CARBON SEQUESTRATION & CARBON MARKETS

ECOLOGICAL & ECONOMIC CONSIDERATIONS FOR SOUTH-CENTRAL COLORADO

Produced by Colorado College Landscape Ecology for Palmer Land Conservancy

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1 INTRODUCTION

CARBON SEQUESTRATION 101

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2) to mitigate the impacts of climate change. It involves removing CO_2 from the atmosphere and securing it in a stable form over long periods of time. Carbon sequestration can occur naturally or through human intervention, and the process plays a critical role in reducing greenhouse gas concentrations. Accordingly, carbon sequestration can be a critical tool to mitigate global climate change impacts.

Two primary types of carbon sequestration exist: biologic and geologic. Biologic carbon sequestration leverages natural ecosystems to absorb carbon and store it over time as part of the carbon cycle, most often via photosynthesis. Biologic carbon sequestration typically offers a more sustainable and cost-effective approach to carbon sequestration compared to geologic sequestration, because it removes carbon from the atmosphere and transforms it into plant tissues (What's the Difference between Geologic and Biologic Carbon Sequestration? | U.S. Geological Survey, 2019).

Carbon sequestration is most effective in highly forested ecosystems as terrestrial vegetation sequesters about 112–169 PgC (1PgC = 1015g carbon) per year (Sha et al., 2022). Forests typically have high sequestration capacity, with rates up to three times that of wetlands and agroecosystems (Carbon Stocks and Sequestration in Terrestrial and Marine Ecosystems: A Lever for Nature Restoration, 2022). The carbon storage capacity of forests is influenced by factors such as species composition, age of trees, and management practices.

Geologic carbon sequestration involves capturing CO_2 from industrial sources or directly from the air and storing it in underground geologic reservoirs to prevent it from releasing into the atmosphere. It uses technologies including chemical absorption, which captures CO_2 using a liquid solvent that reacts chemically with the gas, or membrane separation, which uses selective membranes to physically separate CO_2 from other gases in a mixture. Once captured, CO_2 is compressed and transferred to the storage site, typically through pipelines, and is then injected into underground geologic formations, like depleted oil and gas reservoirs, deep saline aquifers, or unmineable coal seams (IPCC, 2005). These formations store the CO_2 under pressure through a combination of mechanisms, including structural, residual, solubility, and mineral trapping (IPCC, 2005).

CARBON MARKETS

Carbon markets are increasingly common and important when considering methods to combat the negative impacts of climate change. Carbon markets operate through companies or individuals who purchase credits in an effort to offset their emissions through organizations that remove or store greenhouse gases from the atmosphere. In the United States, carbon markets function in two ways: voluntary and government mandated. Voluntary markets are the most common form of participation in carbon markets, and companies are largely inclined to participate based on consumer pressure. Government mandated carbon markets, such as California's cap-and-trade market, mandate many of the largest polluting companies in the state to reduce their emissions and incentivize participation in practices that have lower greenhouse gas emissions (California Cap and Trade, 2021).

Carbon credits are calculated by assessing the amount of carbon that has the potential to be stored or sequestered within the credit as opposed to the status quo scenario. The amount of carbon to be stored or sequestered can be determined via several different monitoring methodologies, such as field sampling or remote sensing (discussed further in Chapter 3 of this report). Once carbon sequestration storage capacity is assessed, it is verified, commonly by a third-party source, and then used to determine the value and eligibility for carbon credits. Numerous companies exist to verify the amount of carbon storage determined to be stored for the landscape being analyzed, such as Verra, a third-party neutral verifier of carbon storage/sequestration. Other verification standards include the Gold Standard, a standard set by the United Nations (UN) and assessed using a digital verification system, the American Carbon Standard (ACS), a standard for the voluntary market and the cap-and-trade system in California, and the Climate Action Reserve (CAR), a standard set for all of North America (Johnson, 2024). Carbon contracts typically last between 30-100 years.

Carbon credits are utilized by firms across many industries to offset their actions, products, and supply chains. Microsoft, Shell, and Chevron have been particularly large drivers of demand in the market. With criticism related to greenwashing of credits, buyers have been increasingly seeking more secure credits with robust certification standards and timeframes attached to them. These robust credits are most often available through carbon credit brokers that compile carbon credits in the form of projects with landowner involvement, which are then sold to firms. There are a variety of forms that carbon credit projects can take, including changing land-use practices to planting trees. Brokers often take on many of the risks and logistics associated with carbon credits, including providing insurance in the case of carbon losses due to unforeseen circumstances, such as disturbance, and support with carbon assessment, verification, and liaising with relevant third parties.

RELEVANCE OF CARBON MARKETS TO EASEMENT HOLDERS

Conservation easements do not exclude landowners from participation in the carbon market, yet they can alter the terms of involvement. Carbon markets can potentially provide an additional monetary opportunity for land trusts and easement holders. However, the concept of additionality is essential when considering the relevance of carbon markets to Palmer Land Conservancy partners. Initial entrance into the carbon market for easement holders requires a baseline calculation of carbon sequestration and storage on the property before additional carbon conservation projects commence. On land managed without conservation easements, the net difference between baseline carbon storage and carbon storage with new management practices is quantified and sold as carbon credits. Due to the legally defined management conditions and the resulting tax credits, a different methodology must be utilized for conservation easements. Conservation landholders cannot gain carbon sequestration offsets from management strategies or land conversion avoidance outlined in the easement conditions, as this would result in double payment for the same action. Specifically, the landowner cannot benefit from payment via tax credits from the conservation easement and carbon credits sold as offsets on the same property. Therefore, carbon credit funding can only be acquired by increasing carbon sequestration and storage through strategies that have not been previously outlined via easement conditions (Chiang *et al.,* 2020). Consequently, many carbon credit partner companies restrict easement landowner participation to those owning timber rights, and who therefore possess the ability to alter forestry management practices.

Other important considerations when entering carbon credit agreements in easements include the ownership of carbon rights and liability (see 2020 Land Trust Alliance report, *Carbon Markets: Are They Right for Your Land Trust*?). First, carbon is associated with specific resources on land, and the owner of that carbon-containing resource generally owns the carbon offset project. To participate in the carbon market and receive carbon credit funds, landowners must possess legal control over the carbon-containing resource (often trees) and its management. It is encouraged that clear ownership rights should be defined before entering a carbon offset plan. If a landowner intentionally manages land in a manner that lowers carbon stocks (*e.g.* undisclosed timber harvesting) or if they provide public access to a part of the easement that is then damaged by a member of the public, both the landowner and land trust can be held accountable for the unmet carbon offsets. Accountability can include responsibility for purchasing replacement credits (Chiang *et al.*, 2020).

While conservation easements may limit participation in the carbon market, under certain conditions, offsets can provide further monetary compensation for effective management and conservation of already conserved lands. Additionally, the practice of carbon-efficient strategies further protects the natural environments under easements and promotes their ecological health.

SOCIAL & ECONOMIC IMPACTS OF CARBON CREDITS

The social impacts of carbon markets are as far-reaching as their economic effects. In recent decades, the carbon credit market has emerged as a nature-based solution to combat the industrial impacts of climate change and encourage organizations and individuals to feel responsible for offsetting their greenhouse gas emissions. As a voluntary market outside the scope of regulatory frameworks, the carbon market offers favorable economic benefits to incentivize landowners to adopt sustainable land management practices. Assigning monetary value to nature and protected resources links ecological benefit with economic reward. With the development of the carbon credit market, consumers are increasingly demanding that large corporations implement more sustainable practices and cleaner energy use. Companies are under pressure to adapt their means of production, buy offsets, and invest in environmentally beneficial projects that reduce or remove carbon from the atmosphere. Currently, most landowners have part-time jobs to supplement their participation in carbon market programs, which often limits the physical labor and time that they can devote to adopting more sustainable land management practices that are oftentimes more costly than traditional practices. However, as the sector continues to develop, the hope is that farmers, ranchers, and landowners will receive sufficient compensation to commit to their land full time. Additionally, due to the rising popularity of the industry, there has been an increase in green jobs related to sustainable energy development, environmental protection, and climate sciences. The development of this industry lays the groundwork for economic expansion while simultaneously protecting the environment, and providing excellent opportunities for landowners, businesses, and citizens alike.

As consumers are showing increasingly more interest and concern about where their products come from and how they are made, they are holding companies accountable for harmful practices that perpetuate climate change and negatively impact the environment. Consumers are demanding integrity from global companies that have previously prioritized production without environmental concerns. Carbon market projects are also often community-driven, and many coalitions and associations of landowners have been created to help facilitate collaboration and discussion of land management practices within a region. The development of carbon markets brings many tangible benefits to local communities, as many can help to improve soil and ecological health, enhance water quality, and reduce regional temperature through increased vegetation and forest cover.

2 NATURAL CARBON SEQUESTRATION

FORESTED ECOSYSTEMS

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Forest carbon storage is a major process within the carbon cycle, which includes atmospheric and terrestrial storage and anthropogenic interactions. By removing CO_2 from the atmosphere via photosynthesis, forests sequester an estimated 7.8 $GtCO_2e$ globally per year. This accounts for 60% of terrestrial carbon stores and removes 15% of human carbon emissions in the U.S. (Hall *et al.,* 2024). The atmospheric carbon removal achieved by forests is fundamental to the stabilization of our earth's climate and the avoidance of future climate catastrophes. This global urgency to curb anthropogenic carbon emissions and correspondingly maintain the health of our natural landscapes makes forest owners prime candidates for involvement in the carbon credit market. While forests already remove a considerable amount of CO_2 from the atmosphere, this proportion could be doubled if landowners implemented more sustainable land management practices (Hall *et al.,* 2024). By implementing land management strategies that promote forest health, landowners can boost the carbon storage potential of their forest and, in collaboration with carbon credit companies, make a profit doing so. These improved strategies, such as extended rotation periods and reforestation, are productive measures for capturing carbon and can be used to create value in the carbon credit market. Although sustainable management approaches can boost a forests' carbon storage potential, forest characteristics such as vegetation type, disturbances, and forest age, will also affect its carbon storage capacity. These characteristics are largely determined by climate, which is rapidly changing across the globe. These disruptions alter the historical functions and dynamics of ecosystems. Climate-driven changes threaten the carbon capacity of forests and consequently baseline carbon crediting yet simultaneously make the industry more necessary than ever. Forest owners who are looking to improve the quality of their land, make positive contributions to global climate issues, and avoid deteriorating their natural resources, can benefit from engaging in carbon credit opportunities. In this section of Chapter 1 ("Forested Ecosystems"), we provide a synthesis of the current state of knowledge gained from an extensive literature review of forest carbon storage impacts and land practices common to carbon credit programs. Additionally, we provide an assessment of the feasibility of carbon sequestration and market considerations as they may apply to forested ecosystems in the state of Colorado.

Factors that influence carbon storage potential in forested ecosystems

Climate

Climate has arguably the most significant influence on a forest's ability to capture and store carbon. Characterized by precipitation and temperature, climate indirectly affects an area's vulnerability to disturbances and ability to rebound from them. It also impacts the frequency, duration, and intensity of disturbances. Accordingly, as we investigate the impacts of factors such as wildfire, drought, and vegetation type, we emphasize that climate is a greater control for how these components present themselves in an ecosystem. Nevertheless, precipitation and temperature alone are significant factors in a forest's carbon capacity as they directly limit plant growth and photosynthesis. Climate change has been more extreme in the Western U.S. than in other regions, limiting water availability and increasing decomposition rates (Hogan et al., 2023). These shifts limit forests' ability to photosynthesize and have been shown to accelerate carbon release into the atmosphere. These effects highlight the critical role of climate change in altering forest carbon storage and the potential for carbon credit programs to operate effectively.

Together with climate, the region where forests exist plays a large role in determining the relative amounts of live and dead carbon that exist, which in turn, helps to define a forest's carbon potential. Relative live and dead carbon refers to the carbon stored in living and previously living organisms, compared to carbon that exists in nonliving matter. Live carbon is added to an ecosystem via sequestration when plants photosynthesize, thereby removing CO_2 from the atmosphere and storing it in their biomass. Live carbon travels through the food web via predation or herbivory but becomes dead carbon once an organism dies. Dead carbon is a critical component in an ecosystem's sequestration potential because when a dead organism decomposes, its CO_2 is released back into the atmosphere. Decomposition can be facilitated by microbes, which break down an organism. Alternatively, dead biomass can serve as fuel that can increase wildfire risk and spread. Regardless of the mechanism, both processes break down and release CO_2 back into the atmosphere.

The Southern Rockies region, consisting of Colorado, Wyoming, and New Mexico, has comparatively less live and dead carbon than the majority of other regions in the Western U.S. (Fig. 2.1). In fact, both live carbon and dead carbon levels are, on average, decreasing in the Southern Rockies (Hall et al., 2024). In particular, Hall *et al.* 2024 found that climate has the greatest impact on carbon potential in areas where live carbon is decreasing, making it the largest limiting factor controlling forest carbon storage and sequestration. While other factors (*e.g.,* topography, disease) may have a more significant impact in other regions, Colorado's notably dry conditions make it more difficult for vegetation to sequester and store carbon since water availability limits plant growth. Consequently, of the regions studied, Hall *et al.* 2024 found that the Southern Rockies have lost the most live carbon between 2005 and 2019 of all regions, with a ~25% change observed. This suggests that while Colorado's forests are viable carbon sinks, their carbon-crediting potential may be less than forests in regions with wetter climates.

While Colorado is particularly limited by its dry climate, the effects of climate change have negatively impacted carbon capacity nationally. It is projected that the carbon capacity of U.S. forests will decrease by 4% by the end of the century (Wu *et al.*, 2023). California and the Intermountain West (including Colorado) are the regions most vulnerable to carbon loss due to annually increasing temperatures and decreasing precipitation. Wu *et al.*, 2023 found that aspen/birch, lodgepole pine, and elm/ash/cottonwood forests were impacted significantly by climate-induced change in carbon capacity. Though a warmer climate may extend the growing season and increase photosynthesis in northern latitudes, heightened water stress due to increased evapotranspiration is expected to outweigh the overall benefits of a warming climate (Wu, 2024). These climate-induced changes to the carbon potential of U.S. forests, and Colorado especially, suggest some potential disruptors to the carbon credit market.

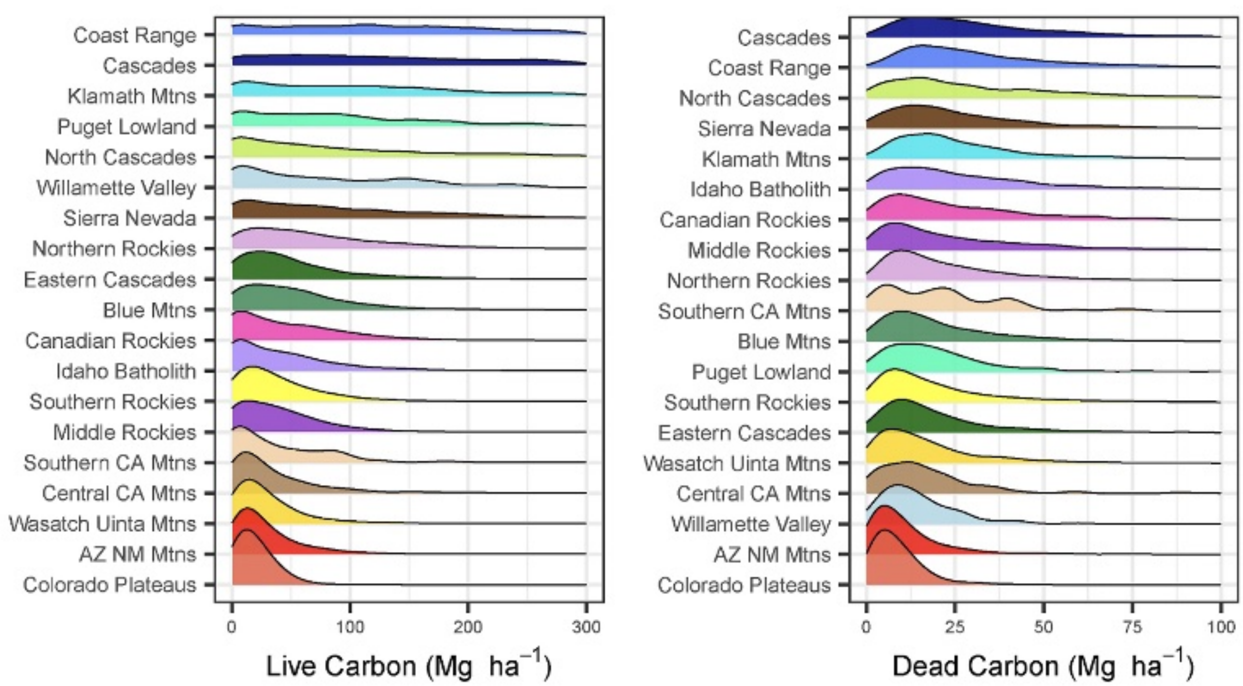

Figure 2.1. Live and dead carbon storage (Mg ha^{-1}) by each forested level-3 EPA ecoregion within the western U.S (n=19). [*From* Hall et al., 2024]

Forest Age

Forest age has been found to be one of the most important factors in determining the carbon sequestration rates and storage capacity of forest ecosystems. Carbon sequestration rate is the rate at which organisms in a forest take in carbon dioxide via photosynthesis, and carbon storage represents how much carbon an organism or group of organisms contains in its biomass. Generally, carbon sequestration potential is the greatest in young forests and lowest in old growth forest, while the trend for stored carbon presents inversely, whereby old forests store the most carbon and young forests generally store the least amount of carbon; Hoover & Smith, 2023). Hoover & Smith (2023) assessed forest inventory data from the contiguous United States and found carbon accumulation rates were highest in young age classes (0-20 years) and decreased with age. The study also found that carbon stock increased with age in most regions. However, in some regions, carbon stock decreased in the oldest age classes, primarily attributed to human disturbances. In the Southern Rocky Mountain region, which summarized data from Utah, Nevada, New Mexico, Arizona, and Wyoming, the mean carbon density was 20.1 tC/ha (Hoover & Smith, 2023). The age class storing the most carbon in the region is 81-120 year old forests, averaging 26.8 tC/ha (Hoover and Smith, 2023). Furthermore, the overall carbon assimilation rate per year for all age classes in the Rocky Mountain South is -0.18 tC/ha/yr (Hoover & Smith, 2023). The negative overall assimilation rate can be attributed to age classes greater than 80 years, which have been found to release carbon at faster rate than it is sequestered. By quantifying the carbon accumulation and stock rates of forests regionally, Hoover & Smith (2023) provided a clear picture of the carbon offset potentials of forests in the Southwest, as influenced by the age of the stand. As well as highlighting the importance of tree age in carbon sequestration and storage, the study further emphasized the impact of regional growing conditions on forest carbon sequestration and storage. Annual net change in live aboveground tree carbon ranged from a low of −0.18 tC /ha/yr in the Rocky Mountain South (see Table 2.1) to a high of 1.74 tC/ha/yr in the Pacific Northwest West (Hoover & Smith, 2023).

Table 2.1. Carbon density and accumulation rates (in units of metric tons C/hectare/year) by age group for the Rocky Mountain South. [Adapted from Hoover and Smith 2023]

Age class	Average carbon density (mt C/ha/yr)	Carbon accumulation rates (mt C/ha/yr)
0-20	3.8	0.03
21-40	7.4	0.02
41-60	10.1	0.10
61-80	17.2	0.03
81-120	26.8	-0.19
121-160	25.6	-0.30
161-300	23.8	-0.28
300+	22.6	-0.14
Overall	20.1	-0.18

Disturbance: Drought

Drought remains a major inhibiting abiotic factor for carbon sequestration and storage in forestlands. Physiological drought refers to when plants cannot access water through soil, even if it is present (Slovak Academy of Sciences, 2009). The effects of climate change are causing warmer and drier conditions to become increasingly common throughout the Western U.S., increasing the frequency and intensity of drought events. These conditions are detrimental to forest growth, especially in Colorado, as Ponderosa Forest establishment primarily occurs in years with above-average moisture availability in the Colorado Front Range (Veblen & Rother, 2017). Additionally, decreased water availability heightens stress levels and mortality rates in trees, ultimately decreasing forest productivity and carbon storage (Hall et al., 2024). A recent study found that a single drought event decreased carbon storage in spruce trees by up to 67% compared to an average precipitation year (Martínez-Sancho *et al.*, 2023). When trees experience a drought period, xylem cells shrink and overall cell production is reduced to conserve available moisture within the tree. The decrease in cell number and size also reduces the available area in which carbon can be stored and causes a significant reduction in overall carbon capacity (Martínez-Sancho et. al, 2023).

Significant forest carbon storage and sequestration reductions via drought may result in decreased payout for landowners participating in the carbon market. However, Ciais *et al.* (2005) found that in some years following drought, trees returned to pre-drought production levels. Furthermore, in some cases, trees presented ~1% higher rates of carbon sequestration than the pre-drought base year (Ciais *et al.*, 2005). Although drought effects can negatively impact the carbon offset value of a forest, areas that experience dry periods may still be viable carbon sequestration investments.

Disturbance: Wildfire

Wildfire, another natural disturbance highly influenced by climate, is widely recognized for its extreme effects on carbon sequestration and storage in forest ecosystems. As one of the most impactful disturbances, fire is the top critical factor concerning dead carbon storage (Lui *et al.*, 2014). While wildfires can be started due to abiotic factors like lightning strikes, according to the U.S. Forest Service, approximately 85% of wildfires in the United States are human-caused (Short, 2022; U.S, 2023). As preventing wildfires is a key element to decreasing abiotic carbon emissions, enforcing human controls is vital to upholding the health of forested ecosystems.

Two main types of wildfires impact the Western United States: forest fires and grass fires. These events vary in size and intensity and are dependent on wind, climate, elevation, and fuel type. Grass fires are more common and burn faster (ranging from hours to days) but release less carbon into the atmosphere than forest fires since grass provides less fuel than trees and understory.

