assumed rate of 5 tons $CO_2$/year, the addition of shrubs can contribute approximately 14,625 tons $CO_2$/year. More research is needed in order to successfully place vegetative species within the clear zones with regard to transportation safety and specifically, energy dissipation. There is potential for significant benefit both from a CO2 sequestration and energy dissipation to place shrubs or other appropriate species within the clear zone.



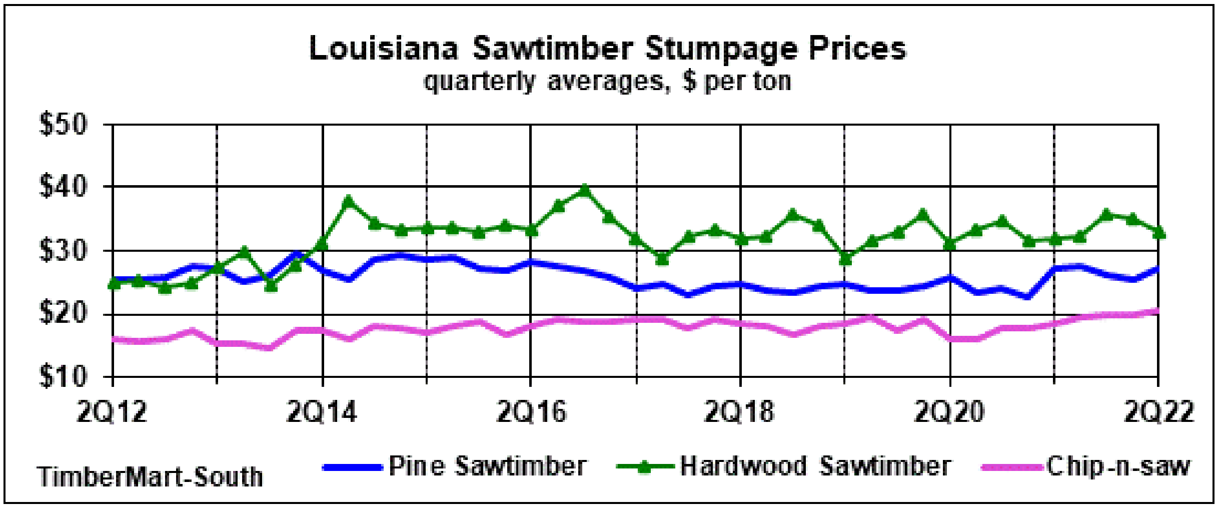


**Figure 27. Stumpage prices of Louisiana Sawtimber and Pulpwood over the past 10 years (Data taken from TimberMart-South web page http://timbermart-south.com/laprices.html)**

