# STRATEGIC REFORESTATION AS A GREENHOUSE GAS MITIGATION TACTIC: A CASE STUDY FOR THE MINING INDUSTRY

by

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April 25, 2017

Masters project proposal submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University

# EXECUTIVE SUMMARY

Direct measurements of the climate system demonstrate that mean global surface temperature is increasing. The warming trend is attributed to increasing atmospheric greenhouse gases (GHG), primarily carbon dioxide ($CO_2$), from natural and man-made sources. While the climatic repercussions are complex and vary in scientific certainty, there is high confidence that heavy precipitation and extreme high sea level will intensify as the warming trend continues.

The mining industry is particularly vulnerable to climate change risk. For example, an impoundment failure caused or accelerated by extreme precipitation could have disastrous social and corporate consequences. Beyond the obvious environmental, safety, and human health repercussions, such a disaster could disrupt operations, sever supply routes, and adversely impact a company's social license to operate. Companies that operate in economically, socially, and environmentally sensitive areas are even more susceptible to these risks.

In response to stakeholder concern, many mining companies have begun to formally manage climate change risk. Strategies include executive-level accountability for climate risk management, completing facility-scale vulnerability assessments, planning for infrastructure adaptation, and undertaking efforts to mitigate the social impact of their own GHG emissions. GHG emission mitigation can be direct (e.g. reducing fuel and electricity use) or indirect (e.g. offsetting operational emissions). The latter method, also known as net operational emission reduction, is at the center of this study.

Reforestation offers an opportunity for mining companies to indirectly reduce net operational GHG emissions long after mining is complete. This is because trees take up (i.e. sequester) $CO_2$ from the atmosphere and store carbon in biomass as they grow. Different tree species sequester $CO_2$ at different rates throughout their lifecycle. There is a large body of easily accessible, publicly available data from annual U.S. Forest Service (USFS) surveys that can be used to estimate $CO_2$ sequestration by forest type and region. Using these data, mining industry professionals can easily estimate the long-term $CO_2$ sequestration potential of their post-mining

land rehabilitation plans. Companies that are serious about mitigating their operational GHG emissions can use these data to strategically design, analyze, and select reforestation alternatives.

Using a former (i.e. rehabilitated) mine in Florida as a case study site, we herein provide a model framework that can be replicated by mining industry professionals to make reforestation decisions for their own operations. We used the Carbon Online Estimator (COLE) tool, which aggregates data from the USFS Forest Inventory Assessment (FIA), to estimate post-mining $CO_2$ sequestration for the planned reforestation scenario and two reforestation alternatives. The social damages of operational emissions and the benefit of post-mining $CO_2$ sequestration were monetized using published Social Cost of Carbon (SCC).

The results show how cumulative $CO_2$ sequestration varies by forest type over a 100-year model period. These results can be weighed against other reforestation goals. For example, we found that the pine-dominated forests sequester more $CO_2$ early in the model period, but offer less biodiversity value because they are typically planted as monocultures. Conversely, the higher-biodiversity pine-hardwood mix sequesters more $CO_2$ at the end of the model period. This information is insightful when making value-based rehabilitation decisions (e.g. Is $CO_2$ valued more highly than biodiversity? What time horizon is important?).

Further, we found that none of the reforestation scenarios fully mitigates operational emissions for the case study site. Even the highest-sequestering scenario only mitigates 30% of cumulative operational emissions over the 100-year model period. Nevertheless, a 100% mitigation outcome is not necessarily the objective of this tool. Rather, the intent is to understand the $CO_2$ sequestration potential of multiple reforestation scenarios and use that information to make value-based land rehabilitation decisions. This tool also allows industry professionals to quantify and communicate the social benefit of their reforestation decisions to stakeholders as part of a broader climate change risk mitigation strategy.

While the methods used in this study can be applied to many mining industry sectors, the results cannot be generalized to the industry or even the corporate scale. The outcome of each assessment depends on local factors such as size of the mine, post-mining land conditions, practicality of reforestation, local and regional climate, regulatory obligations.

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# INTRODUCTION

Direct measurements of the climate system demonstrate that global mean surface temperature has steadily increased since the mid-19$^{th}$ century (IPCC, 2013). Climatic implications of this warming trend vary in intensity and certainty, but could include fewer cold days and nights; more frequent and intense hot weather; and increased drought intensity, heavy precipitation, tropical cyclone activity, and extreme high sea level (IPCC, 2013).

The warming trend is caused by anthropogenic and natural substances released into the atmosphere that alter the earth's energy budget (IPCC, 2013). Specifically, atmospheric carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and other greenhouse gases (GHG) have increased steadily since the industrial revolution (IPCC, 2013). In 2011, the atmospheric concentrations of these greenhouse gases exceeded pre-industrial levels by about 40%, 150%, and 20%, respectively (IPCC, 2013). There is high confidence in the scientific community that more than half of the observed increase in global average surface temperature is caused by anthropogenic GHG emissions (IPCC, 2013).

Environmental and social consequences of climate change include ecosystem alteration; disruption of migratory patterns; food and water supply disruption; infrastructure damage and inadequacy; and population displacement (IPCC, 2013). Potential human health consequences include increased heat-related illness and mortality (Curriero 2002); increased respiratory disease due to ozone pollution (Bell et al. 2007); increased allergen-induced illness (Singer et al. 2005); and the spread of infectious disease (e.g. dengue fever, malaria) due to changes in density and distribution of mosquitos and other vectors (Haines et al. 2006).

Despite scientific evidence that anthropogenic GHG emissions are driving potentially severe environmental, social, and health consequences, the United States has not enacted meaningful regulatory intervention. Many energy and climate-related regulatory actions under President Obama's administration were rescinded soon after President Trump took office. In his March 28, 2017 Executive Order, President Trump requires federal agencies to review regulations that "*potentially burden the development of or use of domestically produced energy resources, and appropriately suspend, revise, or rescind those that unduly burden the*

*development of domestic energy resources beyond the degree necessary to protect the public interest or otherwise comply with the law*" (Exec. Order No. 13783, 82 FR 16093). This Executive Order specifically requires review of the Clean Power Plan, which is intended to reduce GHG emissions by regulating the energy sector.

Further, the United States has yet to endorse international climate accords, despite widespread global collaboration. In the 1990s, private sector leaders partially influenced President Bush's decision not to ratify the Kyoto Protocol (Selin, 2010). At the United Nations Framework Convention on Climate Change (UNFCC) 21st Conference of the Parties (COP21), President Barack Obama pledged U.S. participation in an international treaty to reduce global GHG emissions (the Paris Agreement) (UNFCCC, 2015). However, consummation of this commitment is questionable in the wake of Executive Order 13783.

Notwithstanding policy uncertainty at the national level, two emerging trends signal support for action to address climate change in the United States: 1) climate legislation at the state level, and 2) voluntary corporate GHG emission reduction and climate risk management. The latter trend is at the center of this study, with specific focus on the mining industry.

Business Risks of Climate Change

Companies across many industry sectors face financial and reputational risks related to the impact of their own operational GHG emissions, as well as the threat of an unpredictable and changing climate. Direct threats to the mining industry include damage and/or disruption to infrastructure and operations; interruption of supply chains and distribution routes; worker health and safety; environmental management vulnerability; increasing pressure points with community relations; and impacts to exploration and future growth (Nelson and Schuchard 2009). Indirect threats include the financial consequences of potential future climate legislation; changes in consumer preference due to increased environmental awareness; and increases in insurance risk premiums due to climate change exposure (Busch and Hoffmann 2007).

Because mines are often located in economically, politically, and socially challenging geographies, a mining company's success or failure in managing climate change risk may

positively or negatively impact corporate reputation, social license to operate, and access to financing (Nelson and Schuchard 2009).

Institutional investors recognize these risks. A document prepared by a coalition of mining industry investors provides guidance for investors to "*stress test*" a mining company's resilience to climate change and carbon risk (IIGCC, 2015). Investor expectations include clearly defined executive-level responsibility for managing climate change risk; GHG emission reduction goal-setting; development and implementation of a climate change risk management strategy; engagement with public policy makers; and transparency in the form of voluntary disclosure (IIGCC, 2015). In response, many companies have developed their own climate change risk management strategies.

In contrast to the Kyoto Protocol mindset of the 1990s, many companies now publicly support regulatory intervention to address the problem of climate change. In advance of COP21, 154 companies endorsed the American Business Act on Climate Pledge, signaling their support for U.S. action on climate change (The White House, 2015). Mining industry signatories included DSM North America, BHP Billiton, DuPont, and RioTinto. This trend appears to continue, as evidenced by a similar open letter addressed to President Trump in advance of UNFCCC's COP22 in 2017 (Business Backs Low-Carbon USA, 2016).

Corporations are increasingly establishing a self-imposed price on carbon (e.g. carbon "tax") to plan for potential future financial risk and, in some cases, to finance GHG-reducing technology investments. The number of companies that report having an internal carbon tax tripled between 2014 and 2015 (CDP, 2015). Of the 435 companies that report having an internal carbon tax, 28 are in the mining and materials sector; examples include Vale, Exxaro Resources, Harmony Gold Mining, Anglo American Platinum, and Sibayne Gold (CDP, 2015).

Mining companies are also undertaking vulnerability assessment, adaptation, and mitigation tactics as part of an overarching climate change risk management strategy. Vulnerability assessment examples include facility-specific infrastructure inspections and modeling to identify and quantify damage and failure risks associated with increased high-intensity storm events, reviewing emergency procedures, and developing contingency plans

(BSR 2009). Adaptation strategies include fortifying existing structures and assets to ensure robust engineering design and construction standards. Mitigation strategies include efforts to reduce net operational GHG emissions (e.g. increasing energy efficiency; investing in renewable energy technologies and alternative fuels; and offsetting greenhouse gas emissions) (BSR 2009).