Different forested areas have differing burn rates and behaviors, causing different amounts of carbon to be released when combustion occurs. Located in lower elevation zones in southern Colorado and the Western Slope, Pinon-Juniper forests historically have long fire regimes, spanning between 200 and 400 years. This low frequency of fire means Juniper and Pinon pines are rarely burned, but when medium to high-intensity wildfires occur, the forests rarely survive (Colorado State University 2006). This rarity makes Juniper and Pinon pine stands a sound investment when considering carbon sequestration, but a larger portion of revenue may be allocated into an insurance pool due to the high risk of total destruction in the event of a wildfire.

Ponderosa pine stands are common at montane elevations. Distributed across Colorado in the foothills and the Front Range, Ponderosas thrive in dry climates and can withstand the effects of low-intensity wildfires given their various adaptations, including thicker bark, deep roots, and the shedding of lower branches after approximately 5-years of growth (National Park Service, 2023). These adaptative traits allow Ponderosa pines to survive small fires, as the lack of low branches makes it difficult for the trees to catch and decreases the risk of crown fires. Ponderosa forests are generally wildfire-resistant, grow for a long time, and are a relatively sound investment when considering carbon sequestration and storage in forested landscapes.

Wildfires pose a major threat to the security of forest carbon offsets but are also a necessary element of ecosystem health in the Western United States. Preventing wildfire spread is vital to conserving carbon sinks. Despite the potential for wildfire to burn forests and release high amounts of stored carbon, regrowth provides a new opportunity for carbon capture. Long-term fire-affected ecosystems can act as sinks when new growth begins to absorb the terrestrial carbon remaining in the ashes (Lorenz & Lal, 2010). Additionally, wildfire-produced charcoal provides long-term carbon storage on the forest floor when buried (Lui *et al.*, 2014).

It is essential for landowners to understand the influence of wildfire on forest ecosystems, especially in the Front Range corridor where fire is an increasingly common disturbance. Fires have the ability to clear entire stands, turning forests from a carbon sink into a source for the following generations. Despite fire's benefits for long-term carbon capture, the loss of carbon via fire makes it a vital consideration for easement holders considering participating in the carbon market. Often, recently burned land that previously received carbon offsets may no longer be eligible to receive carbon credits, thereby also terminating payouts to landowners. While carbon crediting companies generally cover the losses via an insurance method, the landowner often receives no further offset payouts.

Biotic Factors: Insects & Disease

Biotic factors, such as disease and insects, can adversely affect carbon offsets of forested land via biomass reduction and slowed tree growth. In 2000 alone, approximately 4.7 million hectares of forest around the globe were adversely affected by disease and 35.7 million hectares by insects (Lorenz & Lal, 2010). One common biotic disturbance in the Rocky Mountain South is the Mountain Pine beetle. While the bark beetle is native to the Western United States, it poses a threat to Colorado forest ecosystems due to a changing climate. From 1990 to 2012 the Mountain Pine beetle caused 3.4 million acres of tree loss in Colorado alone (Negrón & Cain, 2018). In a study of invasive bark beetles in Norway Spruce forests, Seidl *et al.* (2008) found that bark beetles dramatically decreased carbon storage and caused emissions of 41.0 tC/ha over a 100-year simulation period. Another modeling study on Mountain Pine Beetles conducted in British Columbia (outside of native range) predicted that, from 2000-2020, 270 megatonnes of carbon will be released from a 374,000 km^2 forest, effectively converting the study area from a net carbon sink to a large net carbon source (Kurz *et al.*, 2008). Both of these studies highlight the potential for biotic factors, specifically bark beetles, to adversely affect the carbon offsets of non-native forested land. However, Reed *et al.* (2014) studied carbon impacts of Mountain pine beetles in native Lodgepole pine forests and found little to no effect on the forest's net carbon storage and minimal variation in maximum CO_2 uptake across a 3-year period, despite tree basal mortality increasing from 30 to 78%. This phenomenon can likely be explained by the increased light availability under the canopy which promotes rapid understory growth (Reed *et al.,* 2014).

Overall, a comparison of net carbon results from bark beetle studies suggest that non-native forests are more susceptible to biotic disturbances than native forests. Due to the increased severity of climate change, forests are increasingly susceptible to biotic disturbances and impacts to forest carbon storage from both native and non-native origins. Biotic factors, such as bark beetles, have varying effects on the carbon storage of a forest, determined by forest composition and the severity of disturbance, which generally increases, even without considering climate change. Furthermore, easement holders with forested land should consider the effects of biotic disturbances on the carbon offset potential of their land when assessing the viability of carbon market participation.

Forest Management for Carbon Offsets

Forest management to offset carbon emissions is a vital tool for mitigating climate change. These strategies are often natural climate solutions (NCS). NCS has many advantages over other solutions due to their easy deployment, low cost, and the positive side effects on biodiversity and property value (Marvin *et al.*, 2023). However, their advantages may be limited by their vulnerability to human, natural, and climatic disturbances. With each management strategy, there are costs and benefits which are largely case and site dependent. Accordingly, understanding the options and optimal strategies for a forest, as well as a landholder's goals, are important in maximizing the property value.

Afforestation

Afforestation is the practice of using newly planted trees for carbon capture in an area where there were no trees before, as opposed to reestablishing past forests (reforestation). This strategy is one of the most effective in carbon capture and has been adopted in countries around the world (Strange *et al.,* 2019). However, maximizing benefits and minimizing the cost of afforestation is still difficult (Li *et al.,* 2021). Afforestation costs and payout depends on site demand and preparation (*e.g.,* soil quality, tree species selection), which drives tree survival and growth (United States Environmental Protection Agency, 2012).

Benefits. The benefits of afforestation include increased drinking water production, recreation, hunting, timber, and property value. The long-term benefits can be seen through increased biodiversity and timber harvest (Strange *et al.,* 2019). Once land is afforested it also increases the surface area of carbon sinks (United States Environmental Protection Agency, 2012). Abandoned mine lands (AML) are often the site of afforestation projects. The EPA's review of the AML project found the most cost-effective implementation occurred on flat terrain with some soil coverage, ordering seedlings from nurseries far in advance, and choosing the optimal season to maximize growth and minimize sapling mortality. Additionally, afforestation projects can help enable the implementation of other practices that serve as further financial sources of the land, such as water quality trading, wetland banking, and land conservation (United States Environmental Protection Agency, 2012). Afforestation can provide benefits in the carbon markets as well as timber harvest. After one year post-planting, an afforested project is confirmed by the carbon registry and carbon payments start (Meta Reforestation).

Restrictions and Costs. The value of afforested land can heavily depend on the quality of the surrounding area (Strange *et al.*, 2019). The perceived value of some afforested areas may also decline as resources from ecosystem services become scarce (Strange *et al.,* 2017; Schroter *et al.* 2005). Investment into afforestation requires funding for costly practices including soil restoration and the planting of trees. For example, Allegheny Energies spent $10,000 to treat the soil and plant 7,000 trees on 17 acres (United States Environmental Protection Agency, 2012). The U.S. EPA estimated that the cost of planting trees and shrubs in the West costs, on average, $1,000 per acre (United States Environmental Protection Agency, 2012).

Companies that prioritize afforestation. Afforestation is one strategy being employed by leading nature-based carbon broker Chestnut Carbon (chestnutcarbon.com). Chestnut Carbon generates high quality forests through the Gold Standard – one of the most rigorous third-party verification standards. Their afforestation projects are long-term and they work to establish biodiversity in marginal crop and pasture lands that are no longer economically valuable. They expand job opportunities, land use, and community processes through their development process. Afforestation projects on AMLs have been used by Allegheny Energy on 17 acres in Pennsylvania (www.alleghenyenergy.com).

Opportunities in Colorado. In Colorado, abandoned mine lands (AMLs) can be restored to their former state to generate carbon credits (United States Environmental Protection Agency, 2012). According to the Colorado Geological Survey, there are an estimated 23,000 abandoned mine sites on both private and public land in Colorado.

For more information on abandoned mine land (AML) projects:
https://semspub.epa.gov/work/HQ/176034.pdf

Reforestation

Reforestation is a management strategy that re-establishes past forests in areas where they had previously persisted but had been removed by human or natural disturbance. Reforestation management includes plantation, passive natural regeneration (PNR), and assisted natural regeneration (ANR). The plantation method involves the planting of monocultures of native or introduced species, while PNR is a passive strategy which uses little human intervention besides protecting sites from factors that may inhibit growth. ANR, on the other hand, adds to the residual seeds, controls burning and machinery use, and uses thinning to reduce competition (Evans *et al.,* 2014; Busch *et al.*, 2024). Reforestation costs per ton of CO_2 change with method and site location (Busch *et al.,* 2024).

Benefits. Reforestation benefits include water quality and erosion control, increased biodiversity, increased property value, timber production, and increased recreational opportunities (Coder, 1996; Strange *et al.*, 2019). Biodiversity reestablishes faster through reforestation than afforestation, which allows for economic benefits to occur sooner (Stuade *et al.*, 2023). The plantation strategy produces more wood products, generates higher revenue through timber production, and in some cases was able to accumulate carbon faster than natural sites (Busch *et al.,* 2024). Natural regeneration (NR) strategies improve biodiversity and water and erosion control and are usually implemented in areas of moderate degradation (Busch *et al.*, 2024; Evans *et al.*, 2014). With NR, the vegetation is more resilient to the environment and disturbance since it is more likely to be made up of native species than plantations, which typically consist of single tree species (Evans *et al.,* 2014). The concentration of native species provides better habitat for local fauna, increasing hunting and recreation value (Evans *et al.,* 2014). The climate resilience of native Colorado species may become vital to sustain sequestration, timber, and ecological benefits in the intensifying climate conditions. Under the plantation regime this can be accounted for by selecting native vegetation for reforestation.

Restrictions and Costs. The restrictions and costs of reforestation depend on the strategy used and site characteristics. While plantation monocultures can maximize timber and carbon sequestration, they can also negatively impact biodiversity, decrease water yield, and increase soil acidity. (Jackson *et al.*, 2005; Lamb *et al.,* 2005, Bekessy *et al.,* 2008). Additionally, plantations typically have higher initial implementation costs from planting and costs associated with ensuring the survival of the vegetation (Evans *et al.,* 2015). The cost effectiveness of each strategy is site-dependent. Busch *et al.* (2024) found similar median abatement costs with both strategies: NR: $23.80 per tCO2, Plantation: $23.00 per tCO2. Plantations had greater variation in abatement costs, and natural regeneration was more cost effective in many regions, which supported previous region-specific studies (Busch *et al.,* 2024).

Companies that prioritize reforestation. The Cameron Peak Reforestation group (CPRG) is currently working to reforest the burn scar of the Cameron Peak fire. This fire burned more than 200,000 acres in northern Colorado, making it the largest fire in Colorado history. Since 2021, they have planted 36,000 trees (Coalition for the Poudre River). Their goal is focused on forest regeneration, and no carbon credits have been sold from this project (Coalition for the Poudre River). Companies that manage reforestation projects include Mast Reforestation (mastreforest.com), ArborGen (arborgen.com), and Anew Climate (anewclimate.com). RenewWest (renewwest.com) also provides evaluations for landowners on their carbon potential with a focus on reforestation leases.

Opportunities in Colorado. Brant *et al.* (2017) found that if all the burned land in Colorado was reforested, the amount of carbon stored would increase by 160 million metric tons of CO_2 (MMT CO_2eq). This would be more than four times the state's reduction goal by 2025 (39 MMT CO_2eq). Mast Reforestation focuses on reforesting after a wildfire, and while fire intensity and frequency is increasing in Colorado (Colorado State Forest Service), these projects will become increasingly necessary to mitigate the carbon storage losses from fires.

For more resources for how Colorado Landowners can get involved:
https://csfs.colostate.edu/2023/05/17/forest-carbon-offsets-for-colorado-landowners/.

Avoided Conversion

Avoided conversion can provide carbon offsets by preventing conversion of forested land to non-forested land. Converting forested land for urban or agricultural use increases carbon emissions by removing vegetation that would otherwise sequester carbon (Marvin *et al.*, 2023). Avoided conversion has the highest carbon storage potential of any single management strategy and accounts for 47% of reduction potential by 2050 (Fig. 2.2; Marvin *et al.*, 2023). It is also referred to as Reducing Emissions from Deforestation and forest Degradation (REDD+). REDD+ was established for the United Nations Framework Convention on Climate Change and was specifically geared towards developing countries (Butler *et al.*, 2024).

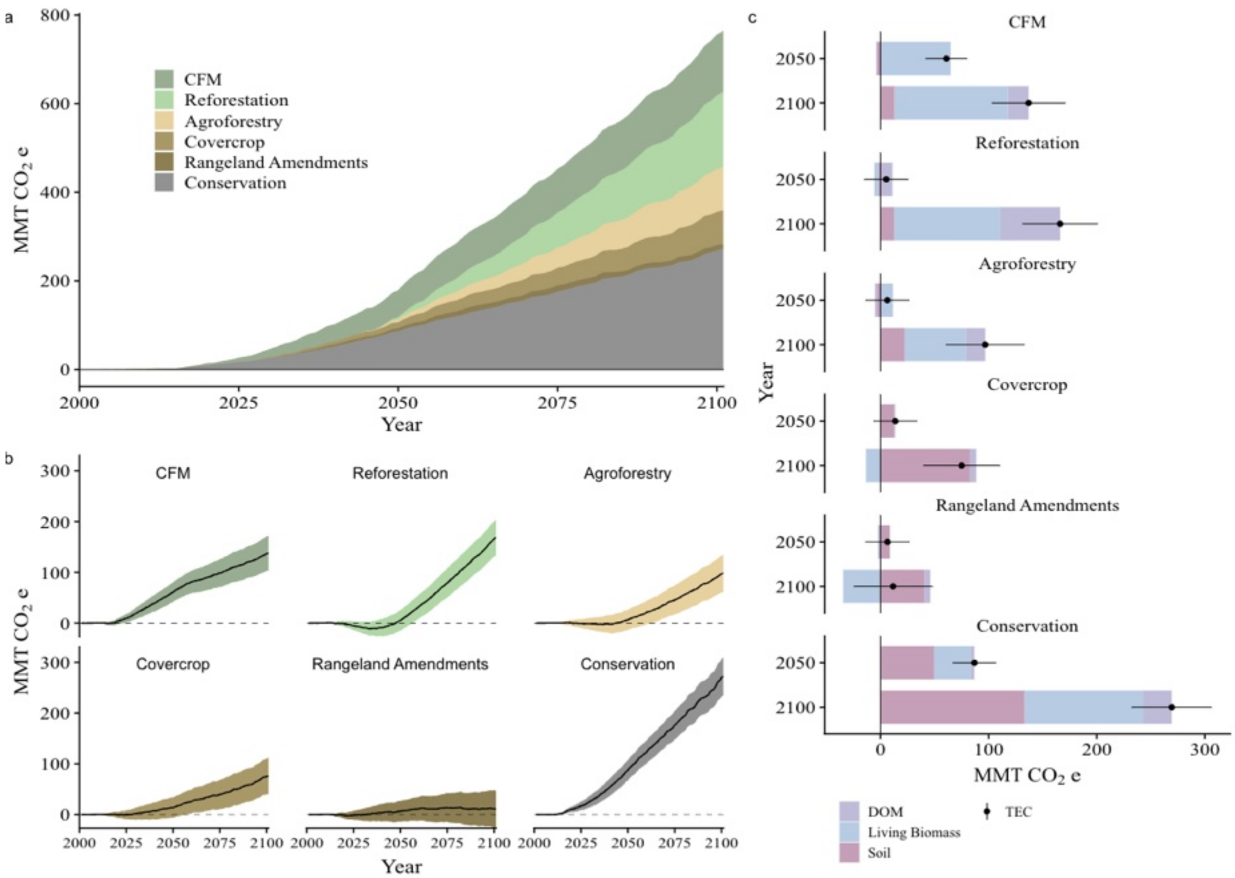

Figure 2.2. Predicted effects of individual natural carbon sequestration interventions on million metric tons of carbon dioxide equivalent (MM CO_2 e) across projected climate futures. [*From* Marvin et al. 2023]

Benefits. Avoided conversion has high carbon storage potential as well as implications for hunting and biodiversity value. The value of preserved undisturbed primary forests remains higher than secondary reforested forests, which are still less efficient at storing carbon and supporting biodiversity compared to undisturbed forests after four decades (Lennox *et al.*, 2018). It is argued that protecting primary forests should be a priority in carbon emission mitigation. Additionally, maintaining pristine habitat does not disrupt the ecosystem, and therefore can also improve hunting and recreation value. Hunting is one of the largest land use activities in the United States and has major economic value. For example, all game hunting in the United States was estimated to be worth $26.2 billion in 2016 (U.S Fish and Wildlife Service, 2016).

Restrictions and Costs. While the highest carbon storage potential remains in avoided conversion (Fig. 2.2), there are costs and tradeoffs associated with it. Firstly, while avoiding conversion of forested lands is a major offset, timber harvesting is often already prohibited under the conservation easement. Accordingly, these lands cannot serve as a carbon stock due to additionality requirements of the carbon contract. Avoiding conversion also means sacrificing immediate profits from timber harvest and conversion of land into urban or agriculture (Chesney *et al.*, 2017). Avoiding land conversion has reduced agricultural and urban land conversion by 55% and 75%, respectively (Marvin *et al.*, 2023), resulting in particularly large implications on missing economic gain from development and agriculture. A conserved forest also remains vulnerable to natural disturbance such as fire which would substantially diminish the carbon stored and economic potential in the carbon market (Marvin *et al.,* 2023). This risk remains a central reason for landowner aversion to this management type.

Companies that prioritize avoided conversion. This strategy is widely used by carbon offset companies. Some companies that use Avoided Conversion management are GreenAssets (https://green-assets.com/), Finite Carbon (https://www.finitecarbon.com), and REDD+ Positive (https://reddpositive.org). The Jager Grassland Conversion is a avoided conversion project by Southern Plains Land Trust (https://southernplains.org/en) conserving 6,600 acres of the Jagers Ranch in southeastern Colorado. The land was put into a land trust to avoid conversion of the land into agriculture or development and is estimated to store and sequester 190,000 tons of carbon dioxide over the next 50 years (Colorado Carbon Fund).

Opportunities in Colorado. In Colorado, it is estimated that conversion of wetlands and grasslands through 205 has the potential to increase carbon stored in those biomes by 68 MMT CO_2. The 2020 Colorado Forest Action Plan states that about "about 10 percent of Colorado's 24 million acres of forest need urgent attention to address forest health, wildfire risk and threats to water supplies."

Carbon Sequestration & Timber Production

In addition to afforestation, reforestation, and avoiding forest land conversion, forest management with regard to timber production presents large potential for additional carbon offsets on conservation easements. Improved forest management measures change from business-as-usual practices, on contracts generally ranging from 60-100 years, and accounts for approximately 95% of current offsets at Forest Carbon Works, a carbon stock partner that works across the United States (Letzing, *personal communication*).

Field research suggests that continuous cover forestry is an effective method to increase sequestration and carbon offset value of forested land. Seidl *et al.* (2007) measured the effectiveness of three forest management techniques as compared to no management on secondary Norway Spruce forests over a 100-year study period. The assessed strategies include: (1) business as usual forestry (age class forestry with rotation of 90 years); (2) continuous cover forestry–selective thinning to maintain age diversity in forest; (3) conversion to mixed broadleaved forests post timber production; and (4) no management or timber production. The study found the unmanaged forest sequestered the most carbon, followed by land managed with continuous cover forestry, suggesting the effectiveness of continuous cover methodology in balancing timber production with carbon sequestration (Seidl *et al.*, 2007). Additionally, the findings from a cost analysis of continuous cover forestry highlighted the potential of effective timber management in sequestering carbon and increasing monetary value of forested land (Seidl *et al.,* 2007). The continuous cover forestry strategy maintains diverse stand age in forests, rather than clear cut forestry which produces mono-stand ages. Accordingly, not only are mixed age forests important for the ecological value of a forest, they also tend to be more productive than mono-aged stands (Letzing, *personal communication*).

Extended rotation periods are also important to consider with respect to impacts on carbon sequestration and storage. Extended rotation periods allow trees to grow larger, capturing and storing more carbon in their tissue, before being cut down for timber. In terms of carbon sequestration in forested ecosystems, longer rotation periods are generally more effective as offsets (Letzing, *personal communication*). However, there are also costs associated with longer rotation periods. Although longer rotation periods provide increased carbon storage and higher biodiversity levels, it may diminish the potential economic gain from timber harvesting and deplete groundwater availability in the area (Başkent & Kašpar, 2023). Additionally, long rotation models pose an increased risk of fire events in forested areas, which could prove detrimental to both the ecosystem health and its carbon offset potential (Diaz-Balteiro *et al*., 2014). Landowners and managers must therefore balance between maximizing carbon capture and minimizing fire risk to achieve forest conditions that uphold carbon sequestration standards.

The optimal rotation period for maximizing carbon storage depends on forest stand characteristics and site quality. In a study of Douglas fir dominated forests by researchers at Oregon State, it was found that 60-year rotations with low intensity thinning on 40-year-old trees had the greatest carbon storage (Hailemariam *et al.,* 2023). Due to maximum carbon storage in the 81-120 year age class in the Rocky Mountain South, longer rotations required thinning of understory vegetation to maximize Douglas fir growth (Hailemariam *et al.*, 2023). However, understory thinning generally decreases the overall biodiversity of the vegetation. Thinning of the overstory trees, on the other hand, can decrease fire severity, while also increasing the understory vegetation density (Willms *et al*., 2017). This maximizes carbon sequestration and ecological health in long rotation forestry. These studies highlight the possible positive feedback loop of thinning over and understory vegetation; however, the optimal thinning rotation for mitigating fire frequency and severity on the whole stand is not acknowledged. In terms of thinning and harvesting, some companies may include stipulations on how much of the harvest timber can be used for wood. For example, Forest Carbon Works typically only allows 30% of timber to be cut after their 80-year extended rotation period (Leizing, *personal communication*). This encourages harvesting on a more sustainable basis. Extended rotation periods are a strategy that landowners can use to boost the carbon credit value of their forests, though proper considerations must be made on a case-by-case basis to determine how to maximize efficiency of this method. Alteration of management strategies, highlighting rotation periods consideration and continuous cover forestry, in easements owning timber rights provides opportunity for significant ecological and economic gain via carbon market offsets.

