Center for Environmentally Sustainable Transportation in Cold Climates

Evaluating Management Options to Increase Roadside Carbon Sequestration

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
ºF	Fahrenheit	5/9 (ºF-32) ºC temperature temperature	Celsius	
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2 m^2
	meters squared	10.764	square feet	ft^2 km^2
	kilometers squared	0.39	square miles	mi^2 ha
	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb mg
	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

32 98.6 212ºF
-40ºF 0 40 80 120 160 200

-40ºC -20 20 40 60 80
0 37 100ºC

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Glossary

Abbreviations, Acronyms and Definitions

C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
CO_2E	carbon dioxide equivalent – a measure to compare various greenhouse gases based on their global warming potential (GWP); usually expressed in metric tons
CCS	carbon capture and storage = carbon sequestration
FHWA	Federal Highway Administration
FLMA	Federal Land Management Agency
GHG	greenhouse gas
GIS	geographic information system
NEE	net ecosystem exchange of CO_2
ROW	right-of-way

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
hectare (ha)	2.471	acre (ac)
gram (g)	0.03527	ounce (oz)
kilogram (kg)	2.205	pound (lb)
mile (m)	1.609	kilometer (km)

Carbon Compound Weight Conversion Factors

1 g CO = 0.43 g C
1 g CO_2 = 0.27 g C
1 g CO_2E (CO_2 emission equivalent) = 0.27 g C

Equivalents

1 megagram (Mg) = 1 million (10^6) grams = 1,000 kilograms = 1 metric ton (t)
1 gigagram (Gg) = 1 billion (10^9) grams = 1,000 metric tons (Mt)
1 teragram (Tg) = 1 trillion grams (10^{12}) = 1,000,000 metric tons
1 petagram (Pg) = (petagram) = 1 gigaton = 1,000,000,000 metric tons

Executive Summary

In the United States, the transportation sector produces more emissions of carbon dioxide (CO_2), a greenhouse gas, than any other sector. Two key strategies to reduce the concentration of atmospheric carbon (C) caused by anthropogenic emissions include capturing and storing CO_2 in either the earth's biosphere (terrestrial sequestration) or in geologic formations deep underground (geologic sequestration). The main focus in the study of terrestrial sequestration is soil organic carbon (SOC), since soils have more carbon than the earth's atmosphere and forests combined.

This project sought to estimate the amount of carbon passively being sequestered along Montana Department of Transportation (MDT) roads and to test three different highway right-of-way (ROW) management techniques to determine whether they have the capacity to increase SOC.

Total ROW acreage owned by the MDT were obtained through geographic information system (GIS) analysis and combined with data on Montana vegetation to determine acreage according to vegetation type. Estimates of annual carbon sequestration from a network of global carbon measurement sites were applied to vegetation classes and used to approximate annual MDT ROW carbon sequestration. We found that ROWs owned by MDT consist of 70% grasslands and the roadsides sequester 75,292 metric tons of carbon per year. One management option analyzed was to convert existing MDT ROW grasslands into shrublands since, in a number of studies, this type of physiognomic transformation has been found to increase SOC. Our analysis found that existing grassland conversion to shrubland, outside the MDT ROW management zone, has the potential to increase carbon sequestration by 16,200 metric tons of carbon per year. This

amount of annual carbon sequestration is equivalent to the removal of 12,505 passenger vehicles from the road per year or the energy use of 5,420 homes per year.

Three areas in Montana were selected to establish experimental transects consisting of a series of 1 meter $(m)^2$ plots within the I-90 (Interstate Highway 90) ROW. The areas were located within the ROW, but outside the "active zone" or managed portion of the ROW, where maintenance of the safe zone, sight lines, mowing, and weed management is a priority. The three transects are located along a 61 km (38 mi) section of I-90 from Three Forks, east to Bozeman Pass in southwest Montana. Each transect successively increased approximately 244 m (800 ft) in elevation, beginning west near the Three Forks exit, near the Bear Canyon exit east of Bozeman, and near Bozeman Pass, furthest east. Within each of the three locations, a transect was established that was relatively level for at least 120 m and parallel to the highway. Each transect had sixty 1 m^2 experimental plots established, and each plot was separated by 1 m.

These transects were used to test three management techniques that, if proved successful, the MDT could easily adopt to increase carbon sequestration in its ROWs. The management techniques were as follows:

1) increase the mowing height of the ROW clear zone from 15 cm (6 inch (in)) to 30.5 cm (12 in),
2) plant the shrub rabbitbrush (*Ericameria nauseosa*) into the ROW dominated by perennial grasses, and
3) include legumes in the perennial grass seed mix of ROW reclamation projects after highway construction or reconstruction.

At each transect, ten test plots were established for each treatment and its control:

- 30.5 cm (12 in) mowing height versus 15 cm (6 in), the standard height currently used by MDT for its I-90 clear zones (control);
- typical MDT perennial grass seed mix with legumes broadcast on bare, disturbed soil versus perennial grass seed mix broadcast on disturbed, bare soil (control);
- five rabbitbrush seedlings planted in existing perennial grass-dominated plots to compare SOC with existing perennial grass-dominated plots (control).

Due to dry growing seasons in 2016 and 2017, many of the rabbitbrush and legume plantings had high rates of mortality, even though they all received supplemental hand-watering many times in the summers of 2016 and 2017. As a result, only one transect, Bozeman Pass, showed successful establishment of rabbitbrush shrubs. Similarly, although perennial grass in the seed mixes became established across all three study sites, by the summer of 2018, legumes were only successfully growing at two of the transects and in diminished amounts. About half of the 10 test plots at each transect had at least 1 legume stem (4 of 10 at Bozeman Pass and 6 of 10 at Bear Canyon).

The second portion of the project tested whether three ROW management practices (increasing the ROW mowing height, planting woody shrubs in grass-dominated ROWs, and adding legumes to seed mixes in simulated post-construction disturbed soils) might influence, over the ~2-year project period, aboveground and belowground carbon stocks along an MDT-maintained segment of I-90 crossing the Gallatin Valley. We selected three roadside sites along I-90 in Montana for experimentation: one near Three Forks (3F), one near the Bear Canyon exit east of

Bozeman (BC), and one at Bozeman Pass (BP) between Bozeman and Livingston. Each of the three sites had a linear transect near, and parallel to, the ROW fence line so that it was well within the unmanaged zone of the ROW. Each transect had a series of sixty 1 m^2 plots, with ten replications of each of six original treatments. The treatments were as follows: control (C), mow height of 6 in. (6), mow height of 12 in. (12), add legumes to reclamation seed mix (L), reclamation seed mix without legumes or legume control (LC), and plant rubber rabbitbrush in grass-dominated sites (R).

We collected and analyzed nearly 1300 soil samples: 720 soil samples were collected from the 6 original treatments (C, 6, 12, L, LC, and R) across the 3 roadside locations in 2016 (18 treatments × site combinations); an additional 560 soil samples were collected from 4 or 5 treatments (C, 6, 12, and LC treatments at each of the 3 sites, in addition to the L treatment at the BC site and the R treatment at the BP site in 2018; 14 treatments × site combinations). Soil samples generally averaged 1.5–3.0% soil organic matter (SOM), or 0.75–1.5% SOC at the 3F site; 5–8% SOM (2.5–4% SOC) at the BC site; and 3–5% SOM (1.5–2.5% SOC) at the BP site.

We also measured soil respiration rates across the 140 (2018) or 180 (2016) 1 m^2 plots over the life of the project. Soil respiration rates were generally highest in June or July at the BC site, averaging ~4 μmol CO_2 m^{-2} $second^{-1}$; converted to mass units per year, this translates to ~1500 g C m^{-2} y^{-1}. Soil respiration rates (pre-water addition) were lower at the BC site in November 2016, at the BP site in June 2018, and at the 3F site in July 2018 (all generally 2–3 μmol CO_2 m^{-2} s^{-1}). The somewhat higher peak growing season (e.g., June/July) soil respiration rates at BC relative to 3F or BP coincided with greater levels of SOC at BC.

Our measurements of both SOC and soil respiration rates enabled us to estimate soil carbon residence times. Small SOC stocks and high soil respiration rates yield very short residence times; conversely, large SOC stocks and low soil respiration rates yield relatively longer residence times. Estimated soil carbon residence times for the three project sites ranged from 3 (3F) to 8 (BP) years, but some notable patterns emerged from within-site comparisons of residence times by treatment. Notably, the generally lower soil respiration rates observed in the L/LC plots (about 30% lower than the control plots) led to longer residence times (~30 y). Aboveground biomass C estimates generally mirrored belowground SOC estimates, with the highest values found at the BC site in non-L/LC plots (~450 g C m^{-2}), about 50% greater biomass C than we measured at non-L/LC plots at either the 3F or BP sites. The LC plot biomass in 2018 was <100 g C m^{-2}, independent of site (3F, BC, BP).

Taken together, our SOC, respiration rate, and biomass findings highlight the value of active experimentation alongside interstate ROWs to determine the most promising strategies for using these extensive areas to sequester carbon while meeting all ROW safety considerations. Specifically, our findings suggest that of the three treatments implemented (raised mowing height, shrub planting, and disturbance), *minimizing disturbance* to soils is likely to make the greatest contribution to the medium- and long-term carbon-storage potential of roadside soils. We originally included these disturbances to simulate post-construction consequences to roadside soils and plant communities. Our simulated disturbances led to sharp reductions in aboveground biomass, an unsurprising result; after all, plots were scraped clear of all vegetation. Unexpectedly, however, these same LC plots showed the sharpest reductions in SOC, as inferred from differences in measured SOC between 2016 and 2018. If these results characterize post-construction shifts in roadside plant and soil carbon levels generally, we could argue that an important carbon sequestration strategy for roadside soils might simply be to minimize disturbance of these extensive ROW areas. Mowing height increases and shrub planting, by contrast, yielded reductions in measured SOC from 2016 to 2018, implying that these types of active ROW management practices could lead to transient short-term reductions in SOC as the roadside plant communities adapt to novel management regimes. Nevertheless, because our findings showed that the greatest reductions in SOC occurred with LC treatments, we conclude that minimizing disturbance in these ROW zones should be an important consideration where efforts are focused on managing ROW soils for improved SOC.

