# City of Boulder Open Space and Mountain Parks Land-Based Carbon Inventory & Nature-Based Solutions

*Photo courtesy of Frank Beck*

Published September 2023

**Suggested Citation**

City of Boulder. 2023. City of Boulder Open Space and Mountain Parks Land-Based Carbon Inventory & Nature-Based Solutions. The City of Boulder, Open Space and Mountain Parks Department. Boulder, Colorado.

**Acknowledgements**

City of Boulder Staff

Alycia Alexander, Brian Anacker*, Dan Burke, Brett KenCairn, Andy Pelster, John Potter, Lynn Riedel, Heather Swanson, Brian Tavernia, Chris Wanner.**

*Brian Anacker is the corresponding author. anackerb@bouldercolorado.gov;

**Many additional OSMP staff contributed to this report.

Consultant Support

*Biohabitats*: Claudia Browne, Aiman Duckworth, Jessica Norris, Susan Sherrod

*SSG*: Yuill Herbert, Luna Menares, Andres Pica-Tellez, Bas Straatman

Technical Advisor Team

Drew Rayburn (TNC), Stefan Reinhold (BCPOS), Tim Seastedt (CU Boulder Emeritus)

## TABLE OF CONTENTS

## EXECUTIVE SUMMARY

Human activities have significantly increased the concentration of carbon dioxide in the atmosphere, contributing to the enhanced greenhouse effect and climate change. Reducing carbon emissions and managing carbon in ecosystems are essential strategies for stabilizing climate change. Properly managed, ecosystems can serve as invaluable carbon sinks, actively capturing and retaining carbon dioxide while also fostering overall ecosystem health and resilience. However, carbon reservoirs in vegetation and soils are at risk of depletion due to disturbances such as catastrophic wildfires, windstorms, and severe droughts. Moreover, accelerating carbon drawdown from the atmosphere by plants is a difficult and complex task.

In this report, we present a first-ever inventory of carbon stocks, annual carbon flux, and vulnerability to carbon loss for the City of Boulder Open Space and Mountain Parks land. The analysis conducted is based on the vegetation cover data provided by OSMP staff intersected with carbon density data found from several sources, including the national SSURGO dataset, the Forest Vegetation Simulator, the DAYCENT model, and literature sources. Carbon values are presented in metric tons of $CO_2$ equivalents (MtCO2e).

OSMP's carbon stock was estimated to be 2,758,600 MtCO2e (+/- ~440,000) assessed across 36,466 acres of land managed by the department. If we apply the observed, average carbon density of 76 MtCO2e $acre^{-1}$ to the additional approximately 10,000 acres of OSMP land that are not otherwise accounted for in this study, the revised estimate of OSMP's total carbon stock is 3,526,365 MtCO2e assessed across the full 46,610 acres of OSMP land. All remaining numbers in the executive summary are presented based on the 2.8M estimate for 36k acres of OSMP managed lands.

Among the land cover types, grasslands were the biggest holder of carbon (1,184,664 MtCO2e, with an average carbon density of 63.6 $ac^{-1}$), while wetlands had the largest carbon density per unit area (112 MtCO2e $ac^{-1}$). When comparing carbon in biomass and soils, soils held most of the carbon (2,114,252 MtCO2e; 76%), representing a relatively stable carbon pool relative to above-ground vegetation. Biomass held much less carbon than soil (644,158 MtCO2e; 24%). If the 644,158 MtCO2e of OSMP's carbon stock that is found in biomass was released to the atmosphere, and we assign a social cost to carbon release calculated by economists to be $140 to $380 per MtCO2e, it could result in $90 million to $245 million in damages, emphasizing the importance of preserving OSMP's carbon stock. Another point of comparison is that the OSMP carbon stock is equivalent to 1.5 times the City of Boulder's annual emissions of 1.8 million MtCO2e; although this relationship is expected to change as the City's emissions are planned to be dramatically reduced to meet the goal of net zero by 2035.

OSMP's land sequesters an additional 12,905 MtCO2e of carbon per year, under average climate conditions with no disturbances and current forestry practices. However, this rate is easily outpaced by land emissions in years with climate-driven disturbances: for example, a 500-acre wildfire can release 14,850 - 26,900 MtCO2e; a 200-acre soil erosion event can release 57 MtCO2e; a very windy day could release up to 12 MtCO2e from a 40-acre prairie dog colony; a drought can lead to the potential loss of 10,833 MtCO2e in a year. Moreover, the 700 tons of wood generated by OSMP forestry operations each year releases 3,850 - 5,320 MtCO2e if it is burned as firewood. Another important source of carbon emissions from the land is livestock grazing, estimated at ~3,000 MtCO2e per year based on 1,800 animals (83% cattle). However, grazing can also reduce grassland emissions where grazing reduces grassland fuels and prevents wildfires.

Regardless, the overall conclusion remains that in some years, OSMP land is likely a net emitter of carbon.

Forests are perhaps the most vulnerable to carbon loss given the vast amount of carbon stored in trees and the increase in the severity of wildfires. We modeled how the current carbon stock in forests of 962,773 MtCO2e may change over 30-years based on acres burned, rates of carbon emissions from fires, and rates of annual drawdown. By 2050, the predictions for forest carbon stock were vast: stock could grow 50% to 1,440,000 MtCO2e or reduce 27% to 574,000 MtCO2e.

We examined ten nature-based solutions that would likely be a good fit for OSMP based on the potential to maintain or improve native ecosystems. The top three in terms of potential for carbon drawdown per acre were beaver dam analogues (2.22 MtCO2e $ac^{-1}$), post-fire restoration (2.23 MtCO2e $ac^{-1}$ $yr^{-1}$), and wetland restoration (1.58 MtCO2e $ac^{-1}$ $yr^{-1}$). The selection of which solutions to implement and where will need to be evaluated based on many criteria, chief among them the potential co-benefits to other ecosystem properties such as biodiversity and water retention.

In summary, OSMP's carbon stock is large, but it cannot reasonably be used to offset City of Boulder annual emissions; moreover, the nature-based solutions reviewed will at best have a modest drawdown potential. However, a simple message of "every ton matters" can guide staff as they begin to modify their land management practices to prevent carbon loss and increase carbon drawdown.

While carbon management is important for climate stabilization, the primary climate action focus for OSMP should be preparing landscapes to be resilient to an inevitably hotter, drier, more extreme climate future. A primary strategy for boosting ecological resilience in a more arid future likely lies in the retention and cycling of water in water-dependent ecosystems. Fortunately, slowing and storing water also often comes with increased biodiversity and improved ecosystem health as well as the co-benefit of carbon storage (e.g., the high carbon densities assigned here to wetland and riparian areas).

## ABSTRACT

This study evaluates the carbon stored in the City of Boulder Open Space and Mountain Parks (OSMP) land, the risk of carbon loss, and opportunities to protect carbon stocks, reduce emissions, and increase storage. The 36,462 acres of natural and working lands examined contain approximately 2.8 million MtCO2e partitioned among forest, wetland, riparian, grassland, and agricultural land types, for the baseline year of 2020. Annually, OSMP's land sequesters an additional 12,905 MtCO2e of carbon in years with average climate conditions. In unfavorable climate years, droughts, wildfires, or wind-blown soil erosion can cause OMSP's lands to become net emitters. Of the landcover types examined, forests appeared to be the most vulnerable to carbon loss: if warming and the frequency and intensity of wildfires continue to increase, models predict a potential loss of up to 389k MtCO2e of forest carbon (or 65% of the forest biomass) on OSMP lands by 2050. Nature-based solutions may help increase the annual carbon drawdown, including beaver dam analogues, post-fire restoration, and wetland restoration. Boulder needs to prevent the loss of current carbon stocks in OSMP lands and continue to evaluate nature-based solutions that may have co-benefits for ecological health and diversity.



**Key Words**: nature-based solutions, carbon, natural and working lands, co-benefits, climate adaptation.

# INTRODUCTION

Land management decisions can significantly alter terrestrial ecosystems and play a key role in the global climate system, with land-based carbon sinks equal to up 30% of total anthropogenic emissions in the global carbon budget (Shukla et al., 2019). Currently, managing land as a carbon sink is the most mature carbon dioxide removal method available, but research is still converging on a specific set of actions that will increase sinks and reduce emissions from land use activities (Griscom et al., 2017). In the long term, researchers assign risk factors to estimated land-based carbon sequestration because climate change impacts can reduce potential storage. On the other hand, many natural carbon sink pathways can increase climate resilience, e.g. by raising groundwater, reducing forest fragmentation, or reducing the risk of catastrophic fires (Shukla et al., 2019).

Nature-based solutions (NBSs) are management strategies that leverage opportunities to enhance climate adaptation while also increasing multiple ecosystem benefits for habitat, water management, agricultural productivity, and visitor experience. As climate mitigation actions, these strategies also bear the risk of reversal, or releasing carbon back into the atmosphere due to disturbances from storms, fire, pests, land use decisions, or other factors (Galik and Jackson, 2009).

In Colorado, carbon emissions from natural and working lands are estimated to comprise approximately 15% of Colorado's net GHG emissions as of 2018/2019 (Taylor 2021). Taylor (2021) reports that agriculture emissions comprise approximately 8% of Colorado's net emissions, while Land Use, Land Use Change, and Forestry comprise approximately 7% of net emissions. Notably, Colorado's forests are currently estimated to be net sources of GHG emissions due to high tree mortality caused by drought stress, insects and disease, and wildfires (Taylor 2021).

The OSMP department owns or manages over 46,000 acres of land in and around the City, ranging from ponderosa pine and mixed conifer forests in the west to a mosaic of diverse grasslands in the east (Fig. 1). More frequent and extreme natural disasters are already apparent on these and nearby natural lands. Examples include the 2013 flood, which caused $27 million in municipal property damage and $300 million worth of private property damage in Boulder, the over 10,000 acres burned in the 2020 Cal-Wood fire (although not on OSMP land), and the devastating 2022 Marshall Fire with $2 billion in damages. A complete inventory of existing carbon stocks on OSMP lands has not been completed previously but see Easter et al. 2014 for a similar analysis on Boulder County Parks and Open Space land.

In July 2019, the City of Boulder declared a climate emergency, which triggered the development of several climate targets to guide city actions. As part of the City's commitment, OSMP is evaluating greenhouse gas emissions from operations (City of Boulder, 2022) as well as in the current study evaluating carbon stored in, and at risk of loss from, its lands, and opportunities for strategic management to increase storage and reduce emissions.

Many land management practices do not yet incorporate the best available science assessing climate-driven risks to ecosystem stability (Anderegg et al., 2020). For this study, we define risk of carbon loss as the intersection of OSMP's natural and working land assets and climate vulnerabilities in terms of exposure to climate change, sensitivity to those changes, and ability to adapt or respond. The sensitivity and response of plant communities to the predicted warming in Boulder will depend on complex interactions with soil water availability and plant and microbial physiological processes (Fay et al., 2011). A brief review of what Boulder's climate future may include is provided in Appendix 1. A brief review of foundational literature for this study is provided in Appendix 2.

In this study, the current carbon stock in lands managed by City of Boulder Open Space and Mountain Parks (OSMP) was estimated, along with annual carbon flux and carbon loss risk; the utility of nature-based solutions was also examined (Fig. 1).