Table 2.2. Key contract conditions of four carbon credit companies that work with owners of forested land in Colorado, including minimum property size, minimum contract length, forest management type(s), harvesting permissions, length of time to generate carbon credits, and steps to apply for credits.

Company	Minimum Property Size	Minimum Contract Length	Management Offered	Can I still harvest?	How long does it take to generate a credit?	Steps to Apply
Anew Climate anewclimate.com	4,000 Acres	▪ 40 years for voluntary projects ▪ 100+ years for compliance projects	▪ Improved Forest Management (IMF) ▪ Avoided Conversion	Case dependent, but has been permitted in projects. If allowed, certification under FSC, SFI, ATFS, or state approved management plan required.	18- 24 months (case dependent)	1. Feasibility Study: No-cost evaluation of project performance and economics. 2. Credit Development: Anew will finance all required action to register and sell carbon credits.
Arbor Gen arborgen.com	40 acres	25 years	▪ Reforestation ▪ Afforestation	Harvesting is permitted after 25 years (estimated 1.5 metric tons of CO_2 captured by 25 years).	1-year post-planting (project is confirmed by carbon registry and ArborGen partner, Chestnut, brokers carbon credits)	1. Contact reforestation advisor (www.renewwest.com to provide evaluation). 2. Prepare land and plant seedlings.
Forest Carbon Works (FCW) forestcarbonworks.org	40 Acres	25 years	▪ Improved Forest Management (IMF)	Yes, though stipulations apply re: where harvesting may occur (*e.g.* no harvesting near streams, limited to 10% of stand)	First down payment in 30 days, then annually for the first 25 years.	1. Submit online application with landowner and property information. 2. Review and sign offer from FCW. 3. FCW evaluates land based on evaluation and start payments in 30 days.
Mast Reforestation mastreforest.com	200 burned acres (Must have burned in last 10 years)	200+ year conservation easement	▪ Reforestation (post wildfire)	Not relevant, as Mast specializes in forest and ecosystem restoration (not commercial harvesting)	1-year post-planting (project is confirmed by the carbon registry and carbon payments start)	1. Scope & Design: Site evaluation from forester; sign letter of intent followed by project agreement. 2. Preparation & Implementation: Mast will prepare site and plant seeds at no cost to landowner. 3. Monitoring & Management: Ongoing for the duration of the project.

Significance & Future Directions

By highlighting various forest management strategies and their relative effects on carbon storage potential, we hope this review can serve to provide insights to land managers and owners on how land management can be used to maximize the value of forested land in the carbon markets. By developing a basic understanding of disturbance and forest properties, as well as their impact on forest net carbon, landowners can evaluate their land and select the management strategy best suited for their property. Our findings highlight that managing forests for the carbon market can increase the value of their land in timber and hunting, through the inherent benefits to the ecosystem. We also provide risks and costs associated with different management strategies, further informing management practices and decisions regarding participation in the carbon market. Private carbon brokers could also use our findings when evaluating their clients' land, by providing a more descriptive cost-benefit analysis through the incorporation of ecosystem processes. With value placed on carbon sequestration and storage, forested ecosystems protected under conservation easements and their landholders can benefit from participation in the carbon market.

This literature review highlights a need for Colorado-specific research on the efficiency of carbon capture and storage in forests. While general trends on carbon capture regarding forest properties, disturbance, and management can inform landowners, additional regionally-specific research would help further inform easement holders in Colorado considering involvement in carbon markets. Carbon offsets can create beneficial opportunities for conservation easement holders, though it is important to thoroughly assess a property, its vulnerability to disturbance, and management strategies.

References

Başkent, E. Z., & Kašpar, J. (2023). Exploring the effects of various rotation lengths on the ecosystem services within a multiple-use management framework. Forest Ecology and Management, 538, 120974. https://doi.org/10.1016/j.foreco.2023.120974

Bekessy, S., & W, B. (2008). Using Carbon Investment to Grow the Biodiversity Bank. Society of Conservation Biology, 22(3), 510-513. https://doi.org/10.1111/j.1523-1739.2008.00943.x

Brandt, N., Brazeau, A., Browning, K., & Meier, R. (2017). Carbon Sequestration in Colorado's Lands: An Integrated Spatial & Policy Analysis. University of Colorado Boulder.

Busch, J., Bukoski, J., Cook-Patton, S., Griscom, B., Kaczan, D., Pottis, M., Yi, Y., & Vincent, J. (2024). Cost -effectiveness of natural forest regeneration and plantations for climate mitigation. Nature Climate Change, 13, 996- 1002. https://doi.org/10.1038/s41558-024-02068-1

Butler, B., Sass, E., Gamarra, J., Campbell, J., Wayson, C., Olguin, M., Carillo, O., & Yanai, R. (2024). Uncertainty in REDD+ carbon accounting: a survey of experts involved in REDD+ reporting. Carbon Balance and Management, 19(22). https://doi.org/10.1186/s13021-024-00267-z

Chesney, M., Gheyssesns, J., & Troja, B. (2017). Market uncertainty and risk transfer in REDD projects. Journal of Sustainable Forestry, 36(5), 535-553. https://doi.org/10.1080/10549811.2017.1326940

Chiang, Cindy, et al. (2020). Carbon Offsets in Conservation Easements. Land Trust Alliance.

Ciais, P. et al. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437(7058), 529-533. https://doi.org/10.1038/nature03972

Coder, R. (1996). Identified Benefits of Community Trees and Forests. University of Georgia. https://nfs.unl.edu/documents/communityforestry/coderbenefitsofcommtrees.pdf

Colorado Geological Survey. (n.d.). Abandoned Mine Lands (AML). https://coloradogeologicalsurvey.org/hazards/aml/#:~:text=Across%20the%20state%2C%20there%20are,both%20public%20and%20private%20land.

Colorado State University, Pacific Biodiversity Institute, National Interagency Fire Center, & Colorado State Forest Service. (2006). Fire Ecology in Colorado. Colorado State University. Retrieved 2024, from https://static.colostate.edu/client-files/csfs/pdfs/ColoradoFireEcologyOverview101712.pf

Diaz-Balteiro, L., Martell, D. L., & Romero, C. (2014, January 03). The optimal rotation of a flammable forest stand when both carbon sequestration and timber are valued: a multi-criteria approach. Nat Hazards, (72), 375–387. https://doi.org/10.1007/s11069-013-1013-3

Evans, M., Carwardine, J., Fensham, R., Butler, D., Wilson, K., Possingham, H., & Martin, T. (2015). Carbon farming via assisted natural regeneration as a cost-effective mechanism for restoring biodiversity in agricultural landscapes. Environmental Science and Policy, 50, 114-129. https://doi.org/10.1016/j.envsci.2015.02.003

Fordham, A., Bucholz, E., Vorster, T., & Woolman, A. (2023, May 17). Forest Carbon Offsets for Colorado Landowners. Colorado State Forest Service. https://csfs.colostate.edu/2023/05/17/forest-carbon-offsets-for-colorado-landowners/

Hall, J., et al. (2024). Forest carbon storage in the western United States: Distribution, drivers, and trends. Earth's Future, 12. https://doi.org/10.1029/2023EF004399.

Hogan, J.A., et al.. (2024). Climate change determines the sign of productivity trends in US forests, Proc. Natl. Acad. Sci. U.S.A. 121 (4) e2311132121, https://doi.org/10.1073/pnas.2311132121

Hoover, Coeli M, and James E Smith. (2023). Aboveground Live Tree Carbon Stock and Change in Forests of Conterminous United States: Influence of Stand Age. Carbon Balance and Management, 18(1). https://doi.org/10.1186/s13021-023-00227-z.

Jackson, R., Jobbagy, E., Avissar, R., Roy, S., Barret, D., Cook, C., & Farley, K. (2005). Trading Water for Carbon with Biological Carbon Sequestration. Science, 310(5756), 1944-1947. DOI: https://doi.org/10.1126/science.1119282

Klaus Lorenz, & R Lal. (2010). Carbon sequestration in forest ecosystems.

Kurz, W. A., Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, A. L., Ebata, T., & Safranyik, L. (2008). Mountain pine beetle and forest carbon feedback to climate change. Nature, 452(7190), 987–990. https://doi.org/10.1038/nature06777

Lamb, D., Erskine, P., & Parrotta, J. (2005). Restoration of Degraded Tropical Forest Landscapes. Science, 310(5754), 1628-1632. https://doi.org/10.1126/science.1111773

Lennox, G., Gardner, T., Thompson, J., Ferreira, J., Berenguer, E., Less, A., & Nally, R. (2018). Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. Global Change Biology, 24(12), 5680-5694. https://doi.org/10.1111/gcb.14443

Letzing, S. (2024, December 3). Forest Carbon Works [Presentation Forest Carbon Works].

Li, Y., Brando, P., Morton, D., Lawrence, D., Yang, H., & Randerson, J. (2022). Deforestation-induced climate change reduces carbon storage in remaining tropical forests. Nature Communications, 13(1964). https://doi.org/10.1038/s41467-022-29601-0

Lui, Y., Goodrick, S., & Heilman, W. (2014, April 1). Wildland fire emissions, carbon, and climate: Wildfire–climate interactions. Forest Ecology and Management, 317, 80-96. ScienceDirect. https://doi.org/10.1016/j.foreco.2013.02.020

Lundeberg, S., Firzgerald, S., Carlisle, C., & Hailemariam, T. (2023). Forest modeling shows which harvest rotations lead to maximum carbon sequestration. Oregon State University Research Forests. https://news.oregonstate.edu/news/forest-modeling-shows-which-harvest-rotations-lead-maximum-carbon-sequestration

Martínez-Sancho, E., Treydte, K., Lehmann, M. M., Rigling, A., & Fonti, P. (2022). Drought impacts on tree carbon sequestration and water use – evidence from intra-annual tree-ring characteristics. New Phytologist, 236(1), 58-70. https://doi.org/10.1111/nph.18224

Marvin, D., Sleeter, B., Cameron, R., Nelson, E., & Plantinga, A., (2023). Natural climate solutions provide robust carbon mitigation capacity under future climate change scenarios. Scientific Reports, 13(19008). https://doi.org/10.1038/s41598-023-43118-6

National Park Service. (2023, January 12). Wildland Fire in Ponderosa Pine: Western United States (U.S. National Park Service. Retrieved December 16, 2024, from https://www.nps.gov/articles/wildland-fire-in-ponderosa-pine.htm

Negrón, J. F., & Cain, B. (2018). Mountain Pine Beetle in Colorado: A Story of Changing Forests. Journal of Forestry, 117(2), 144–151. https://doi.org/10.1093/jofore/fvy032

Reed, E. D., Ewers, B. E., & Pendall, E. (2014). Impact of mountain pine beetle induced mortality on forest carbon and water fluxes. Environmental Research Letters, 9(10), 105004. https://doi.org/10.1088/1748-9326/9/10/105004

Rupert Seidl, et al. (2007). Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. Forest Ecology and Management, 248(1–2), 64-79, https://doi.org/10.1016/j.foreco.2007.02.035.

Schroter, D., Cramer, W., Leemans, R., Prentice, C., Araujo, M., Arnell, N., Bondeau, A., & Bugmann, H. (2005). Ecosystem service supply and vulnerability to global change in Europe. Science, 310(5752). 10.1126/science.1115233.

Seidl, R., Rammer, W., Jäger, D., & Lexer, M. J. (2008). Impact of bark beetle (Ips typographus L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. Forest Ecology and Management, 256(3), 209–220. https://doi.org/10.1016/j.foreco.2008.04.002

Short, K. C. (2022). Spatial wildfire occurrence data for the United States, 1992-2020. [FPA_FOD_20221014], 6th Edition. https://doi.org/10.2737/RDS-2013-0009.6

Slovak Academy of Sciences. (2009). Physiological drought- How to quantify it? Springer. https://link.springer.com/content/pdf/10.1007/978-1-4020-8876-6_7.pdf

Staude, I., Weigelt, A., & Wirth, C. (2023). Biodiversity change in light of succession theory. Oikos, 2023(11). https://doi.org/10.1111/oik.09883

Strange, N., Jacobsen, J., & Thorsen, B. (2019). Afforestation as a real option with joint production of environmental services. Forest Policy and Economics, 104, 146-156. https://doi.org/10.1016/j.forpol.2019.04.015

United States Environmental Protection Agency. (2012). Carbon Sequestration through Reforestation A LOCAL SOLUTION WITH GLOBAL IMPLICATIONS. https://semspub.epa.gov/work/HQ/176034.pdf

U.S. Department of the Interior, U.S. Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. 2016 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation.

Veblen, T. T., & Rother, M. T. (2017). Climate Drives Episodic Conifer Establishment after Fire in Dry Ponderosa Pine Forests of the Colorado Front Range, USA. Forests (19994907), 8(5), 159. https://doi.org/10.3390/f8050159

Wildland Fire in Ponderosa Pine: Western United States (U.S. (2023, January 12). National Park Service. Retrieved December 16, 2024, from https://www.nps.gov/articles/wildland-fire-in-ponderosa-pine.htm

Willms, J., Bartuszevige, A., Schwilk, D., & Kennedy, P. (2017). The effects of thinning and burning on understory vegetation in North America: A meta-analysis. Forest Ecology and Management, 392, 184 -194. https://doi.org/10.1016/j.foreco.2017.03.010

RANGELANDS AND AGRICULTURAL ECOSYSTEMS

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Rangelands are one of the dominant ice-free cover types on Earth and comprise primarily grasslands, woodlands, scrublands, wetlands, and semi-deserts (Godde *et al.*, 2020 & Alkemade *et al.*, 2013). Rangelands are most commonly used to produce domestic grazing livestock and provide several ecosystem services (Godde *et al*., 2020). Healthy rangelands are vital to many communities and can regulate flooding and greenhouse gas production, contribute to carbon sequestration, and support wildlife habitat, biodiversity, and pollination (Waterhouse *et al.*, 2023). Conversely, degraded rangelands can contribute to the introduction or persistence of invasive species, habitat loss and fragmentation, greenhouse gas emissions, an increase in water runoff, decreased water storage, and soil erosion (Waterhouse *et al.,* 2023).

Rangelands hold a great amount of potential for carbon sequestration and already store between 10 and 30% of terrestrial and soil organic carbon. However, the rate of sequestration is lower than that of croplands or other ecosystems possibly due to drought and heavy grazing (Derner & Schuman, 2007). Many factors can impact carbon sequestration on rangelands including grazing management, vegetation, elevation, soil type, and erosion (Waterhouse *et al.*, 2023, Ayoma *et al.*, 2022). Around 11% of Colorado is made up of rangelands (Kleist et al., 2022), so understanding the ecology of rangelands is vital to inform use and management and give context into how potential carbon sequestration practices may influence the ecosystem.

Similarly, the agricultural industry offers a promising opportunity to develop carbon sequestration practices and positively impact both the environment and landowners. Given that agricultural lands cover 38% of land globally, focusing efforts on researching management methods such as cover cropping, no-till practices, and perennialization is essential for extracting the full potential of soil and vegetation to work as a carbon sink, instead of source.

Herein, we provide a literature review of rangeland carbon storage at local and global scales. We provide an overview of various rangeland and agricultural management practices and summarize their benefits and limitations. We also researched companies specializing in carbon markets in rangeland and agricultural ecosystems, and provide an overview of cost, longevity, ease of implementation, and success for both the environment and landowners. Finally, we were fortunate to speak with several individuals working in the carbon credit market and with conservation easements, including Sally Letzing from Forest Carbon Works, as well as Jack Adams and Nick Nugent from Grassroots Carbon.

Rangeland Carbon Sequestration Practices

Continuous grazing is a common and widely used practice on many ranches in which a herd of cattle has unrestricted access to a pasture for an extended period of time with little to no rest for the vegetation. However, there are alternative grazing practices that are showing promising results in ecosystem services as well as economic gain (Teague & Kreuter, 2020). Continuous grazing has not only been found to decrease carbon stores, but also decrease biodiversity, organic matter transfer to soil, nutrient cycling, and topsoil (Teague & Kreuter, 2020). Regenerative grazing goes beyond rotational grazing, because it focuses on strategic rest periods and has more promising carbon storage results (Bartley *et al.*, 2022). Many articles have found that regenerative grazing practices increase carbon storage in the soil by a significant amount (Díaz de Otálora *et al.*, 2021, Teague & Kreuter, 2020). In one study, regenerative rotational grazing was found to have 3.6% higher topsoil carbon storage than continuous grazing after 5 years (Díaz de Otálora *et al.*, 2021). It's also important to note that trampling by livestock deposits organic matter in the soil and when the plants are then given time to rest, it allows the roots to grow deeper without tilling or plowing, and in turn sequesters more carbon without releasing it which is also an important part of regenerative grazing. Regenerative grazing practices enhance carbon storage and sequestration among several other ecosystem services (Teague & Kreuter, 2020).

Manure can also significantly improve carbon stocks, which is already an aspect of regenerative grazing strategies but could be something to consider for the management of land in other circumstances as well (Owen *et al.*, 2015). Other practices that have shown some potential for increased carbon storage include revegetation and removal of invasive vegetation. Rangeland revegetation involves prescribed burns and then seeding the area with the desired vegetation species. In rangelands, reseeding native grasses is shown to reduce invasive annual grasses which provides many beneficial ecosystem effects and has the potential to increase carbon sequestration (Davies *et al.*, 2024 & Silviera *et al.*, 2024). Revegetation of native species could be very beneficial in Colorado; however, it may not increase carbon sequestration as much as in other areas due to the arid environment and sequestration potential of the native plants. The removal of invasive woody species is important on rangelands because it allows for an increase of native vegetation and resilience to disturbances like wildfires. One ongoing study in Oregon found 2.6 times higher root carbon stocks in areas that were treated by the removal of an invasive juniper species. However, the untreated areas showed 5.8 times higher above-ground carbon stores (OSU Ecohydrology, Abdallah *et al.*, 2020).

Grassland management could also lead to higher carbon sequestration on rangelands. In a study from Boulder County, Colorado, Lasky (2020) found that increased plant diversity in grasslands was linked to higher soil organic carbon. Lasky (2020) also found that mesic big bluestem prairies also store the most carbon while xeric tallgrass prairies had the highest species diversity and therefore high potential for carbon storage (Lasky 2020). Grasslands may also be extremely beneficial for long-term carbon storage. Dass *et al*. (2018) found that California grasslands may be a more reliable carbon sink than forests, particularly in response to fires. This research highlights the importance of grasslands and the carbon sequestration opportunities it presents. Some practices that may be beneficial to implement on Colorado rangelands include planting or reseeding native grasses and increasing plant diversity. Many studies have shown other factors besides grazing intensity can affect carbon storage and sequestration on rangelands; however, more research needs to be done to be confident in the effectiveness of these management practices and to understand how best to implement them.

Currently, regenerative grazing appears to be the most effective management practice for carbon sequestration in rangeland ecosystems, as well as a large factor for carbon market companies. Startup cost varies by equipment, size of grazing units, and size of ranches, but it does not appear to be prohibitively expensive to implement and has been shown to increase annual profit, particularly for larger ranches. There are also carbon credit companies that work with landowners of rangeland properties to implement practices that will increase carbon sequestration and encourage their participation in the carbon market. One example is Grassroots Carbon, which facilitates the process to get landowners in contact with professionals to help them evaluate their management practices. Grassroots Carbon advocates specifically for regenerative grazing and even provides funding for equipment such as fences to implement these strategies. Regenerative grazing is the most studied and highly effective practice for carbon sequestration on rangelands that are also allowed by conservation easements, but other practices such as the revegetation of native grasses should also be considered.

Agricultural Carbon Sequestration Practices

Given the widespread presence of agricultural land, understanding the potential of these lands to either store or release carbon is crucial for mitigating the immediate effects of climate change. To achieve this, it is essential to assess how soil and vegetation contribute to carbon sequestration.

In many agricultural systems, soils are barren for large portions of the year when unfavorable weather conditions prevent crops from growing. This leads to a reduction in biomass and is a missed opportunity for carbon capture. One method to address this is through cover cropping, a practice that not only benefits soil health by suppressing weeds and increasing fertility but also enhances carbon sequestration by maintaining vegetation during the off-harvest seasons (Cerri 2021). Cover cropping includes planting crops after a harvest to maintain soil function and promote fertilization. Perennial crops such as alfalfa or ryegrasses can be great cover crops because they take few resources to maintain yet provide great benefits for increasing biodiversity and promoting prolonged soil health. Cover cropping was widely adopted by farmers before the introduction of synthetic fertilizers and remains a valuable tool for increasing carbon storage in soils.

No-till farming, which is now used on over a third of U.S. cropland, represents another common agricultural practice. This method reduces soil disturbance by avoiding tillage and relies on chemical fertilizers and genetically modified crops. While studies have shown that no-till practices can increase soil carbon storage, challenges arise when farmers revert to tillage practices (Kane 2015). In many cases, the carbon stored in the soil is quickly released, demonstrating that strict adherence to no-till practices is crucial. These findings suggest that better management practices and stricter guidelines are necessary to ensure consistent carbon benefits. This poses a challenge to carbon companies working within the industry as oversight is incredibly difficult. If no-till farming practices are to be implemented to show additional benefits, it is vital to stress the danger of breaking protocol.

Another area of focus is the role of belowground biomass in carbon sequestration. Annual crops typically have shallow root systems, which do not sequester carbon as effectively as the deeper roots of perennial crops. Research shows that increasing belowground biomass, especially through the introduction of deep-rooted perennial grasses and crops, can significantly enhance carbon storage in soils. However, the widespread use of synthetic fertilizers, which reduce microbial activity in the soil, complicates this potential (Kane 2015). Fertilized plants typically have less complex root systems and may not fully take advantage of the carbon-sequestering potential of deep roots. Given the widespread use and benefit of fertilizers, this issue may only persist in the future.

Across all agricultural practices, it is important to track whether or not more carbon is being stored than released. One way to do this is by determining the saturation limit. This can be described as the point at which “the soil carbon protecting processes of aggregation, adhesion to mineral particles, and biochemical protection cease to protect new carbon. When soils reach this limit, they either turn into a carbon source or remain in a steady state. Any additional carbon, then, might be considered “free” and vulnerable to microbial attack” (Kane 2015). Understanding this concept and monitoring deep soil carbon levels will be necessary for landowners looking to gain additional benefits from agricultural practices.