CHAPTER 1.0 INTRODUCTION

The increased atmospheric concentration of greenhouse gases (GHGs) over the past century has contributed to global warming and has spurred the search for opportunities to reduce the atmospheric concentration of carbon dioxide (CO_2), a major GHG. From 1990–2013, CO_2 constituted 82.5% of total GHGs in the United States (EPA 2015). According to the Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2013, the transportation sector had the greatest emissions of CO_2 of any sector in 2013 other than electricity generation, 1722 million metric tons of CO_2 equivalent (MMT CO_2E; 1000 million metric tons is mathematically 1 billion metric tons, or 1 gigaton [GT] or 1 petagram [Pg]), and it represented 27% of total U.S. GHG emissions in 2013 (EPA 2015). Within the sector, vehicles on roads are responsible for 84% of the emissions. Between 1990 and 2010, GHG emissions in the transportation end-use sector increased more in absolute terms than any other end-use sector (industrial, agriculture, residential, commercial).

By 2016, total GHG emissions were the same for both the transportation and the electricity sectors, at 28% of the total 6511 MMT CO_2E emitted nationally (EPA 2018).Thus, it is incumbent on the transportation sector to address GHG reduction as best it can to play its part in the overall national effort to reduce atmospheric CO_2 concentrations through a number of natural (i.e., dissolution in the oceans) and human-driven processes.

Two key strategies to reduce the atmospheric carbon (C) concentration caused by anthropogenic emissions include capturing and storing CO_2 in either the earth's biosphere (terrestrial sequestration) or in geologic formations deep underground (geologic sequestration) (Lal 2008). The main focus in the study of terrestrial sequestration is soil organic carbon (Lal 2010), since soils have more carbon than the atmosphere and forests combined (Donovan 2013). This concept underlies the recent global initiative to increase soil organic carbon (SOC) levels by 0.4% per year (http://4p1000.org/understand), as well as numerous state initiatives, such as California's recent $7.5 million Healthy Soils Program (www.cdfa.ca.gov/oefi/healthysoils/).

Vegetation and soils along U.S. roads are of interest terrestrial carbon sequestration. The nation's transportation infrastructure comprises more than 6.4 million (M) km (4 M miles (mi)) of public roads, managed by various entities including federal, state, county, tribal, and metropolitan agencies. Public roadsides are easily accessible, and state, tribal, and local transportation agencies could benefit in two ways: reduced costs for vegetation management and increased revenue if sequestered C is sold on carbon offset markets (Proudfoot et al. 2015).

1.1 Roadsides Could Sequester 10 Million Metric Tons of Carbon Annually

Interest in roadside vegetation and soils as a means to capture and store carbon has increased recently. There have been three estimates of existing annual carbon sequestration occurring along U.S. roadsides. First, the Federal Highway Administration (FHWA) estimated carbon sequestration along its Federal Aid Highways, the major roads that include the interstate highway system, via its Carbon Sequestration Pilot Program (FHWA 2010). An estimate of roadside carbon capture and storage for use by federal land managers, those of the eight federal land management agencies such as the National Park Service and the U.S. Forest Service, was recently completed (Ament et al. 2014). It has been estimated that collectively, federal highways and federal land roadsides are sequestering approximately 10 million metric tons (MMT) of carbon annually (Table 1). For context, total U.S. emissions in 2016 were estimated to be ~6500 MMT of CO_2E (EPA 2018), or ~1770 MMT of CO_2-C (using the mole fraction of C to CO_2 of 12/44). Thus, in 2016, roadside sequestration potential represented about 0.6% of total U.S. anthropogenic emissions.

Table 1. Summary of two FHWA studies of carbon sequestration potential on federal highways and roads. The FHWA 2010 estimate translates to an areal average sequestration rate of ~1.1 MT/acre/year; the FHWA 2014 estimate translates to an areal average sequestration rate of 2 MT/acre/year.

Roadside Carbon Sequestration Study	Public Roads Type	Road Length (miles)	Portion of U.S. Public Roads (Percent)	Roadside Definition	Estimated Area of Vegetation and Soils (Million Acres)	Estimated Annual Carbon Uptake (Million Metric Tons)	Equivalent Annual Passenger Car Emissions (Millions)
FHWA – 2010	National Highway System	164,125	4.1	Right-of-Way	3.4	3.6	2.6
FHWA – Federal Lands 2014	Federal Land Mgmt. Agencies	258,282	6.4	Road Effect Zone	14	6.9	5

The Florida Department of Transportation (DOT) estimated its roadside carbon sequestration contribution as part of a larger study on ecological services provided by rights of way (ROWs) (Harrison 2014). The Florida DOT study also valued the carbon being captured and stored along ROWs at $157–363 million per year, using a conservative price for marketable C.

All three of these studies were estimates based solely on the *passive* management of existing soils and vegetation, areal carbon storage rates, and acreage along roads. Collectively, these studies demonstrate the promise for using *active* carbon sequestration techniques along easily accessible roadsides. Unfortunately, little information is available to identify and quantify roadside management techniques that increase carbon sequestration rates in roadside soils and vegetation while meeting safety requirements.

1.2 The Carbon Cycle

The carbon cycle comprises the fluxes of carbon among five main carbon reservoirs (listed in decreasing amounts of carbon: oceanic pool, geologic pool (includes fossil fuels), soil pools that include SOC, and soil inorganic carbon (SIC), the atmospheric pool, and the biologic pool (Lal 2008, and Figure 1). The soil and biologic pools combined are termed the terrestrial carbon pool.

The terrestrial carbon cycle captures carbon from the atmosphere primarily via plant photosynthesis and stores it in the soil through root residues and excretions and via dead microorganisms and in wood and other durable plant parts aboveground. Carbon is lost to the atmosphere via plant and soil respiration.

Belowground carbon comprises both SOC and SIC, though the focus of this project is SOC, which is primarily derived from humus—decomposed plant and animal matter, also known as soil organic matter (SOM). Soil organic matter is about half SOC, with the remaining mass composed primarily of structural oxygen. A glucose molecule, for example, is 53% oxygen, 40% carbon, and 7% hydrogen by mass. Over half of the carbon in the terrestrial pool resides in soils. As roots and microscopic animals die each year, carbon accumulates in the soil. Across arid and semiarid landscapes in general, and in Montana particularly, SIC also accumulates as salts, such as calcium carbonate buildup. It is not uncommon in some southwestern Montana soils to have SIC:SOC ratios >10 in the upper 12 in. of a soil profile (e.g., Hartshorn et al. 2017).

The net gain or transfer of atmospheric carbon into soils and plants of the terrestrial system is called biological carbon sequestration. Carbon sequestration can also transfer carbon from the atmosphere into other pools, such as geologic or oceanic pools. Much of the effort in increasing terrestrial carbon stores is to locate it in soils. Carbon sequestration occurs when SOC increases over time, although some carbon can be stored aboveground, primarily in forests.

CHAPTER 2.0 BACKGROUND

The rapid increase in atmospheric concentration of GHGs over the past century has contributed to global warming and spurred the search for opportunities to reduce the atmospheric concentration of CO_2. This project will determine if DOTs in cold climates have management options for actively increasing the terrestrial carbon being captured and stored in plants and soils along roadsides, and whether seeking to actively manage roadsides to increase carbon stores is a worthwhile pursuit for managers.

We have already estimated how much carbon is passively sequestered along MDT roadsides, and within this roadside acreage, the potential to actively increase roadside carbon sequestration (Cote 2015, see Appendix A). In the second component of this project, we field-tested three active management techniques to determine if roadside carbon stores can be increased, and if so, by how much.

The first exploration of active management techniques for increasing carbon stores along roadsides was led by the New Mexico Department of Transportation (NMDOT). This agency investigated whether stamping divots in ROW soils to capture and hold moisture and nutrients, planting legumes into existing vegetation in the unmanaged zones of roadsides or increasing the mowing height of vegetation in the managed zone of ROWs increase carbon stocks (Dunn 2013). Unfortunately, the seeded legumes did not establish, and the experiment with stamped divots did not significantly increase carbon stocks. Increasing the mowing height was the only promising approach for increasing SOC (Romig et al. 2016).

Our project along I-90 in Montana builds on the initial NMDOT study of an arid portion of the southwest U.S. with experiments designed to quantify carbon management outcomes for colder ecosystems farther north. Three management actions were tested in Montana: (1) an altered mowing regime such as that in New Mexico, (2) planting of low woody shrubs in existing grassy roadsides, and (3) including legumes in seed mixes to revegetate simulated post-construction roadsides.

2.1 Results of Spatial Analysis of Montana Roadsides

We first sought to estimate how much roadside acreage exists and how much carbon is currently being passively captured and stored along MDT roadsides. This effort resulted in a professional paper by Chris Cote (Cote 2015), in partial fulfillment of his Master of Science (M.Sc.) degree from Montana State University, Land Resources and Environmental Sciences Department (Appendix A).

The MDT ROWs are separated into two management zones: the “active zone,” which is within 4.6 m (15 ft) of the paved road shoulder, and the “passive zone,” which is from 15 ft away from the road’s shoulder to the boundary of the ROW (MDT 2002). It is estimated that MDT has 165,829 acres (ac) of ROW, with 18,780 ac in the “active zone,” where the agency mows to provide a clear zone adjacent to the paved surface (Cote 2015). The MDT has an estimated additional 147,049 ac in the “passive zone,” where no mowing occurs outside the clear zone (Cote 2015).

