Final Report - Preliminary

CO_2-C sequestration potential of native ecosystems of Nevada: a review of reported values and methodologies for accurate greenhouse gas accounting

Presented to:

Nevada Division of Natural Heritage (NDNH)

and

Nevada Division of Environmental Protection (NDEP)

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List of Abbreviations

BREB	Bowen ratio energy balance
CCT	Carbon Calculation Tool
CO_2	Carbon dioxide
DAYCENT	Daily Century Model
EC	Eddy covariance
EPA	Environmental Protection Agency
FACE	Free-air CO2 Enrichment
FIA	Forest Inventory Analysis
GHG	Greenhouse gas
LULUCF	Land use, land use change and forestry
MGCF	Mojave Global Change Facility
NDEP	Nevada Division of Environmental Protection
NDVI	Normalized Difference Vegetation Index
NEE	Net ecosystem efflux
NEP	Net ecosystem productivity
NRI	National Resources Inventory
NWL	Natural and working lands
PAR	Photosynthetically active radiation
R_h	Heterotrophic respiration
SIT	State Inventory Tool
WRI	World Resource Institute

Introduction

Like many other states, Nevada is in the process of reducing greenhouse gas (GHG) emissions. Nevada Senate Bill 254 ordered a quadrennial inventory of statewide GHG emissions to, and net removals from, the atmosphere associated with various sources and sinks, including land use and land cover. The objective of the inventory is to identify policies that could reduce GHG in the atmosphere that are causing climate change. One of the more difficult assessments for GHG inventories is knowing quantitatively what the net balance is between how much carbon dioxide (CO_2, the most important GHG) is taken up by various types of vegetated land surfaces (through plant photosynthesis) and how much CO_2 is released back to the atmosphere by these same land surfaces (through the process of biological respiration from plants and soil microorganisms). This balance is called net ecosystem CO_2 exchange (NEE) or net ecosystem CO_2 flux at any moment in time. NEE measured and summed over hours, days, months, or a year is termed net ecosystem productivity, or NEP, and approximates the annual rate of net ecosystem carbon sequestration. The State of Nevada has a total land area of 70,859,448 acres (2.86758×10^{11} m^2), of which approximately 10,200,000 acres (15%) are forested, and 57,000,000 acres (80%) are covered by some type of non-forested or agricultural vegetation (Homer et al. 2015). The predominant non-forested vegetation types in Nevada consist of shrublands, grasslands, and wetlands, with shrublands accounting for more than 75% of non-forested land. Thus, obtaining accurate measurements of Nevada's shrubland NEE and NEP is essential to robustly inventorying the state's GHG budget and developing appropriate land management mitigation strategies.

However, accurate measurement of NEE and NEP for all terrestrial ecosystems is methodologically challenging and labor intensive, but particularly for states like Nevada with diverse types of land cover and large differences in climate resulting from the state's large ranges in latitude, longitude, and elevation. Consequently, NEE and NEP of Nevada's ecosystems are not well understood, even though land cover is an important component to GHG inventories and mitigation strategies (IPCC 2022). Potential CO_2-C sequestration (throughout this report CO_2-C sequestration, CO_2 sequestration, carbon sequestration, and NEP are all used interchangeably) by vegetated terrestrial ecosystems is highly variable and is closely tied to environmental factors such as precipitation and air temperature (Kwon et al. 2008) and biotic factors such as type of vegetation, extent of vegetation cover, and leaf area index (e.g., Wohlfahrt et al. 2008). In Nevada's Mojave Desert shrublands, intra- and interannual variation in NEE and NEP appear to be driven strongly by variations in precipitation (Wohlfahrt et al. 2008; Biederman et al. 2018). Climate change (e.g., drought) has the ability to significantly change the NEP of vegetated lands by disrupting the processes of CO_2 uptake (photosynthesis) and CO_2 release (respiration) (Kwon et al. 2008). Changes in land use (e.g., over-grazing livestock, feral horses) can also affect a native ecosystem's NEP/ability to sequester CO_2 (e.g., Milchunas & Lauenroth 1993, Polasky et al. 2011; Bates and Davies 2014; Eldridge DJ et al. 2015; Copeland et al. 2021) because of changes in plant species abundance and productivity, which also includes changes resulting from invasion of native ecosystems by non-native plant species, such as the annual grass species Bromus tectorum (cheatgrass, in Great Basin shrublands—e.g., Obrist et al. 2003) or Bromus rubens (red brome, in Mojave Desert shrublands—e.g., Smith et al. 2000). Examples from Nevada of the likelihood that climate change and other global changes are already impacting NEE, NEP, and hydrology of native shrubland ecosystems include reductions in NEE and NEP observed under anthropogenic increases in atmospheric CO_2 in Mojave Desert arid shrublands (Jasoni et al. 2005) and altered NEE, NEP (Obrist et al. 2003; Prater et al. 2006), and ecosystem soil water infiltration and lateral distribution observed with the increasing presence of invasive annual plant species following wildfire in sagebrush ecosystems (Obrist et al. 2004). Although NEE and NEP of Nevada's sky island or Nevada's Sierra Nevada forests have yet to be adequately measured directly though the quantification of CO_2 fluxes, estimates of NEP in forested lands using FIA data (https://www.fia.fs.usda.gov/) and protocols that incorporate FIA data appear to differ widely from forest to forest making it difficult to accurately assign a single average NEP value for these forested ecosystems. In addition to vegetated areas, studies have shown that biological soil crusts that cover the soil surface in many arid shrublands in Nevada (e.g., Belnap et al. 2003; Belnap 2006) may contribute significantly to NEP (e.g., Darrouzet-Nardi et al. 2015; Jasoni et al. 2010), both increasing or decreasing it, while also having the benefit of holding soil in place during windy weather or high surface water flows (e.g., Belnap et al. 2003). All of this information points to the need to expand replicate measurements of NEE and NEP across Nevada's diverse ecosystems to improve the accuracy of the estimates for making land use management decisions that will maximize and sustain net CO_2-carbon removal from the atmosphere by vegetated lands in the State.

Annual carbon sequestration of native and agricultural ecosystems can vary from year-to-year due to changes in climate, land use, and fire (Houghton & Nassikas 2017; Svejcar et al. 2008; Flerchinger et al 2020). Accurately accounting for this carbon sequestration can be challenging given that very little data are available and online tools/software available vary in their accuracy. States, environmental protection agencies, and other land managers need the most accurate ecosystem carbon sequestration data to make the most informed policy and land use decisions. It is also important that these agencies keep current on peer reviewed and grey literature (reports and other non-peer reviewed publications) whose results and recommendations generally precede changes in existing and/or outdated online or other tools designed to estimate ecosystem carbon sequestration. Keeping up to date on literature and resource tools will allow agencies to be at the forefront of the current state of knowledge.