Some U.S. mining companies voluntarily purchase forest carbon credits as a mitigation tactic, in an effort to offset GHG emissions (BSR 2009). However, there is little evidence that mining companies are evaluating their land rehabilitation in an effort to mitigate GHG emissions through post-mining reforestation.

Reforestation as a GHG Emission Reduction Opportunity

Through photosynthesis, trees and other plants take up (i.e. sequester) carbon dioxide ($CO_2$), release oxygen ($O_2$) as a by-product, and store carbon (C) in their trunks, limbs, roots, and leaves. In the United States alone, forests sequestered 787 million metric tons (MT) of $CO_2$ in 2014 (USEPA, 2015). This is equivalent to approximately 11.5 percent of gross domestic GHG emissions in 2014. Globally, trees act as a valuable carbon "sink" that is capable of significantly mitigating greenhouse gas emissions (Pan et al. 2011).

Forestry practices can reduce net GHG emissions by increasing the amount of $CO_2$ that is sequestered by trees. Examples include reducing deforestation, reforestation (planting trees on recently deforested land), afforestation (planting trees on land that has been deforested for more than 10 years), and managing timberland to increase carbon stocks (Peterson et al. 2014).

Many studies highlight the variable $CO_2$ sequestration potential of deforested land. Peterson et al. (2014) found that 8 million hectares of deforested land in the United States could sequester 50 million MT of $CO_2$ annually (6.3 MT $ha^{-1}$). Sperow (2006) estimated that 567,000 hectares of mine land in seven Appalachian states have the potential to sequester 0.7 to 2.2 million MT of carbon annually (1.2 – 3.9 MT $ha^{-1}$). Van Rooyen et al. (2012) found that a 27-year old rehabilitated indigenous forest in South Africa had thus far captured two-thirds of the carbon stock that existed prior to mining.

In addition to GHG sequestration, reforestation offers co-benefits including improved biodiversity (Díaz et al. 2009), air quality (Kroeger et al. 2014), cultural / aesthetic value (Laband 2013), and property value (Thorsnes 2002). Mining companies are often publicly criticized for past and present environmental and social impacts, which has resulted in a global trend toward Corporate Social Responsibility (CSR) in the mining industry (Hamann 2003, Jenkins and Yakovleva 2006, Dashwood 2012, Fonseca et al. 2013, Vintró et al. 2014). Due to the broad co-benefits, reforestation may provide an additional opportunity for mining companies to advance their CSR and climate change risk mitigation objectives.

Study Objectives

This study demonstrates a method to estimate the $CO_2$ sequestration potential of multiple reforestation alternatives, and the extent to which each alternative mitigates operational GHG emissions. We used a single-case study method to demonstrate use of this framework for a former (i.e. reclaimed) mining operation in Florida. The mining company and location are not disclosed, and planted areas for each forest type were rounded. While these confidentiality measures impede direct replication of our results, the primary contribution of this work is the framework itself rather than the site-specific results.

It is important to note that the results of this study do not apply to the mining industry as a whole, as carbon sequestration potential for each mine will vary depending on various operational, geographical, and climatological factors that influence tree planting. Further, a 100% mitigation outcome is not necessarily the objective of this tool. Rather, the intent is to understand the $CO_2$ sequestration potential of multiple reforestation scenarios and use that information to make value-based land rehabilitation decisions. This tool also allows industry professionals to quantify and communicate the social benefit of their reforestation decisions to stakeholders as part of a broader climate change risk mitigation strategy.

# METHODS

We selected a 2,800-hectare former mine in Florida as the case study site. This site was selected due to accessibility of comprehensive land rehabilitation records (including reforestation planting plans) in online public record databases. Mining at the case study site began in 1975 and ended in 2005; land rehabilitation and reforestation was completed in 2010.

Following selection of the case study site, we accessed publicly available regulatory documents to identify the planned post-mining reforestation plan for the case study site. Next, we queried the free online USFS Carbon Online Estimator (COLE) tool to obtain carbon stock and growth-yield data for forest types represented in the reforestation plan. These data were used to estimate annual and cumulative (over a 100-year study period) carbon sequestration for each forest type in the planned reforestation scenario. We then developed two alternative reforestation scenarios. For each reforestation scenario, $CO_2$ sequestration was estimated over a 100 year study period. Published social cost of carbon (SCC) values were used to compare the damages of operational $CO_2$ emissions to $CO_2$ sequestration estimates for each reforestation scenario.

## Identification of study area and planned reforestation scenario

Planned post-mining landforms were tabulated based on publicly available information contained within permits issued by the Florida Department of Environmental Protection (FDEP) in accordance with the Florida Land Use, Cover and Forms Classification System (FLUCFCS) (FDOT, 1999). To better define the study area, the dataset was refined as follows. First, Non-vegetated landforms and landforms less than 1 acre (0.4 ha) in size were excluded from the study area because these areas would minimally contribute to the post-mining carbon budget (Table 1).

**Table 1**. Landform categories excluded from the study area

| Landforms from FDEP permit | Study Area Status |
|---|---|
| Bay Swamp | Included |
| Coniferous Plantation | Included |
| Coniferous Plantation/Wet Prairie | Included |
| Cypress | Included |
| Cypress/Gum Swamp | Included |
| Enhanced Forested Wetlands | Included |
| Freshwater Marsh | Included |
| Gum Swamps | Included |
| Hardwood Conifer Mix | Included |
| Herbaceous | Included |
| Lake | Excluded – Not vegetated |
| Loblolly Pine Wetland | Included |
| Manmade Ditch | Excluded – Not vegetated |
| Mixed Wetland Forest | Included |
| Other Open Land - Food Plot | Excluded – Not vegetated |
| Pine Flatwoods | Included |
| Pine Mesic Oak | Included |
| Reservoir | Excluded – Not vegetated |
| Roads and Highways | Excluded – Not vegetated |
| Shrub and Brushland | Included |
| Upland Coniferous Forest | Included |
| Upland Mixed Forest | Included |
| Vegetated Non-Forested Wetland | Included |
| Wet Prairie | Included |
| Wetland Coniferous Forest | Included |
| Wetland Scrub | Excluded – less than 1 acre |
| Xeric Oak | Included |

Next, Florida state land-use designations were reclassified for consistency with USFS Forest Inventory Analysis (FIA) forest types. This step was necessary so FIA sample plot data could be used to estimate carbon sequestration for the study area. To accomplish this, vegetative descriptions within the FLUCFCS manual were compared to descriptions within the FIA manual, and reclassified as closely as possible based on species composition. A vegetative description for each reclassified landform type is provided in Table 2.

**Table 2**: Reclassification of Florida land use designations (FDOT, 1999) for compatibility with USFS FIA designations (USDA, 2016)

| **USFS FIA Forest Type** | **USFS FIA Forest Type – Description** | **Florida State Land Use Designation** | **Florida State Land Use Designation - Description** |
|---|---|---|---|
| Bald Cypress/ Pond Cypress | More than 50% bald cypress. Other species may include black gum, willow, red maple, American elm, persimmon, overcup oak, and sweetgum. | Cypress | Dominated by cypress |
| | | Cypress/ Gum Swamp | |
| Loblolly Pine | Loblolly pine is dominant. Other species may include sweetgum, southern red oak, post oak, blackjack oak, black gum, yellow-poplar, and pond pine. | Loblolly Pine Wetland | Wetland coniferous plantation with at least 66% loblolly pine. |
| Mixed Upland Hardwood | Any mixture of hardwood species with at least some oat present. | Upland Hardwood Forest | Minimum 66% naturally generated upland hardwood species. |
| Non-Stocked (Upland) | Uplands characterized by a) >10% stocked by trees, seedlings, and saplings, and not classified as cover trees, or b) where stocking standards not available, >10% cover of trees, saplings, and seedlings. | Herbaceous | Non-wetland, treeless upland prairie. Predominantly includes grasses, sedges, rushes and other. Some saw palmetto may be present. |
| | | Shrub and Brushland | Predominantly includes saw palmetto, but other woody shrubs also present (gallberry, wax myrtle, coastal scrub and other shrubs and brush. Short herbs and grasses also present. |
| Non-Stocked (Wetland) | Wetlands characterized by: a) >10% stocked by trees, seedlings, and saplings, and not classified as cover trees, or b) where stocking standards not available, >10% cover of trees, saplings, and seedlings. | Vegetated Non-Forested Wetland | Marshes having 10% or less canopy. |
| | | Freshwater Marsh | One or more wetland emergent herbaceous species dominant; 10% or less canopy. |
| | | Wet Prairie | Grassy wetland vegetation; 10% or less canopy. |
| Slash Pine | Slash pine is pure or dominant. Other species may include moist-site hardwoods, pond pine, and pond cypress (moist sites), and dry-site hardwoods, longleaf, loblolly, and sand pine (dry sites). | Upland Coniferous Forest | Natural canopy at least 66% coniferous species. |
| | | Pine Flatwoods | Slash pine, longleaf pine and/or pond pine are dominant. Understory includes saw palmetto, wax myrtle, gallberry, other brush, and herbs. |
| | | Coniferous Plantation | Planted pine, typically characterized by high density, uniform size, and row appearance. |