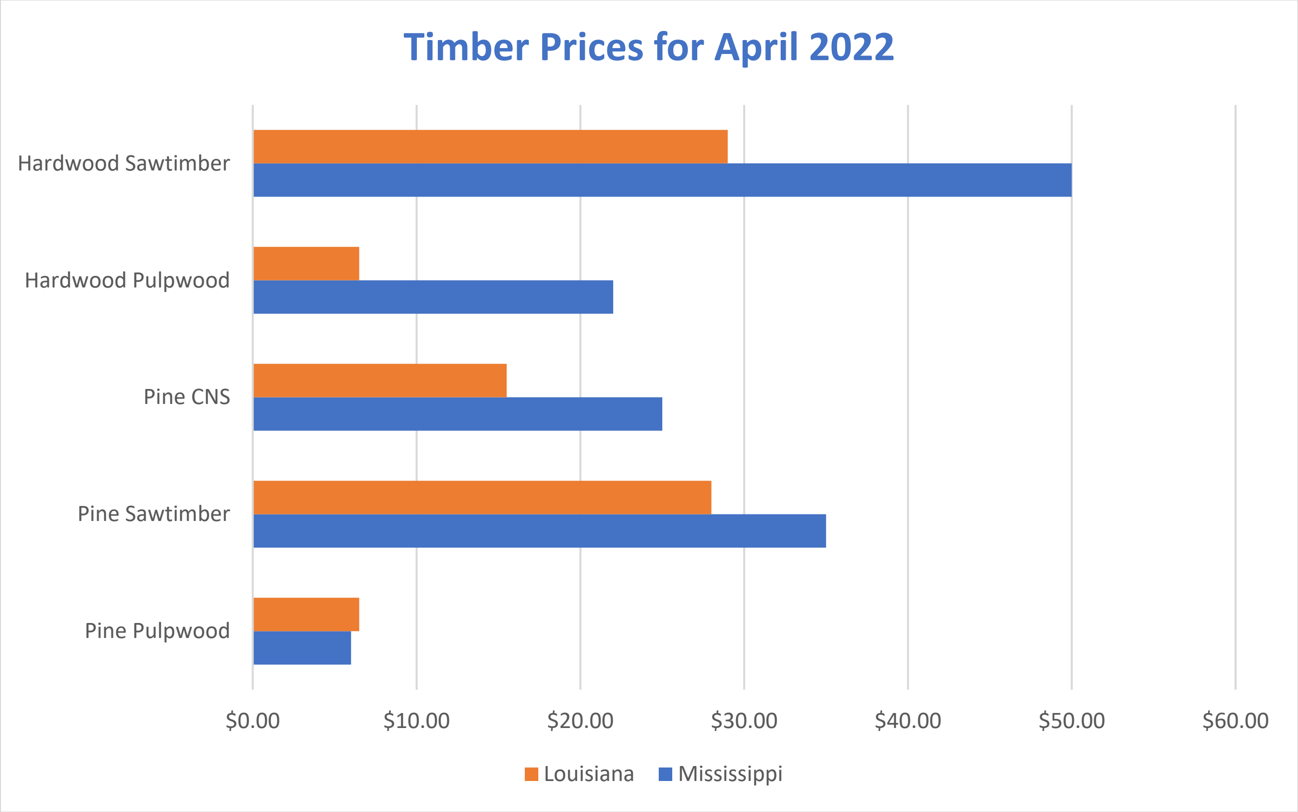


**Figure 28. Timber prices for April 2022 in Mississippi and Louisiana. The data is based on per ton stumpage price. Prices are based on an average calculated from a sample of timber buyers across the U.S., and only intended to provide an estimate of trends and current prices. Actual prices may vary. Data compiled from Timber Update website https://timberupdate.com/timber-prices/**

LUMBER Commodity

650.00 -18.80 (-2.81%)

04:01:00 PM MI Indication

**Figure 29. Lumber commodity prices over the past year with moving average trendline. Price is USD per 1000 board feet. Data taken from Market Insider website https://markets.businessinsider.com/commodities/lumber-price**

Table 8. Prices of various species of hardwood sawtimber with price per 1000 board feet. Pricing reflects data collected from Northwest Georgia, East Tennessee, and Western West Virginia. June 2022 Timber price for spices of hardwood. Data taken from Timber update https://timberupdate.com/timber-prices/

| SPECIES | PRICE - $/1000 BF |
|---|---|
| Red Oak | $300.00 |
| Black Oak | $185.00 |
| Scarlet Oak | $150.00 |
| White Oak | $515.00 |
| Chestnut Oak | $300.00 |
| Sugar (Hard) Maple | $275.00 |
| Red (Soft) Maple | $125.00 |
| Hickory | $175.00 |
| Yellow Poplar | $225.00 |
| Cucumber | $185.00 |
| Yellow Poplar Peelers | $185.00 |
| Cucumber Peelers | $175.00 |
| Basswood | $145.00 |
| Black Walnut | $725.00 |
| Black Cherry | $250.00 |
| Ash | $180.00 |

| | |
|---|---|
| Misc. | $125.00 |
| Tie/Low Grade/Pallet | $155.00 |
| White Pine | $70.00 |
| Yellow Pine | $60.00 |

for potential carbon sequestration is a plausible choice for increasing Louisiana's overall GHG sequestration capacity.

2. The proposed approach would be relatively simple to implement and perhaps show significant benefit toward helping the state meet its 2050 net neutrality goal.

Utilizing the interstate right-of-ways (ROWs) within Louisiana showed that significant carbon dioxide tonnage could be sequestered into tree biomass.

On average, including the different group combinations (conifer vs. hardwood), 0the $CO_2$ sequestration potential of ROW lands is estimated to be 73,543 and as large as 653,987 US tons $CO_2$ annually by 2050 on a baseline forest management plan that does not include thinning or replanting. This represents a conservative estimate, considering additional findings that tree thinning and replanting forest management strategies can potentially increase the sequestration capacity significantly.

2. Conifers proved to be much more efficient in annual carbon dioxide sequestration, generally about twice the sequestration tonnage with conifers versus hardwoods.

The annual $CO_2$ sequestration potential tends to increase as the trees develop until it peaks after decades of planting, and it is highly influenced by the group of species selected for planting.

3. Afforestation management by thinning resulted in a one to three times benefit, in terms of annual carbon dioxide sequestration tonnage, over unmanaged planted forests within the ROWs.