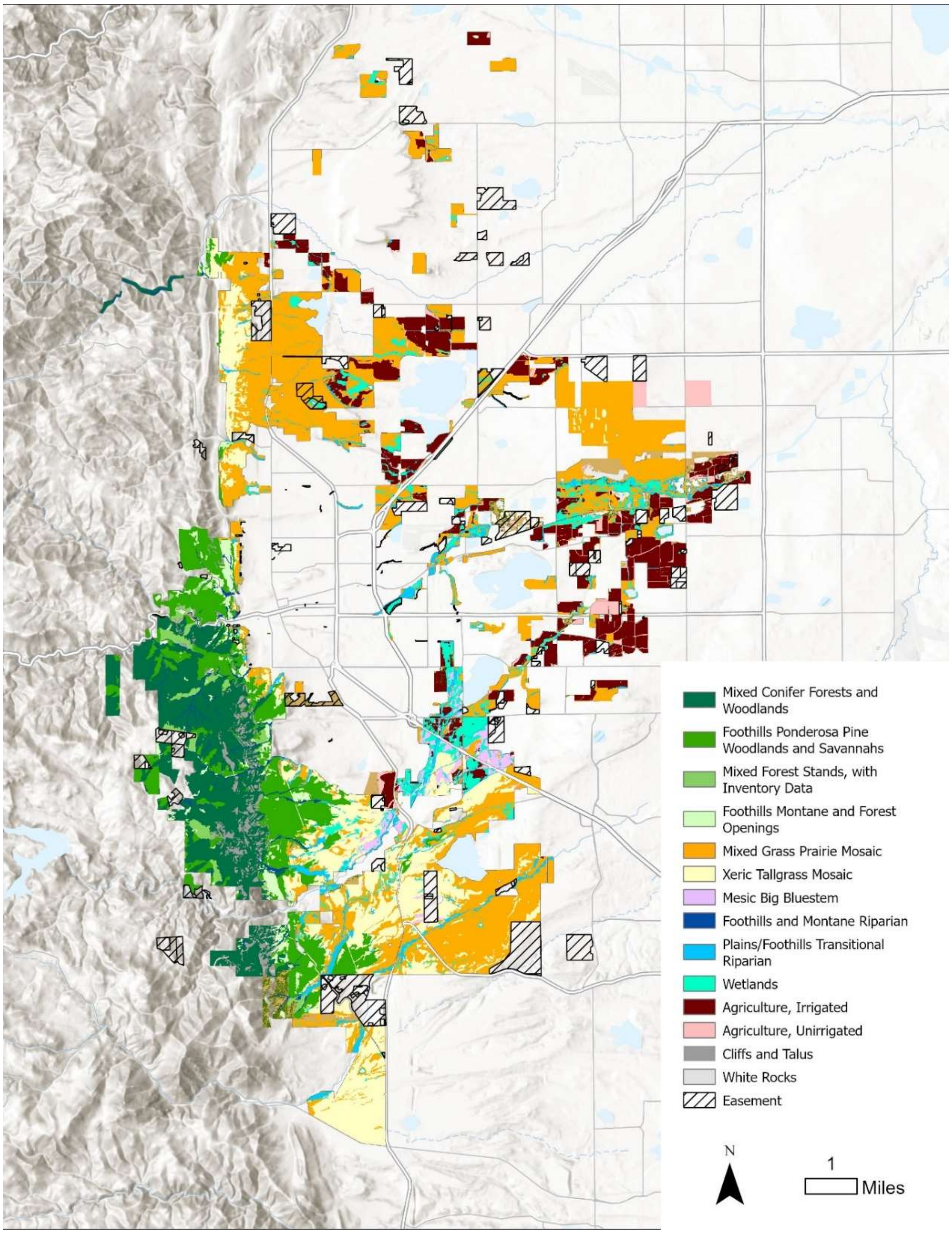


**Fig. 1.** Map of OSMP property overlaid with land cover types.

# METHODS

Methods were developed in close collaboration between the Biohabitats' team and City staff during the period of Fall 2022 to Summer 2023. Additionally, a technical advisory team of subject matter experts, knowledgeable about OSMP lands and practices, was consulted at key milestones in the project to test assumptions, gather additional input, and confirm completeness.

The analysis was based on the vegetation cover data provided by OSMP staff intersected with carbon density data found from several sources, including the national SSURGO dataset, the Forest Vegetation Simulator, the DAYCENT model, and literature sources. The baseline stock and flux values were inputted into the visual software program Analytica (Lumina Decision Systems) to conduct the analysis and allow for multiple assumptions and scenarios to be tested. Ranges of potential carbon flux values, and conditions from which those values were derived were also incorporated for carbon loss risk analysis. Nature-based solution fluxes were generally derived from a literature review of multiple sources to select a value most applicable to study conditions. Carbon values are presented in metric tons of $CO_2$ equivalents (MtCO2e). More methodological detail is provided in Appendix 3.

## Carbon Stock

Study Area

The study area is defined as the properties managed by Open Space and Mountain Parks (OSMP) as shown in Fig. 1. Of 46,610 acres classified as OSMP properties, private lands with easements were excluded from the analysis. Three properties (American Millsite at Boulder Falls, 4$^{th}$ of July Campground, and Luckie No. 3 at Boulder Falls) were also excluded from analysis because they were small, mostly unvegetated rocky areas and/or provided limited management potential. Finally, we excluded 726 acres that were not classified as being vegetated (e.g., cliffs and open water). Of course, water bodies also contain carbon in their sediments, which can change with changing flows and water levels; but to focus this study on land-based carbon and management, water bodies were excluded by the City in the initial scoping process. The remaining 36,464 acres were considered as the study area for the current project, although a coarse estimate for carbon stock is also provided for the omitted ca. 10,000 acres representing the properties mentioned above and easements.

Land Cover Data

Land cover and soils data were used as the basis of the carbon stock inventory. Land cover was assimilated from three data sources:

1. OSMP Conservation Targets (defined below; OSMP 2019 and 2022),
2. OSMP forest stands with forest sampling data, and
3. Denver Regional Conservation Assessment land cover (2 m resolution mapped in Biohabitats, 2022) to fill in study area gaps that were not covered by the other two data sources.

Conservation Targets are used by OSMP and described in the OSMP Master Plan (2019) as "Aspects of biological diversity identified in the Grassland Plan that best serve as the basis for setting objectives, taking action and measuring success." Note, conservation targets were developed and defined by the Grassland Ecosystem Management Plan and the West Trail Study Area (TSA) Plan (both available online). The City's geospatial datasets for conservation targets were developed by OSMP staff from field mapping and using aerial photographs over a period of several years, including a staff-led update to refine agricultural areas during the current project. Overall, the conservation targets were categorized into six major types with several subcategories based on plant communities:

1. Forest
    a. Mixed Conifer Forests and Woodlands
    b. Foothills Ponderosa Pine Woodlands and Savannahs
    c. Mixed Forest Stands
    d. Foothills Montane and Forest Openings
2. Grassland
    a. Mixed Grass Prairie Mosaic
    b. Xeric Tallgrass Mosaic
    c. Mesic Big Bluestem
3. Riparian
    a. Foothills and Montane Riparian
    b. Plains/Foothills Transitional Riparian
4. Wetlands
5. Irrigated Agriculture
6. Unirrigated Agriculture

At the subcategory level for forest, grassland, and riparian, the City's database includes additional details about plant alliances, disturbances, and other attributes, which were retained throughout this analysis to allow verification of the grouping decisions, evaluation of heterogeneity in the data categories and flux estimates, and for future management consideration. Table 1 presents the distribution of the summary land cover categories in OSMP lands.

<u>Carbon Stock Densities</u>

Carbon data for above and below ground biomass and soils were researched and evaluated from multiple sources for each conservation target, and the density values considered the best fit for the project were selected in collaboration with OSMP staff. Brief descriptions of the data sources are listed here and see Appendix 3 for additional methodological detail.

1. Soil carbon stock densities to a depth of 100 cm, except for agricultural areas, were sourced from the USDA Soil Survey Geographic Database (SSURGO), dated 8/18/22.
2. Easter et al. (2014) modeling for Boulder County agricultural lands utilizing DAYCENT was sourced for irrigated and unirrigated agriculture to a depth of 20cm and for riparian biomass.
3. Forest biomass carbon was calculated from OSMP forest sampling data utilizing the US Forest Service Forest Vegetation Simulator (FVS) program (Crookston and Dixon, 2005) applied to the most recent inventory year of each stand.
4. SSURGO rangeland productivity data were utilized to estimate grassland and wetland biomass.

Area-weighted means were calculated from spatial data and from OSMP forest sampling data to identify average representative carbon stock values by land cover category. Also, a statistical analysis to find the best-fit distribution for each land cover category was carried out, but the results were not conclusive, so assumed normal distributions for stock were developed based on the area-weighted means previously calculated.

### Carbon Flux

A variety of detailed input data are typically used to model the biogeochemical processes related to carbon fluxes and estimate annual sequestration rates. Some of these variables are captured in the FVS modeling as described below for forests. Other than forests, however, such detailed modeling is beyond the scope of the current study. Therefore, the innate variability in inter-annual carbon flux and differences based on soils, moisture regimes, etc. were acknowledged using high and low estimates for each land cover type.

1. Forest. The US Forest Service FVS program was used to process and review OSMP's forest sampling data. Forest flux was modeled in FVS for all stands in the data set starting from the most recent sampling date and projecting to 2050. A 30-year period was selected somewhat arbitrarily, but the intent was to have several decades to model future change based on climate warming impacts to disturbance regimes. Annual forest flux for each stand was averaged over the 30-year period from 2020 to 2050. Forest flux was then averaged on an area-weighted basis by stand area for three forest types (Mixed Conifer Forests and Woodlands, Foothills Ponderosa Pine Woodlands and Savannahs, and Mixed Stands not dominated by either Ponderosa Pine or Mixed Conifers) to calculate a summary flux for all forest.
2. Wetland. Minimum, mean, and maximum flux for wetlands were selected from Brandt (2017, MAST table and select references). Note, while wetlands can also be sources of greenhouse gas emissions under certain hydrologic conditions, these emissions were not included so as to focus the current study on carbon sequestration potential.
3. Riparian. COMET's reported value for riparian areas (Swan 2018) was used as an average annual flux: and a range of minimum and maximum riparian flux values were then calculated as described below.
4. Agriculture. Flux values were selected from Easter (2014) soil carbon flux rates reported for Boulder County, where the rate for mixed hay fields was used for irrigated lands and the winter wheat rate was used for unirrigated lands (Tables 14 and 15 respectively in Easter 2014). A range of minimum and maximum agricultural flux values were calculated from the average reported values (from Easter, 2014) as described below.
5. Grassland – An average flux value for grassland was selected from Brandt (2017), with maximum and minimum values calculated as described below.

For agriculture and grassland land cover categories, average values from the literature were used as baseline flux rates, and maximum and minimum estimates were calculated based on +31% higher than normal and -28% lower than normal to represent favorable and unfavorable years respectively, based on ranges of net primary productivity in Boulder County (USDA). A definition for "favorable" is not explicitly provided by USDA other than to note favorable precipitation conditions. This emphasis on precipitation follows Sala et al. (1988), whose seminal review of the relationship between precipitation and grassland productivity found that precipitation explained 90% of the variability in net primary productivity of grasslands across 9500 sites (up to 1400 mm precipitation/year). They defined favorable years as the wettest 10% of the years in the record and the unfavorable years as the driest 10% of the years. For carbon flux, negative numbers indicate carbon sequestration and positive values indicate carbon emissions.

**Carbon Loss Risk**

Carbon loss is a possibility in any given year or land cover type depending on management practices and disturbances. For example, OSMP's current operations result in loss from vehicle emissions (as described in City of Boulder, 2022) and from land management such as wood harvest and prescribed burns (which are relatively small areas and assumed to be captured within the fire scenarios in this analysis). Inputs and assumptions used in the carbon loss analysis are summarized herein.

Firewood Program

Discussions with OSMP staff summarized the department's 2021 forest thinning as including:

1. Harvesting a total of 236 trailer loads of wood from thinning, which is estimated to be roughly 500 cords of wood or about 700 tons of wood (note, this the weight of freshly cut wood), and
2. Diverting the majority of wood went to the firewood program and a few smaller diversions including:
   a. Firewood lot = 597 tons of wood
   b. Biochar facility in Berthoud CO = 45 tons
   c. Moved to the woodlot but remained after the 2021 season= 36 tons
   d. Other uses like OSMP fencing and restoration projects= 30 tons

Carbon emissions from thinned wood used as firewood were estimated based on a literature review focused on similar forest types (Strauss and Schmidt, 2012, Wei et al., 2012). Based on an average emission rate and tons of wood diverted per year, an average rate of 4,445 MtCO2e $yr^{-1}$ was included to capture indirect emissions from wood burning of harvested material.