| | | | |
|---|---|---|---|
| | | Coniferous Plantation/ Wet Prairie | Coniferous plantation with understory meeting wet prairie description. |
| | | Wetland Coniferous Forest | Greater than 10% canopy of naturally generated coniferous species. |
| Slash Pine/ Hardwood | Slash pine intermixed with hardwood species, typically including sweetbay, blackgum, loblolly bay, pondcypress, pond pine, Atlantic white cedar, red maple, ash, and water oak. | Pine Mesic Oak | Slash, longleaf and loblolly pine intermixed with oaks and other hardwoods, including Southern red oak, water oak, white oak, laurel oak, hickories, sweetgum and dogwood. Gallberry, wax myrtle and saw palmetto may be present in the understory. |
| | | Hardwood Conifer Mix | Upland forests where neither conifers nor hardwoods achieve 66% canopy closure. |
| Southern Scrub Oak | Common species include turkey oak, blackjack oak, dwarf live oak, Durand oak, and scrub oak. | Xeric Oak | Common species include live oak, bluejack oak, turkey oak and sand post oak. |
| Sweetbay/swamp tupelo/red maple | Predominant species include blackgum, Florida maple, water birch, gum bumelia, water locust, loblolly bay, magnolia, red maple, Ogechee tupelo, red bay, water-elm, Oglethorpe oak, loblolly pine, pond pines, and American elm. | Bay Swamp | Bay species are dominant, including loblolly bay, sweetbay magnolia, swamp bay. Loblolly and slash pine may also be present. Understory typically includes gallberry, fetterbush, wax myrtle and titi. |
| | | Gum Swamps | Swamp tupelo (blackgum), water tupelo (tupelogum), or Ogeechee tupelo are dominant. Other species may include bald cypress and other wet-tolerant species. |
| | | Mixed Wetland Hardwoods | Wetland hardwood forest where no species is clearly dominant. |
| | | Enhanced Forested Wetlands | Previously disturbed mixed wetland hardwood habitats which have been enhanced by supplemental planting. |

Table 3 provides the size of each forest type within the study area, as reclassified for consistency with USFS FIA forest types. The study area includes nine FIA forest types and totals 2,760 hectares. This represents the "planned" reforestation scenario. In other words, these landforms and vegetative communities were approved by FDEP and the mining companies have a regulatory obligation to return the land to these conditions.

**Table 3**: Study Area Forest Types (Planned Reforestation Scenario)

| USFS FIA Forest Type | Florida State Land Use Designation | Study Area (ha) |
|---|---|---|
| **Bald Cypress/Pond Cypress** | Cypress | 59 |
| | Cypress/Gum Swamp | 1 |
| | | **60** |
| **Loblolly Pine** | Loblolly Pine Wetland | **3** |
| **Mixed Upland Hardwood** | Upland Hardwood Forest | **212** |
| **Non-Stocked (Upland)** | Herbaceous | 236 |
| | Shrub and Brushland | 33 |
| | | **269** |
| **Non-Stocked (Wetland)** | Vegetated Non-Forested Wetland | 4 |
| | Freshwater Marsh | 6 |
| | Wet Prairie | 16 |
| | | **26** |
| **Slash Pine** | Upland Coniferous Forest | 33 |
| | Pine Flatwoods | 2 |
| | Coniferous Plantation | 1652 |
| | Coniferous Plantation/Wet Prairie | 3 |
| | Wetland Coniferous Forest | 26 |
| | | **1716** |
| **Slash Pine/Hardwood** | Pine Mesic Oak | 70 |
| | Hardwood Conifer Mix | 6 |
| | | **76** |
| **Southern Scrub Oak** | Xeric Oak | **34** |
| **Sweetbay/swamp tupelo/red maple** | Bay Swamp | 88 |
| | Gum Swamps | 2 |
| | Mixed Wetland Hardwoods | 131 |
| | Enhanced Forested Wetlands | 143 |
| | | **364** |
| | **Study Area Total** | **2,760** |

Once the study area and planned reforestation scenario were defined, the project proceeded to estimate annual and cumulative carbon sequestration of each forest type, using data from the USFS Carbon Online Estimator (COLE).

*Carbon Online Estimator (COLE)*

COLE is a free online tool that uses a combination of annual FIA forest census data and published equations to generate basic carbon inventory and growth-yield estimates for forest types within a selected study area (https://www.fs.usda.gov/ccrc/tools/cole). The COLE tool can generate carbon inventory reports based on statewide queries, or queries of regional FIA survey units (e.g. northeast, southeast, south central, etc.).

A COLE query for the northeast Florida survey unit did not yield data for all forest types within the study area. However, all forest types were represented in the state-wide query report. We used carbon inventory data from the state-wide COLE report because they were similar to the northeast Florida survey unit data for most forest types in the study area. For example, mean non-soil carbon stock for the slash pine forest type was 70.9 MT/ha for the state-wide query and 68.3 for the northeast FL survey unit query. Loblolly pine was 68.9 MT/ha (state-wide) and 70.9 (northeast FL). Slash pine / hardwood was 70.2 MT/ha (state-wide) and 70.8 MT/ha (northeast FL). Southern scrub oak was 39.0 MT/ha (state-wide) and 31.3 MT/ha (northeast FL). Mixed upland hardwoods was 79.3.0 MT/ha (state-wide) and 76.9 MT/ha (northeast FL). Sweet bay / swamp tupelo / red maple was 83.4 MT/ha (state-wide) and 81.1 MT/ha (northeast FL). Bald cypress / pond cypress was 84.6 MT/ha (state-wide) and 97.6 MT/ha (northeast FL).

COLE reports include carbon estimates for the following carbon pools: live tree, dead tree, understory, down dead wood, soil, and forest floor. Soil carbon was intentionally excluded because COLE carbon estimates are expected to be higher than actual conditions in rehabilitated mine soils (Schwenke et al. 2000). Because this study focuses on reforestation as a carbon-enhancing reclamation strategy, excluding the non-soil carbon pool does not materially impact the results of the study.

For each forest type, the COLE report provides a carbon stock estimate (by age class) for two scenarios: afforestation and reforestation. Conceptually, reforestation refers to planting trees on recently deforested land, whereas afforestation pertains to lands that have been deforested for much longer (typically greater than 10 years). In the context of COLE reports, the terms functionally differ in the carbon pools used to generate the carbon stock estimates. The afforestation values do not include the down dead wood and forest floor carbon pools. Even though portions of the study area were forested before mining, this study uses values for the afforestation scenario because mining would have eliminated the dead wood and forest floor carbon pools. A sample COLE carbon stock table (COLE table) is provided as Plate 1.

**Plate 1:** Carbon Stock by Age Class for Slash Pine (from Table 6 of the COLE Report)

Table 6: **Slash pine - Carbon Stocks by Age Class for Florida: Afforestation**

| Age Class | Mean volume | Live tree | Dead tree | Under story | Down dead wood | Forest floor | Soil | Total non soil |
|---|---|---|---|---|---|---|---|---|
| years | $m^3$/hectare | tonnes carbon/hectare | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 83.27 | 0 |
| 5 | 6.54 | 4.68 | 0.01 | 5.54 | 0.25 | 2.98 | 83.55 | 13.45 |
| 10 | 28.52 | 18.25 | 0.07 | 5.53 | 0.97 | 5.22 | 84.36 | 30.04 |
| 15 | 55.14 | 32.31 | 0.18 | 5.31 | 1.71 | 6.98 | 85.66 | 46.48 |
| 20 | 78.52 | 42.95 | 0.34 | 5.18 | 2.28 | 8.38 | 87.38 | 59.12 |
| 25 | 96.31 | 50.01 | 0.52 | 5.1 | 2.65 | 9.53 | 89.41 | 67.82 |
| 30 | 108.87 | 54.39 | 0.72 | 5.06 | 2.88 | 10.49 | 91.67 | 73.55 |
| 35 | 117.37 | 57.02 | 0.92 | 5.04 | 3.02 | 11.31 | 94.03 | 77.31 |
| 40 | 122.97 | 58.57 | 1.11 | 5.03 | 3.11 | 12.01 | 96.4 | 79.82 |
| 50 | 128.96 | 60 | 1.46 | 5.01 | 3.18 | 13.15 | 100.82 | 82.79 |
| 60 | 131.42 | 60.47 | 1.73 | 5.01 | 3.21 | 14.03 | 104.46 | 84.46 |
| 70 | 132.42 | 60.63 | 1.95 | 5.01 | 3.22 | 14.74 | 107.12 | 85.54 |
| 80 | 132.82 | 60.68 | 2.11 | 5.01 | 3.22 | 15.33 | 108.89 | 86.34 |
| 90 | 132.98 | 60.7 | 2.22 | 5.01 | 3.22 | 15.81 | 109.94 | 86.96 |
| 100 | 133.05 | 60.7 | 2.31 | 5.01 | 3.22 | 16.22 | 110.52 | 87.46 |
| a | 133.09 | 60.71 | 2.51 | | | | | |
| b | 0.09 | 0.11 | 0.04 | | | | | |
| se | 93.28 | 43.19 | 3.44 | | | | | |
| n | 1026 | | | | | | | |

Calculating annual and cumulative $CO_2$ sequestration by forest type

As shown in Plate 1, the COLE tables provide carbon stock (MT/ha) by age class for each forest type. These values are provided in 5-year time increments from year 5 -40 (after planting) and 10-year time increments from year 41 – 100. Annualized carbon sequestration

rates were estimated in 5-year increments using these data. For example, the year-5 carbon stock value was divided by 5 years to obtain an annualized carbon sequestration rate for Years 1-5. This assumes a constant rate of sequestration for years 1-5. To calculate the annual sequestration rate for years 6-10, the year-5 carbon stock value was subtracted from the year-10 carbon stock value, then divided by 5 years to annualize. For years 41-50, the 40-year carbon stock value was subtracted from the 50-year carbon stock value and divided by 10 years to annualize. Carbon values were multiplied by 3.67 to convert to carbon dioxide ($CO_2$). Throughout the remainder of this text, sequestration is reported as $CO_2$ unless otherwise noted.