Montana DOT ROW acreage is classified as 70% grassland vegetation, 15% montane forest, 8% shrubland, and 7% a mix of other types (Cote 2015). The C sequestration rate in MDT ROWs was estimated to be 75,292 metric tons of C per year (MT C yr^{-1}), with an areal average sequestration rate of 0.45 MT C $acre^{-1}$ $year^{-1}$. This estimated annual C sequestration rate in MDT ROWs is equivalent to the annual emissions of over 58,000 passenger vehicles. Under one change of management scenario, that of transforming MDT ROW grasslands into shrublands, it is estimated that an additional 16,200 MT C yr^{-1} would be sequestered—the equivalent of the annual emissions of an additional 12,505 passenger vehicles (Cote 2015). This initial estimate highlights the potential in transforming MDT ROWs that are currently predominately grasslands into shrublands.

CHAPTER 3.0 EXPERIMENTAL DESIGN

3.1 Introduction

With the GIS spatial estimations of MDT ROWs complete, we developed field experiments to evaluate simple changes to three ROW management techniques to determine if such adjustments led to increased carbon sequestration, and if so, to quantify the increase in aboveground carbon in woody vegetation, when appropriate, and the belowground carbon pool. We evaluated alterations to the following three standard management techniques:

1. Increase the active zone mowing height from 6 in. to 12 in.

Changing the mowing height of the plants in the managed zone of the ROW has the potential to increase carbon sequestration. Our project was designed to test mowing heights similar to the study along roadsides in New Mexico. In the only empirical carbon study along highway ROWs in the U.S. (Romig et al. 2016), carbon stocks were found to increase when mowing height was increased from 6 to 12 in.

Independent of mowing heights, various plants can build SOM, and thereby sequester SOC. For example, New Mexico's arid environments are dominated by C_4 plants (one water-use-efficient, photosynthetic pathway for fixing atmospheric carbon in arid ecosystems). In Montana, by contrast, roadside vegetation is dominated by C_3 plants, a less water-use-efficient photosynthetic pathway. Grasses that are C_4 use nitrogen (N) more effectively than C_3 plants and thus may have an advantage over C_3 species to increase SOC (Knops and Tilman 2000, Matamala et al. 2008). However, a restored C_4

grass-dominated, tallgrass prairie showed SOC *losses* of 0.12 MT C $acre^{-1}$ y^{-1} after 33 years (Ampelman et al. 2014).

2. Incorporate woody shrubs in grass-dominated roadsides by planting small shrubs in the non-managed zone of the ROW.

Converting roadside grasslands to shrublands has the potential to increase carbon sequestration. Various studies have demonstrated that a transition from grassland to shrubland can increase aboveground and/or belowground carbon stocks (Emmerich 2007, Knapp et al. 2008, Petrie et al. 2015). A synthesis of published studies of woody plant encroachment into North American grasslands found that ecosystem carbon increased across most species and ecoregions (Barger et al. 2011). In a global synthesis of shrub encroachment of grasslands, SOC was found to significantly change, ranging from -50% to +300% (Li et al. 2016).

Based on the AmeriFlux eddy covariance towers (see *http://ameriflux.lbl.gov/*) that measure, among other things, the net ecosystem exchange of carbon, North American grasslands average an uptake of 0.40 MT C $acre^{-1}$ $year^{-1}$ compared with 0.54 MT C $acre^{-1}$ yr^{-1} for shrublands. Based on these empirical data from the AmeriFlux tower network, North American shrublands might, on average, capture 35% more carbon per unit area per year than grasslands (Ament et al. 2014).

Another study of transitioning grassland to shrubland in the northern Chihuahuan desert reported increased carbon sequestration from 31 g C m^{-2} yr^{-1} (1 g C m^{-2} yr^{-1} is equivalent to 0.004 MT C $acre^{-1}$ y^{-1}) to 49 g C m^{-2} yr^{-1} (an increase equivalent to 0.07 MT C $acre^{-1}$ y^{-1}; Petrie et al. 2015). Cold desert shrublands are also a target for carbon sequestration due to the storage of much of the carbon belowground and at rates much higher than other biomes for the same surface area (Meyer 2012). Incorporating woody shrubs in existing ROW grasslands could increase soil carbon stores.

3. Add legume seeds to typical MDT perennial grass seed mixes for use in post-construction revegetation projects.

Restoring disturbed roadsides after highway construction has the potential to store SOC over a long time. Reclamation of roadside vegetation and habitat after disturbance from construction is an ideal time to seek to increase carbon sequestration, although recovery of carbon after disturbance is often a slow process, as these environments can be quite challenging for plant establishment. A study in prairie restoration indicated that carbon recovered (at 95% pre-disturbance levels) after 13 years, while nitrogen stocks took over 20 years (Matamala et al. 2008). Positive carbon annual sequestration rates in restored grasslands have been documented for over 27 years (Ampelman et al. 2014).

Increasing the amount of nitrogen (N) in soils can increase SOC. It is anticipated that the symbiosis between roadside plant communities with their member species that fix N, such as legumes, can increase plant community productivity and thus positively influence the soil carbon pool. Legumes were shown to be important drivers for higher aboveground biomass (Spehn et al. 2002, Maquard et al. 2009) in restoration studies. The presence of legumes and C_4 grasses increased soil carbon accumulation between 193% and 522% in a 12-year grassland study in Minnesota (Fornara and Tilman 2008).

Inter-seeding yellow alfalfa into South Dakota rangelands increased SOC by up to 17% compared with untreated rangelands (Mortenson et al. 2004). Similar results of increasing carbon sequestration by using N fertilizer in agricultural systems have been demonstrated (e.g., Alvarez 2005, Liu and Greaver 2009). Thus, we sought to determine if adding legumes to seed mixes for revegetation purposes after highway construction will boost carbon sequestration.

3.2 Hypothesis Development for Field Experiments

Based on various studies regarding the increase of terrestrial carbon, we tested the following three hypotheses to determine if changes to traditional management of roadside vegetation can result in greater amounts of carbon sequestration.

Hypothesis 1 (H1): Increasing the mowing height within the ROW managed zone will increase SOC.

Hypothesis 2 (H2): Increasing physiognomic diversity by planting native woody shrubs in existing perennial grass-dominated roadsides will increase both aboveground carbon and belowground SOC.

Hypothesis 3 (H3): Including a nitrogen-fixing forb in a seed mix of perennial grasses will increase belowground SOC compared with a seed mix of only perennial grasses, commonly used to stabilize ROW slopes and restore ROW vegetation after highway construction.

3.3 Experimental Treatments to Test Each Hypothesis

We developed three different experimental treatments to test each hypothesis.

Hypothesis 1: Increasing the mowing height in the managed ROW zone will increase SOC.

A. Control for H1: Mow experimental plots at 6 in. (15 cm) height, once per growing season (typical MDT mowing height and frequency along the experimental segment of I-90 in southwestern Montana).

B. Treatment for H1: Mow experimental plots at 12 in. (30.5 cm) height, once per growing season. This treatment will determine if allowing for taller plant height each year, and thus more leaf area, will result in more photosynthesis and root growth and ultimately a higher level of stored SOC.

Hypothesis 2: Incorporating woody plants in grass-dominated roadsides in the unmanaged ROW zone will increase aboveground carbon stocks and SOC.

A. Control for H2: Do nothing to perennial C_3 grass-dominated plots.

B. Treatment for H2: Plant low native shrubs in existing established perennial grass-dominated plots. We selected rubber rabbitbrush, *Ericameria nauseosa* (Pall. ex Pursh G.L. Nesom & Baird), since it is a common shrub broadly distributed across all of western North America. This plant is often found growing along roadsides. It can tolerate many different environments, from hot valley floors in the intermountain region to openings in mountain forests, and it grows on sandy, loamy, gravelly or clay soils from 450 to 8000 ft in elevation (Scheinost et al. 2010).

Hypothesis 3: Adding a nitrogen-fixing legume to perennial grass seed mixes will increase SOC in post-construction revegetation sites.

To simulate a post-construction revegetation treatment, all of the existing perennial grasses and forbs were removed from each experimental plot. The plot was then either rototilled or hand dug with shovels and turned over to a depth of 6 in. (15 cm). In removing the vegetation and mixing the topsoil, we sought to simulate the typical highway revegetation method of removing and storing the roadside topsoil near the site before construction begins, then returning it to the slopes when construction is completed and spreading it to revegetate the area.

A. Control for H3: Removing the existing vegetation and tilling the topsoil or turning it over with shovels; revegetate by broadcasting a standard MDT seed mix of perennial grasses.

B. Treatment for H3: Removing the existing vegetation and tilling the topsoil or turning it over with shovels; revegetate by broadcasting seed mix of MDT perennial grasses and add a legume to the mix.

American vetch (*Vicia americana* Muhl. Ex Willd.) was the first legume selected for the project. This plant is a widely distributed native legume that covers most of North America except the southeastern United States. It is a rhizomatous perennial, can be found in moist to arid environments, is drought tolerant, and is often used for reclamation projects (Allen and Tilley 2014).

After the first growing season ended in 2016, a field review determined that the American vetch tublings that were planted at the beginning of the project were not viable, so a new legume was needed. Small burnet, *Sanguisorba minor* Scop., is a non-native legume, selected because it does well in roadside plantings in Montana (personal communication, Phil Johnson, MDT Reclamation Specialist) and could be seeded in the experimental plots in autumn 2016. The plant does well in full sunshine to partial shade and tolerates both slightly saline and acidic soils. It is not highly invasive; but can slowly move beyond its original planting area (USDA-NRCS 2012).

3.4 Other Experimental Design Considerations

The segment of I-90 in Montana chosen for our experiment is an east-west 4-lane highway that gradually rises in elevation between Three Forks (elevation ~4000 ft) in the western terminus of the study area, to its highest point at Bozeman Pass (elevation ~5700 ft) at the eastern terminus of the study area, over a distance of ~38 mi. We elected to establish three test areas along this elevational gradient to determine if climate differences, primarily soil moisture and air and soil temperatures, have any influence in carbon sequestration. Derner and Schuman (2007) showed that moisture, as measured by mean annual precipitation, is an important factor for soil carbon flux to go from negative (more SOC respired than CO_2 photosynthesized to SOM) to positive in western U.S. rangelands. Our original expectation was that the greater effective precipitation of the highest-elevation site would coincide with greater SOC sequestration rates, relative to the driest lowest-elevation site.