Rangeland Carbon Markets

The potential for carbon credits on cropland and rangeland in Colorado is a hugely growing field and one that is still mostly unexplored. Colorado soil has a relatively low carbon sequestration potential compared to other areas of the country, particularly in the East Coast. This makes carbon credits less profitable for ranchers and farmers in the state compared to other regions, but with enhanced regenerative land management strategies, the Southwest still holds significant potential for carbon credit profitability. The Nature Conservancy conducted an analysis of the potential for soil carbon stock throughout the United States in 2038 if improved cropland management measures were taken and found that large portions of Colorado have the potential to hold more carbon in the soil than they currently do (Bossio, 2020). This provides opportunities for farmers and ranchers to join the carbon credit market and profit from improving their land management practices.

There are a number of different options for ranchers and farmers to choose from if they are thinking about entering the carbon credit market. Currently, Colorado is excluded from many carbon credit companies specializing in rangelands or croplands because of lower soil carbon sequestration potential, but as the market continues to grow, there will undoubtedly be more opportunities for Colorado landowners to participate. Most carbon credits for ranchers/farmers operate on 10-30-year contracts, with specific land management requirements that landowners must follow to store additional carbon in their soils that was not previously there. Table 2.3 synthesizes five available carbon credit companies for ranchers and farmers with their associated land-use type, contract lengths, property requirements, payment schedules, and protocols used. The first four companies are available for landowners in Colorado, while the fifth is not yet accessible but is expected to expand into the region in the coming years. These organizations are a good starting point for landowners exploring carbon markets. However, the field is rapidly evolving and new carbon credit opportunities are constantly emerging. Landowners should carefully evaluate the available options before deciding on one, as programs vary significantly in terms of payment estimations, eligibility, and protocols used. Depending on the goals and current land management practices of the landowner, certain programs may offer a better fit than others.

Participation by Landowners with Conservation Easements

Conservation easements, while not a requirement for participation in carbon market programs, provide significant benefits by ensuring that the land remains undeveloped, supporting long-term carbon sequestration goals. Easements strengthen the permanence and durability standards required by programs like Verra's Verified Carbon Standard, which mandates permanence to issue carbon credits. Easements also facilitate market incentives by enabling regenerative practices, such as rotational grazing or soil conservation, which are maintained over time through contract. Numerous carbon credit programs exist in the United States that specifically focus on providing carbon credits for ranchers with rangeland properties (see Table 2.3).

One caveat of entering carbon market programs with land that is conserved through an easement is the concept of additionality. This refers to landowners getting compensated through carbon market programs for protecting resources that are already protected in the easement. For example, if a landowner is already prohibited from logging in an easement on their property, they cannot be compensated for protecting those trees in carbon market programs as there is no additionality shown. That said, landowners with conservation easements on their properties are not necessarily excluded from participating in the carbon market, given that the language within the easement allows for flexibility in land management practices. In most easements, landowners are able to alter their practices as long as they remain in accordance with "sound grazing practices". This phrasing thereby may allow landowners to amend their practices in accordance with sustainable methods that improve ecological health.

Table 2.3. Comparison of Carbon Credit Programs for Farmers and Ranchers in the United States, including Contract Terms, Eligibility, Payment Structure, and Protocols.

Company Name	Land-Use Type	Contract Length	Minimum Property Size	Payment Estimations	Payment Schedule	Protocols Used
Grassroots Carbon	Rangeland	30 years (measured every 5 years)	> 500 acres; grazing cattle	80% of carbon credit sale	Annually (conservative estimate for first 5 years)	Regenerative Standard & Verra standard for carbon measurements and soil sampling.
Kateri Carbon	Rangeland	30 years (10 years for practice change + 20-year conservation period)	Not publicly available.	Not publicly available.	Continuous payments as credits are measured and sold.	Adaptive multi-paddock grazing; uses GPS tracking, remote sensing, soil sampling, and biogeochemical modeling.
Indigo Ag	Cropland	5-year renewable contract	>150 acres Must grow 1 of 18 supported crops	75% of carbon credit sale. $45/metric ton of C sequestered +10% growth/yr.	Annually	Climate Action Reserve's Soil Enrichment Protocol
Agoro Carbon Alliance	Cropland & Rangeland	10 years	> 500 acres	Link on website to calculate payment estimates by region.	Annual payments during early years to compensate for initial practice changes or lump-sum payments based on carbon results.	Verra's pasture & rangeland modeling requirements
Bayer Carbon Program *[not currently available in CO]*	Cropland	15-30 years (5-20 years for performance + 10 years for retention)	>10 acres (must grow one of the accepted cash crops)	Up to $12/acre for adoption of no-till/strip-till & cover crops.	Annually	Model & protocol agnostic; may work with existing carbon accounting models and protocols.

Significance & Future Directions

This literature review provides an overview of rangeland ecology and outlines practical and tangible recommendations for carbon sequestration practices across rangelands and agricultural systems. Regenerative grazing strategies help to sequester and store more carbon in rangelands than continuous grazing, and there is great potential for grassland management in rangelands as well. These practices are important to highlight, and their implementation not only creates tangible benefits in terms of increased biodiversity, improved soil health, and economic diversification, but it also contributes to broader conservation goals at a regional and global scale. For example, sustainable practices will improve soil health through organic matter and nutrient cycling, diversify habitats, and create greater carbon sinks. These practices can significantly contribute to regional conservation efforts by reducing land degradation and restoring habitats.

While the field of agricultural carbon sequestration is still emerging, and much research is needed to develop effective strategies for sustainable practices, the potential for agriculture to become a net carbon sink, through the right combination of practices such as cover cropping, no-till, and perennialization, is promising. With continued research and investment, agriculture can play a pivotal role in addressing climate change and contributing to the global effort to mitigate its effects.

On a broader scale, integrating sustainable management across properties can create connected ecosystems that support biodiversity and ecosystem services, mitigating the increasing effects of fragmentation. Landowners will simultaneously benefit from these practices economically. For example, integrating tree planting with carefully managed grazing systems can generate income from timber, livestock, and carbon credits. By offering clear, practical strategies for soil carbon sequestration and sustainable agriculture, this research will help shape policies and initiatives that balance environmental goals with landowner needs.

References

Abdallah, M. A.B., Mata-González, M., Noller, J. S. & Ochoa, C. G. (2020). Ecosystem carbon in relation to woody plant encroachment and control: Juniper systems in Oregon, USA. Agriculture, Ecosystems & Environment, 290, https://doi.org/10.1016/j.agee.2019.106762

Alkemade, R., van Oorschot, M., Krol, M. & Lammers, J. (2013). Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. Proceedings of the National Academy of Sciences, 110(52), https://doi.org/10.1073/pnas.1011013108

Ayoma, L., Bartolome, J. W., Silva, L. & Silver, W. L. (2022). Using ecological site descriptions to make ranch-level decisions about where to manage for soil organic carbon. California Agriculture, 76(2-3), 85-92. https://doi.org/10.3733/ca.2022a0007

Bartley, R., Abbott, B. N., Ghahramani, A., Ali, A., Kerr, R., Roth, C. H., & Henderson, A. K. (2022). Do regenerative grazing management practices improve vegetation and soil health in grazed rangelands? Preliminary insights from a space-for-time study in the Great Barrier Reef catchments, Australia. The Rangeland Journal, 44(4), 221-246. https://doi.org/10.1071/RJ22047

Bayer Carbon Program. ForGround by Bayer. (n.d.). https://bayerforground.com/carbon-initiative

Bossio, D. (2020). Solid Ground: Earth's Soils Reveal Climate, Biodiversity & Food Security Solutions. The Nature Conservancy. https://www.nature.org/en-us/what-we-do/our-insights/perspectives/soils-revealed-climate-biodiversity-food-solutions/

Cerri, C. (2021). Soil carbon sequestration by sustainable management practices: Potential and opportunity for the Americas. Inter-American Institute for Cooperation on Agriculture, https://repositorio.iica.int/bitstream/handle/11324/19315/BVE21128138i.pdf

Dass, P., Houlton, B. Z., Wang, Y. & Warlind, D. (2018). Grasslands may be more reliable carbon sinks than forests in California. Environmental Research Letters, 13. DOI 10.1088/1748-9326/aacb39

Davies, K. W., Boyd, K. S., Svejcar, L. N. & Clenet, D. R. (2024). Long-term effects of revegetation efforts in annual grass-invaded rangeland. Rangeland Ecology and Management, 92, 59-67. https://doi.org/10.1016/j.rama.2023.10.001

Derner, J. D. & Schuman, G. E. (2007). Carbon sequestration and Rangelands: A synthesis of land management and precipitation effects. Journal of Soil and Water Conservation, 62(2), 77-85. https://www.jswconline.org/content/62/2/77.short

Díaz de Otálora, X., Epelde, L., Arranz, J., Garbisu, C., Ruiz, R. & Mandaluniz, N. (2021). Regenerative rotational grazing management of dairy sheep increases springtime grass production and topsoil carbon storage. Soil Biology and Biochemistry, 125, 107484. https://doi.org/10.1016/j.ecolind.2021.107484

Godde, C. M., Boone, R. B., Ash, A. J., Waha, K., Sloat, L. L., Thornton, P. K. & Herrero, M. (2020). Global rangeland production systems and livelihoods at threat under climate change and variability. Environmental Research Letters, 15(4), 044021. https://doi.org/10.1088/1748-9326/ab7395

Grassroots Carbon. (2024). https://grassrootscarbon.com/

Carbon sequestration in rangelands: An introduction. (n.d.). Idaho Rangeland Resources Commission. https://idrange.org/range-stories/eastern-idaho/carbon-sequestration-in-rangelands-an-introduction/#:~:text=Rangelands%20store%20about%2012%20percent,the%20earth's%20atmosphere%20and%20plants

Indigo AG: Sustainable Agriculture Solutions. Indigo Ag | Sustainable Agriculture Solutions. (n.d.). https://www.indigoag.com/

Kane, D. (2015). Carbon sequestration potential on agricultural lands: A review of current science and available practices. National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, https://static1.squarespace.com/static/5f02acd72c338a1f503e2739/t/6021a884fb79996f52594f1f/1612818566387/Carbon+Sequestration+Potential+on+Agricultural+Lands.pdf

Kleist, N., Domschke, C. T., Litschert, S. E., Seim, J. H. & Carter, S. K. (2022). Quantifying aspects of rangeland health at watershed scales in Colorado using remotely sensed data products. Rangelands, 44(6), 398-410. https://doi.org/10.1016/j.rala.2022.09.003

Collinge, S. (2020, November 8). Plant diversity linked to higher levels of carbon storage in Boulder's grassland ecosystems. Center for Sustainable Landscapes and Communities. https://cslc.colorado.edu/2020-trends/plant-biodiversity-tied-to-higher-levels-of-carbon-storage-in-the-soil

Carbon sequestration in rangeland and pasture ecosystems. Oregon State University Ecohydrology. (n.d.). https://ecohydrology.oregonstate.edu/project/carbon-sequestration-rangeland-and-pasture-ecosystems#:~:text=Well%2Dmanaged%20rangeland%20and%20pasture,water%2C%20and%20vegetation%20conditions%20overall

Agoro Carbon Alliance. (n.d.). https://agorocarbonalliance.com/our-carbon-program/

Owen, J. J., Parton, W. J. & Silver, W. L. (2015). Long-term impacts of manure amendments on carbon and greenhouse gas dynamics of rangelands. Global Change Biology, 21(12), 4533-4547. https://doi-org.coloradocollege.idm.oclc.org/10.1111/gcb.13044

Wang, T. (2013). Rotational grazing improves stocking capacity and ranch profitability. SDSU Extension. https://extension.sdstate.edu/rotational-grazing-improves-stocking-capacity-and-ranch-profitability

Silviera, M. L., Rodrigues da Cruz, P. J., Bueno Vendramini, J. M., Boughton, E., Bracho, R. & da Silva Cardoso, A. (2024). Opportunities to increase soil carbon sequestration in grazing lands in the southeastern United States. Grassland Research, 3(1), 69-78. https://doi.org/10.1002/glr2.12074

Teague, W. R., & Kreuter, U. P. (2020). Managing grazing to restore soil health, ecosystem function, and ecosystem services. Frontiers in Sustainable Food Systems, 4. https://doi.org/10.3389/fsufs.2020.534187

Cattle and land use: Differences between arable land and marginal land, and how cattle use them. (n.d.). UC Davis. Clear.ucdavis.edu,https://clear.ucdavis.edu/explainers/cattle-and-land-use-differences-between-arable-land-and-marginal-land-and-how-cattle-use

Unlocking Your Grasslands Carbon Potential. Kateri. (n.d.). https://katericarbon.com/

Climate-smart mitigation activities for managing invasive vegetation and improving carbon sequestration. (n.d.). USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/climate/climate-smart-mitigation-activities

Waterhouse, H., Aburto, F., Rees, G., Griffin-LaHue, D. E., Salls, W. B., Rippner, D. A., Tian, Z., Scow, K. & O'Geen, A. T. (2023). Diversified vegetation types on rangelands promote multiple soil-based ecosystem services. Land Degradation & Development, 35(3), 1011-1028. DOI10.1002/ldr.4967

CASE STUDY: SOIL CARBON CONTENT ACROSS CONSERVED PUBLIC PROPERTIES IN SOUTHCENTRAL COLORADO

Background

Soils have the potential to store substantial amounts of carbon and help slow climate change. Soil carbon content varies across life zones, and is influenced by climate, land cover, and soil texture. Soil organic carbon is a measurable component of soil organic matter. Organic matter makes up just 2–10% of most soil's mass and plays an important role in the physical, chemical and biological function of soils. For example, organic matter contributes to nutrient retention and turnover, soil structure, moisture retention and availability, degradation of pollutants, and importantly, carbon sequestration. The organic carbon content of soils in Colorado typically ranges between 0.7% and 4% (Colorado State Forest Service 2022), although it can be as low as 0.3% for desert soils and as high as 14% for intensive agricultural soils.

Given the interest in carbon markets in southcentral Colorado, we conducted a case study to evaluate soil carbon percentage across public conserved properties that varied across life zones. Given differences in vegetation communities across life zones, we were interested in assessing potential associated differences in carbon soil storage.

Sampling Design

Study sites

To obtain a general estimate of regional soil carbon percentages, we collected soil samples from eight separate sampling sites – two conservation easements across each of four life zones in southcentral Colorado (Plains, Foothills, Montane, and Sub-alpine life zones; Fig. 2.3). Additionally, we collected elevation data from the center of each sampling site plot using a 10-m digital elevation model (DEM) from USGS in ArcGIS Pro.

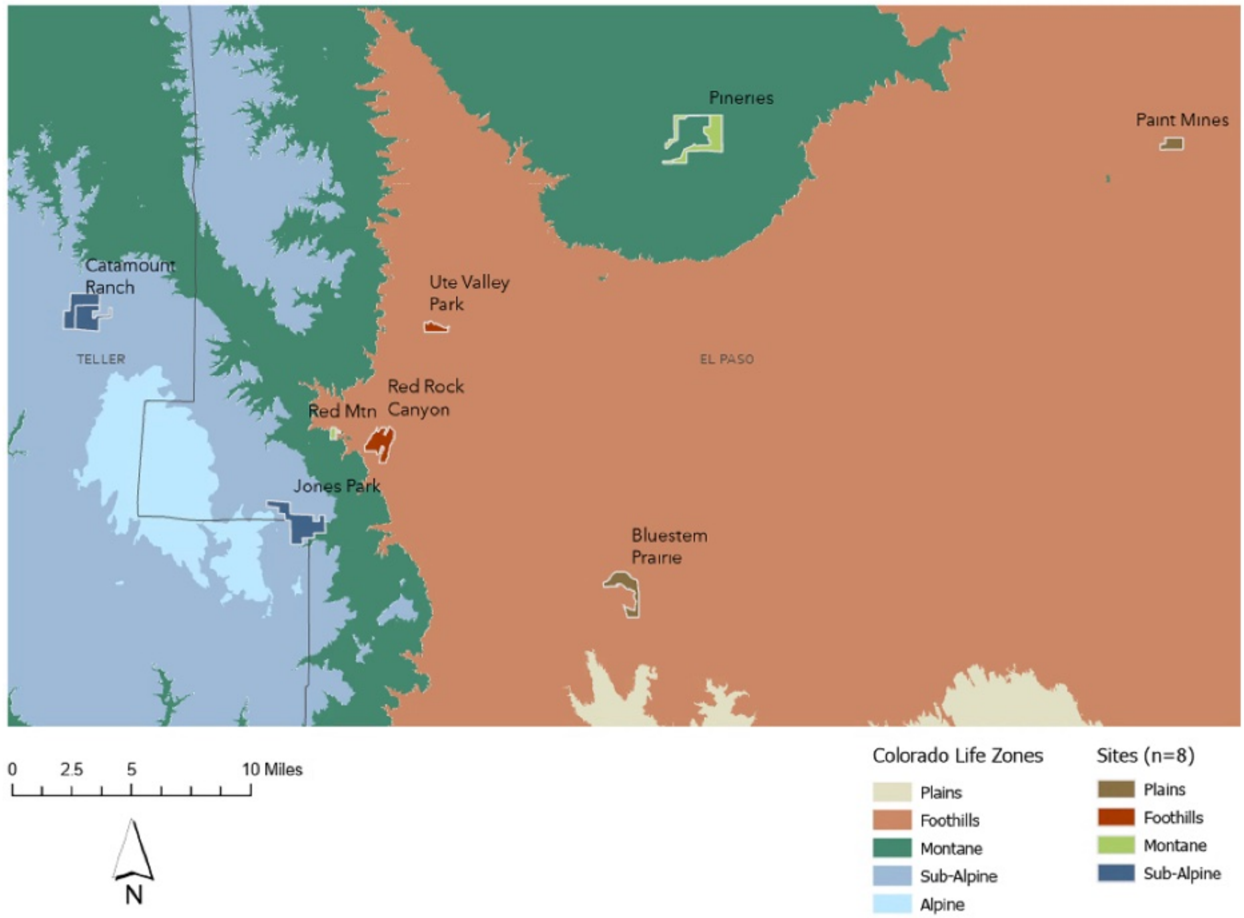


Figure 2.3. Soil sampling sites (n=8) across the Plains, Foothills, Montane, and Sub-alpine life zones in El Paso County and Teller Counties, Colorado, U.S.A.

Soil sampling

We collected soil samples across the span of four days in September 2024 (September 24-27, 2024). By collecting samples within a short duration of time, and during the non-growing season, our aim was to minimize the impact of plant growth on soil carbon content.

We randomly selected 3 sample sites per property, each within 2 miles from road-access for logistical purposes. At each sample site, we used a clean trowel to dig a hole to a minimum depth of 30 cm. We chose this depth as many voluntary carbon markets requiring samples to be taken from 0-30 cm depth or deeper. We then used a 12-inch soil core probe to collect a soil sample. We collected 3 individual cores from a 25 m^2 quadrat that was placed on a homogenous area (*e.g.* same slope, similar aboveground vegetation) at each sample site; these cores were then mixed together to create a composite sample. This was done to get a representative sample that also accounted for potential local variability in soil carbon content.

Soil carbon analysis

We measured soil carbon content using two different methods: (1) elemental analysis of relative percentage of carbon in each sample using an NC2100 Elemental Analyzer; and (2) estimated percentage of organic material via weight difference before and after drying the sample at high heat.

Prior to analysis, we sieved each soil sample using a 2-mm sieve. The sieve and metal capture basin were cleaned between each sample so as to prevent cross contamination. After sieving each sample, we used tweezers to pick out any medium-large roots or other organic matter that made it through the sieve. Next, we placed each sieved sample into a metal oven dish labeled with its site ID and placed it in a 60˚C oven overnight.

ThermoQuest NC2100 Soil Elemental Analyzer (Colorado College)

After the sample was dried, it was pulverized, and a small (20 mg) sample was analyzed using a ThermoQuest NC2100 soil analyzer. The ThermoQuest NC2100 measures the relative abundance of carbon and nitrogen in soil samples by combusting samples in the presence of high-purity oxygen, oxidizing the combustion products in a chromium trioxide column, reducing the oxides with a reduced copper column, drying the sample via manganese perchlorate, separating the analysts with a chromatography column, then by detecting the separated components with a thermal conductivity detector.

Findings

Overall, across the eight surveyed publicly conserved properties sampled, soil carbon percentages were relatively low. Across all soil samples, soil carbon percentages ranged from 0.715-3.796% (Table 2.4). The lowest average percent carbon by property was found at Pineries Open Space (1.252%; Fig. 2.4 & 2.5), whereas the highest average percent carbon was found at Red Mountain Open Space (2.187%; Fig. 2.4 & 2.5). Soil carbon varied most across samples collected in the Montane life zone (Fig. 2.4), which could be a result of the most heterogeneous vegetation communities present therein. We did not find elevation to be a significant variable controlling differences in soil carbon between sites (Fig. 2.6).

While soil-based carbon sequestration is a valuable method for global sequestration efforts, tree-based carbon sequestration often considered more readily quantifiable than soil-based sequestration as trees generally store a larger amount of carbon per unit area compared to soil, primarily due to the biomass in their trunks and branches. Accordingly, future studies might instead consider assessing above-ground carbon for a more accurate evaluation of carbon storage potential of a landscape.

Table 2.4. Percent soil carbon (%C), nitrogen (%N), and total organic material (% organics) from soil samples (n=24) collected from public conserved lands in El Paso County and Teller County, Colorado, U.S.A.