Cumulative sequestration for each forest type [Cumulative $(CO_{2\text{-}seq})_f$] was calculated as the sum of annual sequestration [$(CO_{2\text{-}seq})_f$] over a 100 year period, as shown in Equation 1.

$$\text{Cumulative } (\text{CO2seq})\text{f} = \sum_{i=1}^{100} \text{CO2}\, seq\ (i)$$

Equation 1

Developing alternative reforestation scenarios

Next, we used annual and cumulative carbon sequestration results for study area forest types to select practical reforestation alternatives. For the purpose of this project, a *practical* reforestation alternative is defined as one that meets regulatory requirements and is expected to sequester more $CO_2$ than the planned scenario.

Regulatory requirements pertaining to revegetation include the following: 1) Upland forested areas must "*resemble pre-mining conditions where practical and consistent with intended post-mining land uses*". 2) At a minimum, 10% of disturbed uplands must be "*reforested with a variety of indigenous hardwoods"* to achieve a stand density of 200 trees per acre, and 3) Disturbed wooded wetlands must be reforested with species present before mining, at a stand density of 200 trees per acre (Florida Administrative Code, Chapter 62C-37).

When selecting alternative reforestation scenarios, forest types that sequester the most carbon in the first 30-years of the 100-year study period were favored due to the increasing possibility of carbon loss over a longer time period. For example, the potential for loss of tree

stock due to natural disaster (e.g. hurricane or wildfire) increases over time. There is also increased potential for future development-related carbon loss as development pressures and policies change over time. Lastly, the company that benefits from reforestation as a climate change mitigation strategy may not persist through a longer study period.

Estimating annual and cumulative sequestration for reforestation scenarios

Annual sequestration for each reforestation scenario [$(CO_{2\text{-}seq})_s$] was calculated as the sum of annual sequestration for each forest type within that scenario, multiplied by the planted area of that forest type (Equation 2).

$$(\mathrm{CO2seq})\mathrm{s} = \sum_{f=1}^{8} (\mathrm{CO2seq})f * (P)f$$

Equation 2

Where:

$CO_{2seq}$ = annual carbon dioxide sequestration (MT $CO_2$/ha/yr)
s= reforestation scenario
f = forest type
P = Planting area (ha)

**Cumulative sequestration** for each reforestation scenario [Cumulative $(CO_{2\text{-}seq})_s$] was calculated as the sum of annual sequestration [$(CO_{2\text{-}seq})_s$] over a 100 year period, as shown in Equation 3.

$$\text{Cumulative } (\mathrm{CO2seq})\mathrm{s} = \sum_{i=1}^{100} (\mathrm{CO2}\,seq)s\ (i)$$

Equation 3

Estimating social benefit of reforestation and damages of operational emissions

*Social Cost of Carbon (SCC)*

In brief, the Social Cost of Carbon (SCC) is the net present value of monetized damages caused by one metric ton of $CO_2$ emitted, or the benefit of one metric ton sequestered.

SCC is used by the Environmental Protection Agency and other federal agencies to compare the benefit of GHG emission reduction to the cost of mitigation policy.

Several complex Integrated Assessment Models (IAM) have been developed by scientists and economists to estimate economic damages far into the future (typically 100 years), due to the persistence of $CO_2$ in the atmosphere. Because the damages from today's $CO_2$ emissions will be realized long into the future, discounting is necessary to compare the cost or benefit of today's actions with the cost or benefit to future generations. Although discounting is commonplace in multi-generational economic analyses, the choice of discount rate is often controversial due to inherent judgment over the value of future versus present welfare.

In 2009, the Interagency Working Group on Social Cost of Carbon (The Working Group), comprised of scientific and economic experts, was established to develop a consistent range of SCC estimates for use by all federal agencies. Using averages from multiple IAM models, The Working Group published SCC values in 5 year increments from 2010-2050 (Interagency Working Group on Social Cost of Carbon, 2015). To acknowledge the controversy over discounting, The Working Group published SCC values at multiple discount rates (2.5%, 3%, and 5%). For example, the "5% average" value for year 2050 is the net present value of all average damages from 2050 to the end of the model period, discounted back to 2007 at a rate of 5%. To demonstrate the range of uncertainty in the models, The Working Group also provides a value at the 95$^{th}$ percentile at the 3% discount rate (Table 4).

**Table 4**: Social Cost of Carbon in dollars per metric ton of $CO_2$ (Source: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866)

| Year of emission or uptake | Value at 2.5% Avg. Discount Rate | Value at 3% Avg. Discount Rate | Value at 5% Avg. Discount Rate | Value at 95$^{th}$ percentile of 3% Discount Rate |
|---|---|---|---|---|
| 2010 | $50 | $31 | $10 | $86 |
| 2015 | $56 | $36 | $11 | $105 |
| 2020 | $62 | $42 | $12 | $123 |
| 2025 | $68 | $46 | $14 | $138 |

| | | | | |
|---|---|---|---|---|
| 2030 | $73 | $50 | $16 | $152 |
| 2035 | $78 | $55 | $18 | $168 |
| 2040 | $84 | $60 | $21 | $183 |
| 2045 | $89 | $64 | $23 | $197 |
| 2050 | $95 | $69 | $26 | $212 |

Estimating Social Damages from Operational Emissions

We obtained GHG emission data for the case study site from corporate public disclosure reports, in the form of aggregated Scope 1 (directly generated onsite by earthmoving equipment and other fuel combustion) and Scope 2 (indirectly produced through the generation of purchased electricity) emissions. While the case study site was mined from 1975-2005, GHG emission data were only publicly reported for years 2001-2007 (Table 5). These data are highly variable, likely due to commodity price-driven fluctuations in production. To address data variability, we averaged the reported emissions for years 2001-2005 to obtain an estimate for annual operational emissions. We then calculated total operational emissions by multiplying the annual operational emissions by the 30-year mine life (Table 5).

**Table 5**: Scope 1 and Scope 2 GHG emissions from corporate disclosure reports

| Year | Scope 1 and Scope 2 Emissions (MT $CO_2$) |
|---|---|
| 2001 | 62,000 |
| 2002 | 59,000 |
| 2003 | 147,000 |
| 2004 | 85,000 |
| 2005 | 217,000 |
| 2006 | 19,000 |
| 2007 | 17,000 |
| Estimated Annual Operational Emissions: | 114,000 |
| Total Operational Emissions: | 3,420,000 |

Social damages were estimated by multiplying the SCC for year 2010 by total operational emissions. We calculated social damage at each discount rate shown in Table 4 to demonstrate the influence of discount rate in estimating social damages.

We recognize the oversimplification of using 2010 SCC values to calculate social damages for the entire 30-year mine life (1975-2005). However, The Working Group does not

provide SCC estimates prior to 2010. While SCC values for earlier decades would likely be lower, we chose to apply 2010 values to the entire 30-year for simplicity. As a result, the estimated social damages of operational emissions are skewed high. We also acknowledge that our social damage estimate is limited by the narrow operational emission dataset, which encompassed only 5 years of operation and 2 years of rehabilitation.

Estimating Social Benefit of Reforestation Scenarios

We similarly calculated the social benefit of $CO_2$ sequestration using SCC values published by the Interagency Working Group on Social Cost of Carbon (2015). To align our annual sequestration results with the published SCC values, we assumed that year 5 (after planting) coincides with year 2010. We then multiplied annual sequestration by the corresponding SCC value for each year.

The social benefit of each alternative reforestation scenario was compared to the planned reforestation scenario (i.e. business as usual) to identify the extent to which either reforestation alternative would offset operational emission damages.