The typical ROW along a highway is a disturbed site, reclaimed after highway construction. Thus, ROW soils are generally not natural and do not fit neatly into a soil classification system. Roadside soils are usually highly disturbed and poorly developed (Figure 1).

This project was an experiment developed along an elevational gradient; if undisturbed, the soils would have developed slowly over a long time in the three varying environments responding to our treatments on top of existing MDT management practices. Unfortunately, due to the disturbed nature of the roadside soils and the diversity of road materials used in the original road construction and in upgrades, it has been a relatively short time (e.g., decades) since the highway was constructed. For example, I-90 in Montana replaced U.S. Highway 10, beginning with a section between Butte and Whitehall, just ~30 mi west of the project area in 1964. The last portion of I-90 was completed in 1987, approximately 15 mi east of the project area (www. Interstate-Guide.com/i-090.html).

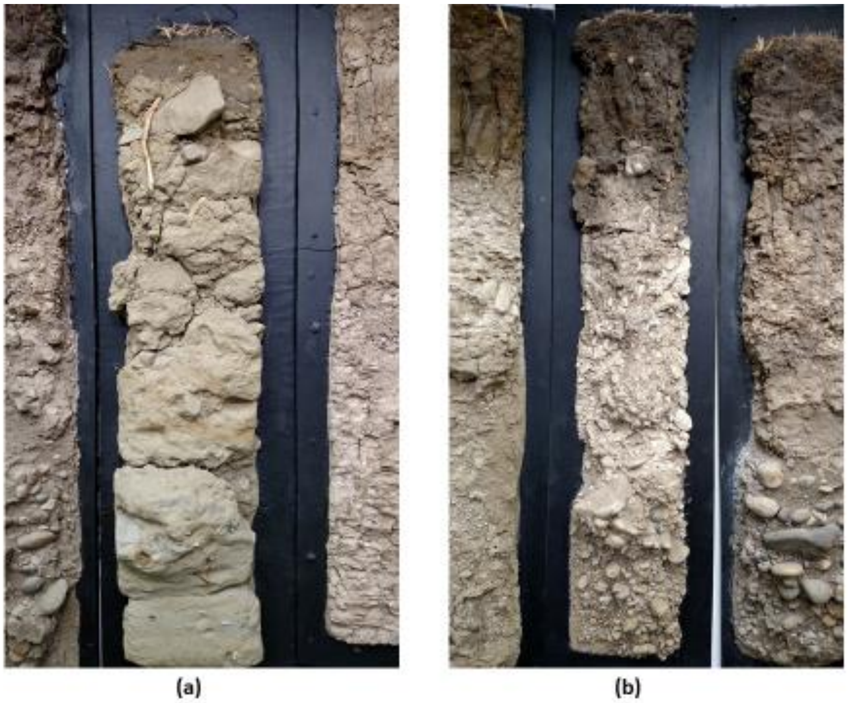


Figure 1. Photos of a typical disturbed (a) and undisturbed (b) soil profile from Montana. Monoliths are approximately 3 ft (0.9 m) tall and can be accessed via the Hayden Ferguson Soils Teaching Laboratory, #246 Leon Johnson, Montana State University. The undisturbed (b) profile clearly shows an accumulation of dark soil organic carbon at the surface and an accumulation of very light soil inorganic carbon in the gravelly subsurface.

In South African grasslands, soil carbon stocks were influenced more by soil parent material than by land use (Mills et al. 2005), indicating the important role of the parent material in carbon sequestration. Thus, our roadside experiment could not benefit from the natural soil profiles with typical horizon development of the soil in adjacent undisturbed lands along I-90 along an environmental gradient. Rather, the three sites for the experimental plots are set in soils that represent disturbed profiles still recovering from construction, with weak horizon development. Therefore, it is possible the carbon storage capabilities of the three sites might be influenced by factors other than the elevational gradient along which they are arrayed.

CHAPTER 4.0 EXPERIMENTAL PLOT CONSTRUCTION

4.1 Site Selection

Three areas were selected to establish experimental transects consisting of a series of sixty 1 m^2 plots within the I-90 right-of-way (ROW). The transects were located within the ROW, but outside the “clear zone” or managed portion of the ROW, where maintenance of the safe zone, sight lines, mowing, and weed management is a priority. The three transects are located along a 61 km (38 mi) section of I-90 in Montana, from Three Forks east to Bozeman Pass (Figure 2). We secured an Encroachment Permit from MDT to conduct our experiments in the I-90 ROW.

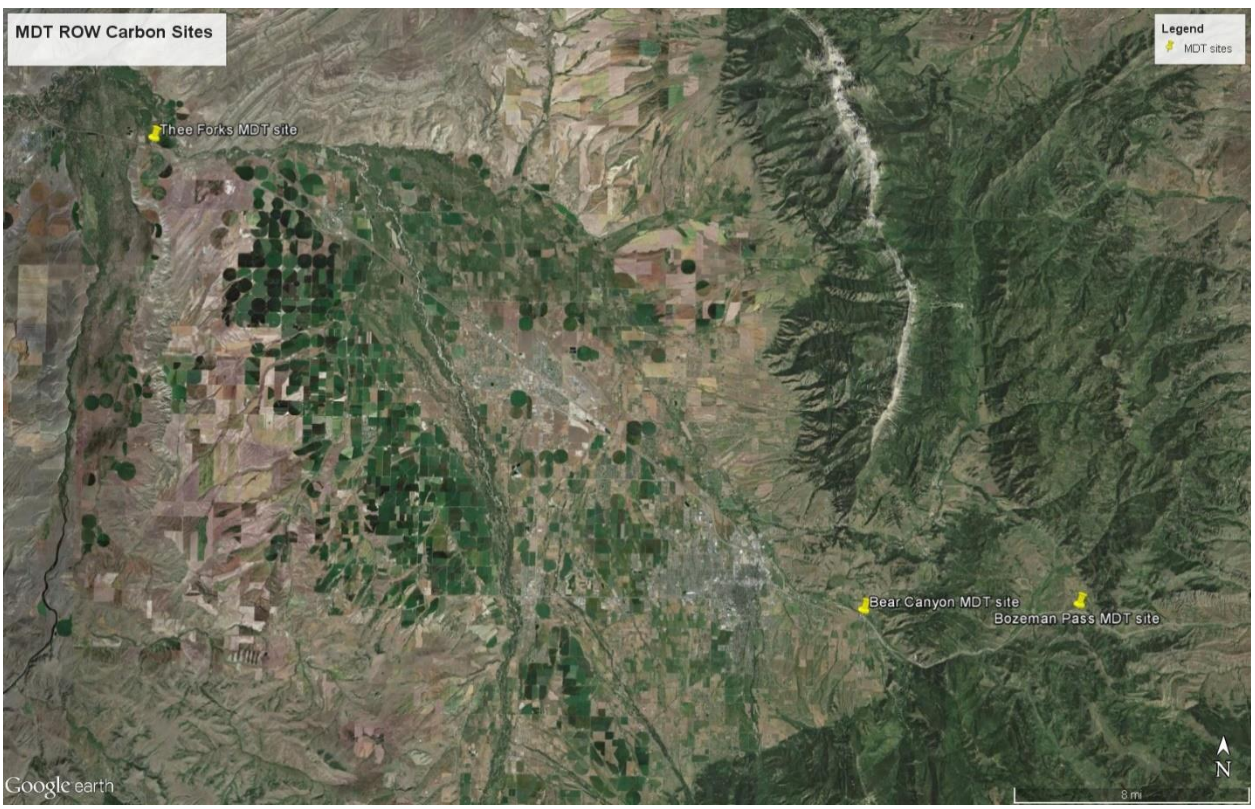


Figure 2. Approximate locations of three experimental sites along I-90 in southwest Montana between Three Forks, MT and Bozeman Pass. The yellow pins indicate the locations.

We distributed the experiment equivalently based on elevation, not in distance (mileage), within the study area (**Figure 3**). Thus, the three transects are located west of the I-90 Three Forks exit near Three Forks at 1250 m (4102 ft) (**Figure 4**), west of the Bear Canyon exit at 1511 m (4956 ft) (**Figure 5**), and near Bozeman Pass, 1741 m (5713 ft) (**Figure 6**). From west to east along the I-90 corridor, each successive transect site is approximately 244 m (800 ft) greater in elevation than the previous site. The Three Forks and Bear Canyon sites were located on the north side of I-90, and the Bozeman Pass site was located on the south side of I-90. The transects were mostly on level areas, with some portions of each transect having slight slopes (< 5%); all slopes face northward (azimuth of approximately 0 degrees).