4. Thinning levels may dictate the long-term dynamics in terms of $CO_2$ sequestration of the highway forest as the 30% thinning showed long-term benefit; however, a more aggressive thinning of 50% achieved a slightly better carbon dioxide uptake than the 30%. This also allows for more biomass for use in commercial sales of forest products. Less biomass appears to provide much better conditions for photosynthesis.

5. Differences in $CO_2$ uptake data by species and modeling assumptions such as planting density had a tremendous impact on the estimated tonnage of $CO_2$ sequestrated annually within Louisiana ROWs.

6. Tree species selection for implementation involves numerous factors to be considered; however, in any case, appreciable $CO_2$ sequestration was observed.

7. The soil-based (no emergent tree impact) $CO_2$ sequestration was found to be significant but one that likely has a minimal opportunity for improvement.

8. A significant financial potential is estimated with harvesting the forested interstate ROWs based on an assessment of today's forest products markets.

9. The addition of shrubs into the ROW system, specifically located within the clear zone at a width of approximately ten feet on both exterior ROWs and the median (30' width total) over the modeled length of I10, I20, I49, and Hwy 90 presented in this report can potentially add 975 total acres to the amenable ROW planting area. At an assumed rate of 5 tons $CO_2$ acre$^{-1}$, the addition of shrubs can sequester approximately 14,625 tons $CO_2$ year$^{-1}$.

10. ROW forests may also function as natural, aesthetically appealing centerline safety barriers with tourist appeal when culturally significant trees and shrubs are used. For example, the Bald Cypress, the state tree ranked at the top of our classification matrix, constitutes a great example of said trees.

11. Planting operations should rely on sound plans to ensure the supply chain, including creating nurseries and establishing seedling distribution schemes. Community inclusion in decision-making processes that may affect ROW lands should be included in implementation management. Poor-quality private operators or a lack of available contractors has been identified as a significant challenge by some states for ROW alternative management studies about the potential to manage ROWs for hay cultivation. Moreover, forestry management of ROWs, especially those that include thinning, can potentially generate multiple new income alternatives from secondary forest products (such as furniture) and help dynamize local economies.

12. Potential timber-based wood values indicated that the thinning/harvested forest within the ROWs evaluated could generate s $10M to as much as $120M over a 50 – 80 year cycle.

13. Clearly, there is a significant yet overlooked $CO_2$ sequestration potential that could be implemented in Louisiana using the vast areas represented by the interstate ROWs (not to mention what additional lands the US highways could contribute).

# Observations and Potential Future R&D Areas

1. Tree species selection needs much more work regarding how the species can handle storm events.

2. Reforestation of ROWs likely will result in a dense land cover needing less maintenance (mowing) than current O&M efforts. This needs to be better defined with more R&D.

3. Optimizing thinning strategies needs to be better defined as afforestation management may dictate the long-term dynamics in terms of $CO_2$ sequestration of the highway forest.

4. Better definition of the most realistic per tree carbon dioxide uptakes and tree growth densities need to be studied and these data refined for forest implementation to increase the accuracy of uptake predictions over large areas.

5. Soil amendments or grass/small bush planting should be evaluated as a means of potentially enhancing the level of $CO_2$ sequestration the ROW ground may contribute.

6. More research is needed in order to successfully place vegetative species within the clear zones with regard to transportation safety and, specifically, energy dissipation. There is potential for significant benefit both from $CO_2$ sequestration and energy dissipation to place shrubs or other appropriate species within the clear zone. This option should be further studied.

7. More integration with detailed Life Cycle Analyses and Techno-economic Assessments are needed for considering the use of the ROW forests as potential profit generators. It is apparent that if thinning is implemented, as the data suggests it should, an off-take vector into the wood markets needs to be better explored.

8. Closer integration with the state's planning team on incorporating highway ROW lands with reforestation and any other open lands within the state should be initiated to ensure that a vast additional natural $CO_2$ sequestration capacity is not overlooked in Louisiana. Especially an initiative with the potential to self-fund.

# Acronyms, Abbreviations, and Symbols

| **Term** | **Description** |
|---|---|
| cm | centimeter(s) |
| $CO_2$ e | $CO_2$ equivalent. It refers to net emissions accounting for the global warming potential of other greenhouse gases. |
| DBH | Diameter at breast height |
| FHWA | Federal Highway Administration |
| ft. | foot (feet) |
| GHG | Greenhouse gas |
| LDOTD | Louisiana Department of Transportation and Development |
| lb. | pound(s) |
| LTRC | Louisiana Transportation Research Center |
| ROW | Right of ways |
| SD | Standard deviation |
| TIRE | Transportation Innovation and Research Exploration. A program within the Louisiana Transportation Research Center. |
| US ton | Short ton = 2000 lbs = 0.9071847 metric tons |

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