Life Zone	Property	Ownership	Sample ID	%C	%N	% organics
Plains	Bluestem Prairie Open Space	City of Colorado Springs	bluestem_01	1.529	0.146	5.91
			bluestem_02	1.486	0.128	7.06
			bluestem_03	1.051	0.104	7.22
	Paint Mines Interpretive Park	El Paso County	paintmines_01	2.241	0.105	13.52
			paintmines_02	2.180	0.197	12.47
			paintmines_03	1.070	0.104	5.45
Foothills	Red Rock Canyon Open Space	City of Colorado Springs	redrockcanyon_01	1.448	0.068	4.95
			redrockcanyon_02	2.939	0.217	7.79
			redrockcanyon_03	0.786	0.044	3.87
	Ute Valley Park	City of Colorado Springs	utevalley_01	1.496	0.067	5.50
			utevalley_02	1.704	0.111	6.76
			utevalley_03	1.635	0.085	3.91
Montane	Pineries Open Space	El Paso County	pineries_01	2.278	0.113	5.59
			pineries_02	0.763	0.032	2.29
			pineries_03	0.715	0.089	1.85
	Red Mountain Open Space	City of Manitou Springs	redmtn_01	1.593	0.086	4.39
			redmtn_02	3.796	0.250	5.32
			redmtn_03	1.173	0.074	3.67
Sub-alpine	Catamount Ranch Open Space	Teller County	catamount_01	1.063	0.042	4.02
			catamount_02	1.165	0.036	4.25
			catamount_03	1.822	0.067	5.59
	Jones Park Open Space	El Paso County	jonespark_01	1.465	0.068	3.81
			jonespark_02	1.925	0.106	4.96
			jonespark_03	2.153	0.135	5.12

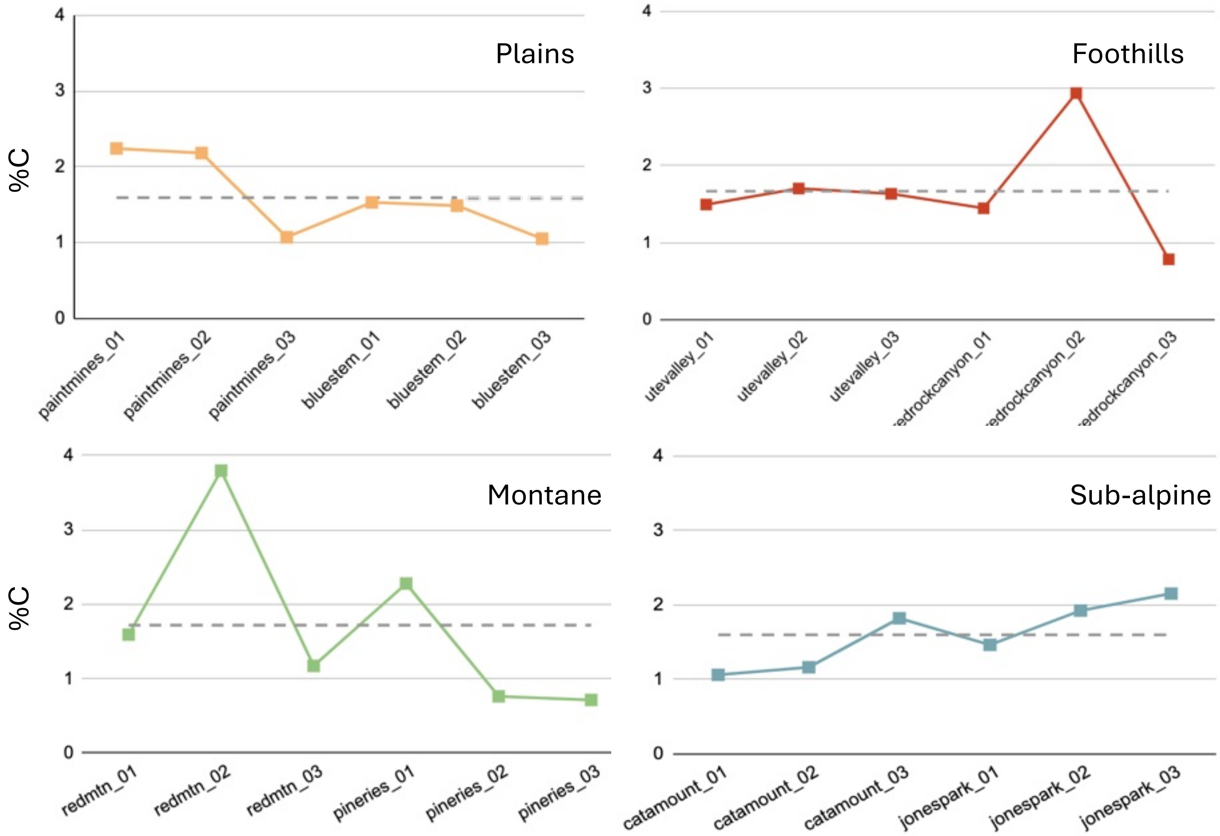


Figure 2.4. Percent soil carbon (%C) of soil samples (n=24) collected from public conserved lands across the Plains, Foothills, Montane, and Sub-alpine life zones in El Paso County and Teller County, Colorado, U.S.A. The dashed grey line in each graph represents the average %C across all samples (n=6) in each life zone.

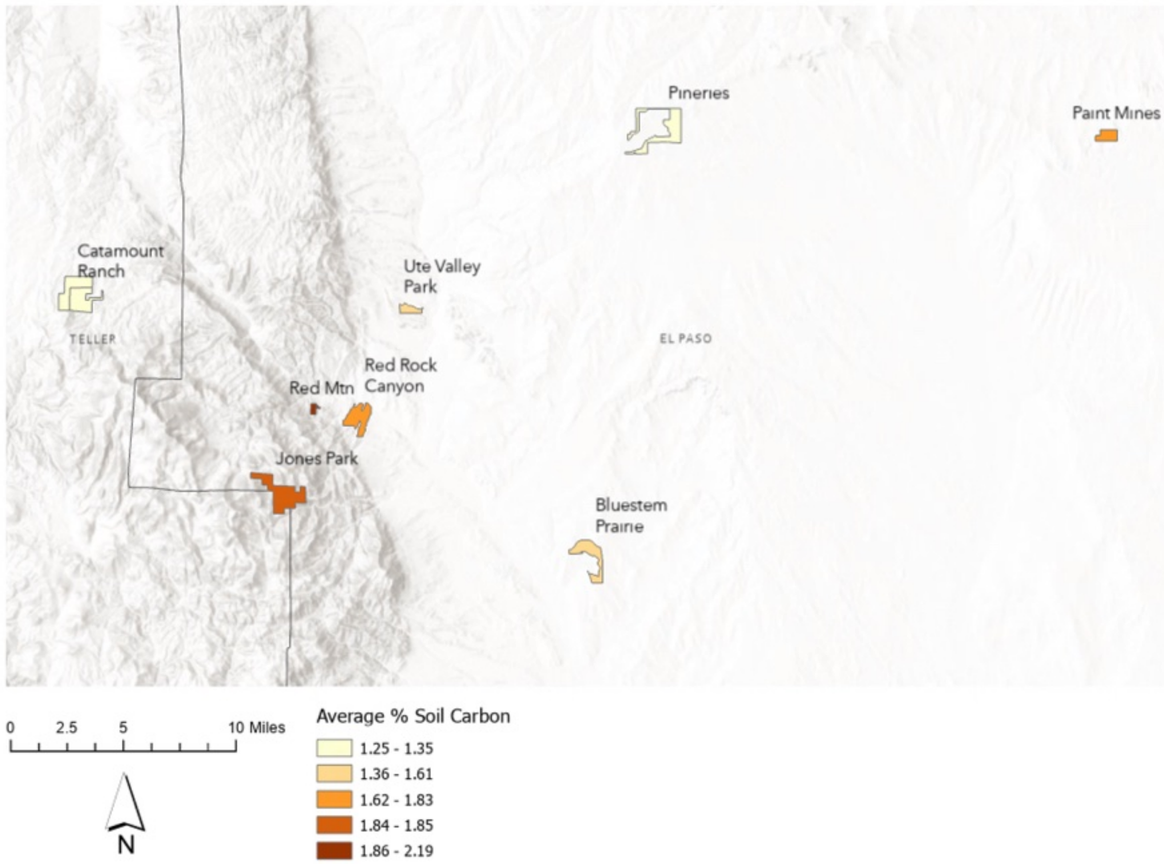


Figure 2.5. Average percent soil carbon (%C) across sites (n=8).

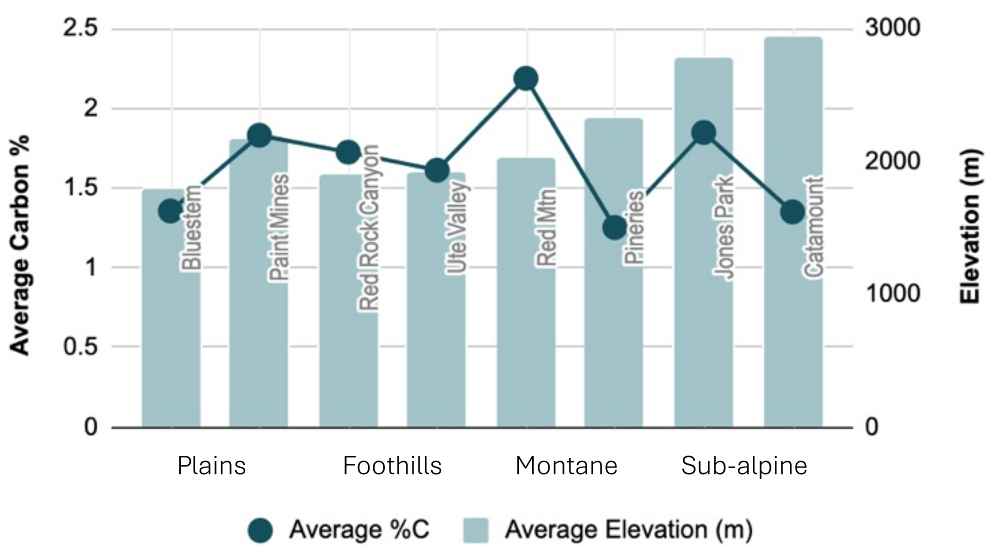
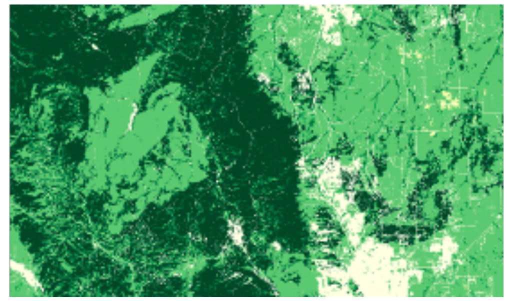


Figure 2.6. Average percent soil carbon (%C) and elevation (m) across sites (n=8).

3 CARBON ASSESSMENT & MONITORING

NICO BRUBAKER, ROBBIE DAY, SACHA LEVINE, SHAELYN SHEAFF





Carbon sequestration within natural landscapes is an increasingly prevalent topic of discussion when considering global climate change mitigation efforts. Preserving landscapes as they naturally occur preserves the carbon that is held, or sequestered, within the biota and soil of the landscape, which can help to counteract industrial emissions. In addition to storing carbon, landscape conservation protects species habitat, landscape connectivity, and biodiversity. Landscapes vary in the degree to which they serve as carbon pools owing to their differential effects driven by regional climate and species composition. As a result, making large-scale estimates of forest carbon storage is difficult, particularly when the study area is highly heterogenous. Nevertheless, while management practices to maximize carbon storage potential vary, it is important to consider the carbon sequestration potential across all landscape types to maximize sequestration efforts across large spatial scales.

In this chapter, we characterized carbon sequestration across multiple landscape types within a 14-county region in southcentral Colorado (Crowley, Custer, Douglas, El Paso, Elbert, Fremont, Huerfano, Jefferson, Las Animas, Lincoln, Otero, Park, Pueblo, and Teller Counties). We selected this study extent as it encompasses the areas that Palmer Land Conservancy (PLC) currently serves and beyond. This research aims to provide a general assessment of carbon storage within the region, which can inform future decision-making about potential opportunities to engage in carbon markets.

Methods for monitoring carbon sequestration across large landscapes

There are numerous tools available to measure carbon storage and carbon storage potentials within a landscape. Variables such as the extent of the study region, level of accuracy/precision desired, and variability within the landscape are all important factors to consider when choosing the most appropriate method to estimate carbon storage levels. Herein, we explore the use of remote sensing, as it is a technology commonly-used by carbon companies for assessment and monitoring of carbon storage (Malerba et al., 2023; Watts et al., 2009) due to its low cost, time efficiency, and the ability to access current data at relatively frequent temporal scales. Shortcomings include the inability to measure carbon storage in the understory and soil of the forest and lower accuracy at large scales to represent diversity of tree species and consequent differences in carbon storage abilities.

Carbon storage can also be measured using process-based methods, including forest yield models and forest inventory approaches. Process-based methods require extensive data collection and can be limited to smaller spatial scales. Forest yield models are economical, cover a large region, including the understory of the forest, but are generally more time consuming to complete (Qureshi et al., 2012). Forest inventory is also comparatively economical and covers a large study area but has lower reported accuracy and excludes the understory from carbon storage estimates (Qureshi et al., 2012).

Using remote sensing to assess changes in carbon storage over time

We used Landsat-9 and MODIS satellite imagery, land cover data, existing soil carbon data, and aboveground and belowground carbon densities. The Landsat-9 satellite takes images of the Earth's surface at a 30-m spatial resolution and covers the Earth every 16 days (Landsat-9, 2021). MODIS imagery has a spatial resolution ranging from 250-1000 m (depending on the band), which limits its ability to detect fine-scale differences in landcover compared to the higher resolution of Landsat. However, MODIS images the entire Earth's surface in 1-2 days, thereby providing high temporal resolution and great utility for frequent monitoring of carbon sequestration over time.

Herein, we investigate three different approaches to estimate carbon storage across the study area. We compare the results across each of the approaches listed below and evaluate the benefits and limitations of each:

1. InVEST Carbon Storage and Sequestration Model (CSSM)
2. Net Primary Productivity (NPP), estimated using the Global Land Evaporation Amsterdam Model (GLEAM)
3. Carbon Sequestration Potential Index (CSPI)

InVEST® Carbon Storage and Sequestration Model (CSSM)

The CSSM is a model developed by the Natural Capital Project — a global collaboration between research universities, conservation-focused nonprofits, and government agencies — that aggregates data about various types of carbon sinks and land cover to estimate the current amount of carbon stored in the landscape (https://naturalcapitalproject.stanford.edu/software/invest).

Methods. The CCSM utilized 4 main spatial data inputs: land cover data, above- and belowground biomass, soil organic carbon, and a statewide estimate of coarse woody debris carbon. First, we classified U.S. Geological Survey Annual Land Cover data into eight individual categories: water, wetlands, forest, grassland, pasture/hay, cultivated crops, developed, and barren. Next, we obtained spatial data layers to characterize various carbon sinks: above- and belowground biomass, soil organic carbon, and a statewide estimate of coarse woody debris carbon. The biomass carbon density is a remotely sensed estimate that we obtained from the Oak Ridge National Laboratory's Distributed Active Archive Center, last updated in 2010 at a 300-meter spatial resolution.

The soil organic carbon data, last updated in 2024, was downloaded from the U.S. Department of Agriculture's Gridded Soil Survey Geographic Database at a 30-meter spatial resolution. We used soil organic carbon estimates from a standard depth of 30-cm. Finally, while carbon density data for dead wood and leaf litter is difficult to sense remotely, we used estimates from the U.S. Forest Service's National Forest Inventory, calculated at the state level and last updated in 2022, as these data are considered reasonable estimates for models of this type (Smith *et al.*, 2022). With these data, we used the Zonal Statistics tool in ArcGIS Pro to calculate average carbon density within each land-cover type for each carbon sink. We found that statewide dead wood and litter carbon was estimated to be 7.61 t C/ha across all land cover types. This analysis returned non-zero values for bodies of water and developed land; accordingly, we replaced these values with zero given their limited potential to sequester carbon. Finally, we input these averages into InVEST Workbench version 3.14.2 to produce a 30-m raster data layer of estimated carbon density, in meters per hectare, for each of the eight land-cover types.

Findings. The InVEST Carbon Storage and Sequestration Index modeled the density, in metric tons per hectare, of carbon stored in Palmer Land Conservancy's service area (Fig. 3.1). The data is uniform within each type of land cover, where darker areas of the map indicate a land cover type with a higher density of sequestered carbon compared to lighter areas. Our findings demonstrated that forests had the highest carbon density (435.6 t C/ha) while wetlands were a distant second (170.3 t C/ha). Notably, cultivated crops (66.0 t C/ha) have lower carbon density than barren land (74.2 t C/ha), while pasture and hay land is comparatively higher (135.6 t C/ha). These results highlight a potential benefit of cropland-to-pasture conversions in the Eastern Plains and Arkansas River Basin, which have been shown to increase soil organic carbon content (Yellajosula *et al.,* 2020). Furthermore, the high proportion of forest cover in the mountains west of Colorado Springs makes this region a large carbon sink deserving of consideration.

Limitations. While the InVEST model does an effective job at showing the density of carbon storage, it faces some limitations. Assigning only one value of carbon sequestered for a landcover ignores the heterogeneity present across that landcover. This is a limit of the method used to calculate InVEST, as the program is designed to assign values in that manner. Reducing the scale of the analyzed area could mitigate this issue. There is a large variation in grasslands true sequestration as they can vary in elevation and environment, but all received the same value. As with any model, the results are only as good as the data put in. Remotely sensed above ground carbon data has some limitations in its accuracy at state scale. Despite these limitations InVEST provided a good estimate of carbon across the working area.

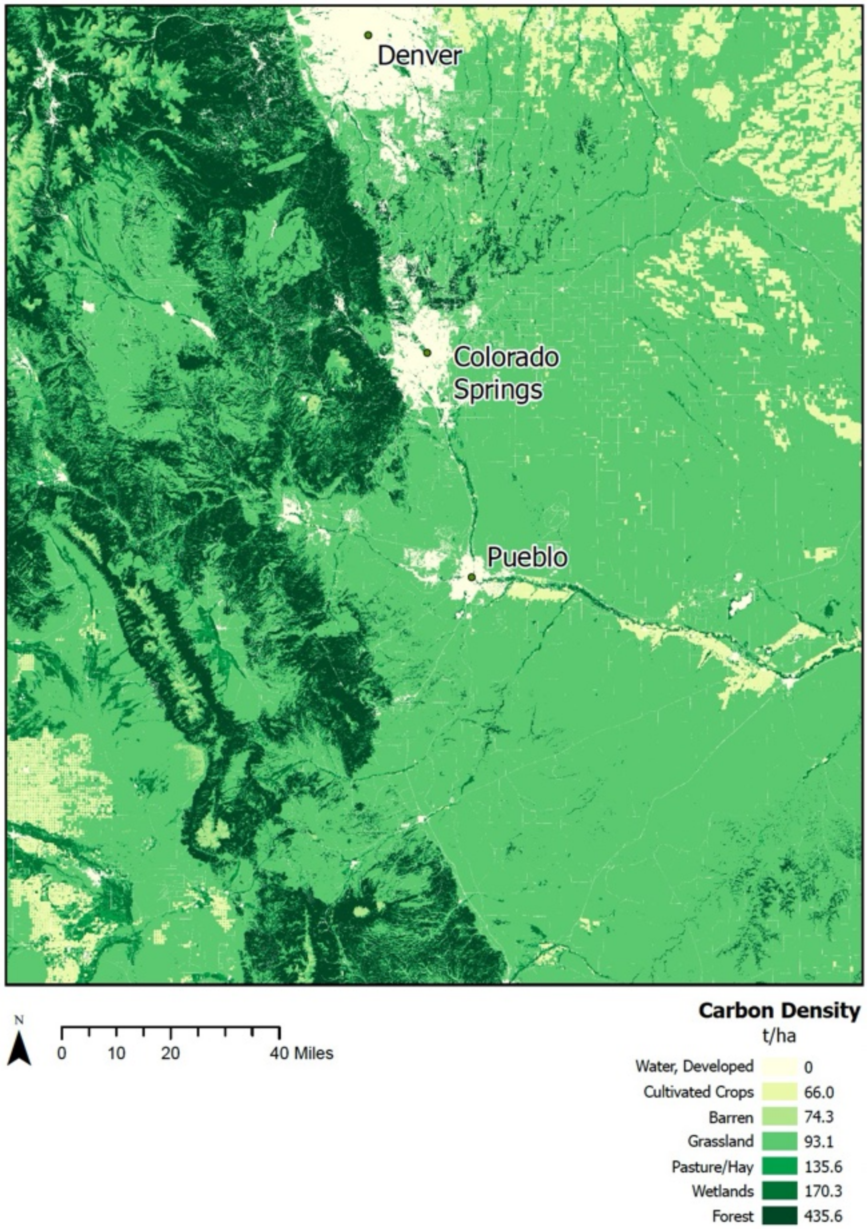


Figure 3.1. Carbon density (in metric tons C/ha) estimated using the InVEST Carbon Storage and Sequestration Index.

Net Primary Productivity (NPP)

Net primary productivity represents the amount of carbon stored long term in plant tissues. Unlike gross primary productivity it accounts for the carbon used by plants in cellular respiration and other processes. However, it does not consider the parts of the plants consumed by primary consumers or destroyed by anthropogenic processes.

Methods. To estimate NPP across the study area, we used data including landcover and estimates of water use efficiency (WUE) and transpiration from the Global Land Evaporation Amsterdam Model (GLEAM). First, we retrieved landcover data from the National Landcover Database (NLCD) - a 30-m raster data layer created by the USGS that classifies the Continental U.S. into 16 landcover types. From this layer, we removed all but 7 land cover types: deciduous forests, evergreen forests, mixed forests, shrub/scrub, grassland/herbaceous, pasture/hay, and cultivated crops. Next, the data was resampled to the 10-km spatial resolution of GLEAM using a bilinear method. To determine water-use-efficiency (WUE) across the study area, we reclassified forest landcover types to dominance by C3 or C4 plants, based off of an assessment produced by Lee & Veizer (2003) of C3 and C4 plant coverage in Mississippi. Deciduous forests, mixed forests, and shrub/scrub were assigned a yearlong WUE of 500 mol H_2O/mol CO_2 whereas grassland/herbaceous, pasture/hay, and cultivated crops were assigned a WUE of 250 mol H_2O/mol CO_2.

The Global Land Evaporation Amsterdam Model (GLEAM) uses estimates of global evapotranspiration and separates it into its component parts based on satellite observations (Miralles *et al.* 2011); GLEAM calculates daily, monthly, and yearly moisture fluxes globally at a 10-km spatial resolution. We calculated transpiration data in mm/day as a daily average for 2023, imported it into ArcGIS Pro as a NetCDF, and clipped the resulting raster layer to the study area extent. Finally, we used the raster calculator geoprocessing tool in ArcGIS Pro to derive Net Primary Productivity (NPP) from WUE and Transpiration using the following equation: NPP = Transpiration * WUE (Lee & Veizer 2003). Units were converted to reach NPP and the final NPP was expressed as metric tons per hectare.