Several difficulties arise when trying to obtain accurate ecosystem carbon sequestration values. Information available in reports and peer-reviewed publications is often difficult to interpret and ascertain if the data contained in these publications is accurate. Second, numerous methodologies can be used to determine carbon sequestration ranging from on-the ground measurements to computer models. Even within these generalized methodologies there are differences in how CO_2 sequestration is estimated (World Resources Institute 2020). Being able to synthesize all the available data and to assign estimates, or even ranges, of CO_2 sequestration values to vegetated lands in Nevada with some level of certainty becomes a challenge and requires thorough investigation of many sources of literature and methodologies and continuing to do these literature and methodology reviews on a regular basis.

Several tools are currently available to help federal agencies and states determine carbon (CO_2) sequestration of native and agricultural ecosystems (e.g., see World Resources Institute 2020).

Each tool has its own advantages and disadvantages depending on the intended ultimate use of the data (e.g., making policy). For example, some tools have insufficient spatial or temporal resolution to be useful. This has led to some states such as California, Washington, and Michigan supplementing these C sequestration tools with their own data collection (e.g., remote sensing, field plots, modeling) and tools they have developed themselves.

To more accurately account for the CO_2-C sequestration potential from all of Nevada's native vegetated land cover, we performed the following main tasks:

1) Conducted a thorough literature review into the state of knowledge on NEE and NEP in all the native vegetated ecosystems found in Nevada starting with the recent Nevada Division of Environmental Protection (NDEP) state-wide GHG inventory reports; and

2) Analyzed existing eddy covariance CO_2 flux data collected from the Great Basin and Mojave deserts.

Methods

Task 1: Gather knowledge about land-atmosphere NEE and NEP in Nevada

We conducted an extensive literature review on the carbon sequestration potential of Nevada's vegetated ecosystems. This literature review consisted of examining: a) peer-reviewed papers for all studies conducted in the Great Basin and Mojave Deserts both within and outside of Nevada and for the major vegetation types (i.e., shrublands, forests, grassland, wetlands, P-J woodlands, endorheic wetlands) and GHGs (but not including methane and nitrous oxide) (when data for ecosystems in Nevada were not available, we sought out studies conducted in analogous ecosystems from nearby states); b) reported methodologies to determine which studies are reliable and contain accurate data for Nevada to determine net annual CO_2-C sequestration; c) methodologies/tools available to improve the accuracy of currently reported CO_2-C sequestration values; d) methodologies that might be available to timely quantify the impact of significant land use changes (e.g., wildfires and the long-term [> one year] consequences of fire on CO_2-C sequestration); and e) the methodology used by NDEP to ensure that their methodology is accurate.

Task 2: Analysis of existing eddy covariance data from the Great Basin and Mojave deserts

The EC method is a micrometeorological technique that is widely used and accepted in the scientific community as a means to directly quantify H_2O and CO_2 exchange between the atmosphere and ecosystem during long time periods (e.g., months to years) (Baldocchi 2003). The eddy covariance (EC) method uses specialized instrumentation and calculations to measure the net flux of CO_2 to and from an ecosystem. The EC calculations for net annual CO_2 fluxes (NEP) are generally reported in g C m^{-2} of land $year^{-1}$, although NEP can be calculated for any period of (shorter or longer) time (e.g., g C m^{-2} of land $month^{-1}$). These EC data provide researchers and land managers insight into the CO_2-C sequestration potential of an ecosystem. If these EC studies are conducted for a long enough period, they can capture interannual variability caused by changes in weather from year-to-year or changes in land use and can help in understanding the environmental drivers of temporal and spatial variation of the CO_2-C sequestration for a particular ecosystem. We followed standard EC analysis methodologies as outlined in Wohlfahrt et al. (2008).

Results and Discussion

Task 1: Literature and Methodology Review

An exhaustive literature search was conducted to find peer reviewed publications related to carbon sequestration potential of Nevada ecosystems, focusing mainly on native ecosystems (shrubland and forested ecosystems). Approximately 200 peer reviewed papers were selected for thorough review, however only 22 contained sufficient and robust carbon sequestration data. Not surprisingly we found a dearth of carbon sequestration studies conducted in arid lands of the western United States. Although there is a low number of carbon sequestration studies, those studies that do exist have mostly indicated that arid lands can sequester carbon and, in some cases, significantly so (e.g., Wohlfahrt et al. 2008; Biederman et al. 2018; Jasoni et al. 2005). There is a need for expanding carbon sequestration studies in arid lands of the western United States, including Nevada, in order to capture the natural intra- and interannual variability in carbon sequestration that is inherent in these ecosystems. Most of this variability in carbon sequestration is due to the large variability in temperature and precipitation and their influence on vascular plant growth and ecosystem biogeochemical processes that modulate NEE (e.g., Arnone et al. 2008). In Nevada and most arid ecosystems, precipitation is the more influential variable.

The literature review section that follows lists each relevant peer reviewed paper individually and a brief summary of the paper. To be considered a relevant paper for this literature review, the study must have:

- Measured NEE/NEP of the entire ecosystem, not upscaled separate measurements of individual shrub NEE and individual intershrub space NEE,
- Measured NEE multiple times during each season of the year in the ecosystem being assessed, and
- Measured NEE during entire 24 h periods including both daylight (when plants can photosynthesize and leaves are taking up CO_2 and all organisms are respiring and emitting CO_2) and nighttime (dark period—no photosynthesis, all organisms still respiring and emitting CO_2) periods.

These criteria were included because they not only include periods of net ecosystem CO_2 uptake (carbon gain) but also periods when ecosystem CO_2 losses to the atmosphere dominate NEE fluxes (nighttime and seasonal periods of no or low photosynthesis but continued plant and soil heterotrophic respiration). Inclusion of these criteria therefore enable these selected studies to robustly infer about ecosystem net CO_2 sequestration. The citation for each paper can be found in the References section of this report, and electronic copies of all papers will be sent along with this report. In all studies summarized below, negative (-) NEP values indicate that an ecosystem during each period of study (e.g., year) was a net sink for CO_2, while a positive (+) NEP indicates an ecosystem was a net source of CO_2 to the atmosphere. The opposite sign convention is used in many of the studies reviewed here. We converted these values to conform to the negative NEP values indicating net ecosystem CO_2 uptake/sink activity and positive NEP values indicating net ecosystem CO_2 emission/source.