# RESULTS

## Annual Sequestration for Study Area Forest Types

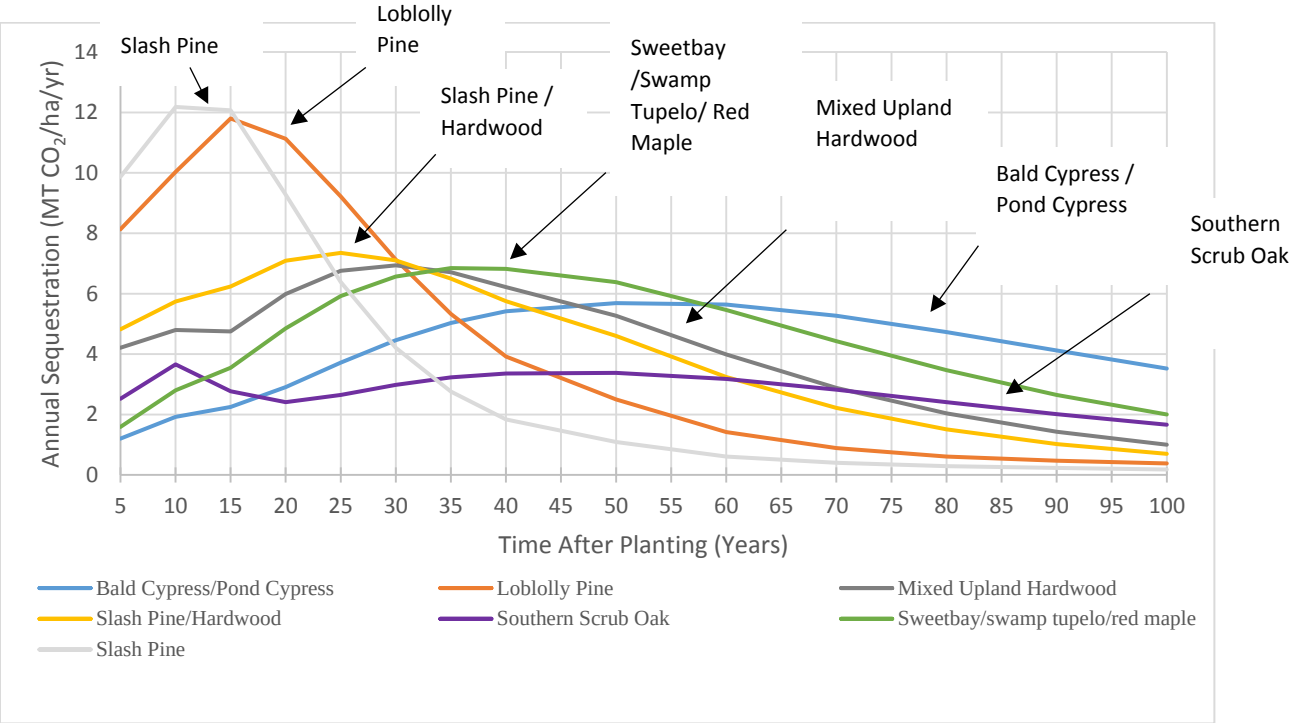
Table 6 provides the calculated $CO_2$ sequestration rate for each forest type studied.

**Table 6**: Annual Sequestration by Forest Type (MT $CO_2$/ha/yr)

| Years After Planting | Bald Cypress /Pond Cypress | Loblolly Pine | Slash Pine | Mixed Upland Hardwood | Slash Pine /Hardwood | Southern Scrub Oak | Sweetbay /swamp tupelo/red maple |
|---|---|---|---|---|---|---|---|
| 0-5 | 1.20 | 8.13 | 9.87 | 4.21 | 4.82 | 2.52 | 1.59 |
| 6-10 | 1.92 | 10.03 | 12.18 | 4.80 | 5.74 | 3.66 | 2.80 |
| 11-15 | 2.25 | 11.80 | 12.07 | 4.75 | 6.24 | 2.77 | 3.55 |
| 16-20 | 2.91 | 11.13 | 9.28 | 5.99 | 7.09 | 2.41 | 4.85 |
| 21-25 | 3.72 | 9.22 | 6.39 | 6.76 | 7.35 | 2.65 | 5.92 |
| 26-30 | 4.46 | 7.13 | 4.21 | 6.94 | 7.10 | 2.98 | 6.57 |
| 31-35 | 5.03 | 5.33 | 2.76 | 6.71 | 6.50 | 3.23 | 6.85 |
| 36-40 | 5.42 | 3.92 | 1.84 | 6.22 | 5.75 | 3.36 | 6.82 |
| 41-50 | 5.69 | 2.50 | 1.09 | 5.27 | 4.60 | 3.38 | 6.38 |
| 51-60 | 5.64 | 1.42 | 0.61 | 3.99 | 3.24 | 3.18 | 5.46 |
| 61-70 | 5.27 | 0.89 | 0.40 | 2.88 | 2.22 | 2.82 | 4.43 |
| 70-80 | 4.73 | 0.61 | 0.29 | 2.04 | 1.51 | 2.41 | 3.47 |
| 81-90 | 4.12 | 0.47 | 0.23 | 1.43 | 1.02 | 2.01 | 2.65 |
| 91-100 | 3.52 | 0.38 | 0.18 | 1.00 | 0.70 | 1.66 | 2.00 |

Results were graphed to visualize how annual sequestration changes over time for each forest type (Figure 1). For all forest types, annual carbon sequestration increases after planting, reaches a peak, and decreases as the forest ages. In pine-dominated forests, carbon is rapidly sequestered in the first years after planting, peaks by year 20, then decreases rapidly as the forest ages. In contrast, hardwood-dominated forests sequester carbon more slowly in the early years, reach a peak in the 30-60 year range, and decrease slowly as the forest ages.

Figure 1: Annual $CO_2$ sequestration (per hectare) for each forest type




Of all forest types studied, slash pine attains the highest annual sequestration, reaching a peak of 12.18 MT $CO_2$/ha/yr at only 6-10 years after planting. Loblolly pine attains the second highest annual sequestration (11.80 MT $CO_2$/ha/yr) and peaks slightly later at 11-15 years after planting. Of the upland hardwood-containing forest types, Slash Pine /Hardwood attains the highest annual sequestration (7.35 MT $CO_2$/ha/yr), followed by Mixed Upland Hardwood (6.94 MT $CO_2$/ha/yr) and Southern Scrub Oak (3.66 MT $CO_2$/ha/yr). Southern Scrub Oak reaches its maximum sequestration earliest (5-10 years), declines from 15-20 years, then gradually increases again between 20-60 years. Slash Pine / Hardwood reaches its maximum in the 21-25 year range, followed by Mixed Upland Hardwood at 26-30 years.

Of the native wetland forest types studied, sweetbay/swamp tupelo/red maple attains the highest annual sequestration (6.85 MT $CO_2$/ha/yr), followed by bald cypress / pond cypress

at 5.69 MT $CO_2$/ha/yr. These peak values are reached at 31-35 years after planting and 41-50 years after planting, respectively.

Cumulative Sequestration for Study Area Forest Types

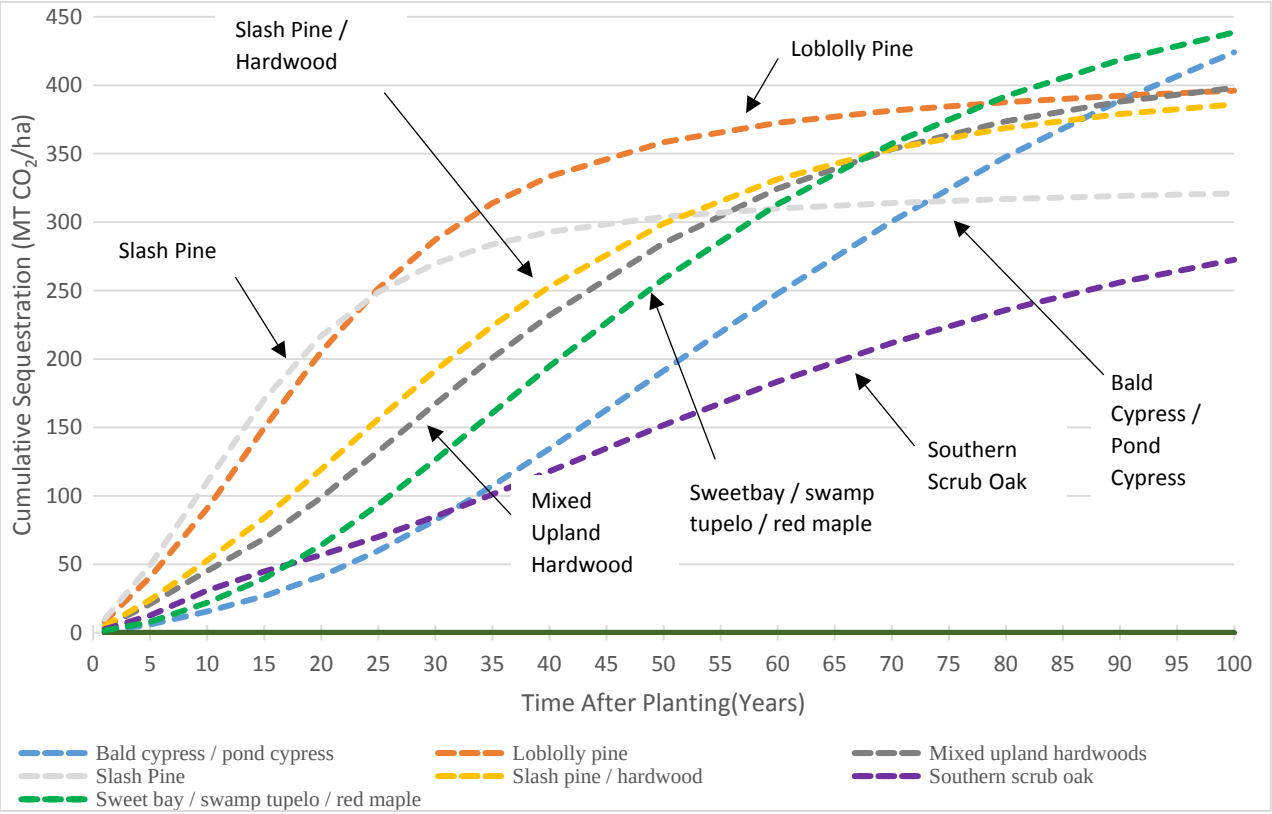
Table 7 and Figure 2 depict cumulative $CO_2$ sequestration for each forest type studied. Figure 2 shows that the pine-dominated forest types rapidly sequester carbon in the first 40 years after planting, then make smaller gains in the latter half of the study period. Conversely, the hardwood-dominated forest types make smaller gains in the early decades, but steadily increase over the middle and latter decades. Thirty years after planting, slash pine sequesters 61% more $CO_2$ than mixed upland hardwoods and 41% more $CO_2$ than slash pine-hardwoods. The loblolly pine forest type sequesters 72% more $CO_2$ than mixed upland hardwoods, and 50% more $CO_2$ than slash pine hardwoods at year 30. The wetland forest types (sweetbay / swamp tupelo / red maple and bald cypress / pond cypress) eventually exceed loblolly pine in cumulative sequestration, but not until years 80 and 90, respectively.