Livestock Grazing

Other indirect carbon loss from OSMP land management practices include agricultural emissions including methane from cattle (2,700 MtCO2e $yr^{-1}$), which is included in the OSMP inventory for operations (City of Boulder, 2022) and therefore not otherwise included in this land-based analysis.

Forest Fire

Wildfire and heat-driven desiccation were selected as analysis parameters because they represent severe climate disturbance risks to OSMP lands in the future, based on literature reviews, recent observations, and the concentration of OSMP's carbon stock in forests and grasslands. Large insect or disease events are another possible source of carbon loss, but these were not evaluated here. Increased flooding due to flashy, intense storm events is also a threat but occurs in more localized riparian areas and is not expected to significantly impact OSMP carbon stocks. Mapping of individual hazards was reviewed to evaluate potential locations and extent of the major threats as described below. Forest wildfire flux in the model was assigned a range of intensity of emissions from burned acres of high at 53.8 MtCO2e $ac^{-1}$, average at 39.8 MtCO2e $ac^{-1}$, and low at 29.7 MtCO2e $ac^{-1}$.

Drought/Aridification

To assess the potential of drought to impact sequestration rates due to reduced productivity, low-end annual flux rates were applied across forest, riparian, and wetland vegetation types. For grassland and agricultural lands, carbon sequestration was assumed to be zero under drought conditions.

Erosion

Wind erosion was evaluated in two ways. First, for areas calculated to have wind erosion, a carbon loss rate of 0.29 $MtCO2e\ ac^{-1}\ yr^{-1}$ was applied. This rate was derived from a 2mm $yr^{-1}$ soil loss applied to the top 20 cm soil carbon stock for grasslands from SSURGO. The soil erosion rate of 2mm $yr^{-1}$ is based on Thaler et al.'s (2022) review comparing agricultural erosion with adjacent native prairie remnants finding a median historical erosion rate of 1.8 ± 1.2mm $yr^{-1}$. As the reference looks at agricultural conditions, this erosion rate may underestimate the loss rate for wind erosion of areas that are denuded throughout the year.

Second, wind erosion data from OSMP prairie dog colonies was extracted from Beals 2015 and converted to $MtCO2e\ ac^{-1}\ d^{-1}$. The minimum estimate was 0.015 $MtCO2e\ ac^{-1}\ d^{-1}$, the average was 0.115 $MtCO2e\ ac^{-1}\ d^{-1}$, and the maximum was 0.30 $MtCO2e\ ac^{-1}\ d^{-1}$. These were multiplied by the average acreage of an OSMP prairie dog colony in 2022, 39.7 acres, which was derived based on the sizes of all 5196 acres of prairie dog colonies in that year. This extent of prairie dog colony acres is representative of 2022, but the extent can fluctuate significantly with changes in prairie dog populations.

**Nature-Based Solutions**

Potential management strategies expected to affect carbon storage were identified based on literature, existing OSMP plans, current practices, additional feasible practices from COMET (Swan et al., 2018), and related tools developed by Colorado State University in conjunction with the USDA and NRCS. OSMP staff then reviewed the list of potential strategies to evaluate expected potential impact to greenhouse gas emissions, drawdown, resilience, diversity, agricultural productivity, and visitor experience. Based on the cumulative experience and input of staff, a subset of current and high-priority management activities was selected to include as OSMP management scenarios. For each management activity, flux values were selected and parameterized (Table 3).

Accelerate or Modify Forest Thinning

With inconclusive data on the net carbon effect of thinning, we assigned thinning a flux value of 0 $MtCO2e\ ac^{-1}\ yr^{-1}$. This value is based on a review of conflicting evidence. Boulder currently thins forest stands to maintain ponderosa pine woodland and savannah where prescribed burns are a more challenging management activity. Foresters have long used thinning to increase growth rates and reduce density, fuel load, and thereby the potential for intense canopy fires. Although Wiedinmyer and Hurteau (2010) modeled a 18-25% reduction in $CO2$ fire emissions from wide-scale prescribed fire in the western U.S., thinning dry, Front Range ponderosa pine/Douglas-fir forest stands did not result in net carbon sequestration unless all of the downed wood was used to replace fuel (Battaglia et al., 2010). Similarly, in an Arizona ponderosa pine forest, thinning could only have resulted in net carbon storage (3351 kg C $ha^{-1}$) if the wood were used for long-lasting products (Finkral and

Evans, 2008). From a carbon standpoint, the thinning of forests to reduce fire hazard may only be effective if a wildfire were to burn over the treated area within the rotation period (Battaglia et al., 2010).

The Cal-Wood fire provided a "natural experiment" to test the effect of fuel reduction and treatments meant to lessen the intensity of wildfire. Buma et al. (2022) found that while thinning or other treatments did reduce fuels and carbon, those plots also retained less carbon after the fire, so little or no protection of carbon stocks was conferred by such treatment. In contrast, prior wildfire was associated with more carbon stock remaining after the Cal-Wood fire. They also saw that treated areas seemed to exhibit a faster recovery, perhaps because the C after the groundcover regrew faster. Buma et al.'s (2022) general conclusion was corroborated by Hettema et al. (2022), who compared the post-fire pools between treated and untreated areas and found that fuels reduction treatments did not reduce carbon loss in the presence of wildfire enough to clearly distinguish post-fire carbon in the treated and untreated areas.

Post-Fire Reforestation

The model input of carbon flux for post-fire reforestation was 0 for years 1-10, followed by -2.23 MtCO2e $ac^{-1}$ $yr^{-1}$, as summarized below. Contemporary wildfires in ponderosa pine forests can produce low density stands or non-forest communities, especially in xeric settings (Rother and Veblen, 2016). Therefore, reforesting burned areas can increase carbon sequestration. Based on reforestation simulations, Battaglia et al. (2010) found that after 90 years, forest CO2 equivalent would range from 34.2 to 80.2 MtCO2e $ac^{-1}$ $yr^{-1}$ for a planting density of 200 trees per acre in the Hayman Fire site. Sites with intermediate moisture (site index 45) planted at 200 trees per acre yielded 54.0M MtCO2e $ac^{-1}$ $yr^{-1}$. Brandt et al. (2017) employed estimates from EPA (2022) to give an estimate of 13.7 M MtCO2e $ac^{-1}$ $yr^{-1}$ for 678,000 ha, a flat annual flux rate of -2.2 MtCO2e $ac^{-1}$ $yr^{-1}$. COMET estimates for the conversion of grassland to a farm woodlot were slightly higher, at -3.0 MtCO2e $ac^{-1}$ $yr^{-1}$, which seemed unreasonable given the dry conditions in the study area.

Ponderosa pine are very responsive to water availability in their growth rate, so we would expect Colorado stands to grow more slowly than northern California stands such as the Whitmore "Garden of Eden" research forest. Nevertheless, growth rates from that forest inform our estimation in that the first 10 years of carbon sequestration is very small, followed by a roughly linear growth rate from years 10-30 (Zhang et al., 2010). Therefore, to add a temporal factor to the flux rates, we estimated negligible (0) carbon sequestration for the first decade, followed by a steady rate of biomass accumulation for years 10-30.

Prescribed Fire for Grasslands

With inconclusive data on the net carbon effect of burning grasslands, we assigned burning a flux value of 0 MtCO2e $ac^{-1}$ $yr^{-1}$**.** This variable is included in the model and developed alongside other strategies so that future users can modify the flux value assumption if needed. This value is based on a review of conflicting evidence as summarized below.

Prescribed fire is frequently used to bolster the short-term productivity of grasslands and maintain their open character. However, a substantive review of frequently burned plots found they experienced a decline in surface soil carbon and nitrogen, having 36 per cent (±13 per cent) less carbon and 38 per cent (±16 per cent) less nitrogen after 64 years than plots that were protected from fire (Pellegrini et al., 2018).

Fire frequency modifies the long-term carbon storage in grasslands, and in dry conditions it can intensify nutrient limitation, which suppresses plant growth and carbon inputs, though it remains unclear to what extent fire regimes regulate above and belowground biomass allocation and carbon storage in shallower and deeper soil profiles (Bai and Cotrufo, 2022).

Soil Erosion Prevention

The value for soil erosion is based on Restoring Highly Disturbed Areas by Planting Permanent Vegetative Cover from COMET, at -0.17 MtCO2e $ac^{-1}$ $yr^{-1}$. Land disturbances from multiple human activities such as construction projects, animal impacts, and natural disasters can cause bare ground to persist and become susceptible to carbon loss via runoff and wind erosion (Munson et al., 2011). Wildfire and prescribed fire can also accelerate erosion (Karban et al., 2022). In Boulder, soil erosion has been observed in both grassland and agricultural lands.

COMET's "Critical Area Planting" (CPS342) addresses establishing permanent vegetation on disturbed lands, and it provides estimates for two scenarios in dry/semiarid conditions and in moist/humid conditions. For the purposes of the current analysis, the dry/semiarid planting of herbaceous vegetation was selected for soil erosion prevention in grasslands. For comparison, Easter et al. 2014, include restoration of degraded rangelands net soil C flux and $N_2O$ emissions as -0.28 MtCO2e $ac^{-1}$ $yr^{-1}$. Therefore, the COMET value appears to be a reasonable, slightly more conservative estimate for the purpose of the current analysis. Future evaluation of agricultural land management strategies could incorporate an additional related COMET strategy for Windbreak/Shelterbreak Establishment (CPS 380), which includes replacing a strip of cropland with 3 or more rows of woody plantings. Depending on if the windbreak replaces cropland, grassland, or expands an existing windbreak, the increased C sequestration values in COMET were -1.20, -1.18, and -0.04 MtCO2e $ac^{-1}$ $yr^{-1}$ respectively.

Grazing Management

In addition to reduced emissions and despite uncertainties, other references highlight soil sequestration potential from Great Plains research, with a conservative accumulation rate of -0.15 MtCO2e $ac^{-1}$ $yr^{-1}$ (Schuman et al. 2002). OSMP staff identified managing livestock grazing as a potential priority practice to maximize soil carbon accumulation, e.g., by varying rotations, establishing grass banks, and adjusting practices to sustain living cover and adjust grazing during droughts. Several ecosystem benefits are associated with these practices as well, such as improving water quality, reducing erosion, and improving food and cover for wildlife. The potential reduction in methane emissions from improved grazing management was not included in the analysis and is noted as a potential area for future investigation.

COMET's "Prescribed Grazing (CPS528)" has been developed for both "Grazing Management to Improve Rangeland or Non-Irrigated Pasture Condition" and "Grazing Management to Improve Irrigated Pasture Condition." COMET-Planner estimates assume managing vegetation removal on "*degraded grazing lands* by replacing extensive pasture management (60% forage removal) with intensively-managed grazing (40% forage removal) at 21-day intervals." The values in COMET reflect a reduction in emissions to achieve a relatively small emission rate of +0.0004 MtCO2e $ac^{-1}$ $yr^{-1}$.

Cropland to Grassland Conversion

Based on the following assumptions, the estimated value for conversion of cropland to grassland cover is -0.02 MtCO2e $ac^{-1}$ $yr^{-1}$. The NRCS practice for Conservation Cover (CPS327) provides several ecosystem benefits including enhanced habitat and reduced risks of soil erosion, which are desirable outcomes for OSMP. Therefore, COMET-Planner's practice to "Convert Irrigated/Non-Irrigated Cropland to Permanent Unfertilized Grass Cover" was used for estimating added carbon sequestration. The practice assumes that conventional agricultural fields (irrigated and unirrigated) stop being tilled, and plant residues accumulate on site. Cessation of nitrogen fertilizer is also included in the estimate, which may or may not be occurring on some of OSMP agricultural lands.