<u>Arid shrublands publications—year-round with 24 h measurements of entire ecosystem NEE</u>

Flerchinger G, Fellows AW, Seyfried MS, Clark PE, Lohse KA (2020) Water and carbon fluxes along an elevational gradient in a sagebrush ecosystem. *Ecosystems* 23: 246-263.

This study was conducted within the Reynolds Creek Critical Zone Observatory in Southwestern Idaho. Mean annual precipitation ranged from 292 mm to 800 mm, and mean annual temperature ranged from 5.6 °C to 9.4 °C. Precipitation and temperature is expressed in a range because the Reynolds Creek Critical Zone Observatory spans an elevational gradient (1425 – 2111 m). Eddy covariance was used to measure NEE and estimate annual NEP in a sagebrush ecosystem. Data were collected over four years along an elevational gradient in the sagebrush ecosystem. NEP ranged from -205 g C m^{-2} yr^{-1} to +1 g C m^{-2} yr^{-1}. **Table 1** is a recreation of Table 2 from this publication and shows NEP and precipitation, but not the other parameters found in Table 2 of the original publication. The results of this study showed that for the majority of years, the sites were sinks for CO_2 and thus sequestered carbon. Differences in NEP (g C m^{-2} yr^{-1}) between elevations were the result of the differences in precipitation patterns and temperature.

Svejcar, T, Angell R, Bradford JA, Dugas W, Emmerich W, Frank AB, Gilmanov T, Haferkamp, M, Johnson DA, Mayeux H, Mielnick P, Morgan J, Saliendra NZ, Schuman GE, Sims, PL, and Snyder K (2008) Carbon fluxes in North American rangelands. *Rangeland Ecology Management 61*: 465-474.

In this study there were two US Intermountain West sagebrush-steppe ecosystems that were studied. One of the study sites was near Burns OR and the other study site was near Dubois ID. Both of these sites are part of the AgriFlux network. The study in Oregon was conducted during the time period of 1995-2000, while the study in Idaho was conducted during the time period of 1996-2001. The following table (**Table 2**) is a recreation of data presented in Figure 2 in Svejcar et al. (2008). We summed monthly NEE shown as g CO_2 m^{-2} $month^{-1}$ in Figure 1 of Svejcar et al. (2008) for each calendar year and expressed these as annual NEP in g C m^{-2} yr^{-1} in Table 2 below. At the Oregon site, the ecosystem was a net sink for CO_2 for four of the six years. At the Idaho site, the ecosystem was a net sink for CO_2 for five of the six years. This indicates that on average, both sites were net sinks for CO_2 during six years of study. There is, however, a large amount of variability from year to year. The differences between the two sites may be due to different temporal patterns of precipitation, with the Oregon site having rain mainly during the fall, winter, and spring months while the Idaho site had precipitation during May and June—even though total annual precipitation of the two sites was quite similar. Overall, this study showed that arid sagebrush shrublands can sequester significant amounts of carbon and are an important part of the total global CO_2 uptake and release.

The NEE flux measurements reported in the Svejcar et al. (2008) paper relied almost exclusively on calculations using the Bowen ratio energy balance (BREB) method, and not the current standard eddy covariance method (e.g., Baldocchi 2003). Alfieri et al. (2009) found that NEE measured using BREB often overestimated NEE net CO_2 uptake by a semiarid grassland relative to NEE net CO_2 uptake measured with eddy covariance. Gao et al.'s (2019) analysis of EC data suggests that even use of the EC method to quantify NEE may be underestimated in sagebrush ecosystems in cases where the surface energy balance does not close. In contrast, though, Angell et al. (2001) found that BREB NEE fluxes corresponded relatively well with NEE values measured with their static chamber (Angell and Svejcar 1999). At present, and in the absence of large, mobile ecosystem and automated NEE flux chambers that use the traditional static chamber principles of operation (e.g., Arnone and Obrist. 2003), we believe the EC method should remain the standard for assessing NEE and calculating NEP.

Table 1. NEP (g C m^{-2} yr^{-1}) and precipitation (mm) for sagebrush ecosystems across an elevation gradient located in Reynolds Creek Critical Zone Observatory in Southwestern Idaho. From Flerchinger et al. 2020, Table 2.

Wyoming Big Sagebrush	**NEP (g C m^{-2} yr^{-1})**	**Precipitation (mm)**
2015	1†	338
2016	-107	267
2017	-103	388
2018	-97	278
Mean	-102	318
SE	3	28
Low Sagebrush		
2015	-158	381
2016	-154	324
2017	-109	463
2018	-110	330
Mean	-133*	374
SE	13	32
Post-fire Sagebrush		
2015	-202	495
2016	-205	465
2017	-107	724
2018	-174	463
Mean	-172	537
SE	23	63
Mt. Big Sagebrush		
2015	-118	744
2016	-173	941
2017	-42	1105
2018	-173	741
Mean	-127	883
SE	31	88

† As far as we are aware this value is correctly reported in Flerchinger et al. 2020.

* We believe this number is in error in the Flerchinger et al. 2020 paper so we changed it to what we believe to be the correct value of -133.

Table 2. NEP (g C m-2 yr-1) and precipitation (mm yr^{-1}) for two (Burns Oregon and Dubois Idaho) sagebrush-steppe ecosystems. From Svejcar et al. 2008, Figure 1.

Burns Oregon (1995 - 2000)	**NEP (g C m^{-2} yr^{-1})**	**Precipitation (mm yr^{-1})**
1995	-55	203
1996	35	389
1997	-166	248
1998	-245	404
1999	-219	184
2000	48	256
Mean	-100	281
SE	52	38
Dubois Idaho (1996 - 2001)		
1996	-39	285
1997	-19	356
1998	-180	318
1999	-264	326
2000	41	245
2001	-56	255
Mean	-86	298
SE	46	18

Yao, J, Yuan W, Gao Z, Liu H, Chen X, Ma Y, Arntzen E, Mcfarland D (2022) Impact of shifts in vegetation phenology on the carbon balance of a semiarid sagebrush ecosystem. *Remote Sensing* 14: 5924-5941.