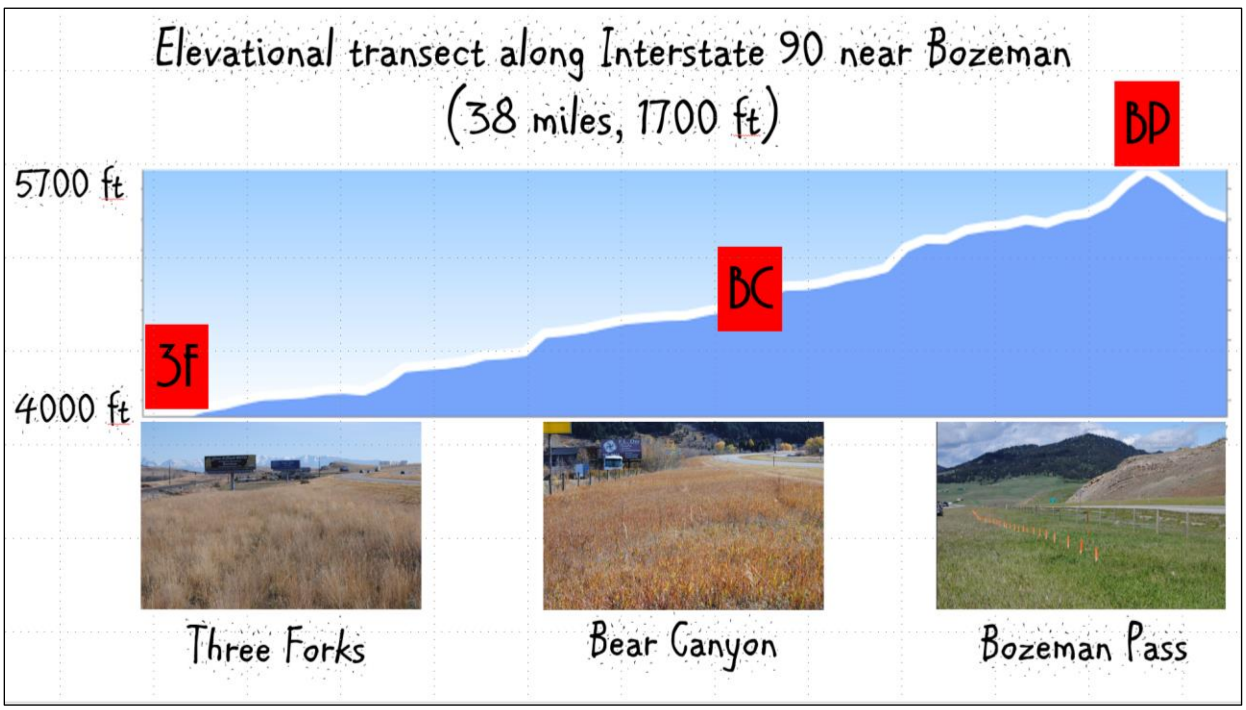
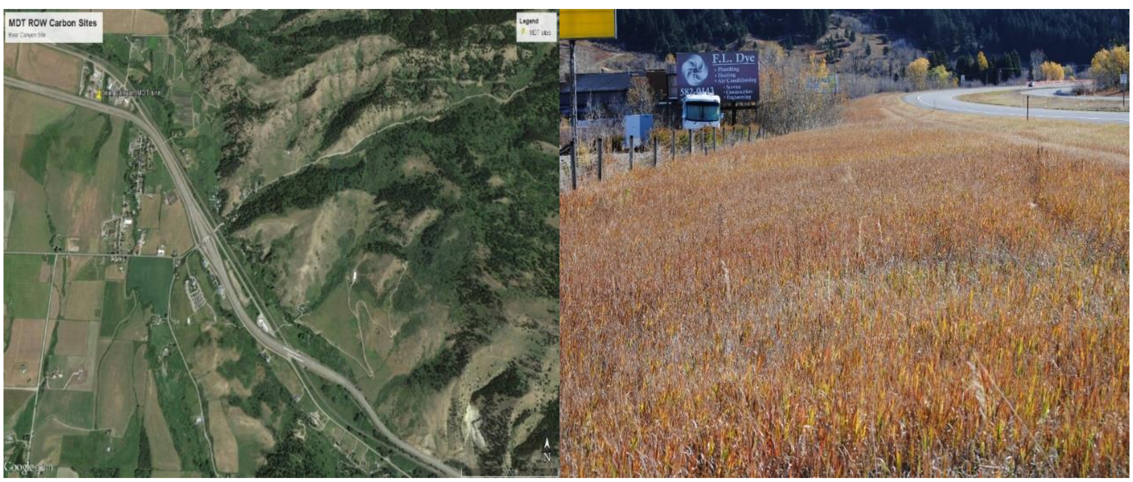


Figure 3. Location of the three transects along I-90 in southwestern Montana. The three transects are referred to with a two-character code: 3F (Three Forks); BC (Bear Canyon); BP (Bozeman Pass).

(a) (b)

Figure 4. (a) Three Forks (3F) transect location near the Logan exit of Highway I-90 in Montana; (b) photo of site looking east.



(a) (b)

Figure 5. (a) BC transect location near the Bear Canyon exit of Highway I-90 in Montana; (b) photo of site looking east.

Figure 6. (a - upper photo) BP transect location near Bozeman Bass, I-90 in Montana; (b – lower photo) photo of site looking east.

4.2 Experimental Plot Construction

4.2.1 Transect establishment

Within each of the three locations, a transect was established that was relatively level for at least 120 m and was parallel to the highway (see Figure 6b). Each transect has sixty 1 m^2 experimental plots established along it. The experimental 1 m^2 plots are 1 m apart along the 120 m transect (**Figure 7** and **Figure 8**). Transects were located and established in mid-May 2016. Additional details on sub-transects established perpendicular to this single 120 m transect can be found in the companion Salt study final report (Fay et al. 2018).

Figure 7. Experimental plot locations staked out along the Bear Canyon (BC) transect in summer 2016. View to east.

Figure 8. Experimental plot locations staked out along the Bozeman Pass (BP) transect in May 2016. View to west.

The three slightly altered management techniques, each with its own type of control, resulted in 6 alternating plots being established along each transect (**Figure 9**). Ten replications of each treatment (n=10) were established along each of the three transects. Thus, each 120 m transect had sixty 1 m^2 plots in total. Since the project had three different transect sites, it resulted in 180 experimental plots being established. Plots were constructed between mid-May and late June 2016.

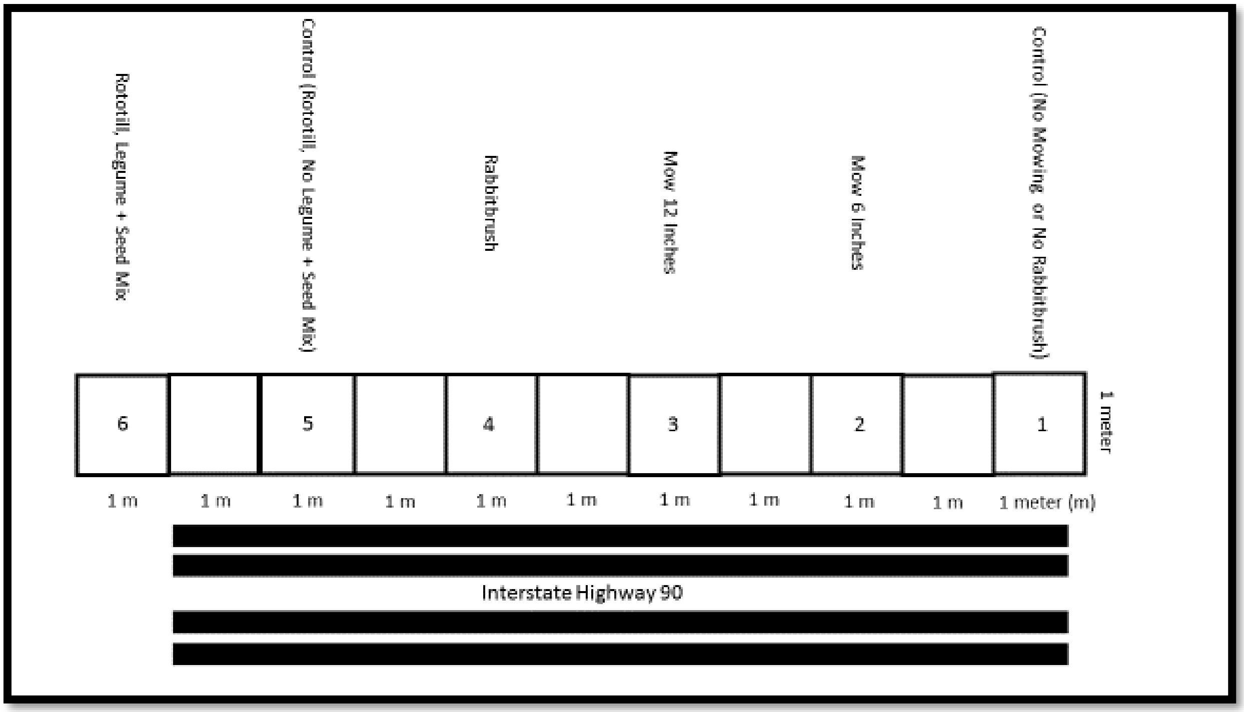


Figure 9. Typical experimental plot design and layout, with each set of 6 treatments (from left to right [west to east]: legume (L), legume control (LC), rabbitbrush (R), 12 in. mow (12), 6 in. mow (6), control (C) replicated 10 times along each of the 3 transect sites in the I-90 right-of-way between Three Forks (3F) and Bozeman Pass (BP). The 3F and BC transects are north of I-90; the BP transect is south of I-90. Figure is not to scale and only shows a single replicate (of 10) for each of 6 treatments.

4.2.2 Experimental plots for altering the mowing height

To test whether mowing ROW active zones at the height of 30.5 cm (12 in) may increase SOC compared with the standard 15 cm (6 in), frames were constructed at those heights to place over each plot (**Figure 10**). In late June or July, each test plot was "mowed" by placing the appropriate frame over the plot and using a weed trimmer to cut all vegetation within the test plot at that height. Any vegetation that emerged above the frame was cut off using an electric rechargeable weed trimmer.

(a) (b)

Figure 10. Frames designed to "mow" ROW vegetation in experimental plots so it did not exceed either (a-upper photo) 15 cm (6 in) or (b-lower photo) 30.5 cm (12 in) height.

4.2.3 Experimental plots for establishing woody shrubs in existing grasslands

Rubber rabbitbrush, *Ericameria nauseosa,* tublings were planted into existing perennial grass-dominated plots to test whether woody shrubs can increase aboveground and belowground carbon stores compared with existing grass-dominated roadsides. These are a potential management action that can be taken for perennial grass-dominated roadsides outside the active zone. Five rubber rabbitbrush tublings were planted in a figure X*:* one in the center and the other four near each corner of the 1 m^2 experimental plots (**Figure 11**). The control for this treatment was to plant nothing.