Findings. We found that NPP varied across Southeast Colorado, ranging from 5 to 87 Mg of CO_2/ha/yr (mean = 26.1 Mg of CO_2/ha/yr) with relatively isolated areas of high NPP observed in the more forested, mountainous parts of the region (Fig. 3.2). The northeast portion of the region has a smooth gradient between cells while most other regions are diverse in their values. The mean value of 26.1 Mg of CO_2/ha/yr (or 7.09 Mg of C/ha/yr) aligns with estimates from Scurlock & Olson (2013), who found that C4 grasslands in Colorado have an estimated NPP of 7.4 Mg of C/ha/yr. High NPP values occur most frequently in mountainous regions and could be explained by highly productive old growth forests. It could also be explained by GLEAM's comparatively lower accuracy in separating transpiration from evapotranspiration in topographically dynamic environments.

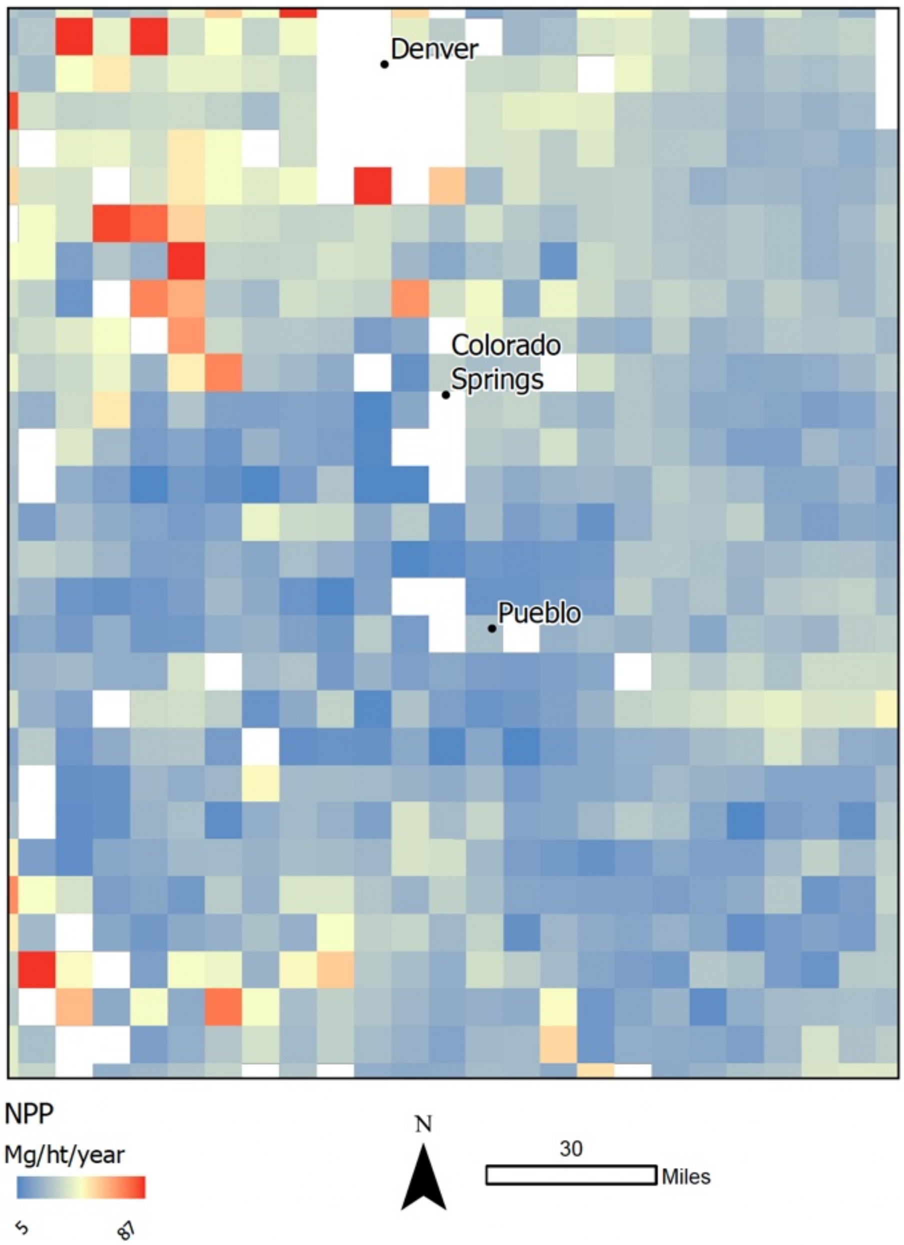


Figure 3.2. Net primary productivity (NPP, in Mg/ha/year) at 10-km spatial resolution across southcentral Colorado. White pixels represent areas where no significant biomass exists (*e.g.*, urban development or barren land).

Limitations. The number one limiting factor in terms of NPP's use as a direct way of quantifying carbon sequestration is the spatial resolution. Having transpiration be homogenous across a 10km^2 resolution limits the variability that can be seen in dynamic mountain environments that cover Southeast Colorado. Microclimates occur and vary on east/west slopes and have varying transpiration rates, however this variability is neglected within GLEAM due to the spatial resolution. Refinements in the model could lead to greater heterogeneity in the map. Despite the dynamic environments present in the landscape area no significant difference in NPP across them is a function of the spatial resolution, not a real pattern.

Carbon Sequestration Potential Index (CSPI)

The Carbon Sequestration Potential Index (CSPI) identifies areas capable of sequestering carbon following afforestation by using near infrared reflectance of vegetation (NIRv), above ground carbon, and forest cover data (Pascual et al. 2021). CSPI can be used to support planting efforts in Colorado to improve carbon sequestration rates. Additionally, CSPI serves as a guide for decision making surrounding sustainable management practices (Pascual et al. 2021). CSPI's methodology is relatively simple and requires data that is readily available through the USGS Earth Explorer platform, making it a useful and accessible tool for conservation efforts.

Methods. To calculate CSPI, we overlaid a 100x100 grid over the study area in ArcGIS Pro to create individual management areas across the landscape. To determine the possibility for carbon sequestration and afforestation, we used Landsat-9 satellite images to calculate NIRv; all of the images were acquired between January 1st, 2023 and December 30th, 2023, and had minimal to no cloud cover. Using the red (band 4) and infrared (band 5) bands, we calculated normalized difference vegetation index (NDVI) using the raster calculator in ArcGIS Pro. Next, NIRv was determined using the equation NIRv = NDVI x NIR. This produced a 30-m resolution raster data layer containing estimates of gross primary production (GPP), which is defined as the rate at which atmospheric carbon is fixed by photosynthesis. Aboveground Carbon Density (ACD) was determined using remotely sensed data updated in 2010 from the Oak Ridge National Laboratory's Distributed Active Archive Center, at a 300-m spatial resolution. Forest cover data (FC) was determined using our land cover data categories and classified as 0, non-forest, or 1, forest. We then used the Zonal statistics tool in ArcGIS Pro to create a raster layer representing the proportion of forest cover for each management area. Finally, we used the raster calculator to calculate CSPI using the following equation: $CSPI = GPP_{NIRv} \times ACD - 1 \times (1 - FC)$. The final raster layer provides a measure of opportunity for restoration and afforestation that accounts for the available space within a management area not occupied by forest vegetation. Low values of CSPI indicate a high level of forest cover (FC) and therefore a lower potential for afforestation. Higher values of CSPI indicate lower levels of FC and ACD, and a higher potential for carbon assimilation. While values of CSPI ranged from 0-944, we rescaled the data to 0-1 for greater interpretability.

Findings. The Carbon Sequestration Potential Index (CSPI) identified the places in southeastern Colorado with high levels of possible carbon sequestration through afforestation and reforestation (Fig. 3.3). The land cover types with the highest CSPI levels include grasslands southeast of Pueblo, grasslands southwest of Colorado Springs and cultivated cropland and grassland to the east of the Sangre De Cristo mountains. Each management area has its own unique value of CSPI which accounts for the space in the management area without forest vegetation.

Reforestation is among the fifteen most effective methods for reducing atmospheric carbon dioxide (Fegyveresi *et al.* 2022). One possible method for reducing atmospheric carbon through afforestation in Colorado is by planting Ponderosa pine trees, one of the most common native tree species in Colorado. Coniferous trees are a major carbon reservoir due to their high storage capacity and ability to assimilate carbon dioxide. A fully mature Ponderosa Pine stand has the potential to sequester 175.1 metric tons of carbon per hectare (Fegyveresi *et al*. 2022). Afforestation of relatively low-production cropland and implementing agroforestry practices are other promising methods to sequester atmospheric carbon.

Remote sensing of carbon capture and sequestration is still a relatively new field. Using CSPI to apply afforestation practices to former agricultural lands could serve as a low-cost way to improve carbon sequestration while more permanent methods of CO_2 sequestration can be developed and implemented. Increasing biomass in agricultural lands could also serve as a renewable energy source and decrease reliance on fossil fuels (Potter *et al.* 2007). Additionally, using CSPI alongside field data such as forest type could greatly improve the accuracy of the index by providing more data about forest coverage and canopy height as well as aboveground carbon density.

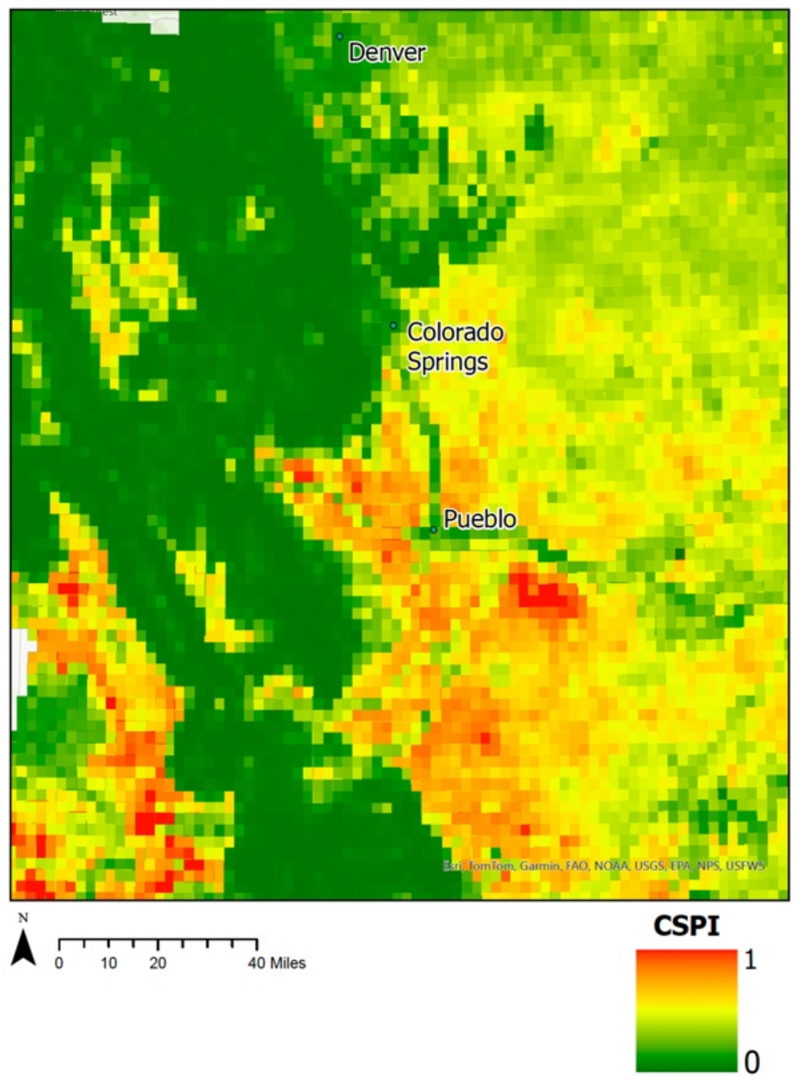


Figure 3.3. Carbon Sequestration Potential Index (CSPI). Areas with CSPI approaching 1 (red) indicate locations with the highest potential for afforestation whereas areas with CSPI approaching 0 (green) represent locations with already high forest cover and therefore have limited potential to undergo afforestation.

Limitations. CSPI is only useful in areas where afforestation can occur, to improve further uses of CSPI in Colorado, more forest data should be collected. CSPI is most accurate when tree canopy height is measured, as well as tree type. Future studies using CSPI could implement light detection ranging (LiDAR) to improve data accuracy of forest height and type. LiDAR is measured at a much smaller extent than Landsat and MODIS images which makes it a useful tool for measuring carbon sequestration across smaller landscapes. LiDAR is typically collected using planes and helicopters with laser sensors attached to them (noaa.gov). While LiDAR is currently not as accessible as the remote sensing technologies used herein, the increasing salience of carbon sequestration in the United States could lead to more extensive LiDAR scans of the continent.

Comparison of Carbon Storage Indices

Each of the three indices used in this study has applications specific to land cover type, as well as scale (Table 3.1). The standalone model, InVest, was the most useful for visualizing current levels of carbon sequestration across our management area. InVest identified the areas in southeastern Colorado that are the densest carbon sinks across the 8 landcover types. However, this model does not provide any data about future expansion or potential of carbon sequestration. CSPI measures potential for carbon sequestration through afforestation and is most useful for people considering implementing agroforestry practices and planting new forest stands. While the areas with high CSPI are clearly identifiable on the map, the individual management areas encompass large areas of land with variability in land type. The NPP model measures atmospheric carbon dioxide that is consumed by plants and turned into biomass each year. NPP is most useful when assessing overall ecosystem productivity; however, it does not account for biomass removed from the ecosystem.

Table 3.1. Mean value for each of the three indices calculated by landcover type.

	InVEST (t C/ha)	NPP (Mg of CO/ha/yr)	CSPI (unitless)
Barren land	74.2	26.1	46.1
Forest	435.6	26.6	12.3
Grassland	93.1	23.2	184.2
Pasture/hay	135.6	24.2	147.4
Cultivated crops	66.0	25.5	146.5
Wetlands	170.3	28.7	125.1

Significance & Future Directions

Carbon sequestration and storage is highly important in the context of conservation, but many other metrics are needed to more holistically understand other factors of ecosystem health and conservation. Some shortcomings of current methodology to estimate carbon sequestration are the, at times, ambiguous methods of measuring carbon across large landscapes that may be poorly understood. It is important to have a context of broader ecological functions within an ecosystem to understand the ways in which carbon cycles throughout the landscape, and therefore how it is stored. Understanding the historical ways in which the land has been managed is also a relevant factor when assessing the amount of carbon that is stored within the landscape (Forest *et al.,* 2003). Taking into account the age of a forest, species diversity, and knowing if a forest replaced a different native landcover types, are all influential factors for understanding carbon storage within a landscape (Foster *et al.,* 2003).

We created data deliverables that can be used to illustrate the potential for carbon credit opportunities in southcentral Colorado. For example, by looking at already existing easements or managed areas, data about current storage of carbon (CSPI) could inform possibilities for additionality. Alternatively, these data could present landowners or other individuals with information about their land if there was potential for afforestation (InVEST). Finally, by using net primary productivity (NPP) values, we can contextualize productive areas throughout the study area to inform which areas may have a greater potential for carbon storage or sequestration.

While indices are useful for providing information on general trends of carbon storage potential across the region, they are limited by the data used. Refining both the input data and verifying the results are important parts of remote sensing. Further improvements could be made by improving both spatial and spectral resolution. Spatial resolution is the main limiting factor in NPP analysis and CSPI requires fine data of tree locations to determine forest cover. Improved spectral resolution could also lead to improvement in remote sensing of soil organic carbon (Nayak *et al.* 2019). By using the VNIR and Mid-NIR spectral ranges carbon content in moist soils can be remotely sensed using commercial drones. In the future with Landsat NEXT's launch around 2030 15 more band designations will be added reaching hyperspectral resolution (NASA 2024). This would make remote sensing of soil carbon possible at varying scales using remote sensing instead of measuring and interpolating like the data used in InVEST. By improving modeling techniques and technologies, carbon sequestration and monitoring could eventually become a fully remote process.

References

California cap and Trade. Center for Climate and Energy Solutions. (2021, August 24). https://www.c2es.org/content/california-cap-and-trade/

Fegyveresi, J. (2022). Carbon sequestration through Ponderosa Pine Reforestation. The Earth Scientist. aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/education/planet-stewards/earthscientists/pdf/Fegyveresi_Article.pdf

Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., & Knapp, A. (2003). The importance of land-use legacies to ecology and conservation. BioScience, 53(1), 77-88.

Johnson, N. (2024, June 3). How carbon credits are verified: The Carbon Credit Verification process. EcoCart. https://ecocart.io/how-carbon-credits-are-verified/

Lee, D., & Veizer, J. (2003). Water and carbon cycles in the Mississippi River Basin: Potential implications for the Northern Hemisphere residual terrestrial sink. Global Biogeochemical Cycles, 17(2). https://doi.org/10.1029/2002gb001984

Malerba, M. E., Duarte de Paula Costa, M., Friess, D. A., Schuster, L., Young, M. A., Lagomasino, D., Serrano, O., Hickey, S. M., York, P. H., Rasheed, M., Lefcheck, J. S., Radford, B., Atwood, T. B., Ierodiaconou, D., & Macreadie, P. (2023). Remote sensing for cost-effective Blue Carbon Accounting. Earth-Science Reviews, 238, 104337. https://doi.org/10.1016/j.earscirev.2023.104337

Miralles, D.G., Holmes, T.R.H., de Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J. Global land-surface evaporation estimated from satellite-based observations, Hydrology and Earth System Sciences, 15, 453–469, doi: 10.5194/hess-15-453-2011, 2011

Miralles, D.G., Bonte, O., Koppa, A., Baez-Villanueva, O.M., Tronquo, E., Zhong, F., Beck, H.E., Hulsman, P., Dorigo, W.A., Verhoest, N.E.C., Haghdoost, S. GLEAM4: global land evaporation datasets at 0.1° resolution from 1980 to near present, in review.

NASA. (2022, March 24). Landsat 9. NASA. https://landsat.gsfc.nasa.gov/satellites/landsat-9/

NASA. (n.d.). Modis web. NASA. https://modis.gsfc.nasa.gov/about/specifications.php

NASA. (2024, September 12). Landsat next. LANDSAT Science. https://landsat.gsfc.nasa.gov/satellites/landsat-next/

Pascual, A., Giardina, C. P., Selmants, P. C., Laramee, L. J., & Asner, G. P. (2021). A new remote sensing-based carbon sequestration potential index (CSPI): A tool to support land carbon management. Forest Ecology and Management, 494, 119343. https://doi.org/10.1016/j.foreco.2021.119343.

Qureshi, A., Pariva, Badola, R., & Hussain, S. A. (2012). A review of protocols used for assessment of carbon stock in forested landscapes. Environmental Science & Policy, 16, 81–89. https://doi.org/10.1016/j.envsci.2011.11.001

Scurlock, J.M.O., and R.J. Olson. 2013. NPP Multi-Biome: Grassland, Boreal Forest, and Tropical Forest Sites, 1939-1996, R1. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/653

Soil Survey Staff. (2024). Gridded Soil Survey Geographic (gSSURGO) Database for Colorado [Dataset]. United States Department of Agriculture, Natural Resources Conservation Service. https://gdg.sc.egov.usda.gov/

Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre, & Royal Swedish Academy of Sciences. (2024). InVEST 3.14.2 Documentation. Natural Capital Project. https://naturalcapitalproject.stanford.edu/software/invest

U.S. Department of Commerce, N. O. and A. A. (2012, October 1). What is Lidar. NOAA's National Ocean Service. https://oceanservice.noaa.gov/facts/lidar.html#:~:text=Lidar%2C%20which%20stands%20for%20Light,variable%20distances)%20to%20the%20Earth.

Walters, B. F., Domke, G. M., Greenfield, E. J., Smith, J. E., Nowak, D. J., & Ogle, S. M. (2022). Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2020: Estimates and quantitative uncertainty for individual states, regional ownership groups, and National Forest System regions [Dataset].

Watts, J. D., Lawrence, R. L., Miller, P. R., & Montagne, C. (2009). Monitoring of cropland practices for carbon sequestration purposes in north central Montana by Landsat Remote Sensing. Remote Sensing of Environment, 113(9), 1843–1852. https://doi.org/10.1016/j.rse.2009.04.015

Yellajosula, G., Cihacek, L., Faller, T., & Schauer, C. (2020). Soil Carbon Change Due to Land Conversion to Grassland in a Semi-Arid Environment. Soil Systems, 4(3). doi.org/10.3390/soilsystems4030043

4 CARBON CAPTURE & STORAGE

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Introduction to Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) is a critical technology for mitigating climate change by reducing carbon dioxide emissions from industrial processes and power generation. CCS projects play a pivotal role in meeting global climate goals as they prevent CO_2 from entering the atmosphere. Broadly, the process involves capturing CO_2 at its source through methods like pre- and post-combustion capture and oxy-fuel combustion, transporting it, and securely storing it in geological formations underground (Global CCS Institute, 2024; Bhavsar *et al.*, 2023). Once captured, the gas is compressed and transported, typically through pipelines, to designated storage sites. It is then injected into deep geological formations such as depleted oil and gas reservoirs, deep saline aquifers, or unmendable coal seams, where it can be securely trapped for long periods of time.

CCS projects offer solutions to reducing CO_2 emissions from point sources, support for clean energy transitions, and the decarbonization of hard-to-abate industries such as cement and steel manufacturing (Global CCS Institute, 2024). However, CCS faces several challenges, including high costs, significant energy requirements, the need for extensive infrastructure, and long-term storage risks (Rode *et al.,* 2023; Salvi *et al.,* 2019) Despite these limitations, CCS is increasingly recognized as a crucial tool for limiting global warming to below 2°C, as outlined in the Paris Agreement (IEA, 2024).