Loblolly pine has sequestered the most carbon by year 30 (287.18 MT $CO_2$/ha), followed by slash pine at 269.93 MT $CO_2$/ha. Of the upland hardwood-containing forest types, slash pine / hardwood (191.68 MT $CO_2$ /ha) and mixed upland hardwood (167.28 MT $CO_2$/ha) have sequestered the most carbon by year 30, and southern scrub oak has sequestered the least (84.96 MT $CO_2$ /ha). Of the wetland forest types, sweet bay / swamp tupelo / red maple (126.39 MT $CO_2$ /ha) has sequestered more than bald cypress/ pond cypress (82.21 MT $CO_2$ /ha) by year 30.

**Table 7**: Cumulative Sequestration by Forest Type (MT $CO_2$/ha)

| Years After Planting | Bald Cypress/ Pond Cypress | Loblolly Pine | Mixed Upland Hardwood | Slash Pine/ Hardwood | Southern Scrub Oak | Sweetbay/ swamp tupelo/red maple | Slash Pine |
|---|---|---|---|---|---|---|---|
| 5 | 5.98 | 40.63 | 21.07 | 24.08 | 16.29 | 7.93 | 49.36 |
| 10 | 15.56 | 90.76 | 45.07 | 52.77 | 30.94 | 21.95 | 110.25 |
| 15 | 26.79 | 149.77 | 68.81 | 83.97 | 44.77 | 39.67 | 170.58 |
| 20 | 41.32 | 205.41 | 98.76 | 119.42 | 56.81 | 63.93 | 216.97 |
| 25 | 59.93 | 251.51 | 132.56 | 156.20 | 70.06 | 93.55 | 248.9 |
| 30 | 82.21 | 287.18 | 167.28 | 191.68 | 84.96 | 126.39 | 269.93 |
| 35 | 107.35 | 313.82 | 200.82 | 224.20 | 101.11 | 160.64 | 283.73 |
| 40 | 134.43 | 333.42 | 231.94 | 252.97 | 117.92 | 194.73 | 292.94 |
| 50 | 191.35 | 358.45 | 284.65 | 298.99 | 151.72 | 258.55 | 303.84 |
| 60 | 247.80 | 372.62 | 324.50 | 331.44 | 183.50 | 313.12 | 309.97 |
| 70 | 300.50 | 381.50 | 353.35 | 353.68 | 211.69 | 357.38 | 313.93 |
| 80 | 347.77 | 387.63 | 373.75 | 368.76 | 235.80 | 392.10 | 316.87 |
| 90 | 388.98 | 392.32 | 388.07 | 379.00 | 255.95 | 418.64 | 319.14 |
| 100 | 424.14 | 396.10 | 398.08 | 385.97 | 272.50 | 438.68 | 320.98 |

Figure 2: Cumulative $CO_2$ sequestration (per hectare) for each forest type



Alternative Reforestation Scenarios

We developed two alternative reforestation scenarios using results for annual and cumulative sequestration by forest type. Of the upland forest types, the highest carbon-sequestering by year 30 (loblolly pine and slash pine) tend to be planted as single-species commercial plantations. While these forest types sequester the most carbon, they offer less biodiversity than those that include a mix of pine and hardwood species. Recognizing the value of biodiversity in land restoration, the reforestation alternatives were designed such that one alternative offers higher biodiversity at the expense of carbon sequestration, and the second alternative offers higher carbon sequestration at the expense of biodiversity (Table 8).

Of the native wetland forest types included in the study area, sweetbay / swamp tupelo / red maple sequesters more carbon over a 30 year period than bald cypress / pond cypress. Therefore, both alternative scenarios include reforestation of the 26 hectare non-stocked wetland as sweetbay / swamp tupelo / red maple. In both alternative scenarios, the bald cypress / pond cypress forest type remains due to permit conditions that require restoration of this habitat type after mining.

In alternative scenario #1, the mixed upland hardwood, non-stocked upland, and slash pine forest types will be planted as slash pine / hardwood. This alternative favors the highest carbon-sequestering forest type that includes species diversity.

In alternative scenario #2, the mixed upland hardwood, non-stocked upland, and slash pine / hardwood forest types will be planted as slash pine. This alternative favors carbon sequestration without consideration for species diversity. Slash pine was chosen over loblolly pine even though it sequesters less carbon by year 30, because the loblolly pine is at the southern fringe of its native range, whereas slash pine is more evenly distributed throughout the state (Burns and Honkala 1990).

In both alternative scenarios, the southern scrub oak forest type is retained due to permit conditions that require restoration of this habitat type after mining. Further, the 295 hectares of non-stocked (non-forested) land present in the "planned" scenario will be reforested in both alternative scenarios. This includes 26 hectares of wetland and 269 hectares of upland.

**Table 8**: Planned and Alternative Reforestation Scenarios

| FIA Forest Type | Habitat Type | Planned Scenario (Hectares) | Alternative Scenario #1 (Hectares) | Alternative Scenario #2 (Hectares) |
|---|---|---|---|---|
| Sweetbay / swamp tupelo / red maple | Native Wetland | 364 | 390 | 390 |
| Bald cypress/Pond cypress | Native Wetland | 60 | 60 | 60 |
| Non-Stocked – wetland | Native Wetland | 26 | 0 | 0 |
| Loblolly Pine | Plantation Wetland | 3 | 3 | 3 |
| Mixed Upland Hardwoods | Upland | 212 | 0 | 0 |
| Non-Stocked – upland | Upland | 269 | 0 | 0 |
| Slash Pine | Upland | 1716 | 0 | 2273 |
| Slash Pine / Hardwood | Upland | 76 | 2273 | 0 |
| Southern scrub Oak | Upland | 34 | 34 | 34 |
| **Total** | | **2760** | **2760** | **2760** |

Annual and Cumulative Sequestration for Reforestation Scenarios

Figure 3 provides the annual $CO_2$ sequestration results for each reforestation alternative. Alternative Scenario #2 attains the highest annual sequestration in the first 20 years after planting, reaching a peak of 29,075 MT $CO_2$/ha/yr. This is followed by the Planned Scenario, which attains 23,743 MT $CO_2$/ha/yr, and Alternative Scenario #1 at 19,368 MT $CO_2$/ha/yr.

**Figure 3**: Annual $CO_2$ sequestration for each reforestation scenario

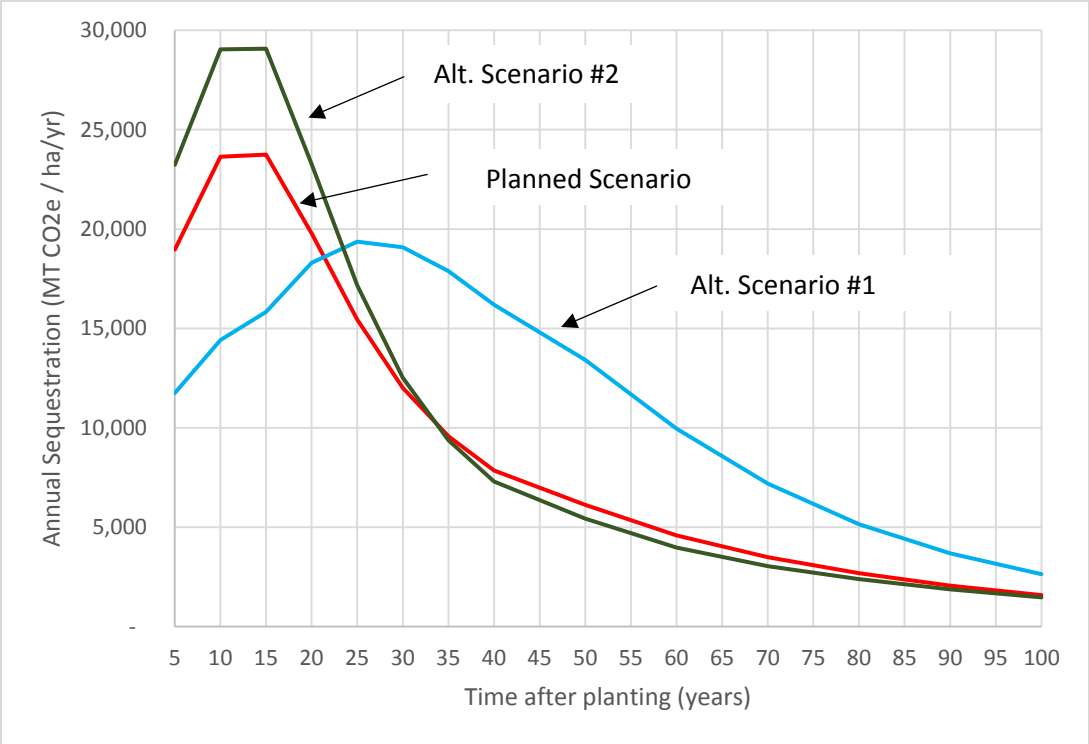
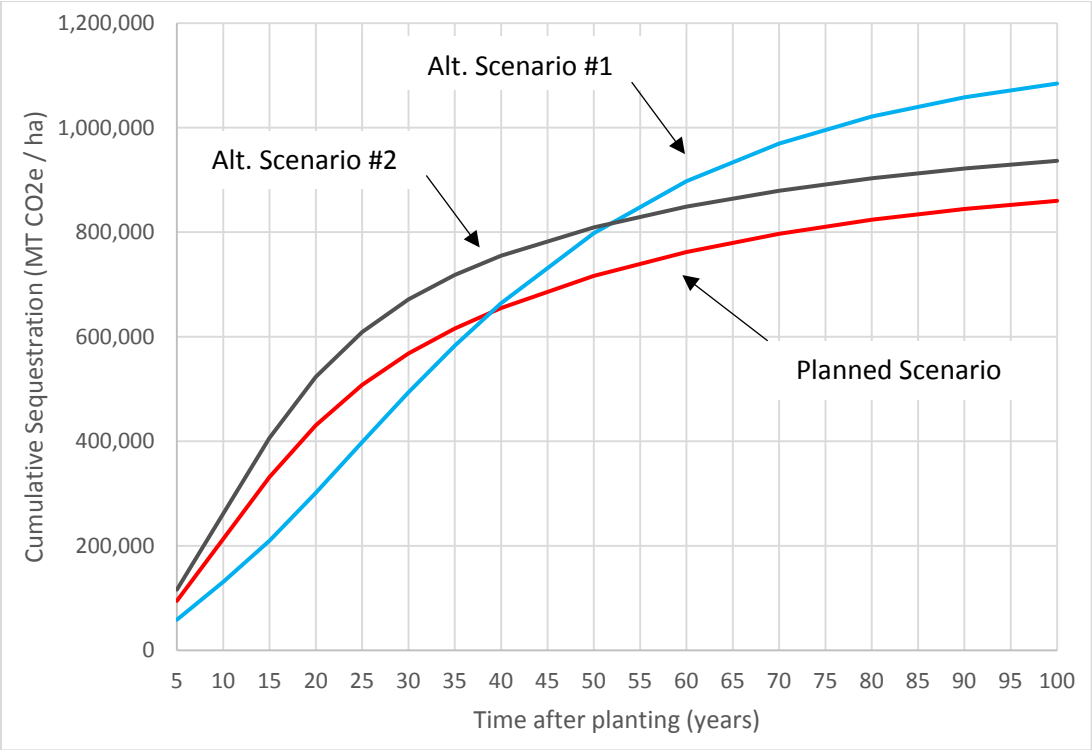