Beaver Dam Analogues

Beaver dam analogues were selected for investigation. However, re-introduction of beavers themselves could also be evaluated, and some of the information presented would remain applicable to the potential outcome of beaver introduction. The mean C stock for partially active dams at 57.7 MtCO2e $ac^{-1}$ was selected as a moderately conservative value for the purposes of the current study. If one assumes as a placeholder a 25-yr period to achieve that stock density, that would be equivalent to roughly -2.22 MtCO2e $ac^{-1}$ $yr^{-1}$.

Beaver activity increases stream corridor heterogeneity, and these alterations have been found to increase carbon storage through a variety of mechanisms including water retention and sedimentation in ponds, enhanced riparian vegetation, debris accumulation, and deposition on adjacent floodplains (Laurel and Wohl, 2019; McCreesh et al., 2019). Beaver-dammed riparian corridors are also less affected by wildfire (Fairfax and Whittle, 2020). Because of the multiple benefits beaver dams provide for habitat, water quality, groundwater recharge, and flood attenuation, there has been a growing interest in the potential to mimic dams as natural infrastructure. An additional benefit observed in CA and OR suggests beaver dams and meadows also act as natural fire breaks (Weirich III, 2021).

Beaver dam analogues (BDAs) are a restoration technique which replicates beaver dams through the placement of large wood across a stream to mimic a natural beaver dam. (Norman et al. 2022, Pollock et al., 2012). Because research into BDAs and carbon storage is only recently getting underway, mean organic carbon (OC) stock values for natural beaver dams were reviewed as being representative of potential uplift that could be achieved through the BDAs. A comparison of active and abandoned beaver meadows on the eastern side of Rocky Mountain National Park (RMNP) reported 446-594 MtCO2e $ac^{-1}$ in relict beaver meadows and 1,709-2,080 MtCO2e $ac^{-1}$ in active beaver meadows" (Wohl, 2013). The amount of carbon storage is associated with the type of stream system, channel configuration, soil depth, vegetation, and level of beaver activity among other factors. A follow-up study in RMNP further evaluated carbon stock using different categories of beaver meadows (abandoned, recently abandoned, partially active, and active) and found mean organic carbon stocks in cores (114 cm deep) ranged from 29.2 to 104.6 MtCO2e $ac^{-1}$ (Laurel and Wohl, 2019).

Landscape Rewetting

We used Callegary et al.'s (2021) estimate of the potential mean annual capture of organic carbon at a rate of 293 - 368 metric tons in a watershed of 7.7 $km^2$, which is equivalent to an average of roughly -0.64 MtCO2e $ac^{-1}$ $yr^{-1}$ to inform this management practice in the model. Note, some of these estimates would be of some relevance to the use of larger structures like check dams, which OSMP is more likely to deploy as a part of riparian restoration efforts.

Organic carbon is likely to be retained in cases where soils remain saturated and have low oxygen concentrations, as in wetland soils (Callegary et al., 2021). This is particularly important after fires when soil loss is high. USGS researchers have developed a substantial body of work based on small-scale dams such as Zeedyk or rock detention structures (RDS) in arid North America. Norman's (2020) research examines RDS that provide flood regulation; water regulation, purification, and provisioning; habitat provisioning; erosion regulation, carbon sequestration and storage; social value and climate regulation. Recent research finds that they can create wetlands in water-scarce riparian zones, with soil organic carbon stock as much as 81 - 567 MtCO2e $ac^{-1}$ in the top meter of soil (Norman et al., 2022). Though not all dry drainages should have water; in other words, some drainages may have always been xeric, and adding water could convert them into different novel ecosystems.

Riparian Restoration and Planting

The COMET estimate of -1.34 MtCO2e $ac^{-1}$ $yr^{-1}$ can be gained from this practice. The NRCS Riparian Forest Buffer (CPS 391) practice focuses on woody plantings, and COMET-Planner assumes "Replacing a Strip of Grassland Near Watercourses or Water Bodies with Woody Plants." This management action assumes the area of rangeland or managed pasture is replanted with woody plants (unfertilized) to establish a riparian forest buffer. Additional benefits include water quality improvements, habitat, and reduced loss from erosion due to stabilized stream banks. As such, future evaluations could address mitigating losses and incorporating additional related COMET strategies such as for "Critical Area Planting" (CPS342). However, historical conditions in the region included far fewer woody plants next to plains streams and there is value to have a diversity of habitats adjacent to streams (as opposed to all stream banks being dense with woody plants).

Wetland Restoration

For simplicity, the wetland restoration strategy was assumed to be equivalent to landscape rewetting strategy described earlier; however, we acknowledge that they are very different strategies with very different results in many circumstances. Callegary et al. (2021) estimated the potential mean annual capture of organic carbon at a rate 293 to 368 metric tons in a watershed of 7.7 $km^2$, which is equivalent to an average of roughly -0.64 MtCO2e $ac^{-1}$ $yr^{-1}$.

Restored wetlands likely sequester more carbon than other ecosystems, though the carbon accumulation rates are variable, which injects uncertainty into rate estimations. In an examination of 549 wetlands in the prairie pothole region, Tangen and Bansal (2020) found less soil carbon in less frequently inundated upland wetlands and those farther from the interior of the catchment, which have fewer emergent wetland species such as *Typha* spp. Interior sites also have finer soils and receive sediment from the edges of the catchments. Time since restoration was a strong factor in restoration rates from studies of single or few sites, with higher annual rates in young restoration sites. Many researchers follow the Intergovernmental Panel on Climate Change (IPCC) Tier 1 estimate that SOC stocks accumulate until replenished by 40 years following restoration. However, the variability in Tangen and Bansal's average annual rate of -0.27 MtCO2e $ac^{-1}$ $yr^{-1}$ was better explained by landscape condition.

**Forest Model**

The visual software program Analytica (Lumina Decision Systems) was used to conduct the analysis and allow for multiple assumptions and scenarios to be tested for the period from 2020 - 2050. The overall structure of the model was based on baseline land cover stock and flux inputs and three future scenarios:

1. Business as Usual (BAU), which includes a range of fluxes to represent climate variability only; note, BAU includes thinned wood fuel burned at average emission rate of 4,445 MtCO2e/year
2. Climate impacts including drought, erosion, and wildfire, with no mitigation
3. Climate impacts with mitigation using nature based solutions

Here, we discuss model configuration and assumptions for forests only. Additional model runs for other habitats are described in Appendix 3 along with instructions for accessing and running the model under different scenarios and select results of those runs are noted in Table 2.

<u>Forest Fire Emissions</u>

Forest wildfire emissions were derived from the Colorado state-level data from the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 (EPA, 2023). Data for annual forest wildfire emissions and area of forest burned were used to calculate the high, average, and low annual wildfire emissions intensities over the 30-year period.

<u>Fire Extents and Frequencies</u>

Four data sets were reviewed to understand past fire frequency and extent, which provided the basis for additional assumptions in the carbon loss risk analysis. Return intervals below indicated the time between fires for a specific stand, while occurrence data indicated the frequency of forest burning anywhere within the geography of the data set.

1. OSMP staff literature review, referencing Kaufmann et al. (2006) and Velben and Donnegan (2005). This literature review assigned Foothills and Ponderosa Pine Woodland and Savannah a fire return interval of 10-30 years, characterized with a typical fire regime of low intensity understory burns. Mixed Conifer Forests and Woodlands were assigned a fire return interval of 40-100 years, with a fire regime of mixed severity to stand replacing that is highly variable across the landscape.
2. LANDFIRE data (La Puma and Hatten, 2022) identifies spatially explicit fire return intervals under the presumed historical fire regime for the study area. These data show a broad range of fire return intervals for forests in the study area, ranging from 10 years to over 100 years, with an area-weighted average fire return interval of 25.6 years.
3. City of Boulder wildfire records. City data depicts recorded wildfires from 1990 to early 2023 in both forests and grasslands. Of these, three larger fires over 185 ac are shown within forest stand areas. Large wildfires (over 185 ac) ranged from 193 ac to 623 ac, averaging 361 ac in size, and having an average occurrence of every 10.7 years within the data time period.
4. Boulder County wildfire records. County data depicts recorded wildfires from 1974 to 2022. This presented an expanded spatial area and temporal record in comparison to City of Boulder data. County wildfire data was added to City wildfire data, County events were removed if they duplicated an event from City data, and the results were reviewed. In forest areas, 14 larger fires over 191 ac occurred, ranging in size from 180 ac to 10,114 ac (the 2020 Cal-Wood fire), averaging 2,086 ac in size, with an average occurrence of every 3.4 years. We acknowledge that 10k ac Cal-Wood fire is an outlier, and it would be interesting to examine the sensitivity of the results to the exclusion of this data point.

Forest wildfires were applied in the model using a 25-year fire frequency, aligning with fire occurring from 2025 to 2050 within the longer 30-year period of the study. As the modeling was conducted in 2023, the decision was made to start fire impacts in 2025 and model into the future. Based on the review of several data sources noted above, the 25-year fire frequency for the study area may underestimate the frequency of fire as indicated by the City and County wildfire records. Moreover, future fire regimes may simply be more extreme than anything indicated in the historical records.

Three sizes of hypothetical affected areas for forest wildfire impacts were applied to the model over the 25-yr period. The four data sets noted above were referenced to establish the orders of magnitude of the three representative wildfire extents. The hypothetical maximum area represented if all forests burned (with some burning more than one time given the low intensity of some fires) was a total of 12,355 ac (5,000 ha), which is plausible based on the 2020 Cal-Wood fire (10,114 ac). For the purposes of the model, this maximum area was evenly allocated across all years (starting in 2025) at an average rate of about 500 ac $yr^{-1}$, evenly distributing the probability of the maximum fire event throughout the model period. Given that there is not a future scenario where *no* wildfires occur, a theoretical minimum condition of roughly 60 ac $yr^{-1}$ and a moderate area affected by wildfire of about 100 ac $yr^{-1}$ were applied in the model for a total of 1,544 ac and 2,471 ac burned by 2050, respectively. The probability of forest wildfire was generated in the Analytica model, though Monte Carlo simulation, to create distributions from the input parameters of fire emissions intensity and fire extents. In future analyses, the fate of forest carbon could be evaluated separately for mixed conifer and ponderosa pine forests, as mixed conifer forests are more likely to burn in a stand-replacing fashion than low-intensity ponderosa pine burns.

**Uncertainty**

Numerous sources of uncertainty exist in this study. Uncertainty exists in how accurately spatial land cover data and carbon estimates represent on-the-ground conditions. This form of uncertainty was reduced to the extent feasible, but not quantified and propagated. To reduce this uncertainty, several spatial data sources were reviewed to select data with the highest confidence of representing existing conditions. When available and covering a majority of the study area spatial extent, field data such as OSMP forest sampling was incorporated directly. When field data was available, but limited in spatial extent, such as with OSMP grassland biomass sampling, the field data was used to validate the selection of more spatially complete data sources.

Boulder's lands also include natural, ecological variability within land cover types and their related stock and flux rates as reflected in the geospatial data for the study area, which includes 63 types of soils and 23 land cover subcategories (mapped in over 600 polygons). Assumed normal distribution ranges of those stock values were calculated and captured in the model. Uncertainty in annual carbon flux was addressed through selected ranges of values found in reference literature and data sources. Carbon loss risk presents significant uncertainty of future conditions which was also addressed through ranges intended to capture the diversity of potential future impacts from fire, drought/aridification, and erosion. The carbon impacts of nature-based solutions add another layer of uncertainty. For these values, multiple literature sources were reviewed and the one most applicable to the study area condition was incorporated in the model inputs for future analyses. The forest model incorporates aspects of all the above forms of uncertainty, layered in through three different scenarios. Uncertainty compounds over time, with the broadest potential ranges existing at the end of the study period in 2050.

**Field Data Verification**

Selection of data sources for stock and flux was supported by OSMP field data as available and described below.