The process of CCS involves three main stages: capture, transport, and storage. The first step, capture, takes place at the point of CO_2 emissions, such as power plants, cement factories, or steel mills. There are several methods for capturing CO_2: pre-combustion capture removes CO_2 before the fossil fuel is burned by converting it into hydrogen and CO_2; post-combustion capture captures CO_2 after combustion, typically using chemical solvents; and oxy-fuel combustion burns fossil fuels in pure oxygen, producing a concentrated stream of CO_2 that is easier to capture (DOE, 2024). Once captured, the CO_2 is compressed into a supercritical state, making it denser and easier to transport (Global CCS Institute, 2024). The second stage – transport – involves moving the captured CO_2 to a storage site. This is usually done via pipelines, which are the most cost-effective method for large-scale CCS projects (Global CCS Institute, 2024). In some cases, CO_2 can be transported by ship or rail if pipelines are not feasible (Global CCS Institute, 2024). Transporting CO_2 requires careful planning and infrastructure to prevent leaks and ensure safety. The final step, storage, involves injecting the captured CO_2 into deep underground geological formations, where it can be securely stored for centuries or longer (Global CCS Institute, 2024). The most common storage sites are depleted oil and gas reservoirs, which have previously contained hydrocarbons and are ideal for CO_2 sequestration (Global CCS Institute, 2024). Once the CO_2 is injected, ongoing monitoring is critical to ensure the gas remains securely trapped. Together, these three stages—capture, transport, and storage—form the backbone of CCS technology, which is considered essential for reducing emissions from sectors that are difficult to decarbonize, such as heavy industry and fossil fuel-based power generation. By securely storing CO_2 underground, CCS plays a crucial role in achieving global climate goals and limiting the impacts of climate change.

CCS Technologies: State of the Field & Environmental Impacts

Although complicated, carbon capture and storage (CCS) technologies are crucial methods needed to facilitate the transition to renewable energy. These mechanisms allow for the continuation of the fossil fuels industry while also pursuing net zero emissions. This literature review will examine the state of the field, specific CCS technologies like Bioenergy with Carbon Capture and Storage (BECCS) and direct air carbon capture and storage (DACCS), and environmental impact assessments conducted.

The state of carbon capture storage and utilization in the present moment act as mechanisms that can help achieve net zero emissions. CCS is the process of extracting CO_2 from the atmosphere and storing it in the ground for an extended period of time or until it can be recycled. Bhavsar *et al.* (2023) conducted an analysis of the commercial uses and challenges associated with CCS technology and emphasized that in order for the implementation of carbon capture utilization and storage (CCUS) to be successful, it needs to be economical, environmentally friendly, and sustainable. Using CCUS technologies to limit CO_2 emissions emphasizes the realities of CCUS and how its application within fossil fuel industries may be critical for achieving net zero emissions. In conjunction with this idea, Lau *et al* (2021) describe the different types of CCS and their applications to the fossil fuel industry along with the restrictions on its implementation due to non-technical barriers. Lau *et al* (2021) acknowledge the potential of oil and gas reservoirs to store two centuries of anthropogenic CO_2 emissions and discuss the importance of transitioning from a high to low carbon economy and the role of CCS in the fossil fuel industry and the production of low-carbon fossil fuel based blue hydrogen. The two main types of CCS that Lau *et al* (2021) discuss are Bioenergy with CCS (BECCS) and fossil fuels with BECCS. The four types of fossil fuels associated with BECCS are post-combustion, pre-combustion, oxy-combustion, and chemical looping. The slow implementation of CCS projects is not due to technical inabilities but non-technical hesitancy with carbon pricing, predictability of energy pricing, CCS regulations, public acceptance, and high capital expenditure and cost of capital (Lau *et al.*, 2021). Lau *et al.* (2021) demonstrate the role that CCS has in the energy transition and its usefulness to companies that may continue to produce greenhouse gas emissions beyond their pledged date. Shu *et al.* (2023) discuss the importance of CCS in completing energy transition goals to limit the rise in global temperatures to below two degrees Celsius, in accordance with the Paris Agreement. The authors consider different carbon capture technologies such as Monoethanolamine carbon capture (MEA) and direct air capture (DAC) as potential avenues to support this transition. Post-combustion CCS is heavily emphasized as a revenue for steel and other metalworking companies to harness the energy that can be recycled through combustion (Shu *et al.*, 2023).

The development of improved guidelines for cost evaluation for CCS industrial applications is critical for projects to understand the feasibility of CCS programs. Roussanaly *et al.* (2021) consider the different heat and supply scenarios that may impact future energy and carbon prices, and the technology maturity that would be required for a successful carbon capture and storage market. This includes understanding the potential effects of CCS on product quality, plant maintenance, and operation of the CCS system under the specific conditions of the industrial facility. Furthermore, Roussanaly *et al.* (2021) signal the industrial sector as a leader in greenhouse gas pollution, being responsible for over a quarter of CO_2. Within the industrial sector, the highest-emitting industry subsectors in 2019 were iron and steel, cement and chemicals. The authors note that one of the most important factors in this field is the development and maturity of the necessary technology. Impacts to consider include potential effects of CCS on product quality, plant maintenance, and operation of the CCS system under the specific conditions of the industrial facility (Roussanaly *et al.* 2021).

When considering CCS and its associated technologies, bioenergy and DACCS should also be taken into account. Kwakye *et al.* (2024) situate Bioenergy with Carbon Capture and Storage (BECCS) by examining its potential and discussing its distinctive contributions to the viability of various bioenergy sources such as organic material to produce heat, electricity, and fuel. By providing real world examples of how BECCS work and contribute to the energy transition, and discussing the mechanics behind how CCS works, Kwakye *et al.* (2024) ultimately suggest that the effects of BECCS on emissions is contested and uncertainties exist in quantifying the long-term carbon sequestration potential and the sustainability of large-scale implementation. Ecological considerations such as land use and land ownership as well as considerations of agriculture and conservation prove to be significant challenges for CCS opportunities. Additional considerations include investments in infrastructure, and cost-effectiveness (Kwakye et al., 2024).

Postweiler *et al.* (2024) further consider the complexities of direct air carbon capture and storage (DACCS) and its viability as a CO_2 removal project. The most recent IPCC reports indicate that CO_2 must be removed from the atmosphere by employing negative emission technologies to achieve the climate goals defined in the Paris Agreement. Postweiler *et al.* (2024) discuss key performance indicators for optimization to alleviate the pressure of energy demand, specific exergy demand, or the equivalent shaft work, and conclude by emphasizing efficiency and plant productivity. DACCS captures carbon from the air for long term storage and is still at an early stage of development. Due to the premature phase of development, DACCS has a high cost and energy requirements. Küng *et al.* (2023) selected high priority actions that need to be undertaken to accelerate research, development, and deployment. These high priority actions are crucial in order to produce a DACCS process that is safe, scalable, and low cost. Küng *et al.* (2023) emphasized that a combination of materials, process design, equipment, system integration, and infrastructure obstacles will have to be overcome for successful implementation of DACCS.

The final component of consideration for the implementation of CCS is an assessment of environmental impact. Sathre *et al.* (2012) developed a framework for assessing the environmental impact of carbon capture and storage systems using an analysis of the key issues and a life cycle assessment (LCA). The authors describe LCA as a method to provide insights into the energy and environmental footprint of CCS facilities and systems. The seven key issues identified by Sathre *et al.* (2012) are emphasized as mandatory considerations when creating a LCA for CCS. These are energy penalty, functional units, scale-up challenges, non-climate environmental impacts, uncertainty management, policy-making needs, and market effects. Ultimately, Sathre *et al.* (2012) emphasize that the decision to employ CCS technologies must be informed by knowledge on the overall costs and benefits and should be supported by a robust life cycle assessment. Singh *et al.* (2012) also assessed the environmental damage that can be attributed to CCS. The study examines three types of fossil fuel-based power plants with CCS using life cycle impact analyses. This included pulverized coal, integrated gasification combined cycle, and natural gas combined cycle. Singh *et al.* (2012) conclude that CCS systems reduce climate change-related damages but increase certain human health and ecological hazards from toxicity, acidification, eutrophication, and resource consumption. Furthermore, they found that the health risks are significantly outweighed by the benefits that CCS technologies have on reducing climate change related harms. This includes a net reduction of 60% to 70% in human health damage and 65% to 75% in ecosystem damage.

To fully understand the impact of CCS on the environment, Koornneef and Turkenburg (2008) provide an analysis of the Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) of proposed CCS projects, specifically in the Netherlands. In this case study, the authors reviewed EIA and SEA procedures in relation to three CSS process steps: capture, transport, and storage of CO_2 using case studies of existing Dutch EIA and SEAs. Koornneef and Turkenburg (2008) concluded that it would be more impactful to combine the three processes into one procedure for the EIA. They state that this would be more helpful for regulators and would facilitate any legal procedures in the future. Additionally, the participation of the public and interested parties in the Netherlands would be important for the drafting of an EIA. This research informs existing processes for clearance and consideration of environmental impact occurring outside of the United States. Recommendations provided by Koornneef and Turkenburg (2008) could prove useful for the implementation of carbon capture and storage technologies within the United States. Overall, while carbon capture and storage as a potential avenue for emission reduction has progressed a long way; however, there is further research that needs to be conducted on the economic, environmental and societal viability of these projects.

Spatial Analysis of Factors Relevant to CCS Development in Colorado

The following section provides a visual overview of key carbon sequestration factors across Colorado, including the distribution of oil and gas wells and their current status (CART, 2017), land cover types (Multi-Resolution Land Characteristics Consortium [MRLC], 2023), fault lines (Central Energy Resources Science Center, 2024), and deep saline aquifers (Central Energy Resources Science Center, 2024). Together, these elements highlight opportunities and challenges for carbon sequestration efforts within the state.

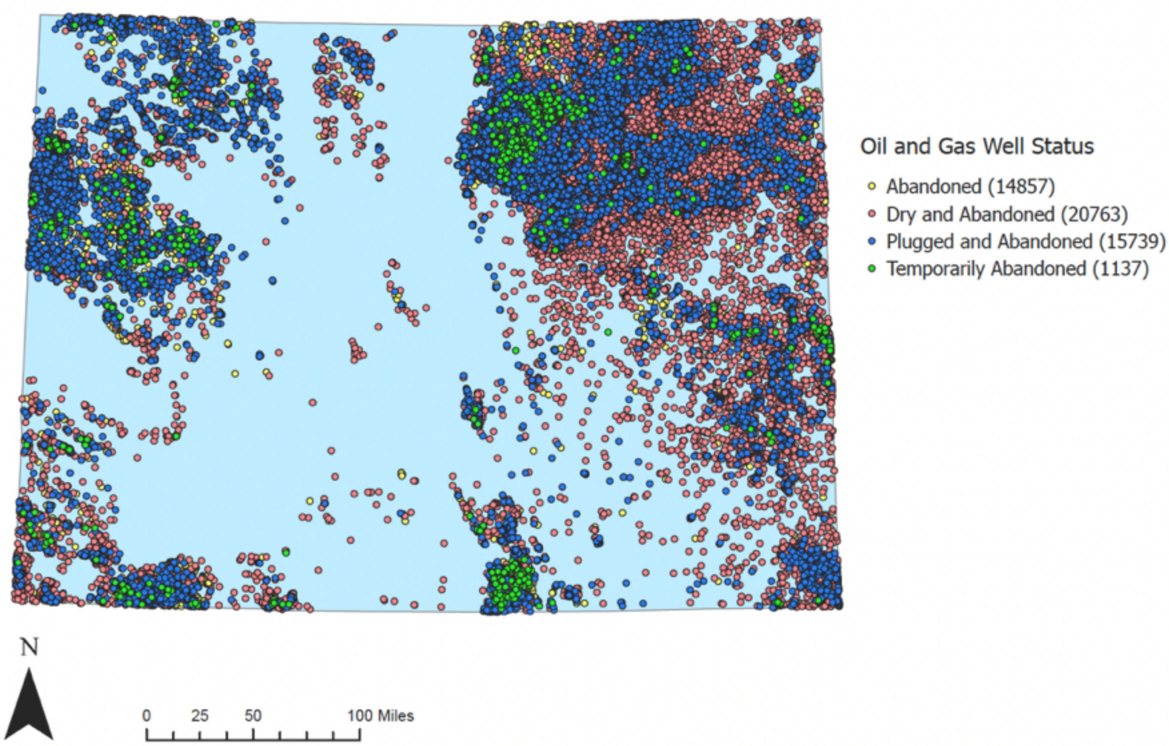

Figure 4.1. Distribution and status of oil and gas wells in Colorado, U.S.A. Colors of each oil and gas well represent their status (abandoned, plugged and abandoned, dry and abandoned, or temporarily abandoned). Data from Colorado Energy and Carbon Management (data last updated *2017).*

Depleted oil and gas wells and saline aquifers represent two of Colorado's most promising options for carbon capture and storage (CCS). Abandoned oil and gas wells, including those that are plugged, dry, or temporarily abandoned, are scattered across the state, with the highest concentrations on the western and eastern edges (Fig. 4.1). These wells, totaling over 50,000 in various stages of abandonment, present both opportunities and challenges for CCS. While many could be repurposed for CO_2 injection, the fact that many were not properly sealed poses significant risks, including methane emissions, groundwater contamination, and CO_2 leakage (Alsubaih *et al.*, 2024).

These wells are considered favorable for CCS due to their established geology and the presence of cap rock that prevents CO_2 from escaping (Zoback & Gorelick, 2012). In regions with high concentrations of abandoned wells, such as northeastern and western Colorado, proper evaluation, sealing, and remediation are critical to prevent environmental hazards. Poorly sealed wells could allow CO_2 to migrate to the surface, undermining CCS efforts, while methane leakage further exacerbates climate change (Alsubaih *et al.,* 2024). To mitigate these risks, ongoing monitoring and well remediation strategies are essential to ensure the success of CCS projects and prevent abandoned wells from becoming sources of contamination.

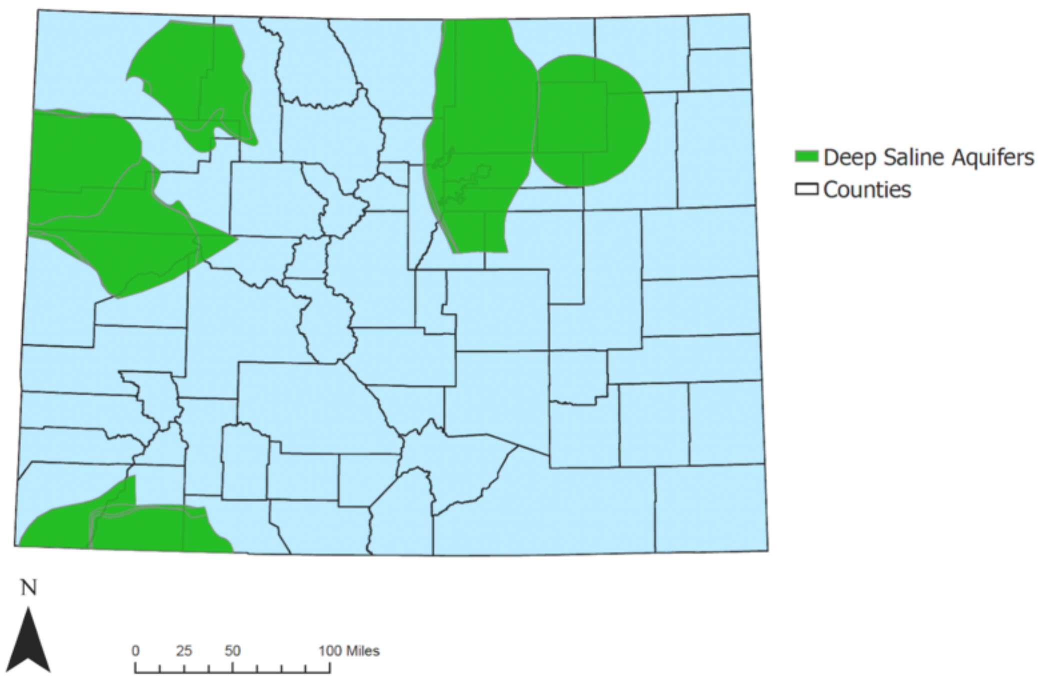

Figure 4.2. Distribution of deep saline aquifers in Colorado, U.S.A. Spatial data from Central Energy Resources Science Center, 2024.

Saline aquifers (Fig. 4.2), located deep underground, offer significant potential for CO_2 storage. These aquifers consist of porous rock formations filled with saline water, typically found at depths greater than 1,000 meters. When CO_2 is injected into these aquifers, it dissolves in the saline water and is trapped by surrounding impermeable rock layers, providing a stable long-term storage solution (Benson et al., 2005). Saline aquifers are a key component of carbon sequestration strategies due to their large-scale storage capacity. In Colorado, these aquifers are primarily located in the north and western parts of the state, with additional deposits in the mid-northern region (Central Energy Resources Science Center, 2024). The primary advantage of saline aquifers is their vast storage capacity, which allows for the injection of CO_2 over extended periods without the risk of overfilling. Additionally, these aquifers are generally isolated from groundwater sources, minimizing the risk of contamination. The deep, high-pressure environments of saline aquifers further enhance the dissolution of CO_2, ensuring that the gas remains securely trapped over geological time scales (Benson *et al.*, 2005).

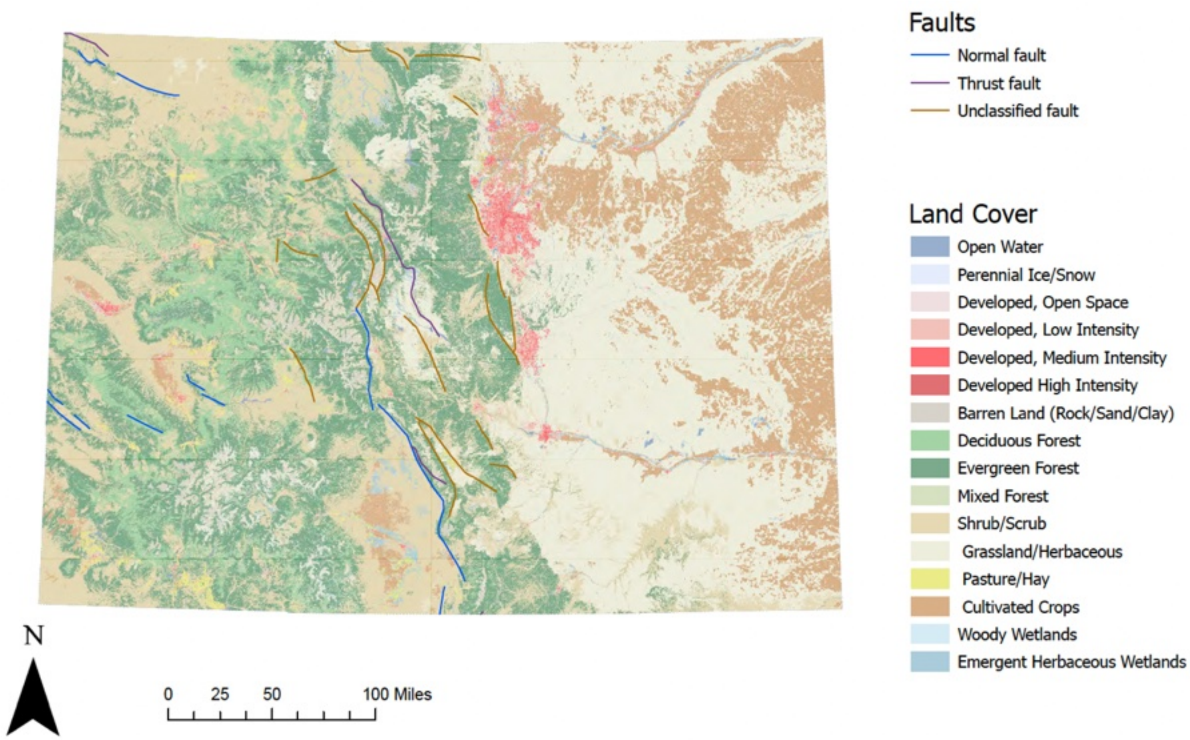

Figure 4.3. Distribution of deep saline aquifers in Colorado, U.S.A. Data from Colorado Energy and Carbon Management. Spatial data for fault lines from Central Energy Resources Science Center (2024) and land cover from the National Land Cover Dataset, Multi-Resolution Land Characteristics Consortium (2023).

Land cover provides important context for natural carbon sequestration potential across Colorado (Fig. 4.3). Forested regions, including evergreen and deciduous forests, are primarily located in the central and western parts of the state, while grassland/herbaceous and cultivated crop areas dominate the eastern plains. These land cover types contribute to biological carbon sequestration, with forests generally storing the highest capacity in live biomass, detritus, and soil. According to the US Forest Service, America's forests sequester over 800 million tons of carbon annually, approximately 12% of the nation's emissions (Rowntree & Nowak, 1991). This makes forests one of the most effective natural carbon capture systems, offering additional benefits such as wildlife habitat and ecosystem services.

In contrast, agricultural lands, including grasslands, croplands, and shrub areas, typically have lower carbon sequestration potential. Practices such as tillage in croplands can release stored carbon, and grasslands may have limited capacity to store carbon compared to forests (Kang *et al.*, 2023). However, carbon capture and storage (CCS) projects on grasslands and croplands can still play a role in mitigating climate change (Minnesota Board of Water and Soil Resources, (2019). These lands are widespread across the eastern part of Colorado, as shown in the figure, and offer potential for carbon sequestration through soil management practices, such as no-till farming and grassland restoration.

The presence of fault lines in Colorado is particularly relevant for CCS projects because geological stability is crucial for ensuring the long-term success and safety of CO_2 sequestration. Fault lines, especially those that are active or poorly sealed, can create pathways for CO_2 to migrate back to the surface, potentially compromising the effectiveness of CCS and causing leakage. Furthermore, injecting CO2 near fault zones may induce seismic activity, including small earthquakes (Khan *et al.,* 2024). Therefore, regions with significant fault activity, particularly in central Colorado as shown in the figure, require thorough evaluation and monitoring to assess their suitability for CO_2 injection.