This study was conducted in central Washington near Hanford (Ameriflux site US-Hn1) during a two-year period (2019-2020) in a semiarid sagebrush ecosystem. The study site receives an annual average of 196 mm of precipitation, most of which occurs during winter and spring. The sagebrush ecosystem mainly relies on soil moisture, meaning that snowfall and rainfall are major drivers for plant productivity. The study used eddy covariance to measure CO_2 fluxes. In 2019, the ecosystem was a net sink for CO_2 (-47 g C m^{-2} yr^{-1}) while in 2020 the ecosystem was a net source of CO_2 (32 g C m^{-2} yr^{-1}) (**Table 3).** The difference in CO_2 uptake between the two years was attributed to differences in precipitation and temperature. Precipitation in 2019 was 215 mm (19 mm higher than the annual average) and precipitation in 2020 was 150 mm (46 mm lower than the annual average). Annual mean temperature in 2019 was 11 °C (0.7 °C lower than the annual average) and the annual mean temperature in 2020 was 12.8 °C (1.0 °C warmer than the annual average). This indicates that environmental factors play a key role in CO_2 uptake and as demonstrated in this study can change the ecosystem within just one year from a CO_2 sink to a CO_2 source.

Table 3. Monthly NEE (g C m^{-2}), annual NEP (g C m^{-2} yr^{-1}), and annual precipitation (mm) for a semiarid sagebrush ecosystem located near Hanford, WA (Ameriflux site US-Hn1). From Yao et al. 2022, Table 1.

	NEE (g C m^{-2})		**Precipitation (mm)**	
Month	2019	2020	2019	2020
January	1	2.4		
February	-3	-9.2		
March	-7	-23.8		
April	-28	-7.6		
May	-18	16.1		
June	-9	13.8		
July	-5	13		
August	13	7		
September	4	3.2		
October	5	7.6		
November	-3	7.6		
December	4	1.2		
	(g C m^{-2} yr^{-1})			
Annual	-47	32	215	150

Jasoni, RL, Smith SD, Arnone JA III (2005) Net ecosystem CO_2 exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO_2. *Global Change Biology* 11: 749-756.

In a 2005 study conducted by Jasoni et al. (2005), it was found that Mojave Desert ecosystems can be significant sinks for CO_2. Although the Mojave Desert (0.430137 x 10^{11} m^2; 10,628,917 acres) occupies a relatively small portion of Nevada compared to the Great Basin (1.43379 x 10^{11} m^2; 35,429,724 acres), it is still an important ecosystem and has been shown to contribute significantly to CO_2 uptake and release. The study was conducted at the Free Air CO_2 Enrichment Facility (FACE) approximately 120 km north of Las Vegas, NV. The site receives an average of 150 mm of precipitation annually that falls mainly as rain in the winter and early spring. Mean annual air temperature for the last 10 years has been 20 °C, with daily means in the winter, spring and summer of 12, 18, and 28 °C, respectively. Mean minimum night-time temperatures in the winter months (December, January, February) have averaged 1.5 °C, while mean maximum daytime temperatures in the summer months (June, July, August) have averaged 38 °C. Data were collected from study plots that were exposed to ambient levels of CO_2 and study plots that were exposed to elevated levels of CO_2. The study was conducted for a one-year period between 2005 and 2006. This study showed that Mojave Desert ecosystems exposed to ambient and elevated levels of CO_2 were net sinks for CO_2, with the ecosystems exposed to ambient levels of CO_2 having an NEP of -90 g C m^{-2} yr^{-1} and the ecosystems exposed to elevated levels of CO_2 having an NEP of -127 g C m^{-2} yr^{-1}. This study showed that arid Mojave Desert ecosystems can play a large role in mitigating global atmospheric CO_2 concentrations. Typically, deserts have been omitted from global atmospheric models because it has generally been believed that deserts play an insignificant role in CO_2 uptake and release; however, the study by Jasoni et al. (2005), and others, have shown that deserts do in fact play a large role in CO_2 uptake and release and should be included in global CO_2 models. Additionally, these ecosystems should be considered when states are determining their CO_2 emissions and uptakes.

Wohlfahrt, G, Fenstermaker, LF, Arnone, JA III (2008) Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. *Global Change Biology* 14: 1475-1487.

Net ecosystem exchange was measured using the eddy covariance method in a Mojave Desert ecosystem during a two-year period (2005-2006). The study site is located approximately 120 km north of Las Vegas, NV at the Mojave Global Change Facility (MGCF). The site receives an average of 150 mm of precipitation annually that falls mainly as rain in the winter and early spring. Mean annual air temperature for the last 10 years has been 20 °C, with daily means in the winter, spring and summer of 12, 18, and 28 °C, respectively. Mean minimum night-time temperatures in the winter months (December, January, February) have averaged 1.5 °C, while mean maximum daytime temperatures in the summer months (June, July, August) have averaged 38 °C. During the two-year study period, the Mojave Desert ecosystem was a net sink for CO_2 resulting in an annual uptake of -102 ± 67 g C m^{-2} yr^{-1} in the first year of the study, and -110 ± 70 g C m^{-2} yr^{-1} during the second year of the study. The main seasonal drivers for variability in net ecosystem efflux of CO_2 were photosynthetically active radiation (PAR) and soil water content. These results indicate that hot arid desert ecosystems can be significant sinks for CO_2 and play an important role in global carbon cycling.

Obrist D, DeLucia EH, Arnone JA III (2003) Consequences of wildfire on ecosystem CO2 and water vapour fluxes in the Great Basin. Global Change Biology 9:563-574

Obrist and collaborators measured NEE monthly during a 426-day period (11 36-hour diel periods) in adjacent intact sagebrush and recently burned post-fire successional ecosystems in Golden Valley, NV (15 km north of Reno, NV). Mean annual precipitation near the site is 308 mm, and mean annual temperature is 10 °C. They established n=6 12 m^2 circular plots in each ecosystem and measured fluxes using a large, translucent polyethylene yurt tent, with each flux measurement lasting for <1.5 min. Summing the diel values for each of the 11 day-night NEE measurements, and including gap-filled values for three missing cold-season months, the sagebrush ecosystem had an annual NEP of ~ -29 g C m^{-2} yr^{-1}, while the post-fire successional ecosystem, comprised of low density invasive annual grasses and forb plant species, had an annual NEP of ~ -63 g C m^{-2} yr^{-1}. They attributed the differences in NEE between ecosystem types to higher rates of soil heterotrophic respiration (Rh) in the intact sagebrush ecosystem. Although the robustness of this study was enhanced because researchers measured NEE of the whole ecosystem within both post-fire and intact sagebrush plant communities and measured around the clock during each diel measurement campaign, the investigators still needed to interpolate NEE values for the periods between months that were not directly measured—to calculate annual NEP values.