Figure 11. Five rubber rabbitbrush seedlings planted in an X-formation in existing undisturbed roadside vegetation. A total of 150 seedlings were transplanted across all three sites in 2016. The 1 m^2 experimental plot is marked by the orange-topped stake in the photo.

4.2.4 Experimental plots for adding legumes to perennial grass seed mix for revegetation purposes

To simulate a post-construction revegetation site, we removed the existing sod (**Figure 12**) and then dug up or rototilled the soil (depending on soil texture) to a depth of 15–20 cm (6-8 in). Soil clods were broken up, large rocks were removed, and the plot was raked smooth (**Figure 13**).

Figure 12. Removal of the sod layer of perennial rhizomatous grass, smooth brome (*Bromus inermis)* 1 m^2 experimental plot that is part of preparation to simulate post-construction revegetation treatment. This test plot is located at the Bear Canyon test site.

Figure 13. Preparation of 1 m^2 experimental plot, simulating post-construction revegetation. This plot was hand dug, and the soil was mixed to a depth of 15–20 cm (6-8 in) and smoothed level. A perennial seed mix was broadcast over the soil and gently tamped by hand to give seeds good soil contact. This test plot was located at the Bozeman Pass test site.

All simulated revegetation treatments were seeded at the time of establishment with a standard MDT seed mix of perennial grasses at a standard rate of application (**Table 2**). The bulk application rate was 0.45 kg or 1 lb of seed mix per 111.5 m^2 (1200 ft^2). This is the equivalent of 36.3 lb of seed mix per acre which equals the 4.03 g of seed mix broadcast over each 1 m^2 experimental plot that was established as either a legume control (LC) treatment plot or a legume (L) treatment plot by adding the legume seedlings after the seed mix was broadcast.

Table 2. Perennial grass seed mix used for simulated post-construction revegetation treatment.

Common Name	Scientific Name (Cultivar)	Seeds/lb	PLS	Seeding Rate (PLS lbs per acre)	Seeds/ft^2	Percent of Seed Mix	Rate kg/ha	Rate: g/m^2
Sheep Fescue	Festuca ovina	680,000	675.648	2.5	39	29%	2.8	0.28
Thickspike wheatgrass	Elymus Lanceolatus	154,000	152,306	2.5	9	29%	2.8	0.28
Canada wildrye	Elymus canadensis	115,000	108,008	2.5	6	29%	2.8	0.28
Canada Bluegrass	Poa compressa	2.500,000	2,441,000	1.25	70	14%	1.4	0.14
		TOTAL		8.75	124	100%		0.98

Plot preparation for the legume (L) treatment was the same as for the legume control (LC) plots: sod removal, soil turnover and mixing, raking the plot smooth, and broadcasting the MDT seed mix (Table 2). The difference was that young seedlings of American vetch were secured from a local conservation nursery and planted at a rate of five seedlings/m^2. The five American vetch seedlings were planted in a figure X*:* one in the center and the other four near each corner of the plot (**Figure 14**).

Figure 14. Five American vetch, *Vicia americana*, seedlings planted and watered in a 1 m^2 experimental plot to test whether legumes added to perennial grass seed mix increases soil organic carbon.

As the first growing season ended, a field review determined that the American vetch seedlings had died at all three transects (30 plots total), so a new legume was selected for the project. Small burnet, *Sanguisorba minor* Scop., was selected because it does well in roadside plantings in Montana (pers. comm., Phil Johnson, Reclamation Specialist, MDT). Its recommended seeding rate by the USDA-NRCS is 20 PLS (pure live seed) per ft^2 (30.5 cm^2) (USDA-NRCS 2012). The seeds were broadcast on each of the 30 experimental plots in early November 2016 before the first snowfall.

CHAPTER 5.0 MEASUREMENTS AND INSTRUMENTATION

5.1 Vegetation Characterization Methods

To describe the type of vegetation that exists at each transect for each treatment, we measured and summarized the vegetation of each 1 m^2 experimental plot in both 2016 and 2018. A measurement of vegetation was taken by visually estimating the canopy cover of the following classes: bare soil, litter, rock/gravel, grass, forb, and woody vegetation (shrubs and trees). Vegetative canopy cover is defined as the vertical projection of the crown or shoot area of a species projected on the ground as a percent of the reference area (Mueller-Dombois and Ellenberg 1984).

For the experimental plots that simulate revegetation after construction disturbance, the canopy cover was not measured and recorded until near the end of the project in Year 3 (2018). That gave the seed mix (LC treatment) and the seed mix with legumes (L treatment) 2+ years to establish and grow. Canopy cover for the other four treatments—undisturbed existing perennial grass (C treatment), existing perennial grass planted with rubber rabbitbrush seedlings (R treatment), 6 in. (15 cm) mow height (6 treatment), 12 in. (30.5 cm) mow height (12 treatment)—were measured at the end of the growing season in Year 1 (2016) and again near the end of the project in Year 3 to detect any significant changes (June 2018).

5.2 Carbon Characterization Methods

For carbon stocks, aboveground and belowground measurements were taken after the first (2016) and third (2018) growing seasons after test plot construction at each of the three sites. Measurements of CO_2 flux from the soil were collected in 2016 and 2017 from the Bear Canyon site, in 2017 and 2018 from the Bozeman Pass site, and in 2018 from the Three Forks site.

5.2.1 Aboveground carbon measurements

All ten 1 m^2 test plots were subsampled at each of the three transects for the following treatments: control, 6 in. mow, 12 in. mow, and legume control. One of ten possible 20 cm by 50 cm quadrats (1000 cm^2) within each 1 m^2 experimental plot was selected randomly (**Figure 15**).

Figure 15. A sample of vegetation and litter was collected from a 20 cm × 50 cm quadrat (bottom right) placed randomly within the 1 m^2 plot for lab tests to determine the amount of aboveground carbon of plots. A 10 cm ring of 20 cm diameter round pipe was installed permanently in each 1 $\mathbf{m^2}$ plot to serve as a "collar" for soil respirometry measurements (bottom center).

To estimate the aboveground carbon in the vegetation and litter for each treatment, all grasses and forbs were clipped at ground level. In addition, loose organic litter was collected from the randomly placed subsample quadrats (Figure 15). The material was collected in bags and transferred to a laboratory at the Montana State University, Land Resource and

Environmental Science Department for drying and weighing; carbon was estimated as half of biomass.

Four of the six treatments had harvestable biomass in 2016: control (C), 6 in. (15 cm) mow (6), 12 in. (30.5 cm) mow (12), and rubber rabbitbrush (R). All ten test plots for each treatment and at each of the three transects were subsampled for aboveground biomass.

In 2018, the same treatments were repeated for subsampling for aboveground carbon: control (C), 15 cm (6 in) mow (6), 30.5 cm (12 in) mow (12), and rubber rabbitbrush (R). Due to the high mortality of rabbitbrush plantings, only one transect (Bozeman Pass) had any surviving rubber rabbitbrush plants, so only the test plots with rabbitbrush were subsampled for aboveground carbon in 2018. Also, in 2018, the legume control (LC) test plots were sampled for aboveground carbon at all three transects. Again, due to legume seedling mortality, only the test plots from two transects with surviving legume seedlings were subsampled for aboveground carbon (Bear Canyon and Bozeman Pass).

Aboveground carbon in rubber rabbitbrush stems was measured using an allometric table predicting shrub biomass (Ross and Walstad 1986). Carbon is approximately 50% of a plant's dry biomass. The allometric equation is based on measurements of the height, width, and breadth of each rabbitbrush shrub to calculate its canopy volume (Ross and Walstad 1986).

5.2.2 Soil carbon measurements

To determine changes in SOC for the three types of management techniques, we quantified soil carbon residence times (in years) as the quotient of volumetric carbon (grams SOC per square meter [$g\ C\ m^{-2}$]) to a depth appropriate to the root zone of perennial grasses (<25 cm) and fluxes of SOC from soil measured as soil respiration rates (grams [g] of CO_2-C per square meter [m] per year [y] [$g\ C\ m^{-2}\ y^{-1}$]). For example, 2500 $g\ C\ m^{-2}$ / 1000 $g\ C\ m^{-2}\ y^{-1}$ would yield an approximate soil carbon residence time of 2.5 years. In lay terms, the shorter the residence time, the less likely the area is sequestering carbon in a way that will contribute to long-term (10–100 year) reductions in atmospheric CO_2 levels. Stated another way, just because plants are growing well and photosynthesizing in an optimum way does not necessarily ensure that soils are sequestering carbon, since root exudates can easily be (and most commonly are) re-respired as a flux of CO_2 to the atmosphere. Indexing soil carbon residence times in this way can help quantify which management practices yield the greatest potential carbon sequestration rates.

5.2.2.1 Measuring organic carbon from soil cores

In 2016, four systematically located soil samples were collected from each of the sixty 1 m^2 test plots (6 treatments × 10 1 m^2 plots/treatment) per each of three sites (total: 4×60×3=720 samples) and analyzed for SOM by loss-on-ignition in a programmable muffle furnace (450°C for 6 hours: LOI_{450}; Chatterjee et al. 2009). All soil samples were sieved to remove any gravels >2 mm and to homogenize samples prior to analysis. Soil organic carbon was estimated as half of SOM (e.g., Hartshorn et al. 2017). In 2018, because four treatments across the three sites were unsuccessful (3F: legume [L], rabbitbrush shrub [R]; BC: R; BP: L), we did not resample these treatments, reducing the total number of samples to 560 (14 instead of 18 treatments [across all 3 sites] × 4 samples/1 m^2 plot × 10 plots/treatment); all 560 samples were analyzed for SOM, but with a slightly modified procedure more appropriate for loess-influenced soils (LOI_{360}; 360°C for 2 hours; Konen et al. 2002 in Chatterjee et al. 2009). Our work (not shown) with a calibration set of soil samples showed that our abbreviated (2 hr) LOI_{360} method accounted for >99% of the variance in the 6 hr LOI_{450} procedure.