1. Forest Stock. Since the mid-1990s, OSMP staff have collected measurements in 362 forest stands. These data were evaluated for quality of the observations and discussed in detail with OSMP's Forester. OSMP forest measurement data was directly incorporated for forest stock calculation in the FVS program.
2. Forest Flux. A subsample of forest plots, with monumented locations and without documented fire or thinning activity, was selected to compare the FVS forest growth model with field measurements over two time periods. Over a 17-to-21-year period, average aboveground biomass predicted by the FVS growth model was within 8.4% of average field measured conditions. As the monumented plot subsample was limited in geographic extent, the FVS growth model was utilized for forest flux.
3. Grassland Biomass. SSURGO rangeland productivity data was compared with field measured observations of aboveground biomass in the study area (Middleton 2022, unpublished). SSURGO rangeland productivity data differed from field measurements by 1% for Xeric Tallgrass Mosaic and <1% for Mixed Grass Prairie Mosaic grassland types. SSURGO data underpredicted Mesic Big Bluestem (MBB) biomass by approximately 14%. As the field data was limited in geographic extent, the SSURGO rangeland productivity data was utilized for grassland biomass.

## RESULTS

### Carbon Stock

The natural and working lands managed by OSMP contain approximately 2.7 million MtCO2e partitioned among forest, wetland, riparian, grassland, and agriculture (Table 1; Fig. 2). Using a set of standard normal distributions by land cover category for soil carbon density and for biomass carbon density, there is a 95% probability that the current stock will fall between 2.3M and 3.2M MtCO2e, which accounts for uncertainty from the different carbon densities for soil and biomass measured for each land category.

**Table 1.** Summary table of carbon stock, density, and flux by OSMP land cover types. Values are derived from a combination of literature and geospatial data sets as described below and detailed in the appendices. See also Figs. 1 and 2.

| Land Cover Class | Area (ac) | Soil Carbon Stock[b] (MtCO2e) | Biomass Carbon[c] Stock (MtCO2e) | Total Carbon Stock (MtCO2e) | Annual Carbon Drawdown Rate (min, mid, max) (MtCO2e $ac^{-1}$) | Annual Carbon Drawdown (MtCO2e $yr^{-1}$) |
|---|---|---|---|---|---|---|
| Grassland | 18,622 | 1,171,324 (62.9 $ac^{-1}$) | 13,594 (0.73 $ac^{-1}$) | 1,184,359 (63.6 $ac^{-1}$) | -0.022, -0.03, -0.039[d] | -558 |
| Forest | 9,946 | 361,040 (36.3 $ac^{-1}$) | 601,733 (60.5 $ac^{-1}$) | 962,773 (96.8 $ac^{-1}$) | 0.11, -1.16, -2. 7[e] | -7,114[i] |
| Irrigated ag | 3,983 | 247,158 (62.1 $ac^{-1}$) | 0 (0 $ac^{-1}$) | 247,158 (62.1 $ac^{-1}$) | -0.27, -0.37, -0.49[f] | -1,483 |
| Wetlands | 1,661 | 183,596 (110.6 $ac^{-1}$) | 1,826 (1.1 $ac^{-1}$) | 185,256 (111.6 $ac^{-1}$) | -0.25, -0.89, -1.91[g] | -1,472 |
| Riparian | 1,493 | 126,522 (84.8 $ac^{-1}$) | 27,005 (18.1 $ac^{-1}$) | 153,527 (102.9 $ac^{-1}$) | -1.07, -1.48, -1.94[h] | -2,211 |
| Unirrigated ag | 761 | 24,613 (32.3 $ac^{-1}$) | 0 (0 $ac^{-1}$) | 25,527 (33.5 $ac^{-1}$) | -0.06, 0.09, -0.12[f] | -68 |
| Totals | 36,466 | 2,114,252 (58 $ac^{-1}$) | 644,158 (17.7 $ac^{-1}$) | 2,758,600[a] (75.7 $ac^{-1}$) | | -12,905 |

***Notes:*** [a] Applying a rate of 76 MtCO2e $ac^{-1}$ to the 10,000 acres of OSMP land not classified in this study increases the stock value to 3,515,168 MtCO2e. [b] 0-20 cm for agriculture; 0-100 cm for all others. [c] Includes above and belowground biomass. [d] Midrange from Brandt 2017, +/- factors for precipitation from USDA. [e] FVS. [f] Mid-range from Easter 2014, +/- factors for precipitation from USDA. [g] Brandt 2017. [h] COMET woody restoration (Swan 2018). [i] 4,445 is added to account for wood burned in the firewood program.

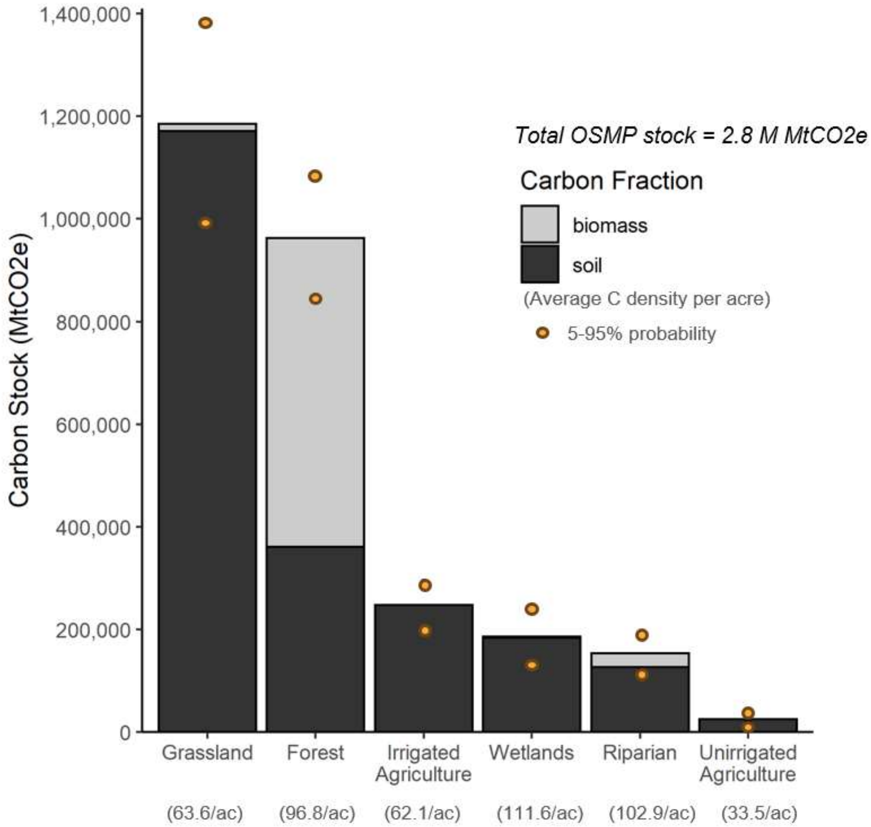


**Fig. 2**. Current carbon stock for OSMP land cover. Most land use categories store most of their carbon in the soil (darker shade), with the notable exception of the forest biomass pool. The variability associated with the total (biomass + soil) carbon estimate is presented by the black points. 95 percent of the modeled values fell above the lower black point and below the upper black point.

The majority of OSMP's total carbon stock, approximately 2.1 million MtCO2e or 77%, is stored in the soil. Around 97% (~602,000 MtCO2e) of the remaining stock is found in forest biomass. The combined carbon in wetland, riparian, and grassland biomass represents only 3% of OSMP's current carbon stock in biomass. If we apply a flat rate of 76 MtCO2e acre$^{-1}$, the estimated average carbon density within the study area, to the additional 10,000 acres of OSMP land that are not otherwise accounted for in this study, the revised estimate of OSMP's total carbon stock is 3,515,168 MtCO2e.

The uncertainty in the stock estimate of each land cover ranged from a few thousand metric tons of carbon dioxide equivalents for irrigated agriculture to a range of almost 400,000 MtCO2e for grasslands.

### Carbon Flux

Using the midrange of annual flux values for each land category, the total carbon stock in OSMP lands is projected to increase by 12,905 MtCO2e yr$^{-1}$ without climate disturbance or management changes (Table 2), driven by the high draw down rates in forests (see flux estimates in Table 1).

### Carbon Loss Risk

Wildfire, drought effects, and erosion pose realistic threats to the stability of carbon stock (Table 2). For example, for forests, a 500-acre wildfire can release 14,850 – 26,900 MtCO2e (Table 2); when modeled to 2050, arid conditions with regular wildfires could result in a loss of up to 388,650 MtCO2e of forest carbon (Fig. 3). For wind erosion from prairie dog colonies, it was estimated that 11.8 MtCO2e could be lost from a single 40-acre prairie dog colony in a single windy day.

**Table 2**. Potential carbon variability year-over-year.

| Driver | Carbon Flux Rate | Carbon Change Estimate |
|---|---|---|
| Normal Climate Conditions | 0.35 MtCO2e $ac^{-1}$ [a] | -12,905 MtCO2e drawdown $yr^{-1}$ |
| Drought Climate Conditions | 0.01 MtCO2e $ac^{-1}$ | Loss of 10,533 MtCO2e vs. a normal yr |
| 500-acre Forest Wildfire | Low: 29.7 MtCO2e $ac^{-1}$ | Low: 14,850 MtCO2e lost per event |
| | Mid: 39.8 MtCO2e $ac^{-1}$ | Mid: 19,900 MtCO2e lost per event |
| | High: 53.8 MtCO2e $ac^{-1}$ | High: 26,900 MtCO2e lost per event |
| 200-acres of Soil Erosion | 0.29 MtCO2e $ac^{-1}$ | 58 MtCO2e lost $yr^{-1}$ |
| Wind Erosion[b] | Low: 0.015 MtCO2e $ac^{-1}$ $d^{-1}$ | Low: 0.6 MtCO2e lost $day^{-1}$ |
| | Average: 0.12 MtCO2e $ac^{-1}$ $d^{-1}$ | Average: 4.6 MtCO2e lost $day^{-1}$ |
| | High: 0.30 MtCO2e $ac^{-1}$ $d^{-1}$ | High: 11.8 MtCO2e lost $day^{-1}$ |
| Forestry Wood Burned as Firewood[c] | Low 5.5 MtCO2e $ton^{-1}$ | Low 3,850 MtCO2e lost $yr^{-1}$ |
| | High 7.6 MtCO2e $ton^{-1}$ | High: 5,320 MtCO2e lost $yr^{-1}$ |

***Notes:*** [a]See Table 1 for habitat-specific flux estimates. [b]Wind erosion from a 40-acre prairie dog colony in one day. Low, average, and high values represent days that are calm, breezy, and very windy. [c]Based on 700 tons. See report for references.