Fellows, AW, Flerchinger GN, Lohse KA & Seyfried MS (2018) Rapid recovery of gross production and respiration in a mesic mountain big sagebrush ecosystem following prescribed fire. *Ecosystems*, 21: 1283-1294.

This study by Fellows et al. (2018) was conducted at the Reynolds Creek Critical Zone Observatory and Reynolds Creek Experimental Watershed in southwestern Idaho. Mean annual precipitation was 537 mm, and mean annual temperature was 6.1 °C. The study site burned in late 2007 and was classified as a "mild-to-moderate intensity crown fire". All aboveground biomass was burned during the fire. The eddy covariance method was used to measure and calculate NEP for two years before the fire occurred and for seven years after the fire. During all years of the measurement period, the site was a sink for CO_2 and NEP ranged from –28 to –271 g C m^{-2} yr^{-1}. It was determined that overall NEP did not change significantly with fire, but there were some indications of effect of fire during 2008 – 2010. The average NEP before the 2007 fire was -103 to -153 g C m^{-2} yr^{-1} and after the fire NEP averaged -122 to -182 g C m-2 yr-1. The authors concluded that sagebrush ecosystems, in the region studied, can recover rather rapidly after fire.

Arid shrublands publications —CO_2 flux measurements only during growing season or daytime, or ecosystem elements (shrub and intershrub areas) measured separately

The following set of peer-reviewed papers did not meet our criteria for direct usefulness by NDEP although they contain useful data and other information about growing season NEE, or daytime NEE, or CO_2 fluxes of ecosystem elements. Some of these studies may be useful because they focus on evaluating the relationships between NEE and environmental variables (e.g., seasonal, annual or interannual variability in precipitation and temperature), or NEE and ecological variables (e.g., years of recovery after disturbances such as fire, percent vegetation cover, leaf area index, soil type and fertility).

A number of papers by Gimanov and colleagues (Gilmanov et al. 2003; Gilmanov et al. 2004; Gilmanov et al. 2006;) have utilized empirical NEE, climate, and satellite data from other publications to explore ecological and environmental controls on sagebrush ecosystem NEE and NEP. However, none of these appear to contain original data. Thus, these papers may not be directly useful for estimating NEE and NEP of arid shrublands. However, they may serve as good references for developing numerical models to predict NEE and NEP from more easily measured variables such as air temperature, precipitation, or Normalized Difference Vegetation Index (NDVI) (satellite-derived imagery; also see Hunt et al. 2004). The same applies to the other papers in the category of incomplete empirical data coverage (i.e., only daytime measurements of NEE, omission of non-growing season NEE, or smaller scale and separate measurement of NEE of ecosystem elements [i.e., shrub vs. intershrub covered surfaces], or heavy reliance on limited empirical data to predict or model annual NEP). These studies include the following: Ivans et al. (2006), Kwon et al. (2008); Cleary et al. (2015); Reed et al (2018); Angell and Svejcar (1999, used 1 x 1 m static chamber); Prater et al. (2005, used 1 x 1 m static chamber); Hunt et al. (2004); Wylie et al. (2003); Provencher et al. (2022). Angell and Svejcar's study also used a 1 x 1 m static chamber to separately measure shrub and intershrub microsite NEE. They measured NEE only during the daytime on one day and reported a one-day mean value for sagebrush plants of –7.6±1.4 µmol CO_2 m^{-2} land s^{-1}) in May.

Forest publications

The closest eddy covariance sites (AMERIFLUX, or FLUXNET) to Nevada that are in the Sierra Nevada are at UC Berkeley's Blodgett Forest Research Station (1315 m elevation, Mediterranean climate with very hot dry summers) about 60 km WSW of Lake Tahoe, CA, but EC tower located above a young (6 years) P. ponderosa plantation; (Goldstein et al. 2000), the Sierra National Forest at Kings River, CA (two relevant mixed conifer sites at 2015 m [Ameriflux site

US-CZ3] and 2710 m [Ameriflux site US-CZ4] elevation, southern Sierra, Mediterranean climate with dry summers and snow in winter, Kelly and Goulden 2016; Barnard et al. 2018, and the UC's Sagehen Creek Field Station near Truckee, CA-Ameriflux site US-SHC). All of these EC tower sites are listed on the Ameriflux and FLUXNET Web sites, but NEE and climate data are not open access and no NEE data have been published from the Sagehen site. Surprisingly, only GEE (gross ecosystem CO_2 exchange) and Reco (ecosystem respiration) data have been published (e.g., Kelly and Goulden 2016) but not NEE data. Thus, it is questionable how accurately these potentially analogous California Sierra Nevada forest sites should be used to estimate NEE and NEP of the higher elevation and seasonally wetter (via greater snowfall) Sierra forests in Nevada (e.g., forest cover begins at ~1900 m in Reno, NV).

Loudermilk, EL, Scheller RM, Weisberg PJ, Yang J, Dilts TE, Karam SL, Skinner C (2013) Carbon dynamics in the future forest: the importance of long-term successional legacy and climate-fire interactions. *Global Change Biology* 19: 3502-3515.

Disturbance caused by climate change and fire were modeled in a forested ecosystem in the Lake Tahoe basin of the Sierra Nevada mountains. The modeling was used to show how forest carbon budgets respond to climate and past and future disturbances such as wildfires and timber harvesting. This study used the Landscape Disturbance and Succession model (LANDIS-II). The LANDIS-II model has been used extensively throughout the US and can integrate many ecosystem processes and different types of disturbances over large spatial scales and long periods of time. The LANDIS-II model is ideal for determining how forests will respond to changes in climate and disturbances. For this particular study the authors looked primarily at temperature and precipitation, as well as legacy logging (1880s) in the area and fires. When temperature and precipitation changes were included in the model these caused limited increases in carbon sequestration potential because of augmented fire activity and reduced establishment ability of subalpine and upper montane trees. Forests responded to higher atmospheric temperature more than it did to changes in precipitation. However, the modeling efforts in this study showed that whether a forest would become a carbon sink or a carbon source, was driven more by major land use disturbances (fire) and land use legacies (logging) than projected climate change. The modeled results, when predicting a future climate with no changes in temperature or precipitation because of climate change, resulted in increases in total carbon accumulation.