5.2.2.2 Measuring carbon dioxide flux of soils

Eddy covariance is the micrometeorological measurement of the exchange of CO_2 and other gases between the atmosphere and the terrestrial system—plants and soil (Goulden et al. 1996). While our budget and timeframe precluded the installation of eddy covariance towers at each of the three test sites, we were able to use a LI-COR® LI-8100A, an infrared gas analyzer with an automated chamber designed to measure soil respiration (**Figure 16** and **Figure 18**a,b). The operating range of this infrared gas analyzer is between -25°C and 45°C, and it has a sensitivity to CO_2 measurements between 0 and 20,000 parts per million (ppm). For context, December 2018 atmospheric CO_2 levels were ~410 ppm (www.co2.earth).

Soil respiration is the combination of root (autotrophic) and microbial (heterotrophic) respiration. As such, soil respiration rates are sensitive to root activity as well as the levels of biological decomposer activity in the soil, which, in turn, is strongly influenced by both soil moisture and soil temperature, but also such factors as substrate (SOM) quality, clay types, and microbial community composition (e.g., Bao et al. 2016, Suseela et al. 2012). In general, soil respiration has been modeled as a parabolic function of soil moisture—it is typically lowest when soils are too dry or too wet and highest when soils are at intermediate moisture (e.g., Frank et al. 2012, Wang et al. 2016). Soil respiration has also been modeled as an exponential function of soil temperature to some biological maximum temperature (e.g., Davidson and Janssens 2006).

Figure 16. LI-COR® Biosciences LI-8100A gas analyzer used to measure carbon loss from soils on individual experimental plots.

(a) (b)

Figure 17. (a) LI-COR® Biosciences LI-8100A gas analyzer's hood placed over an 8 in. diameter PVC pipe that is permanently placed in an experimental plot; (b) LI-COR® Biosciences LI-8100A gas analyzer's hood placed over an experimental plot's vegetation and connected to a laptop computer as data are collected to quantify C losses from soils.

We obtained one soil respiration measurement from each of the treatment plots across the three sites at least once. For each measurement, the chamber lowered over the 20 cm diameter (8 in. diameter) PVC ring preinstalled in each plot for approximately 1 minute (Figure 16 and Figure 17); every second, the "headspace" CO_2 levels were measured with sub-part-per-million (ppm) resolution by the LI-COR 8100A instrument. A flux was calculated as the best-fit line (slope) of the increase in CO_2 concentration over time with units of micromoles CO_2 per square meter per second. These mole units can be converted to g CO_2-C m^{-2} s^{-1} using the molar mass of carbon (12 g per mole) and CO_2 (44 g per mole [each atom of oxygen contributes 16 g per mole]). These mass-based units were then converted into estimated daily values of g CO_2-C m^{-2} d^{-1} before making seasonal extrapolations to an annual basis (g C m^{-2} y^{-1}). Two measurements were typically obtained immediately prior to and immediately following the addition of a set volume of water (500 ml, or the depth-equivalent of 16 mm [2/3 inch] when averaged across the 31,400 mm^2 cross-sectional area of the rings), in order to index the effect of added water (simulated high-intensity rainstorm) on soil respiration rates. The infrared gas analyzer was calibrated with both CO_2-free and 10,000 ppm CO_2 standard calibration gases.

After measuring soil respiration rates in the field, quality-control procedures were followed to assess data quality. For example, coefficients of variation (CV = standard deviation divided by arithmetic mean) were calculated for every "pre-watering" and "post-watering" pair of soil respiration measurements. In general, CVs between pairs of measurements were <25%. With Three Forks measurements in June 2018, for example, 81 pairs of soil respiration measurements were obtained, and 26 (32%) of those pairs of measurements exceeded 25%. Not unexpectedly, of those 26 high-variance pairs of measurements, 23 were obtained from post-watering pairs, as the rapid (and potentially uneven) wetting of soils can lead to greater variances in soil respiration rates.

To aid in quality control, each set of 4 measurements (2 pre- and 2 post-) were separated by a “clear” measurement, where the respirometer was removed from a soil ring. As a result, most fluxes measured during these clear measurements between rings were either 0 or slightly negative.

A quick check was also made of the ratio of post-watering to pre-watering fluxes. Our expectation was that within-growing-season measurements should result in a pronounced increase from before watering to after watering, as these soils and their associated plant communities are often water-limited. Again for Three Forks measurements from June 2018, post-to-pre ratios of soil respiration fluxes ranged from 0.4 to 6.2, averaging 2.1 (across all four treatments: controls [C], 6 in. mow [6], 12 in. mow [12], and legume control [LC]). In other words, post-watering soil respiration rates were typically about double pre-watering soil respiration rates. Across the four treatments, C and 6 and 12 treatments showed the greatest differences between pre- and post-watering fluxes (all 2.5–2.7), whereas the LC treatments showed a sharply lower ratio of 0.7±0.3, meaning that for this most-disturbed treatment, pre-watering soil respiration rates were generally greater than post-watering soil respiration rates (post/pre ratio <1).

CHAPTER 6.0 RESULTS

6.1 Characterization of Vegetative Cover

6.1.1 Vegetative canopy cover

The experimental plots at the Three Forks site, located just west of the I-90 Three Forks exit, are dominated by crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.), an exotic perennial bunchgrass commonly seeded in the western United States. At the Bear Canyon (BC) and Bozeman Pass (BP) transects, the dominant plant species is smooth brome (*Bromus inermis* Leyss.), an exotic perennial cool season grass that spreads by rhizomes. The most dominant grass species for each of the treatments exceeds a mean canopy cover of over 50% for 11 of the 12 treatments. Only the rubber rabbitbrush plots at Bozeman Pass had a perennial grass canopy cover that averaged less than half of the plots, smooth brome with 42% mean canopy cover (Table 3). This growth demonstrates how dense and established the perennial grasses are at each of the roadside areas that were selected for the experiment. The only difference is that the Three Forks transect was dominated by bunch grass, although crested wheatgrass does have rhizomes, and the other two sites were dominated by sod-forming grasses.

Table 3. Summary of the mean canopy cover of the two most dominant species and total grass cover for each experimental treatment and its control at the three test sites along I-90 in southwest Montana.

Transect n=10	Sample Size (n)	Treatment	Dominant Species – Mean Canopy Cover (%)	2nd Most Dominant Species – Mean Canopy Cover (%)	Total Mean Grass Canopy Cover (%)	Mean Rock & Gravel Canopy Cover (%)	Mean Litter Canopy Cover (%)	Mean Moss Canopy Cover (%)	Mean Bare Soil Canopy Cover (%)
Logan	10	Control	Agropyron cristatum – 65	Stipa viridula – 3	68	0	0	11	19
Bear Canyon	10	Control	Bromus inermis – 79	Poa spp. – 19	98	0	0	0	20
Bozeman Pass	10	Control	Bromus inermis – 54	Elymus trachycaulus – 5	59	18	0	6	13

Transect n=10	Sample Size (n)	Treatment	Dominant Species – Mean Canopy Cover (%)	2nd Most Dominant Species – Mean Canopy Cover (%)	Total Mean Grass Canopy Cover (%)	Mean Rock & Gravel Canopy Cover (%)	Mean Litter Canopy Cover (%)	Mean Moss Canopy Cover (%)	Mean Bare Soil Canopy Cover (%)
Logan	10	Mow 6 inches	Agropyron cristatum – 65	Bouteloua gracilis – 1	49	0	0	22	29
Bear Canyon	10	Mow 6 inches	Bromus inermis – 81	Poa spp. - 17	98	0	0	0	0
Bozeman Pass	10	Mow 6 inches	Bromus inermis – 53	Poa spp. – 3	56	19	0	10	9
Logan	10	Mow 12 inches	Agropyron cristatum – 60	Bouteloua gracilis – 1	61	14	0	15	12
Bear Canyon	10	Mow 12 inches	Bromus inermis – 87	Poa spp. – 11	98	0	0	0	0
Bozeman Pass	10	Mow 12 inches	Bromus inermis – 66	All other spp. <0.5	66	15	0	3	9
Logan[1]	10	Post Construction Broadcast Seed	Festica ovina – 22	Agropyron cristatum – 3	26	5	4	0	53
Bear Canyon	10	Post Construction Broadcast Seed	Poa compressa – 8	Festuca ovina – 4	12	0	0	0	58
Bozeman Pass	10	Post Construction Broadcast Seed	Bromus inermis – 10	Festuca ovina – 4	14	19	0	0	63
Bear Canyon	5	Post Construction Broadcast Seed with Legumes	Sanguisorba minor – 6	Poa compressa – 6	15	0	0	0	61
Bozeman Pass	4	Post Construction Broadcast Seed with Legumes	Bromus inermis – 14	Sanguisorba minor – 3	17	15	0	0	59
Bozeman Pass	9	Plant Rabbitbrush	Bromus inermis – 26	Ericameria nauseosus – 3	26	0	42	0	27

[1] Annual weeds were 25% of canopy cover.

The Three Forks test site was dominated by the non-native crested wheatgrass, *Agropyron cristatum*. This site had an average canopy cover of 60–65% (Table 3). All other species of grass or forbs at the Three Forks test site under any treatment had a mean canopy cover of 3% or less.

The Bear Canyon site was dominated by a sod-forming, non-native perennial grass, smooth brome, *Bromus inermis*. The site had a mean canopy cover of 79–87%. Bluegrass was the other highly successful perennial grass at this site, with a mean canopy cover of between 11% and 19% (Table 3). Combined, the two species made for a dense cover of perennial grass for each of the treatments.

Undisturbed Bozeman Pass test plots had a mean canopy cover dominated by smooth brome, averaging between 53% and 66% (Table 3) and were not as densely covered with grasses as the other two test sites.