In conclusion, the spatial distribution of oil and gas wells, saline aquifers, land cover types, and fault lines across Colorado presents a complex landscape of opportunities and challenges for carbon capture and storage (CCS). The high concentration of abandoned wells in northeastern and western Colorado offers potential for repurposing these sites for CO_2 injection, though careful management is necessary to mitigate risks such as leakage and contamination. Simultaneously, the state's saline aquifers provide substantial long-term storage potential, particularly in the western and northern regions, where deep, high-pressure environments enhance CO_2 dissolution and trapping. Forested areas, central to Colorado's carbon sequestration potential, offer significant benefits for biological carbon storage, while agricultural lands in the east present opportunities for soil management practices to support CCS efforts. The presence of fault lines further emphasizes the need for geological assessments to ensure the stability of CO_2 storage sites. Together, these factors underscore the importance of a comprehensive, region-specific approach to CCS, balancing infrastructure opportunities with environmental safeguards. By leveraging both geological and biological systems, Colorado can make significant strides toward meeting its carbon sequestration goals while fostering sustainable land management practices.

Current CCS Projects

Global & Regional CCS Projects

Carbon capture and storage (CCS) projects are gaining momentum globally, reflecting a growing commitment to address climate change. The 2024 Global Status of CCS report showcases remarkable progress in CCS technologies, underpinned by increasing investment, policy support, and technological advancements. CCS plays a crucial role in achieving net-zero emissions by mitigating CO_2 emissions from heavy industries, power generation, and other sectors that are difficult to decarbonize.

Countries like the United States, Canada, and the United Kingdom have implemented grand policies and financial incentives to accelerate CCS adoption. In North America, enhancements to tax credits like the U.S. 45Q, a merit-based tax credit to incentivize investing in CCS projects (Congressional Research Service), have driven substantial growth in new CCS facilities. In Europe, projects in industrial clusters are expanding, supported by initiatives like the EU Innovation Fund. Emerging economies in the Asia-Pacific region, including China, Japan, and Australia, are also advancing CCS capabilities through strategic investments and regulatory frameworks (Global CCS Institute, 2024).

As of 2024, the number of CCS facilities worldwide has continued to increase, with many transitioning from early development to advanced stages (Fig 4.4). There is a sharp increase in CO_2 capture capacity from 2017 to the present and additionally, an increase in operational facilities around the world (Fig 4.4). There has also been an overwhelming increase in projects, especially those under advanced development, between 2023 and 2024 (Fig. 4.5). The global push for CCS projects not only aims to reduce emissions but also support job creation, industrial innovation, and economic resilience. With a strong alignment between policy, private sector investment, and technological advancements, CCS is emerging as a cornerstone of global climate mitigation efforts.

One example of a global, high-impact CCS project is the oxyfuel combustion carbon capture project run by China United Cement Company which opened in January 2024 and has since captured 200 ktpa of CO_2 (Global CCS Institute). Oxyfuel combustion requires that fossil fuels are burned in pure oxygen which restricts the process to fossil-fuel power plants, cement plants, and iron and steel production - facilities that generate CO_2 during the combustion process (Hua *et al.*, 2023). Another company prioritizing carbon capture and storage is Exxon Mobil which has situated itself at the top with 30+ years of CCS experience. Exxon was the first company to achieve 120 million tons of carbon capture, and in 2019 was responsible for 23% of all CO_2 captured (ExxonMobil Corporation).

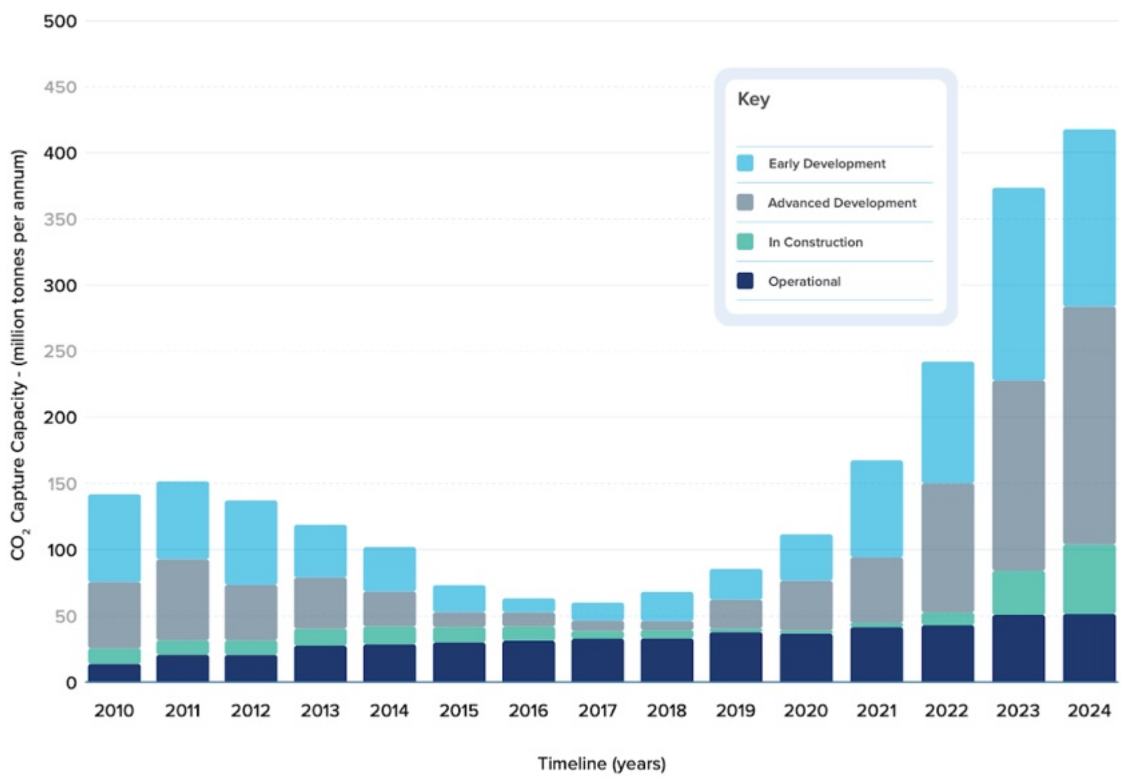

Figure 4.4. CO_2 capture capacity (million tonnes per annum) of commercial CCS facilities since 2010. Dark blue represents operational facilities, green represents facilities under construction, grey represents advanced development, and light blue represents facilities under early development. [From the 2024 Global Status of CCS Report, Global CCS Institute, 2024]

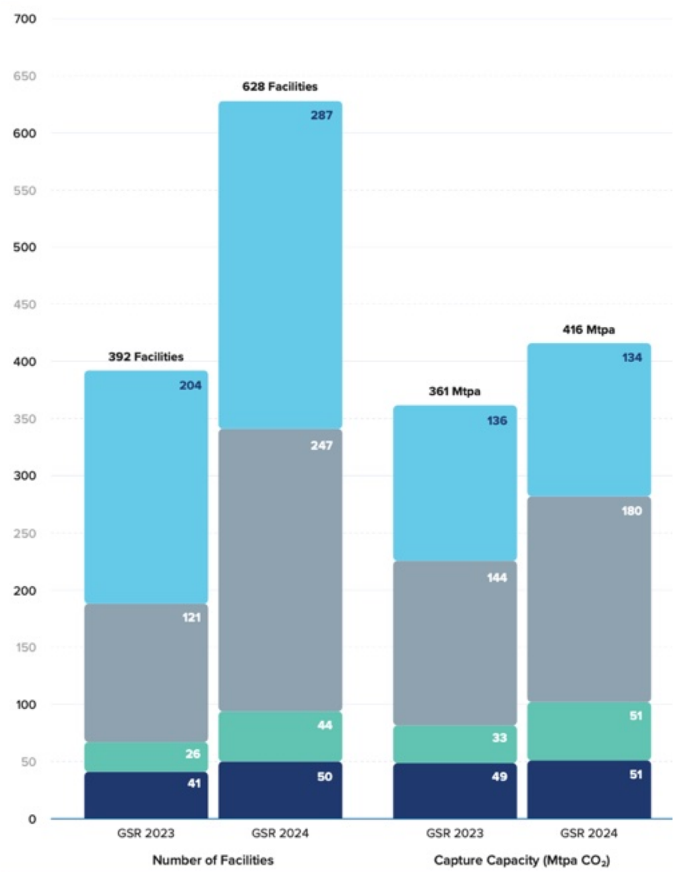

Figure 4.5. Commercial CCS facilities by number and total capture capacity (Mtpa CO_2) in 2023 and 2024. Dark blue represents operational facilities, green represents facilities under construction, grey represents advanced development, and light blue represents facilities under early development. [From the 2024 Global Status of CCS Report, Global CCS Institute, 2024]

Colorado CCS Projects

In 2023, the United States was deemed the leader in capturing carbon, capturing 22.5 metric tons (Mt) per year and contributing to 40.9% of global carbon captured, second only to Brazil who captured 10.6 Mt, 19.3% of carbon captured globally, per year during the same year (Bellefontaine, 2024). Colorado itself has an ambitious goal reaching net zero emissions by 2050. In the meantime, Colorado has set science-backed reduction goals of 26% by 2025 when compared to 2005 emission levels (Colorado Official State Web Portal).

Currently, all CCS project facilities in Colorado are “in development” (Fig. 4.6 & Table 4.1) but their plans for capturing or storing carbon are predicted to help Colorado reach their goals. One particular Colorado-based carbon capture company, Carbon America, aims to gather 350,000 tons of CO_2 from ethanol fermentation and force it into underground wells for storage. Sterling Ethanol and Yuma Ethanol are the first commercial companies to report the sequestration of such significant amounts of carbon in the state (Booth, 2022). Future plans for this project are to build a stable pipeline to deliver carbon from ethanol plants into underground wells.

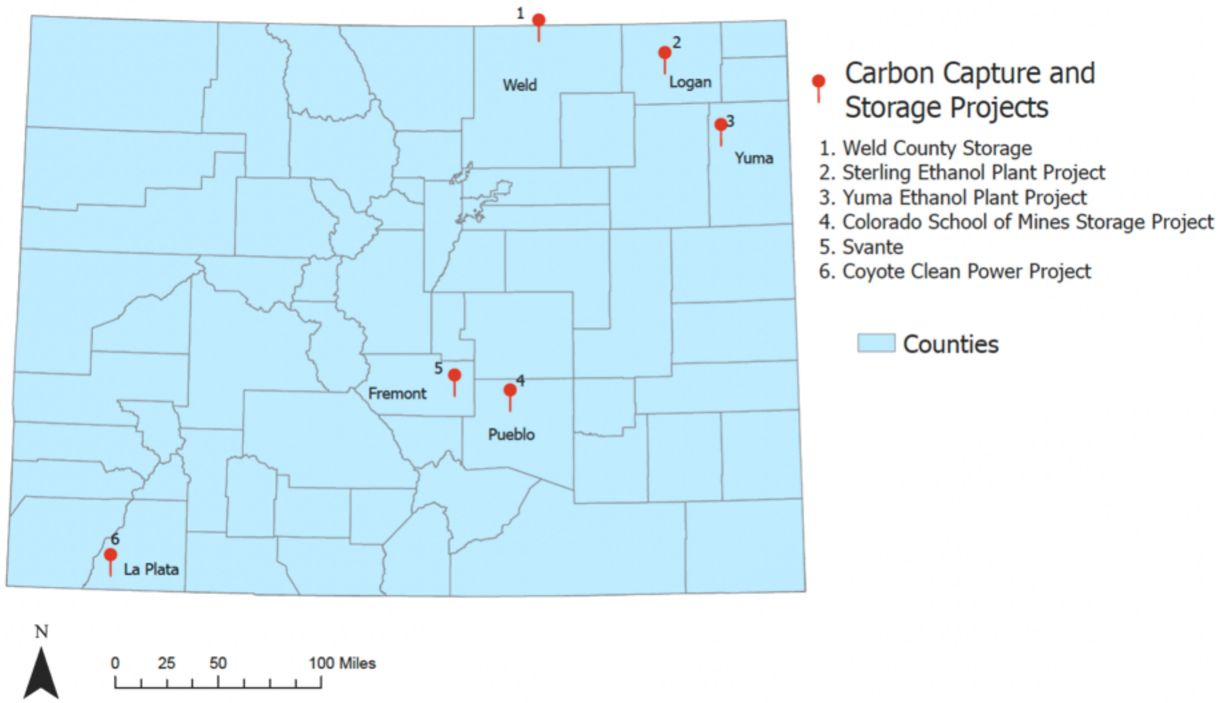

Figure 4.6. Ongoing carbon capture and storage projects in Colorado. Data from Clean Air Task Force (2024).

Table 4.1. Description of CCS project sites in the state of Colorado, including location, section or subsector, storage type and capacity (in metric tons of CO_2/year), and current status. From the Clean Air Task Force CATF_CCUS_dataset (2024).

Project #	Name	Location in CO	Sector/ subsector	Storage method	Capacity (metric tons CO_2/yr)	Status
1	Svante	Florence	Industrial, Cement	Saline storage	725,000	In development
2	Colorado School of Mines Storage Project	Pueblo	Storage, Storage Hub	Saline storage	Unavailable	In development
3	Coyote Clean Power Project	Southern Ute Indian Reservation	Power, Natural Gas	Saline storage	865,000	In development
4	Weld County Storage (Class II & VI)	Weld County	Storage, Storage Hub	Saline storage & Enhanced oil recovery	Unavailable	In development
5	Sterling Ethanol Plant Project	Sterling	Industrial, Ethanol	Saline storage	175,000	In development
6	Yuma Ethanol Plant Project	Yuma	Industrial, Ethanol	Saline storage	175,000	In development

Significance

This research provides a clear understanding of CCS technologies and their potential applications in Colorado, equipping stakeholders—such as landowners, carbon industry, and conservation groups—with the knowledge to make informed decisions. By reviewing current CCS technologies, key considerations, and relevant case studies, this research offers valuable insights that can help stakeholders navigate the nuance of bringing together CCS and land management strategies. These insights facilitate collaboration across sectors, supporting the development of strategies that balance environmental, economic, and social goals. In a broader context, incorporating CCS into conservation and land management practices offers a promising way to reduce carbon emissions while supporting biodiversity and ecosystem services, contributing to global efforts in climate change mitigation and natural resource management.

References

Alsubaih, A., Sepehrnoori, K., & Delshad, M. (2024). Environmental Impacts of Orphaned and Abandoned Wells: Methane Emissions, and Implications for Carbon Storage. *Applied Sciences*, 14(24), 11518.

Bellefontaine, R. (2024, October 8). Visualized: Which countries capture the most carbon? Visual Capitalist. https://www.visualcapitalist.com/sp/visualized-which-countries-capture-the-most-carbon/

Bhavsar, A., Hingar, D., Ostwal, S., Thakkar, I., Jadeja, S., & Shah, M. (2023). The current scope and stand of carbon capture storage and utilization ~ A comprehensive review. Case Studies in Chemical and Environmental Engineering, 8, 100368–100368.

Booth, M. (2022, May 12). Here's where Colorado wants to capture and bury 350,000 tons of carbon dioxide each year. The Colorado Sun. Retrieved December 16, 2024. https://coloradosun.com/2022/05/12/carbon-capture-colorado-ethanol-plants-greenhouse-gas -emissions/

CCS explained: The basics. Retrieved from https://www.globalccsinstitute.com/resources/ccs-101-

Carbon Capture and Storage Database. (n.d.). Netl.doe.gov. https://netl.doe.gov/carbon-management/carbon-storage/worldwide-ccs-database.

Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration? (2022). European Environment Agency.

CART0 (2017, April 27). Denverpostdata. [Colorado Oil and Gas Wells]. https://denverpostdata.carto.com/viz/3ec962a6-2c6b-11e7-b3d3-0ee66e2c9693/public_map

Central Energy Resources Science Center. (2024, April 3). World Geologic Maps | U.S. Geological Survey. www.usgs.gov/centers/central-energy-resources-science-center/science/world-geologic-maps.

Clean Air Task Force. (2024). US Carbon Capture Activity and Project Table. [CATF_CCUS_Database]. Highland Energy Analytics, LLC. https://www.catf.us/ccsmapus/

Colorado Geological Survey. (2024). [RS-45 CO2 Sequestration Potential of Colorado]. https://coloradogeologicalsurvey.org/publications/co2-sequestration-potential-colorado/

Colorado Official State Web Portal. Climate change goals & actions. Colorado Climate Action. (n.d.). https://climate.colorado.gov/colorado-goals-actions-main-page.

Congressional Research Service. (2023, August 25). The section 45Q tax credit for carbon sequestration. https://crsreports.congress.gov/product/pdf/IF/IF11455

ExxonMobil Corporation. The global leader in carbon capture and storage (CCS). (2021).

https://corporate.exxonmobil.com/-/media/Global/Files/carbon-capture-and-storage/CCS-Infographic.pdf

Fahey, T. J., Woodbury, P. B., Battles, J. J., Goodale, C. L., Hamburg, S. P., Ollinger, S. V., & Woodall, C. W. (2010). Forest carbon storage: ecology, management, and policy. Frontiers in Ecology and the Environment, 8(5), 245-252.

How forests store carbon. Penn State Extension. (2023). extension.psu.edu/how-forests-store-carbon

Hua, W., Sha, Y., Zhang, X., & Cao, H. (2023). Research progress of carbon capture and storage (CCS) technology based on the shipping industry. Ocean Engineering, 281, 114929.

IPCC. (2005). CARBON DIOXIDE CAPTURE AND STORAGE Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf

IPCC. (2023). Synthesis report of the IPCC Sixth Assessment Report (AR6) Summary for Policymakers. In IPCC. Intergovernmental Panel on Climate Change. www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Kang, M., Boutot, J., McVay, R. C., Roberts, K. A., Jasechko, S., Perrone, D., & Peltz, A. S. (2023). Environmental risks and opportunities of orphaned oil and gas wells in the United States. Environmental Research Letters, 18(7), 074012.

Khan, S., Khulief, Y., Juanes, R., Bashmal, S., Usman, M., & Al-Shuhail, A. (2024). Geomechanical Modeling of CO_2 Sequestration: A Review Focused on CO2 Injection and Monitoring. Journal of Environmental Chemical Engineering, 112847.

Küng, L., Aeschlimann, S., Charalambous, C., McIlwaine, F., Young, J., Shannon, N., Strassel, K., Nichole Maesano, C., Kahsar, R., Pike, D., van der Spek, M., & Garcia, S. (2023). A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. Energy Environ. Sci, 16, 4280–4304.

Koornneef, J., Faaij, A., & Turkenburg, W. (2008). The screening and scoping of Environmental Impact Assessment and Strategic Environmental Assessment of Carbon Capture and Storage in the Netherlands. Environmental Impact Assessment Review, 28(6), 392–414. https://doi.org/10.1016/j.eiar.2007.08.003

Kwakye, J. M., Ekechukwu, D. E., & Ogundipe, O. B. (2024). Reviewing the role of bioenergy with carbon capture and storage (BECCS) in climate mitigation. Engineering Science & Technology Journal, 5(7), 2323–2333. https://doi.org/10.51594/estj.v5i7.1346

Lau, H. C., Ramakrishna, S., Zhang, K., & Radhamani, A. V. (2021). The Role of Carbon Capture and Storage in the Energy Transition. Energy & Fuels, 35(9), 7364–7386. doi.org/10.1021/acs.energyfuels.1c00032

Minnesota Board of Water and Soil Resources. (2019). Carbon sequestration in Grasslands. Carbon Sequestration in Grasslands | MN Board of Water, Soil Resources.

Postweiler, P., Engelpracht, M., Rezo, D., Gibelhaus, A., & Assen, N. von der. (2024). Environmental process optimisation of an adsorption-based direct air carbon capture and storage system. Energy & Environmental Science, 17. https://doi.org/10.1039/D3EE02970K\

Roussanaly, S., Berghout, N., Fout, T., Garcia, M., Gardarsdottir, S., Nazir, S. M., Ramirez, A., & Rubin, E. S. (2021). Towards improved cost evaluation of Carbon Capture and Storage from industry. International Journal of Greenhouse Gas Control, 106, 103263. https://doi.org/10.1016/j.ijggc.2021.103263

Rode, D. C., Anderson, J. J., Zhai, H., & Fischbeck, P. S. (2023). Six principles to guide large-scale carbon capture and storage development. Energy Research & Social Science, 103, 103214. doi:10.1016/j.erss.2023.103214

Rowntree, R. A., & Nowak, D. J. (1991). Quantifying the role of urban forests in removing atmospheric carbon dioxide. Arboriculture & Urban Forestry (AUF), 17(10), 269-275.

Sathre, R., Chester, M., Cain, J., & Masanet, E. (2012). A framework for environmental assessment of CO_2 capture and storage systems. Energy, 37(1), 540–548. https://doi.org/10.1016/j.energy.2011.10.050

Salvi, B. L., & Jindal, S. (2019). Recent developments and challenges ahead in carbon capture and sequestration technologies. SN Applied Sciences, 1(8), 885. doi:10.1007/s42452-019-0909-2

Sha, Z., Bai, Y., Li, R., Lan, H., Zhang, X., Li, J., Liu, X., Chang, S., & Xie, Y. (2022). The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management. Communications Earth & Environment, 3(1). https://doi.org/10.1038/s43247-021-00333-1

Shu, D. Y., Deutz, S., Winter, B. A., Baumgärtner, N., Leenders, L., & Bardow, A. (2023). The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment. Renewable and Sustainable Energy Reviews, 178, 113246. https://doi.org/10.1016/j.rser.2023.113246

Singh, B., Strømman, A. H., & Hertwich, E. G. (2012). Environmental Damage Assessment of Carbon Capture and Storage. Journal of Industrial Ecology, 16(3), 407–419. https://doi.org/10.1111/j.1530-9290.2012.00461.x

What is carbon sequestration? | U.S. Geological Survey. (2019, March 22).https://www.usgs.gov/faqs/what-carbon-sequestration

What's the difference between geologic and biologic carbon sequestration? | U.S. Geological Survey. (2019, March 22). Usgs.gov. https://www.usgs.gov/faqs/whats-difference-between-geologic-and-biologic-carbon-sequestration

Why carbon capture technologies are important – the role of CCUS in low-carbon power systems – analysis. Retrieved from https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems/why-carbon-capture-technologies-are-important

Zoback, M. D., & Gorelick, S. M. (2012). Earthquake triggering and large-scale geologic storage of carbon dioxide. Proceedings of the National Academy of Sciences, 109(26), 10164–10168.