Figure 4 provides cumulative sequestration over the 100 year study period. Alternative scenario #1 sequesters 1.08 million MT $CO_2$ over the 100-year study period, followed by alternative scenario #2 at 0.92 million MT $CO_2$ and the planned scenario at 0.86 million MT $CO_2$. However, alternative scenario #2 sequesters the most carbon in the first 30 years after planting (671,524 MT $CO_2$), followed by the planned scenario (567,919 MT $CO_2$) and alternative scenario #1 (493,675 MT $CO_2$). The cumulative sequestration value for alternative scenario #1 does not surpass the values for alternative #2 and the planned scenario until years 40 and 60, respectively.

**Figure 4**: Cumulative $CO_2$ sequestration for each reforestation scenario




Social damages of operational emissions

As shown in Table 5, we estimate that the case study operation emitted, on average, 114,000 MT $CO_2$ per year, or 3,420,000 MT $CO_2$ over the 30-year mine life. As previously noted, operational emission damages were estimated using the SCC values published for year 2010 since values are not available prior to this date. Operational damages range from $1.1 million per year to $5.7 million per year depending on discount rate (Table 9). Over the 30-year mine life, total operational damages range from $35.2 million to 171 million.

**Table 9**: Social damages of operational emissions at varying discount rates

| Discount Rate | Annual Damages ($USD/yr) | Cumulative Damage ($USD) |
|---|---|---|
| 2.50% | $5,700,000 | $171,000,000 |
| 3% | $3,534,000 | $106,020,000 |
| 5% | $1,140,000 | $34,200,000 |

Social benefit of reforestation alternatives

Table 10 depicts the social benefit of annual sequestration for each reforestation alternative at all published SCC years and discount rates. Figures 5 and 6 graph annual and cumulative social benefits at the 3% discount rate, which was chosen as the mid-range value. Other discount rates were not graphed because the relative shapes and curves for each scenario would not change, although the scale would change.

**Table 10**: Social benefit of reforestation alternatives at varying discount rates

| Reforestation Scenario | Year | Benefit of Annual Sequestration at 2.5% Discount Rate | Benefit of Annual Sequestration at 3% Discount Rate | Benefit of Annual Sequestration at 5% Discount Rate |
|---|---|---|---|---|
| Planned Scenario | 2010 | $947,955 | $587,732 | $189,591 |
| | 2015 | $1,323,835 | $851,037 | $260,039 |
| | 2020 | $1,472,039 | $997,188 | $284,911 |
| | 2025 | $1,345,376 | $910,107 | $276,989 |
| | 2030 | $1,127,651 | $772,364 | $247,156 |
| | 2035 | $936,776 | $660,547 | $216,179 |
| | 2040 | $804,099 | $574,356 | $201,025 |
| | 2045 | $698,783 | $502,496 | $180,584 |
| | 2050 | $581,829 | $422,591 | $159,237 |
| Alternative Scenario #1 | 2010 | $587,246 | $364,092 | $117,449 |
| | 2015 | $806,950 | $518,753 | $158,508 |
| | 2020 | $981,345 | $664,782 | $189,938 |
| | 2025 | $1,244,290 | $841,726 | $256,177 |
| | 2030 | $1,413,889 | $968,417 | $309,893 |
| | 2035 | $1,488,656 | $1,049,693 | $343,536 |
| | 2040 | $1,501,932 | $1,072,808 | $375,483 |
| | 2045 | $1,440,958 | $1,036,195 | $372,382 |
| | 2050 | $1,274,306 | $925,549 | $348,757 |
| Alternative Scenario #2 | 2010 | $1,162,003 | $720,442 | $232,401 |
| | 2015 | $1,626,325 | $1,045,495 | $319,457 |
| | 2020 | $1,802,656 | $1,221,154 | $348,901 |
| | 2025 | $1,582,371 | $1,070,428 | $325,782 |
| | 2030 | $1,253,123 | $858,304 | $274,657 |
| | 2035 | $975,928 | $688,155 | $225,214 |
| | 2040 | $787,197 | $562,283 | $196,799 |
| | 2045 | $649,528 | $467,076 | $167,856 |
| | 2050 | $515,901 | $374,707 | $141,194 |

**Figure 5**: Social benefit of Annual $CO_2$ Sequestration at 3% discount rate ($USD/yr)

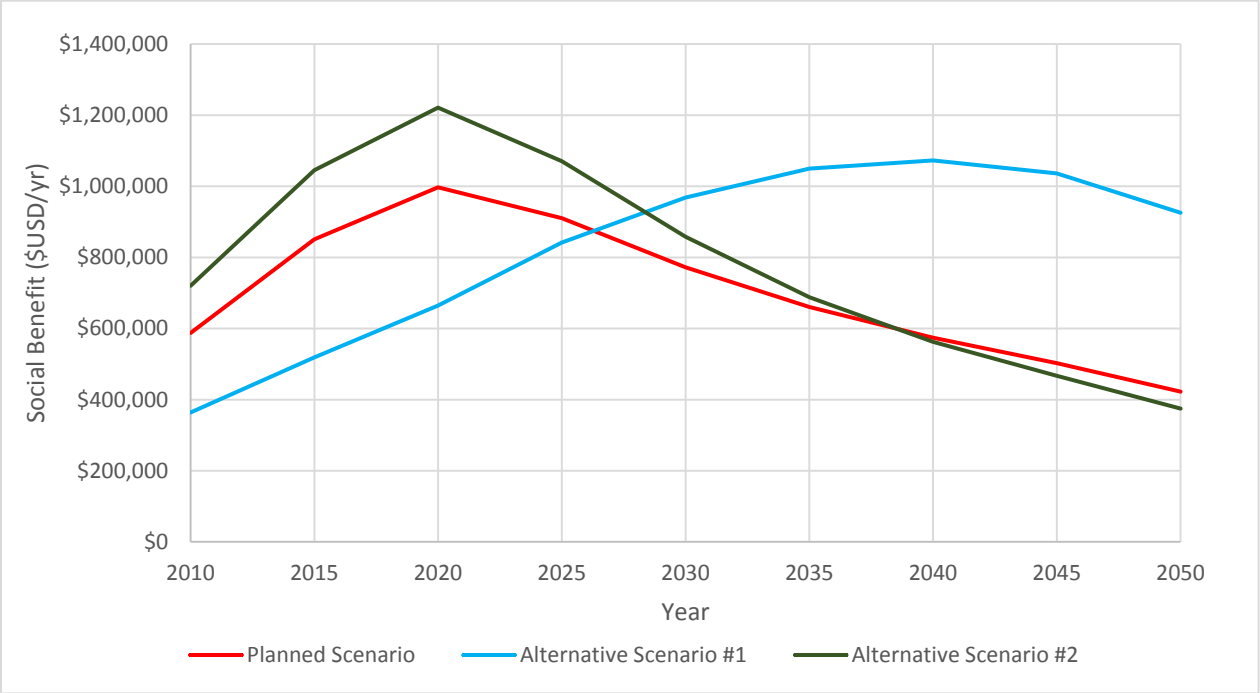
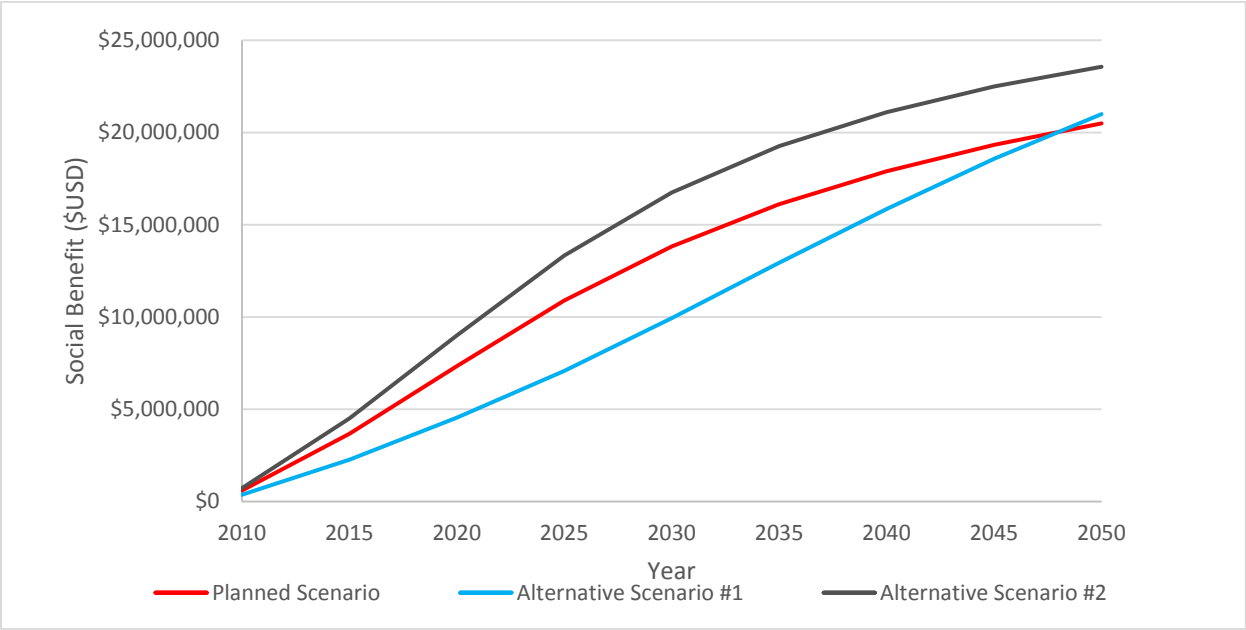