Pinyon-Juniper publications

Most publications for Pinyon-Juniper ecosystems from arid regions are related to measurements of standing biomass and changes in biomass or soil carbon storage (Fusco et al. 2019), but not NEE fluxes of CO_2 to and from the ecosystem. The limited amount of data is not surprising because as with most flux data, very little is available for arid regions, mainly because these arid regions have mostly been ignored when accounting for carbon sequestration.

Wetlands publications

Saline wetlands, like those occurring in Nevada and the arid intermountain West and other arid regions of the world, account for 0.3% of Earth's land area and ~7.3% of total ITW area. Remarkably, though, no CO_2 or CH_4 flux studies have been conducted in saline wetland ecosystems in arid climates. In Nevada, nearly all wetlands (excluding mountain wetland meadows) are classified as saline with many of these located at the terminus of streams or rivers.

If the biogeochemical processes in these wetlands are similar to those in other inland terrestrial wetlands (ITW), albeit more highly constrained by water limitations from low precipitation and high evapotranspiration (ET), these areas may contribute significantly to Nevada's GHG budget. Net emissions of these GHGs have yet to be included in the State's GHG emissions inventory.

Summary of peer reviewed literature

Fortunately, our literature search and survey found the greatest number of peer-reviewed papers for the most dominant ecosystem in Nevada—the sagebrush arid shrublands of the Great Basin and the creosote bush-mixed arid shrublands Mojave Desert that together cover 75% of the state's land (e.g., Jasoni et al. 2005, Wohlfahrt et al. 2008, Biederman et al. 2018, and analogue studies conducted in these ecosystems in neighboring states). Taken together, the carbon sequestration values from the shrubland ecosystem publications summarized in this report ranged from -236 g C m^{-2} yr^{-1} (sink) to 115 g C m^{-2} yr^{-1} (source). While this large range in carbon sequestration values is not unexpected, somewhat surprisingly, many of these shrublands acted as net CO_2 sinks in many of the years NEE and NEP were measured These results suggest that improvements in the holistic ecological management Great Basin sagebrush and Mojave Desert mixed species shrublands could even enhance net CO_2 sequestration in the long term. It is unclear, though, how projected warming and drying of Nevada's shrubland ecosystems may affect NEE and NEP (e.g., de Graaff et al. 2014). Reductions in vegetation cover that could result would suggest an overall reduction in net CO_2-C sequestration. Of course, many factors play a role in CO_2 uptake and release from vegetated arid ecosystems, with precipitation and temperature playing a large role in modulating CO_2 uptake and release (NEE) because they affect vegetation photosynthesis, respiration of all biota in the ecosystem (Arnone et al. 2008), and ecosystem biogeochemical and hydrologic processes (e.g., Johnson et al. 2014; Johnson et al. 2016). NEE in these ecosystems will likely remain highly variable from year to year with this interannual variation perhaps becoming more pronounced at different periods of the growing season, even in the cold season months if anthropogenic climate change results in greater wintertime or nighttime warming (e.g., Tang and Arnone 2013; Tang et al. 2015). These changes could result in larger interannual swings in NEP, with arid shrublands being a sink of CO_2-C one year and a source of CO_2-C the next.

Reliable CO_2 flux data, or any studies at all, from forests, wetlands, and P-J ecosystems in arid environments is so sparse that even approximate ranges of annual NEP are difficult to determine. The following sections discuss methodologies to estimate carbon sequestration, albeit that these methodologies come along with their own limitations and uncertainty.

Natural & Working Lands Inventory Improvements: A Guide for States (2020)

This publication (guide) is prepared by the World Resources Institute (WRI). The WRI provides technical support to states working on GHG inventories on natural and working lands (NWL). The guide is intended to help states improve their GHG inventories by providing methods and guidelines for proper GHG inventories on NWL. The guide outlines methods that are currently used by states, discusses limitations to these current methods, and suggests several methodological improvements to the current methods. The guide does note that even the suggested improvements have their limitations, but the improvements, overall, help to refine GHG emission and uptake estimates. The authors of this current report found this guide to be a wealth of information and the suggested improvements were valid and are worthy of consideration by the state of Nevada to include in future estimates of GHG emissions and uptake. For this current report, we have synthesized the information from the guide for states and incorporated this synthesized information into the appropriate sections in this report. The information in the following sections (up to the start to the *Nevada Statewide Greenhouse Gas Emissions Inventory and Projections (1990-2042)* section), relied heavily on information contained in the WRI 2020 publication/presentation. We cited the WRI publication/presentation in several places below but want to explicitly state here that the following sections are a synthesis of the WRI 2020 publication/presentation.

Methodologies for estimating carbon sequestration in forests

Environmental Protection Agency State Inventory Tool (SIT)

The Environmental Protection Agency (EPA) State Inventory Tool (SIT) (https://www.epa.gov/statelocalenergy/state-inventory-and-projection-tool) is a spreadsheet model that is free of charge and can be used to estimate state-level GHG emissions. The SIT is used by several states, including Nevada, to help estimate GHG fluxes from NWL and has become a convenient method because of its ease of use and because it is updated annually by the EPA. The SIT uses similar methodologies to those used by the National Greenhouse Gas Inventory and SIT contains similar data sets. Although the SIT is updated annually, some data sets within SIT are not. Therefore, the date range of available data in the SIT often "lags" behind the date range of the National GHG Inventory, especially for NWL. The following table (**Table 4**) outlines the benefits and limitations of using the SIT.

United States Department of Agriculture Forest Service Forest Inventory and Analysis (FIA)

Data available in the SIT are calculated from FIA (https://www.fia.fs.usda.gov/) data that uses a stock-difference method through the Carbon Calculation Tool (CCT), and carbon flux from wood products are estimated from Forest Service publications. The US Forest Service plans on making annual updates to the FIA data that will be included in SIT, "but with some delays" (World Resources Institute 2020). With the new annual updates to FIA, states will be able to request state-level uncertainty analysis. Although the FIA data will be published annually, there are still some limitations to using FIA data. These limitations include (directly from World Resources Institute, 2020): 1) double accounting of forests and urban trees due to different estimation methods, 2) no spatially relevant or regional estimates of carbon sequestration or CO_2 fluxes, 3) short-term CO_2 fluxes/carbon sequestration are not able to be determined because of the rolling average approached used in FIA, and 4) difficult to attribute changes in carbon storage to a particular cause. It is recommended that states improve the quality and amount of FIA data that is published. Although the improvements come along with their own limitations, the improvements should, overall, improve the FIA data from forests. These improvements include: 1) using satellite imagery, 2) using LIDAR, 3) increase statistical power of FIA by individual states adding more FIA study plots, 4) implement a "field-based" inventory for urban trees, and 5) improve the accounting of wood products. States that have improved on the FIA data include California, Maryland and Delaware, Wisconsin, and Washington. California has estimated that it will spend approximately \$1.2M/year to increase the frequency of FIA data collection from 10 years to 5 years. California has also estimated that it will cost an additional \$750K for "initial prep work" (World Resources Institute 2020).