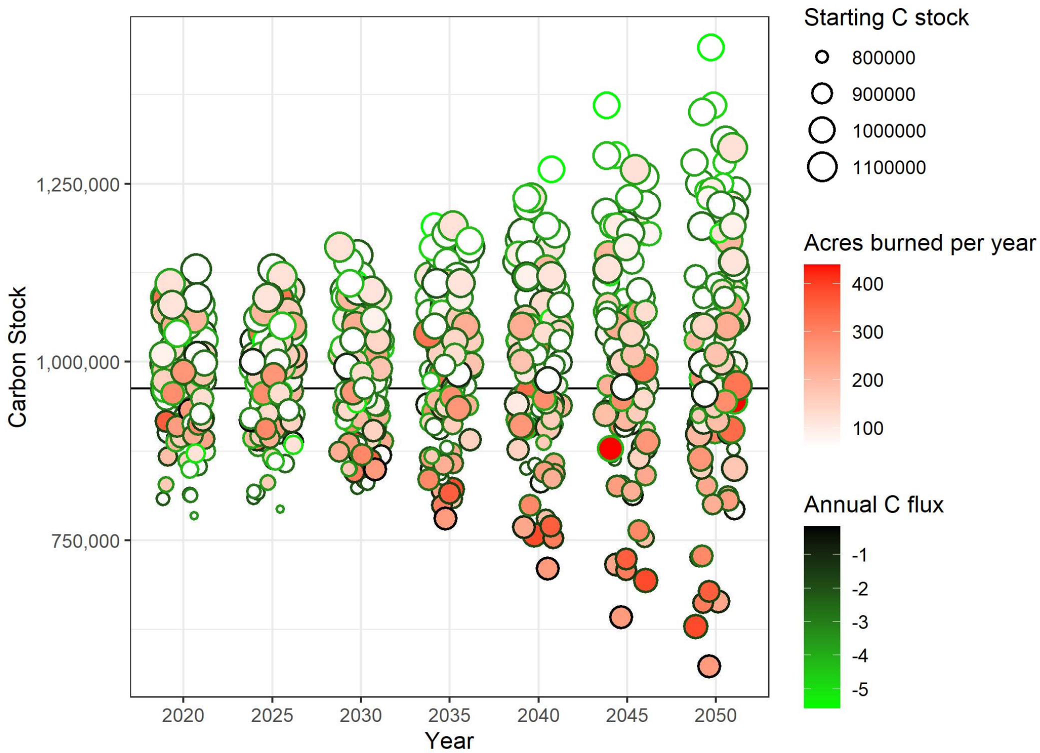


**Fig. 3**. Modeled fate of forest carbon. Each dot is 1 of 100 model predictions of forest carbon. The horizontal line is the mean for 100 forest carbon estimates in 2020. In 2050, the lowest forest carbon stock estimates (bottom right corner of the graph) are those that have a low starting carbon stock (smaller size), a high number of acres burned in a wildfire (red fill), and low annual carbon drawdown rates (black borders). Likewise, the highest forest carbon stock estimates in 2050 (top right corner of the graph) are those that have a high starting carbon stock (larger size), a low number of acres burned (white fill), and high annual carbon drawdown rates (green borders). The model predictions also incorporate uncertainty in carbon emissions rates during wildfires (not shown).

## Nature-Based Solutions

The drawdown estimates for ten different nature-based solutions are presented in Table 3. Among the most impactful per acre are beaver dam analogues, post-fire restoration/planting, and riparian and wetland restoration, while the most scalable were related to fire and grazing management. Note, initial model runs were also conducted to estimate sequestration potential of these NBS strategies across the OSMP system; however, results were considered nonconclusive given the uncertainty of spatially explicit locations for applications.

**Table 3.** Flux estimates for nature-based solutions.

| Nature Based Solution | Modeled Flux Estimate in MtCO2e $ac^{-1}$ $yr^{-1}$ | Reference |
|---|---|---|
| Beaver dam analogues | -2.22 | Various, see text |
| Post-fire restoration | 0 for years 1-10, then -2.23 | Brandt et al. (2017) |
| Riparian restoration and planting | -1.34 | COMET (Swan et al., 2018) |
| Wetland restoration | -0.64 | Callegary et al. (2021) |
| Landscape rewetting | -0.64 | Callegary et al. (2021) |
| Soil erosion prevention | -0.17 | COMET (Swan et al., 2018) |
| Grazing management | -0.15 | Schuman et al. 2002 |
| Cropland to grassland conversion | -0.02 | COMET (Swan et al., 2018) |
| Accelerate or modify forest thinning | 0 | Various, see text |
| Prescribed fire for grasslands | 0 | Various, see text |

# DISCUSSION

The dual threat of climate change and biodiversity loss has motivated land managers to inventory the carbon in vegetation and soils and to pilot an array of nature-based solutions (NBS) to maintain and grow carbon stocks and improve ecological health and resilience.

Part of the motivation for these efforts is the growing awareness of the social costs of carbon emissions. Based on US EPA's current assessment (EPA, 2022), each ton of carbon emitted results in $140 - $380 impacts in 2030 (based on 2020 USD and a 2% discount rate). At that rate, Boulder's carbon stock in biomass (618,599 MtCO2e) has an avoidance value of over $86M - $235M of economic damages; if the carbon in soil (2,140,001 MtCO2e) is included, that loss estimate more than triples.

The City of Boulder OSMP actively manages a large portfolio of land for a variety of ecological and social values and is interested in better understanding the potential NBS strategies that could achieve the most benefits including:

1. Reduction in carbon emissions from its land use
2. Store additional carbon from the atmosphere in its lands
3. Improve ecosystem resilience to climate impacts
4. Impact to or co-benefits for agricultural productivity, farmer and rancher financial sustainability, income diversification, and agro-ecosystems
5. Impact to, or co-benefits for recreational access, visitor experience, and public enjoyment
6. Potential for outcome-based payment for carbon storage based on several feasibility and reliability related metrics

The potential to have an impact and achieve these stacked benefits will result from the combination of existing stock in conservation target areas, their rate of annual flux, the risk of loss, and the flux changes associated with NBS.

### Carbon Stock

The current total carbon stock estimate in OSMP lands is estimated to be 2.7M MtCO2e (with range of 2.3 to 3.2) and has an average density of 75.7 MtCO2e $ac^{-1}$. The predominance of carbon stock in grassland soils (55%) and its relative stability, highlights the significant role grassland ecosystems can play in the region, and in addition to their habitat significance, provides further rationale to avoid conversion to development. This value may be somewhat lower than expected based on prior studies in the region. One possible reason is that USFS literature-based values, likely used by other studies, are based on more densely stocked forest types than what is found on OSMP lands. The forest category in this study ranges from dense mixed conifer forests to ponderosa pine woodland and savannah with less tree biomass. A second reason may be that carbon stock associated with shrubs is underestimated as a component of the grassland inventory presented here.

If the stock assets are compared to a bank account, the current and future stock are a relatively small "savings" account, when compared to the annual "expenses" of the City's emission rate of 1.8 million MtCO2e. The current stock can only account for 1.5 to 2 years of annual emissions by the city. Note, however, the city's climate is goal is to reduce its emissions to net zero by 2035.

### Carbon Flux

Total annual flux in the OSMP managed lands is estimated to be roughly 12,905 MtCO2e. This annual drawdown rate more than covers OSMP's annual emissions from departmental operations of 3,700 MtCO2e (i.e., from stationary energy, procurement, etc.) and agricultural and forestry land use practices of roughly 2,800 to 3,000 MtCO2e (based on 2018 and 2021; City of Boulder, 2022). However, OSMP's annual drawdown from flux is far short of being able to cover emissions from visitor travel to and from OSMP trailheads (~15,000 MtCO2e per year; City of Boulder, 2022).

Forest biomass offers the largest potential annual increase in carbon based on large land area (under a no loss scenario). Although forest age and growth rates change (and could decline) over time, the OSMP flux number is modeled out to 2050 based on the starting conditions and condition of the trees including age. Specifically, the rate was generated from the FVS model using OSMP stand data, which is based on growth curves and the dynamics of different forest measurements, such as tree species, diameter, height, condition, quantity, and stand density. The rate of annual flux under baseline conditions is controlled in large part by precipitation and available water, thus retaining water in the soil will be key to helping maintain annual flux rates.

Grasslands had the lowest carbon flux rate of all the habitats examined. This low flux rate suggests that grasslands should not be used to accelerate carbon drawdown. Rather, the carbon management focus for grasslands should be avoiding conversion.

### Carbon Loss Risk

OSMP lands will be exposed to increased temperature, drought, wildfires, and windblown erosion impacts which makes their portions of the stock pools vulnerable. Forests cover the second largest area after grasslands and contain 36% of the carbon. Given the size and condition of forests, the greatest exposure of risk of carbon loss is expected to be in forests under worst case scenarios of large-scale wildfire. While the predictions for forests were trained on long-term data, it is worth bearing in mind that long-term data may underestimate the frequency and intensity of fires in the future. To preserve existing and potential future stock will require protecting the most vulnerable portions of carbon stock in strategic locations.

### Nature-Based Solutions

While the potential to increase sequestration using NBS is evident by modest drawdown estimates per acre, even if deployed at a large extent, initial test model runs suggest NBSs will not offer a "silver bullet" for mitigating City emissions. Instead, it is more relevant to focus on the co-benefits of nature-based solutions which likely far outweigh their potential for carbon management. In forests for example, combining NBSs to enhance soils may simultaneously prevent forest carbon loss risk reduction and improve hydrology.

Emissions from OSMP forests include release from wildfires and wood burning of harvested material. The largest potential to reduce or manage greenhouse gas emissions is to reduce the forests' vulnerability to wildfires. Because forest fires are inevitable and may increase in the future, managing the loss risk through intentional units and fire breaks could help reduce wildfire extents. Combining forest management NBS strategies such as selective thinning and inoculated woodchips to improve forest health in locations that could facilitate broader mountain meadows and landscape rewetting not only could help reduce risks of extreme fires but also create healthier soils and more resilient and diverse habitat features. The diversion of thinned wood to storage options that do not result in emissions through burning are also recommended.

**Take Care of What We Have**

Climate action includes protecting and growing OSMP's carbon stock while reducing the department's emissions. These actions must be completed in a way that has co-benefits for the department's charter purposes, especially protecting biodiversity and supporting agriculture. Yet, trade-offs are inevitable. For example, there may be many emissions associated with the heavy machinery required to restore a landscape into a higher functioning, climate resilient state. And there's no guarantee that the restored landscape will ultimately store more carbon, even if it is in a more natural state, that the rate of drawdown will be quick and stable, nor whether the newly realized carbon stock will be permanent. On top of these complexities, the comparison of OSMP's carbon stock with city emissions may make carbon management using OSMP's lands feel like less of a priority or a distraction.

Yet, land managers must do what they can to understand the carbon cycle, minimize catastrophic carbon releases, and drawdown additional carbon, when possible, all while reducing their carbon footprint, because "every ton matters." Every ton of carbon release into the atmosphere has the potential to exacerbate climate warming and disasters, causing $140 - $380 (USEPA, 2022) worth of damage, and will live in the atmosphere for 50 years. Every country, institution, municipality, and individual have a role to play in climate change mitigation, including the OSMP department and its staff. Including carbon considerations in City priorities may also mean additional planning measures to address innovative transportation alternatives to open space.

The bottom line is that OSMP's risk of carbon loss is much greater than its opportunities to accelerate carbon drawdown. Given this, OSMP needs to take care of the carbon stock it has, avoiding emissions of carbon through extreme disturbances that are outside the range of historic variability, avoiding landcover conversions (e.g., forests remain forests), and managing for ecosystem health and resilience.

**Unanswered Questions and Areas for Further Research**

This study uncovered several areas for further research, including the following (not listed in priority order):

1. Develop carbon risk loss estimates into a spatially-explicit, parcel-scale predictive model of climate risk and resilience.
2. Improve the carbon stock and flux estimates using enhanced remote-sensing methods and field verification, including possible refinement of potential carbon inventory to better account for shrubs in grasslands.
3. Review forest sampling approach, including the addition of forest plot monuments, for the purposes of calibrating forest growth modeling to study area conditions.

4. Partner with climate scientists to downscale large-scale regional scale models to local conditions.
5. Add an investigation of carbon loss related to disease and pest outbreak events.
6. Investigate the potential to divert harvested wood from thinning to storage or other beneficial uses such as biochar: but prior to large application of biochar, study long-term impacts of shifting C:N ratio on native biodiversity.
7. Research opportunities to manage wildfire risks through strategic burn unit designs, planning fire breaks with stacked benefits (e.g., riparian enhancements and trails), and directional felling to slow water runoff and prevent soil loss.
8. Research opportunities to recouple grassland prescribed burns with grazing for dual benefits of holistic range management and reduced methane production from cattle.
9. Examine the ability to scale-up nature-based solutions for wetlands and riparian areas.
10. Look outside of OSMP lands for opportunities to avoid conversions through acquisition or partnership.
11. Improve documentation and categorization of the historical and current status of agricultural lands, including tracking of irrigation, crop type, tilling history, and grazing records, and how these activities relate to carbon stock and flux.
12. Use the results and discussion above to compile a prioritized list of recommendations to protect and grow OSMP carbon stocks.