**Figure 6**: Social benefit of Cumulative $CO_2$ Sequestration at 3% discount rate ($USD)




## DISCUSSION

Mining companies are increasingly implementing climate change risk management strategies that include voluntary GHG emission reduction. Reforestation provides an opportunity to mitigate operational GHG emissions while providing environmental co-benefits. By understanding the $CO_2$ sequestration potential of post-mining forests, mining industry professionals can include the social benefits of GHG emission reduction in their broader climate change risk management communications.

This study demonstrates a method to evaluate the $CO_2$ sequestration potential of multiple reforestation alternatives for a case study site, and the extent to which each alternative mitigates the social damages of operational GHG emissions. It is not the intent of this study to identify the "right" reforestation alternative for the case study site. Instead, we demonstrated how post-mining $CO_2$ sequestration is influenced by forest type, length of study, and other factors. The methods applied in this study can be replicated by industry professionals when considering $CO_2$ sequestration as a goal of land rehabilitation.

Influence of Forest Type and Project Length on $CO_2$ Sequestration Potential

We found that upland pine-dominated forest types (slash pine and loblolly pine) in the study area cumulatively sequester more $CO_2$ than hardwood-containing forest types (slash pine / hardwood, mixed upland hardwood, and southern scrub oak) in the early decades after reforestation. However, the hardwood-containing forest types eventually surpass slash pine forest in cumulative $CO_2$ sequestration. These findings are similar to a study by Amichev et al. (2008), which used field data from tree, litter, and soil carbon stocks to determine the sequestration of fourteen reforested historic mine sites in the Midwestern and Appalachian coalfields (tree stand age 19-50 years). Amichev et al. found the highest carbon in restored pine stands, followed by hardwood, and mixed pine-hardwood.

However, the pine-dominated forest types are typically planted as a row-crop monoculture and therefore offer less biodiversity compared to a hardwood-containing forest. Based on these findings, an environmental manager who values rapid $CO_2$ sequestration over biodiversity may choose to maximize the area of pine-dominated forest relative to hardwood-containing forest. Alternative Scenario #2 reflects this reasoning, as it substitutes slash pine for all non-stocked and mixed upland hardwood forest types in the Planned Scenario. As expected, we found that Alternative #2 sequesters more $CO_2$ than the Planned Scenario over the entire duration of the 100-year study period.

Recognizing that an environmental manager might value biodiversity over $CO_2$ sequestration, Alternative Scenario #1 includes a balance of pine and hardwood species, thereby prioritizing biodiversity over rapid $CO_2$ sequestration. We found that Alternative Scenario #1 sequesters less $CO_2$ than the Planned Scenario and Alternative Scenario #2 until years 40 and 50 respectively, but sequesters 26% and 16% more than these scenarios at the end of the 100-year study period. Therefore, Alternative #1 may be favored by the environmental manager if biodiversity is valued over rapid $CO_2$ sequestration, and/or the risk of near-term carbon loss can be mitigated through land management and development restrictions.

Net GHG Emission Reduction

None of the reforestation scenarios fully offset operational emissions for the case study site. Even Alternative Scenario #2, which sequesters the most $CO_2$ over the 100-year study period, only comprises 30% of cumulative operational emissions. Net emission reduction would be lower, and possibly even negative, if carbon losses from pre-mining deforestation were included in total operational emissions.

The procedural concepts of 'additionality' and 'permanence' further limit the net GHG emission reduction potential of reforestation. Forest offset protocols require demonstration that sequestration is additional to what would have occurred in the normal course of business and that carbon is stored permanently (e.g. trees that die from natural or man-made causes would need to be replaced) (Thamo and Pannell 2015). The impact of 'additionality' is demonstrated by comparing cumulative sequestration of the Planned and Alternative Scenarios. In this case, the Planned Scenario represents 'business-as-usual', as this scenario was designed to meet regulatory land rehabilitation requirements, and was approved by regulatory agencies. At the end of the 100-year study period, Scenario #1 exceeds the Planned Scenario by 220,000 MT $CO_2$. Scenario #2 exceeds the Planned Scenario by 160,000 MT $CO_2$. These drastically-reduced values represent the GHG emission reduction that is legitimately 'additional' for the case study site.

The Impact of Carbon Pricing

Using the SCC value for 2010, we estimated that total GHG emission damages from the case study operation range in value from $34 million to 171 million depending on the discount rate (Table 9). The drastic impact of discount rate presents a challenge when using SCC for carbon pricing. Further, much uncertainty and controversy surround the models that estimate long-term economic benefits and damages of today's actions and the discount rates used to

represent those values in present day terms. Considering this, an alternative approach is to use market pricing, rather than social cost, as a basis for estimating emission damages and benefits.

Two carbon markets currently exist in the United States. Under the Regional Greenhouse Gas Initiative (RGGI), seven northeastern and Mid-Atlantic States adopted a regulatory program to reduce GHG emissions from the power sector. The RGGI program caps emissions from the power sector through quarterly emission allowance auctions; regulated entities buy and sell allowances on the open market (Raymond 2016). In California, AB 32 likewise authorizes the California Air Resources Board (CARB) to implement a cap-and-trade program with the goal of reducing emissions to 1990 levels by 2020 (AB32, 2006).

The California cap-and-trade market did not exist in 2010. However, in 2015, carbon was priced at about $13/MT on the California cap-and-trade market (Kossoy et al. 2015). Using this market price, total operational emission damages would be valued at $45 million. RGGI reports 2015 market value at approximately $6/MT (2015), which would price total operational emissions at $20 million.

The methods applied in this study are useful to estimate the economic liability of operational GHG emissions, should future climate legislation necessitate the purchase of carbon offsets. The increasing popularity of this so-called 'carbon pricing' strategy demonstrates its usefulness in planning for potential future financial risk. As previously stated, over 400 companies reported using carbon pricing as a climate change risk mitigation strategy. Of those, nearly 100 companies publicly disclose their internal price. Prices range drastically, from $1/MT to $357/MT (CDP 2015).

Strategic Reforestation as a Climate Change Risk Mitigation Tactic for the Mining Industry

Our results demonstrate the influence of forest type, project length, and carbon pricing on the practicality of reforestation as a GHG mitigation tactic for the case study site. While the methods used in this study are applicable across many mining sectors, the results cannot be

generalized to the industry or even the corporate scale. The $CO_2$ sequestration potential of each reclaimed mine depends on local factors such as size of the mine, post-mining land condition, practicality of reforestation, local and regional climate, and many other factors. The practicality of this GHG mitigation tactic depends on regulatory obligations, additionality, permanence, cost of reforestation, and other economic influencers.

The methods applied in this study are not necessarily intended to produce a 100% GHG mitigation outcome. Instead, this study provides a tool to inform value-based land rehabilitation decision-making. While the methods of this study are useful to estimate post-mining $CO_2$ sequestration potential and operational GHG emission mitigation, industry professionals should consider all corporate land rehabilitation goals and requirements when making land rehabilitation decisions.

## ACKNOWLEDGMENTS

Special thanks to Dr. Christopher Galik of North Carolina State University who provided prompt technical guidance and sincere mentorship through the duration of my degree program. Additional appreciation for the respective work of Dr. Deborah Gallagher and Bruce Rauhe whose commitment to advancing sustainable business practice has inspired my career trajectory.

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