Table 4. Benefits and limitations to the Environmental Protection Agency (EPA) State Inventory Tool (SIT). Adapted from World Resources Institute (2020).

Benefits	Limitations
Interactive spreadsheet that covers all major inventory sectors	Many of the natural and working lands data in SIT are old and not as updated as the National GHG Inventory
Greenhouse gas fluxes at the state level are estimated using methods similar to those in the National GHG Inventory	SIT has a limited set of natural and working lands in its database compared to the National GHG Inventory
SIT is easy to use and free of charge	SIT does not report GHG fluxes in NWL according to IPCC standards
SIT is updated annually by EPA (not all data sources are updated annually - see Limitations column)	SIT does not provide margin of errors for GHG flux estimatesin at the state-level
States can use pre-loaded state-level NWL data or enter their own data	Data within SIT is not spatially "explicit" (can't be mapped)
	Data are averaged over multiple years, and therefore, GHG estimates can not be attributed to a particular year or cause (e.g., fire)
	In some cases, SIT data related to urban trees are double counted because they are also classified as forests

California made refinements to its forest ecosystem carbon sequestration estimates by incorporating geospatial data. The use of this geospatial data resulted in significantly different estimates of annual carbon sequestration from forests in California. The improved analysis resulted in differences in carbon sequestration from those obtained from SIT analysis. **Figure 1** is taken directly from the World Resources Institute for US Climate Alliance States, 2020 publication/presentation (slide 56) and shows the difference in carbon sequestration resulting from the California NWL inventory and SIT. Maryland and Delaware used Light Detection and Ranging (LIDAR) data along with field measurements from FIA and field plots of their own. This methodology resulted in higher resolution estimates that are spatially “explicit” (World Resources Institute 2020). Maryland and Delaware plan on replacing SIT with this newer methodology that uses Laser Detection and Ranging (LADAR). Finally, the state of Wisconsin has approximately doubled the number of FIA plots statewide since 1996. There are approximately 3,750 additional FIA plots in Wisconsin (World Resources Institute 2020). The monetary cost to the state has been approximately $390,000/year to maintain and collect data from these plots. In a similar vein, Washington is spending $500/plot to use state-owned forest land to improve estimates form forests. Washington is not planning on integrating this data into the FIA database (World Resources Institute 2020).

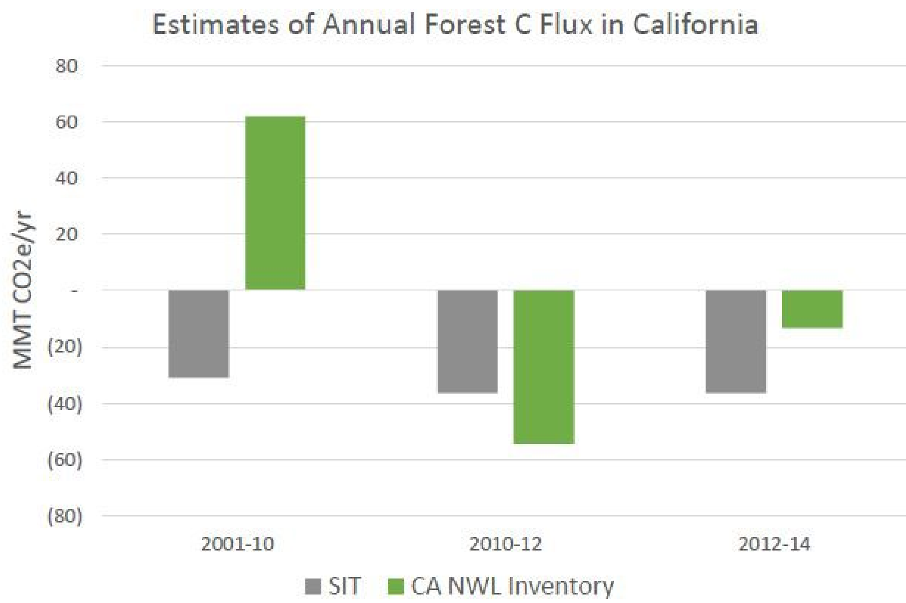

Figure 1. Differences in annual carbon sequestration from California forests using the California Natural and Working Lands (NWL) Inventory compared to SIT. Figure 1 was taken directly from World Resources Institute 2020. Page 56 – California Natural & Working Lands Inventory.

LANDFIRE

LANDFIRE is administered through the US Forest Service and the US Department of Interior. These two agencies have developed a free tool that provides geospatial data for vegetation types, land use, land use changes, vegetation types, canopy cover, height of trees, and land disturbance (e.g., fire). Currently LANDFIRE is updated to 2022 (https://landfire.gov/). Data from LANDFIRE can be used with FIA, and other measurements from forests, to estimate CO_2-C fluxes at the landscape level. LANDFIRE is a "spatially explicit" data set which is an advantage over using FIA alone (World Resources Institute 2020). Some limitations to using LANDFIRE include: 1) generally a 2–3-year period between data collection and data release, 2) newer LANDFIRE products are not always compatible with older LANDFIRE products (i.e., difficult at times to make comparisons to older data sets), and 3) some states (e.g., California) have found that LANDFIRE does not represent timber harvests accurately. LANDFIRE has the possibility of being able to help with the timely quantify of the impact of significant land use changes (e.g., wildfires and the long-term [> one year] consequences of fire on CO_2-C sequestration), especially when combined with other data.