## LITERATURE CITED


Anderegg, W.R., Trugman, A.T., Badgley, G., Anderson, C.M., Bartuska, A., Ciais, P., Cullenward, D., Field, C.B., Freeman, J., Goetz, S.J., 2020. Climate-driven risks to the climate mitigation potential of forests. Science 368, eaaz7005.

Bai, Y., Cotrufo, M.F., 2022. Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science 377, 603–608.

Battaglia, M.A., Nelson, K., Kashian, D., Ryan, M.G., 2010. Forest Biomass and Tree Planting for Fossil Fuel Offsets in the Colorado Front Range. Integr. Manag. Carbon Sequestration Biomass Util. Oppor. Chang. Clim. 81.

Beals, Stower Charles, 2015. Re-Evaluating The Ecological Role Of A Keystone Species at th Urban-Wildland Interface. University of Colorado thesis in partial fulfillment of the Doctor of Philosophy Department of Ecology and Evolutionary Biology.

Brandt, N., Brazeau, A., Browning, K., Meier, R., 2017. Carbon Sequestration in Colorado's Lands: A Spatial and Policy Analysis. University of Colorado Boulder, pp. PA11C-06.

Buma, B., Vorster, A., Twadell, E. 2022 in press.Fuels treatments and their impact on carbon stocks and fire severity in Boulder and Jefferson Counties and the City of Boulder.

Callegary, J., Norman, L., Eastoe, C., Sankey, J., and A. Youberg. 2021. Preliminary assessment of carbon and nitrogen sequestration potential of wildfire-derived sediments stored by erosion control structures in forest ecosystems, Southwest USA. Air, Soil and Water Research 14.

City of Boulder. 2022. City of Boulder Open Space and Mountain Parks department, Greenhouse Gas Inventory Report. Calendar years 2018 and 2021. The City of Boulder, Open Space and Mountain Parks Department. Boulder, Colorado.

Crookston, N.L., Dixon, G.E., 2005. The forest vegetation simulator: a review of its structure, content, and applications. Comput. Electron. Agric. 49, 60–80.

Davey Resource Group, 2018. City of Boulder Urban Forest Strategic Plan.

Debinski, D.M., Wickham, H., Kindscher, K., Caruthers, J.C., Germino, M., 2010. Montane meadow change during drought varies with background hydrologic regime and plant functional group. Ecology 91, 1672–1681.

Easter, M., Swan, A., Williams, S., 2014. Greenhouse Gas Inventory from Agriculture, Forestry and Other Land Uses for Boulder County, Colorado Parks and Open Space.

EPA, 2023. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021.

EPA, N.C. for E.E., 2022. Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances.

Fairfax, E., Whittle, A., 2020. Smokey the Beaver: beaver-dammed riparian corridors stay green during wildfire throughout the western United States. Ecol. Appl. 30, e02225.

Fay, P., Blair, J., Smith, M., Nippert, J., Carlisle, J., Knapp, A., 2011. Relative effects of precipitation variability and warming on tallgrass prairie ecosystem function. Biogeosciences 8, 3053–3068.

Fink, M., Decker, K., 2014. Colorado wildlife action plan enhancement: climate change vulnerability assessment.

Finkral, A., Evans, A., 2008. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. For. Ecol. Manag. 255, 2743–2750.

Fitzpatrick, M.C., Dunn, R.R., 2019. Contemporary climatic analogs for 540 North American urban areas in the late 21st century. Nat. Commun. 10, 1–7.

Galik, C.S., Jackson, R.B., 2009. Risks to forest carbon offset projects in a changing climate. For. Ecol. Manag. 257, 2209–2216.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. 114, 11645–11650.

Hettema, S., Rogers, J., Sugiura, I., and E. Twaddell. 2022. Carbon on the Front Range Impacts of Forest Mana gement and Wildfire on Forest Carbon Storage: 2020 Cal-Wood Fire, Colorado.

ICLEI - Learn Report., 2021. GHG Inventory for Forests and Trees Outside Forests, 2008 to 2016.

Karban, C.C., Miller, M.E., Herrick, J.E., Barger, N.N., 2022. Consequences of piñon-juniper woodland fuel reduction: prescribed fire increases soil erosion while mastication does not. Ecosystems 25, 122–135.

Kaufmann, M.R., Veblen, T.T., Romme, W.H., 2006. Historical fire regimes in ponderosa pine forests of the Colorado Front Range, and recommendations for ecological restoration and fuels management. Front Range Fuels Treat. Partnersh. Roundtable Find. Ecol. Workgr.

Knapp, A.K., Carroll, C.J., Denton, E.M., La Pierre, K.J., Collins, S.L., Smith, M.D., 2015. Differential sensitivity to regional-scale drought in six central US grasslands. Oecologia 177, 949–957.

La Puma, I.P., Hatten, T.D., 2022. LANDFIRE data and applications (No. 2327–6932). US Geological Survey.

Laurel, D., Wohl, E., 2019. The persistence of beaver-induced geomorphic heterogeneity and organic carbon stock in river corridors. Earth Surf. Process. Landf. 44, 342–353.

Loik, M., Redar, S., Harte, J., 2000. Photosynthetic responses to a climate-warming manipulation for contrasting meadow species in the Rocky Mountains, Colorado, USA. Funct. Ecol. 14, 166–175.

Lotus Engineering, 2022. Community-wide Greenhouse Gas Emissions Summary Report, Calendar Year 2021.

McCreesh, R.K., Fox-Dobbs, K., Wimberger, P., Woodruff, K., Holtgrieve, G., Pool, T.K., 2019. Reintroduced beavers rapidly influence the storage and biogeochemistry of sediments in headwater streams (Methow River, Washington). Northwest Sci. 93, 112–121.

Munson, S.M., Belnap, J., Okin, G.S., 2011. Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. Proc. Natl. Acad. Sci. 108, 3854–3859.

Norman, L.M., 2020. Ecosystem services of riparian restoration: a review of rock detention structures in the Madrean Archipelago Ecoregion. Air Soil Water Res. 13, 1178622120946337.

Norman, L.M., Lal, R., Wohl, E., Fairfax, E., Gellis, A.C., Pollock, M.M., 2022. Natural infrastructure in dryland streams (NIDS) can establish regenerative wetland sinks that reverse desertification and strengthen climate resilience. Sci. Total Environ. 849, 157738.

Parton, W., Scurlock, J., Ojima, D., Gilmanov, T., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J., Seastedt, T., Garcia Moya, E., 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Glob. Biogeochem. Cycles 7, 785–809.

Pellegrini, A.F., Ahlström, A., Hobbie, S.E., Reich, P.B., Nieradzik, L.P., Staver, A.C., Scharenbroch, B.C., Jumpponen, A., Anderegg, W.R., Randerson, J.T., 2018. Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. Nature 553, 194–198.

Rondeau, R.J., 2013. Vegetation response in a Colorado grassland-shrub community to extreme drought: 1999–2010. Am. Midl. Nat. 170, 14–25.

Rother, M.T., Veblen, T.T., 2016. Limited conifer regeneration following wildfires in dry ponderosa pine forests of the Colorado Front Range. Ecosphere 7, e01594.

Sala, O.E., Parton, W.J., Joyce, L.A., Lauenroth, W.K., 1988. Primary production of the central grassland region of the United States. Ecology 69, 40–45.

Saleska, S.R., Harte, J., Torn, M.S., 1999. The effect of experimental ecosystem warming on CO2 fluxes in a montane meadow. Glob. Change Biol. 5, 125–141.

Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.O., Roberts, D., Zhai, P., Slade, R., Connors, S., Van Diemen, R., 2019. IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Strauss, W., Schmidt, L., 2012. A Look at the Details of CO2 Emissions from burning Wood vs. Coal, FutureMetrics, January, 2012, Access: https://policycommons.net/artifacts/1961653/a-look-at-the-details-of-co2-emissions-from-burning-wood-vs/2713418/.

Swan, A., Easter, M., Brown, K., Layer, M., Paustian, K., 2018. COMET-Planner: Carbon and Greenhouse Gas Evaluation for USDA-NRCS Conservation Practice Planning.

Tangen, B.A., Bansal, S., 2020. Soil organic carbon stocks and sequestration rates of inland, freshwater wetlands: Sources of variability and uncertainty. Sci. Total Environ. 749, 141444.

Taylor, T., 2021. Colorado Greenhouse Gas Inventory Update.

Thaler, E.A., Kwang, J.S., Quirk, B.J., Quarrier, C.L., Larsen, I.J., 2022. Rates of historical anthropogenic soil erosion in the midwestern United States. Earths Future 10, e2021EF002396.

US Department of Agriculture (USDA), Soil Survey Boulder County Area. CO643. Table 6 Rangeland Productivity. (See also Methods Appendix for discussion of use of SSURGO database.)

U.S. Environmental Protection Agency (USEPA), 2022. Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances September 2022 National Center for Environmental Economics Office of Policy Climate Change Division Office of Air and Radiation U.S. Environmental Protection Agency Washington, DC 20460 in Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review" EPA External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. Docket ID No. EPA-HQ-OAR-2021-0317 September 2022.

Veblen, T.T., Donnegan, J.A., 2005. Historical range of variability for forest vegetation of the national forests of the Colorado Front Range. USDA Forest Service, Rocky Mountain Region Golden, CO.

Wei ,Wen, W. Zhang, D. Hu , L. Ou , Y. Tong, G. Shen, H. Shen, X. Wang, 2012. Emissions of carbon monoxide and carbon dioxide from uncompressed and pelletized biomass fuel burning in typical household stoves in China. Atmospheric Environment, V 56 (2012), 136-142.

Weirich III, J.J., 2021. Beaver moderated fire resistance in the north cascades and potential for climate change adaptation.

Wiedinmyer, C., Hurteau, M.D., 2010. Prescribed fire as a means of reducing forest carbon emissions in the western United States. Environ. Sci. Technol. 44, 1926–1932.

Wohl, E., 2013. Landscape-scale carbon storage associated with beaver dams. Geophys. Res. Lett. 40, 3631–3636.

Zavyalov, N., 2014. Beavers (Castor fiber and Castor canadensis), the founders of habitats and phytophages. Biol. Bull. Rev. 4, 157–180.

Zhang, J., Powers, R.F., Skinner, C.N., 2010. To manage or not to manage: the role of silviculture in sequestering carbon in the specter of climate change. Presented at the Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate. Proceedings of the 2009 National Silviculture Workshop, Boise, Idaho, USDA Forest Serv. Proc. RMRS-P-61, Rocky Mtn. Res. Stn., Ft Collins, CO, pp. 95–110.

# APPENDICES

## Appendix 1. Likely Future State of Boulder's Climate

1. **Temperatures will increase**. Colorado will experience substantial future warming, with statewide average annual temperatures projected to warm by +2.5°F to +5°F by 2050 above the 1971–2000 baseline in a medium-low emissions scenario or +3.5°F to +6.5°F in a high emissions scenario (Gordon and Ojima, 2015). In Boulder, more than half the summer days will reach 95°F or hotter.
2. **Precipitation will change**. Precipitation change projections are less clear. Foothill and montane grasslands are projected to experience winter precipitation levels within the current range, but annual precipitation levels are projected to be lower than the driest end of the current range for nearly half of the lower elevation distribution, and drought days are projected to increase in some areas (Fink and Decker, 2014). Importantly, some precipitation that now falls as snow will be in the form of rain and thereby alter spring snowmelt patterns.
3. **Soil moisture will decrease**. Soil moisture is often the primary mediator of the plant response (Loik et al., 2000). In experimental heating of a montane meadow, net carbon flux decreased by about 100 g carbon $m^{-2}$ in dry conditions and was unchanged in moist conditions (Saleska et al., 1999). The primary mechanisms of reduced flux were related to soil moisture, either by direct physiological response or a longer-term shift in plant community composition to less productive, more drought-tolerant species. Research in tallgrass prairie suggests that earlier green-up and higher winter soil efflux prompted by higher temperatures is counterbalanced by a composition shift to forbs, which have lower NPP, and reduced summer soil efflux, respectively (Fay et al., 2011). Both the community composition and soil efflux dynamics are mediated by local soil moisture. Plant community composition can shift under drought conditions, as documented in eastern Colorado following the 2002-2003 drought (Rondeau, 2013), where shrub cover increased as grass cover decreased, and even after recovery, blue grama (*Bouteloua gracilis*) never recovered its dominance of the grass community.
4. **Evapotranspiration will increase**: Not only will plant communities be impacted by hotter temperatures and water availability, but also by changes in vapor pressure deficit and evapotranspiration. Vapor pressure deficit (VPD) is the difference between the vapor saturation (or humidity) of two environments, in this case between the atmosphere and plant tissue and/or soil space. The lower the atmospheric vapor pressure, the greater the evaporative "pull" on water from soil and leaves. Even if precipitation is unchanged, in the semi-arid environment of Colorado higher temperatures will reduce relative humidity (RH), which in turn will increase the VPD and evaporative demand. So even with unchanged annual rainfall, higher temperatures, lower RH, and VPD will compound to significantly increase soil and plant evapotranspiration (McDowell and Allen 2015) and related stress.
5. **Drought will increase**. Prolonged droughts result in aridification which in turn could result in a number of different scenarios depending on geography and original plant community composition. As a rule of thumb, drought reduces NPP and annual carbon flux, with drier communities generally most vulnerable to the aridification tipping point (Knapp et al., 2015). According to Debinski et al (2010), drought can increase extent of bare ground and decrease forb coverage, especially in more xeric grasslands. Soil texture can also influence

on this relationship (Parton et al., 1993). For example, the "inverse texture hypothesis" posits that for dry regions, grasslands on coarse, sandy soil that absorbs water quickly are more productive and resilient to drought than grasslands on fine-textured soil because less water is lost from the surface and roots are morphologically adapted to accessing water from depth (O' Sala et al 1988).

6. **Climate-drive disturbances will increase**. In addition to chronic stresses from climate change, increases in episodic disturbances are also expected including e.g. wildfires, windblown erosion, and flooding. For OSMP lands, the largest exposures are to wildfires and windblown erosion (described in Section 2.3). Windblown erosion risks increase due to degraded soil conditions (loss of soil structure and protective crusts and increased bare ground) resulting from a variety of management stresses including overgrazing, oil and gas wells and recreational pressures (Dunaway et al., 2019).
7. **Boulder will inherit current-day climate of New Mexico.** Climate analogues offer other indications of how chronic stress from the changing climate may alter plant communities and land cover changes. Climate analogues are vegetative communities that currently exist in what are projected to be the future climatic conditions of another area. Fitzpatrick and Dunn (2019) report that the current climate of Clovis, NM, is most similar to Boulder's projected climate in the year 2080 under both optimistic and unmitigated emissions scenarios (RPCs 4.5 and 8.5, respectively). The typical summer in Clovis, New Mexico is 9.2°F (5.1°C) warmer. Note, however, that Clovis is 46.9% wetter than current summer conditions in Boulder, which is counter to the drought prediction made above. While climate analogues can be useful for visualizing and predicting long-term climate, hydrologic, and habitat changes that may result from climate change, they also have limitations. The vegetative habitat of any area is influenced by non-climate factors such as topography, geology, soil type, and aspect that are not accounted for in the climate analogue models.

**Literature Cited (see main report body)**

## Appendix 2. Annotated Bibliography of Carbon in CO

This appendix synthesizes the findings of a substantial body of work at the state and local levels, as well as following frameworks for carbon sequestration from national and international sources. The key documents and their relationship to this report are briefly summarized below.

**Brandt, N., Brazeau, A., Browning, K., Meier, R., 2017. Carbon Sequestration in Colorado's Lands: A Spatial and Policy Analysis. University of Colorado Boulder, pp. PA11C-06.**

This thesis collaboration, sponsored by the Nature Conservancy, focuses on understanding total carbon sequestration in the state. The findings highlight the importance of forest fires on the future of Colorado land management, and the need to plan for anticipated fires. Currently, forests and woodlands together hold 68% of the land carbon in the state. Reforesting large burn scars in the state would increase the amount of carbon stored in forests up to 160 million MtCO2e, which represents over four times the cumulative emissions reduction goal of 39 million MtCO2e by 2025.

Avoiding all projected conversion of wetlands and grasslands in Colorado through 2051 would increase the carbon stored in those lands by 68 million MtCO2e. The authors highlight wetlands and grasslands because wildfire will drive most of the projected forest conversion, so avoidance isn't easy to model. And they concluded that it is not yet clear whether management to reduce fire risk will have measurable effects.

**City of Boulder, 2022. Community-wide Greenhouse Gas Emissions Summary Report.**

The GHG Emissions Report is a 42-page summary of GHG emissions indicates a 15% reduction in emissions from the 2018 baseline year and focuses briefly on nature-based solutions (City of Boulder, 2022). Select summary tables included here.

| Emission Type by Sector | Emissions ($mtCO_2e$) | | |
|---|---|---|---|
| | 2005 | 2020 | 2021 |
| Commercial and Industrial Buildings | 977,220 | 658,541 | 675,507 |
| Residential Buildings | 311,427 | 240,013 | 240,323 |
| Transportation (with transboundary aviation) | 801,206 | 451,104 | 553,517 |
| Transportation (without transboundary aviation) | 320,257 | 157,307 | 165,921 |
| Solid Waste | 53,840 | 24,042 | 29,396 |
| Wastewater Treatment | 1,800 | 658 | 571 |
| **Total Gross Emissions (with transboundary emissions)** | **2,145,493** | **1,373,552** | **1,499,314** |

| Land Use Sequestration: City Only | Emissions ($mtCO_2e$) | | |
|---|---|---|---|
| | 2005 | 2020 | 2021 |
| Forests Remaining Forests | (1,073) | (1,041) | (1,041) |
| Forests Converted to Other Lands & Disturbances | 748 | 641 | 641 |
| Other Lands Converted to Forests | (6) | (2) | (2) |
| Sequestration from Urban Trees | (8,795) | (8,898) | (8,898) |
| Emissions from Urban Trees | 2,688 | 58 | 58 |
| **Total Net GHG Removals** | **(6,403)** | **(9,243)** | **(9,243)** |
| **Total (Net) GHG Emissions without transboundary emissions and removals** | **1,658,141** | **1,070,511** | **1,102,475** |

| Land Use Sequestration: City + OSMP Lands | Emissions (mt $CO_2e$) | | |
|---|---|---|---|
| | 2005 | 2020 | 2021 |
| Forests Remaining Forests | (16,685) | (16,542) | (16,542) |
| Forests Converted to Other Lands & Disturbances | 11,759 | 16,611 | 16,611 |
| Other Lands Converted to Forests | (20) | (14) | (14) |
| Sequestration from Urban Trees | (21,055) | (20,962) | (20,962) |
| Emissions from Urban Trees | 995 | 10 | 10 |
| **Total Net GHG Removals** | **(26,001)** | **(20,773)** | **(20,773)** |
| **Total (Net) GHG Emissions with transboundary emissions and removals** | **2,119,492** | **1,352,779** | **1,478,541** |

**Colorado's Strategic Plan for Climate-smart Natural and Working Lands (CO DNR and CO DOA, 2021)**

This 35-page statewide strategic plan does not provide detailed inventory of stock and flux, rather it summarizes priority actions across Colorado's landscapes to reduce emissions, increase carbon sequestration, and create a climate-resilient Colorado.

**Davey Resource Group, 2018. City of Boulder Urban Forest Strategic Plan.**

Davey Resource Group (2018) used i-Tree Canopy (v6.1) to calculate the environmental services provided by the entire Boulder tree canopy (street and park trees but not OSMP). Trees sequester 18,709 tons of carbon and trap or absorb 139 tons of air pollutants each year. Boulder's tree canopy also reduces stormwater runoff volume in Boulder by more than 15 million gallons per year. using precipitation data from 2005-2012. This is approximately 5,408 gallons per acre of tree canopy. Based on an estimated stormwater treatment cost of $0.0118 per gallon, tree canopy contributes $177,016 annually to stormwater services.

**Easter, M., Swan, A., Williams, S., 2014. Greenhouse Gas Inventory from Agriculture, Forestry and Other Land Uses for Boulder County, Colorado Parks and Open Space.**

The purpose of the Easter et al (2014) report was to establish a baseline of carbon stock in BCPOS lands. They found that at the end of 2013, BCPOS lands and conservation easements held a total of 6.6 million metric tons of sequestered soil organic carbon in the top layers of the soil and biomass carbon, with agricultural lands holding 1.46 million Mg $Co_2$ in soil carbon, non-agricultural lands holding 1.36 million Mg, agricultural conservation easements holding 1.3 million Mg, and non-agricultural forest and shrub lands holding 2.47 million Mg $CO_2$ in 2013.

Easter et al (2014) found that at least 40% or 2.6 million metric tons of the protected carbon sequestered in these lands is vulnerable to rapid decomposition to atmospheric $CO_2$ if the land is developed. They also modeled how management changes such as tillage reduction, fertilizer reduction, reduced fallow frequency, manure/compost additions as a substitute for synthetic fertilizer nitrogen, cover crops, organic cropping, change to biofuel crops, and cessation of grazing would affect carbon stocks.

**ICLEI - Learn Report., 2021. GHG Inventory for Forests and Trees Outside Forests, 2008 to 2016.**

ICLEI is a large international network of local governments devoted to solving the world's most intractable sustainability challenges. Their Land Emissions and Removals Navigator (LEARN) tool was developed to help communities in the United States estimate the local GHG impacts of their forests and trees and provides a first-order approximation of annual GHG impacts over a given time period.

In 2020, the city participated in ICLEI's cohort to calculate the total GHG emissions, removals (i.e., sequestration or sinking potential), and carbon storage (i.e., sink) from land use and land use changes in the city and its Open Space and Mountain Parks (OSMP) lands, with the aim of integrating the results into the city's annual inventory process. The results show that the total amount of carbon stored in Boulder's forests and trees within the city boundary are ~350,000 metric tons as of the latest period of analysis (2016-2019), with the large majority (69%) stored in urban tree canopy with the remaining 31% stored in forest. The impact that the city's nature-based sequestration is having in tackling local emissions therefore makes up about 1-2% of the emissions (ICLEI - Learn Report., 2021). When including the city's OSMP lands within the boundary of analysis, the amount of carbon stored is ~2.3 million metric tons, with the vast majority (75%) within forested lands.

**Taylor, T., 2021. Colorado Greenhouse Gas Inventory Update.**

The 2021 inventory primarily relies upon the U.S. Environmental Protection Agency's (EPA) State Inventory Tool (SIT) for estimating GHG emissions in Colorado. Colorado's GHG Inventory tracks GHG emissions – carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) - and carbon sequestration from certain agriculture, forestry, and other natural and working lands, including cropland, rangelands, forests, and urban trees. The module includes estimates of $CH_4$ and $N_2O$ emissions from forest fires.

Carbon emissions from natural and working lands are estimated to comprise approximately 15% of Colorado's net GHG emissions as of 2018/19 (Taylor, 2021). Agriculture emissions comprise approximately 8% of Colorado's net emissions, while Land Use, Land Use Change and Forestry would comprise approximately 7% of net emissions if they were included in the state's net emissions. Colorado's forests are estimated to be net sources of GHG emissions due to high tree mortality caused by drought stress and our warming climate, insects and disease, and wildfires (Taylor 2021).

**Appendix 3. Supplementary Notes.**

Available upon request. This appendix contains notes regarding methods and modeling used as part of this project that may be of use by the authors in the future.