Methodologies for estimating carbon sequestration in agricultural lands

EPA state inventory tool

The SIT that is used for forests can be used for agricultural land (separate module for forests and agricultural lands). The data in the SIT are downscaled from the National GHG Inventory. The inventories are produced from land use histories and land activity data from the National Resources

Inventory (NRI), other federal data and the Daily Century Model (DAYCENT) (World Resources Institute 2020). Emissions of N_2O and CH_4 from agricultural soils are available in SIT, but not in the agricultural module. The 2021 – 2022 updated SIT will correct some limitations found in older versions of the SIT. One of the more significant changes to SIT in the latest update is the ability of SIT to now "disaggregate" CO_2-C fluxes between croplands and grasslands. This was done to enable the National GHG Inventory to provide CO_2-C fluxes as time series data. The SIT will then be consistent with the IPCC land use categories. Even with some improvements to the SIT for agricultural lands, there are still limitations to the SIT agricultural module. Some of these limitations include: 1) there is an approximately three-year wait for data to be integrated into SIT from the NRI, 2) no regional or "spatially explicit" estimates of CO_2-C fluxes, and 3) little amounts of available CO_2-C flux field data (World Resources Institute 2020).

States can improve their estimates of carbon sequestration from agricultural soils estimated using SIT by implementing remote sensing technologies to gain better spatial resolution and to create a soil carbon monitoring network – on farm, regionally, statewide, and nationally. Minnesota has implemented a remote sensing program along with filed plot transects that has allowed it to spatially scale farming practices with soil conservation efforts to then help with estimates of carbon sequestration. This has helped the state of Minnesota with tracking farming trends from the past (i.e., used satellite data from the past to track trends to the present time). Additionally, states can use the US Soil Survey. The US Soil Survey includes information about soils (e.g., bulk density and organic matter content). The US Soil Survey product is available in both a fine resolution and a coarse resolution version. The fine resolution data provides county-level information, and the coarse resolution product gives regional and state-level information. The data in the US Soil Survey is from transect data, uses aerial imagery and is available for the entire United States. This data is relevant for use in estimating carbon sequestration on a decadal time scale (i.e., changes in soil organic C content) in NWL at the state-level and is currently used in several computer models (e.g., DAYCENT) and in The National GHG Inventory (World Resources Institute 2020).

Methodologies for estimating land use and land use changes

The land use, land use change and forestry (LULUCF) module in SIT can be used to estimate CO_2-C fluxes resulting from land use change. States can improve their estimates of CO_2-C fluxes by also using land cover databases (e.g., National Land Cover Database [NLCD]), and/or implementing remote sensing programs (e.g., using LIDAR). Some limitations to using landcover databases include: 1) they are not updated on a regular basis; 2) the NLCD only being updated every five years; and 3) the inability of some remote sensing methodologies to "see" seedlings planted in forests (e.g., as the result of reforestation efforts) and therefore may underestimate state-level carbon sequestration values (world Resources Institute 2020).

Nevada Statewide Greenhouse Gas Emissions Inventory and Projections (1990-2042)

This report is published by the Nevada Division of Environmental Protection (NDEP) and provides GHG emissions and uptake for the state of Nevada. Our current report is most relevant to the "Land Use, Land Use Change, and Forestry" and the "Agriculture" sections of the state inventory and projections report, but specifically to the methodologies used to generate the CO_2 emissions/uptake values for land use, land use change, forestry, and agriculture. Data for these sections were obtained from the SIT. Many states rely on SIT for determining emissions and uptake from various sources, but as discussed in a previous section of our report, data from SIT has several inherent limitations. The limitations to the SIT can be mitigated by incorporating several different methodologies to complement the SIT tool and to refine CO_2-C emissions estimates. These additional methodologies in themselves have limitations, but overall, integrating these methodologies should enhance the accuracy of quantifying net CO_2 emissions from (or uptake by) forests, agricultural lands, and LULUCF. We recommend incorporating, or implementing, as many of these methodologies as possible in future estimates of GHG emissions that are reported in the Nevada Statewide Greenhouse Gas Emissions Inventory and Projections report. These methodologies have been outlined in the previous sections of this current report.

Task 2: Analysis of existing eddy covariance data from the Great Basin and Mojave deserts

While developing the scope of work for this project, it was decided to include the possibility of being able to analyze and then report on several years' worth of eddy covariance CO_2 flux data collected by the Desert Research Institute (DRI). Going into this project, it was unknown whether the CO_2 data were usable because the project that the CO_2 data originated from was an evapotranspiration study conducted in 2005 - 2009 and not a CO_2 study. Because of this, the CO_2 data were never QA/QC'd and analyzed. During the analysis of the CO_2 data for this current project, we noticed anomalies and irregularities in the data. We performed a few analysis techniques to determine the cause of these anomalies and irregularities, but none of them corrected the data or gave insight into the problem. Because of this we didn't feel comfortable using this data and continuing to investigate the problem may have taken a lengthy amount of time and taken away from the other components of this current project. Therefore, we stopped the analysis of the EC data and concentrated on the other parts of this current project.

Summary of current CO_2 sequestration in Nevada: Arid shrublands

Collectively, we compiled 46 site-years of annual NEP data from "relevant" arid shrublands across the Intermountain West from a total of nine study sites (and nine peer-reviewed papers). Forty-one (41) of these sites showed net annual CO_2 uptake (-NEE values). For sagebrush ecosystems, 35 of the 40 site-years showed net annual CO_2 uptake. This corresponds to a mean±SE of -111±13 g C m^{-2} yr^{-1} (which is equivalent to -407±48 g CO_2 m^{-2} yr^{-1}) removed from the atmosphere from sagebrush (*Artemesia tridentata*) ecosystems of the Intermountain West during the mid- to late-1990s to the 2010s. It should be noted that annual NEP site-year data for sagebrush ecosystems mostly came from sites north of Nevada (in Idaho, Oregon, and Washington) where precipitation is greater, and temperatures are cooler, than in Nevada sagebrush ecosystems. For Mojave Desert shrublands dominated by *Larrea tridentata* (Wohlfahrt et al. 2008; Jasoni et al. 2005; Biederman et al. 2018; Arthur et al. 2012 cited in Biederman paper) with NEP measured during late-1990s and mid-2000s (n=6 site-years), all of the site-years showed net CO_2 uptake (-NEE values). This translates to a mean±SE of -93±14 g C m^{-2} yr^{-1}, or -341 g CO_2 m^{-2} yr^{-1}.

Clearly more eddy covariance measurements and other types of data collection and analysis are needed to improve the quality of CO_2 sequestration estimates for Nevada's sagebrush, Mojave Desert, wetlands, and sky-island forest ecosystems under climates specific to Nevada.

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