There were very few forbs or shrubs in the experimental plots for any of the experimental treatments. The greatest amount of bare soil for the undisturbed plots was the 6 in. mowed plots at the Three Forks transect (29%) and the rabbitbrush-treated plots at Bozeman Pass (27%) (Table 3).

Overall, Bear Canyon's undisturbed test plots (control, 6 in. mow, 12 in. mow, rabbitbrush) had the densest vegetative cover, with an average of 98% mean canopy cover for grasses; it was dominated by rhizomatous grass species. Three Forks and Bozeman Pass transects had less mean grass canopy cover than Bear Canyon, varying between 59% and 68% mean grass canopy cover (Table 3). A key difference was that Three Forks was dominated by a bunchgrass, crested wheatgrass and Bozeman Pass by a sod-forming grass species, smooth brome.

All fifty rubber rabbitbrush seedlings that were planted in each of the test plots at the Three Forks and Bear Canyon test sites died by 2018. However, they successfully established and grew at Bozeman Pass in nine of the ten plots. Although the most prolific species in the rabbitbrush test plots was smooth brome, with a mean canopy cover of 26%, rubber rabbitbrush was the second most-dominant species with a mean canopy cover of 3% (Table 3). Thus, it has become well established at Bozeman Pass and is projected to grow and thrive.

The disturbed sites, those that were hand dug with shovels or rototilled to simulate post-construction roadside conditions, were bare in 2016 after they were created. The perennial grass seed mix was spread on the control plots and those test plots receiving legume seeds, small burnet, *Sanguisorba minor*. By 2018, no legumes survived at the Three Forks test site. At Bear Canyon, five test plots had surviving small burnet stems, and at Bozeman Pass, there were four test plots with legumes.

Of the species that were broadcast seeded onto the post-construction simulated test plots, two were common, sheep fescue, *Festuca ovina*, and Canada bluegrass, *Poa compressa.* The two species were in both the legume control and legume test plots at the three test sites. Two of the species in the seed mix failed to establish: thickspike wheatgrass, *Elymus lanceolatus*, and Canada wild rye, *Elymus canadensis*.

At the two test sites where it established, small burnet was the dominant species in the legume test plots; Bear Canyon had a mean canopy cover of 6%, and small burnet was the second most dominant species at Bozeman Pass with a mean canopy cover of 3% (Table 3).

6.1.2 Seedling survival

Two species were planted as seedlings: American vetch and rubber rabbitbrush. All of the American vetch seedlings were severely desiccated and eventually succumbed to dry weather by the end of the growing season in 2016. This loss was despite the fact that the seedlings were hand watered by project personnel on a weekly to bi-weekly basis in July and August if no rain fell. In fall 2016, American vetch, *Vicia americana*, was broadcast seeded on each of the 10 legume test plots at all 3 test sites to try and salvage the legume experiment.

At the end of the growing season in 2016, the seedlings of rubber rabbitbrush, *Ericameria nauseosa*, did much better than the legumes, as this species is better adapted to drier environmental conditions. Overall, at the most mesic site, Bozeman Pass, there was an 88% survival rate by rubber rabbitbrush as measured at the end of the growing season in 2016 (Table 4). The Bear Canyon site had intermittent rain and the rubber rabbitbrush seedlings were watered, but the plant had to compete with the well-established stand of smooth brome at this transect, creating a sod-forming thatch that made it difficult for the shrub seedlings to compete with the grass. At the ten experimental plots at Bear Canyon, seedling survival averaged only 30%. At the driest site, Three Forks, there was no survival of any rubber rabbitbrush seedlings at the end of the 2016 growing season.

Table 4. Seedling survival of rubber rabbitbrush at the project sites in 2016.

Study Site - Transect	Treatment	Rabbitbrush Seedling Survival Rate	Date Evaluated
Three Forks	Rabbitbrush	0	10/26/2016
Bear Canyon	Rabbitbrush	15	10/27/2016
Bozeman Pass	Rabbitbrush	44	11/4/2016

By 2018, all the legumes and rubber rabbitbrush had died at the Three Forks test site (Table 5). No rubber rabbitbrush survived at the Bear Canyon test site either. Small burnet established and grew in five plots at Bear Canyon and in four plots at Bozeman Pass (Table 5). Rubber rabbitbrush only thrives at one test site: Bozeman Pass. One possible explanation is that the Bozeman Pass test site has porous gravelly soil, which favors rabbitbrush. There is also much less competition with grasses. The mean canopy cover of grasses was lower at this test site than at the Bear Canyon or Three Forks test site.

Table 5. Seedling survival of rubber rabbitbrush and small burnet at the three test sites in 2018.

PLANTING SURVIVAL	TRANSECT																				
	Logan[1]	Bear Canyon										Bozeman Pass									
SPECIES	Number of Stems Surviving in Each Replication																				
Replication	All	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Rubber rabbitbrush, Ericameria nauseosa	0	0	0	0	0	0	0	0	0	0	0	**2**	0	**3**	**2**	**3**	**4**	**3**	**3**	**4**	**5**
Small flowered burnet, Sanguisorba minor	0	**5**	0	**4**	0	**1**	0	**1**	0	0	**1**	**2**	**2**	0	0	**1**	0	0	0	**5**	0

[1] The Three Forks/3F transect had no survival of either species in any of the test plots.

6.2 Aboveground Carbon Measurements

Dry biomass is typically ~50% carbon. Table 6 presents aboveground biomass averages for 2016 and standard deviations, as well as measures of within-treatment and within-site variance, via the coefficient of variation (CV). Table 7 presents the corresponding 2018 results.

Table 6. Average aboveground biomass values (n=5; grams per 1000 cm^2) by site (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and by treatment (C=control, 6=6 in. mow, 12=12 in. mow, and R=rabbitbrush). Standard deviations (SD) and coefficients of variation (CV) are also provided. There was insufficient biomass in the remaining two treatments (legume control [LC], legume [L]) for harvest in 2016.

Site	Treatment	Avg	SD	CV
3F	C	18	10	0.57
3F	6	20	11	0.57
3F	12	40	19	0.47
3F	R	20	5	0.36
BC	C	73	14	0.19
BC	6	77	11	0.15
BC	12	80	10	0.12
BC	R	63	13	0.20
BP	C	71	74	1.04
BP	6	81	60	0.75
BP	12	65	68	1.03
BP	R	28	32	1.16

Table 7. Average aboveground biomass values (*n*=10; grams per 1000 cm^2) by site (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and by treatment (C=control, 6=6 in. mow, 12=12 in. mow, L=legume, LC=legume "control," and R=rabbitbrush). Standard deviations (SD) and coefficients of variation (CV) are also provided. Biomass was not harvested from four treatments because of poor establishment (3F L, 3F R, BC R, BP L) in 2016.

Site	Treatment	Avg	SD	CV
3F	C	47	14	0.30
3F	6	51	16	0.31
3F	12	65	25	0.39
3F	R	11	10	0.92
BC	C	103	21	0.20
BC	6	87	30	0.35
BC	12	90	26	0.29
BC	L	16	12	0.70
BC	LC	18	10	0.58
BP	C	72	64	0.89
BP	6	59	64	1.08
BP	12	63	99	1.57
BP	LC	6	6	1.06
BP	R	52	75	1.44

Averaging across all four treatments in 2016, Bear Canyon and Bozeman Pass had higher biomass (73 and 61 g 1000 cm^{-2}, respectively) than the Three Forks site (24 g 1000 cm^{-2}). In 2018, across four to five treatments for which we collected biomass, the average biomass at BC and BP (63 and 50 g 1000 cm^{-2}, respectively) was higher than at the 3F site (44 g 1000 cm^{-2}). These trends were consistent with our observations and expectations that higher effective precipitation would lead to greater aboveground productivity.

Within the Three Forks site in 2016, three of the four treatments had comparable biomass. The anomalous treatment was the 12 in. mow plots, which contained double the biomass as the other three treatments, including the 6 in. mow plots. In 2018, the LC plots showed anomalously low biomass relative to the other three treatments, though this treatment also showed the greatest variability (0.92).

Within both the Bear Canyon and Bozeman Pass sites in 2018, anomalously low biomass was associated with the L or LC treatments (compared with the remaining three or four treatments), though the magnitude of the anomaly was greater for Bozeman Pass. The Bear Canyon biomass values were notable for their very low CVs, which were all ≤0.2 in 2016 and ≤0.7 in 2018.

Within the Bozeman Pass site in 2016, the rabbitbrush plots had biomass levels less than half those of the other treatments (28±32 g 1000 cm^{-2}). The CVs were very high at Bozeman Pass. For example, dry biomass for the specific “control” plot (#1) at Bozeman Pass, illustrated in Figure 18, was 190 g, or the equivalent of 1900 g m^{-2}. Other “control” plots at this same Bozeman Pass site, however, registered between 4 and 74 g per quadrat, or 40–740 g m^{-2}, for an average (±1SD) dry biomass value of 710±740 g m^{-2}

(CV 1.04). The 6 in. and 12 in. mowed plots showed comparable (and comparably variable) biomass: 810±600 g m^{-2} and 650±680 g m^{-2}, respectively. Rabbitbrush plots, by contrast, showed far lower biomass: 280±320 g m^{-2}.

At Bozeman Pass in 2018, the 12 in. mow and rabbitbrush plots showed the greatest variability (CV≥1.44). These results can be traced to great between-plot variability, with mowed plots showing a range of 10–320 g 1000 cm^{-2} and rabbitbrush plots showing a range of 6–247 g 1000 cm^{-2}.

Assuming that biomass is 50% carbon, aboveground carbon values in 2016 ranged from a low of 89 g C m^{-2} for control plots (at both the Three Forks and Bozeman Pass sites) to a high of 401 g C m^{-2} for the 6 in. mow plots (at Bear Canyon; **Figure 18**).

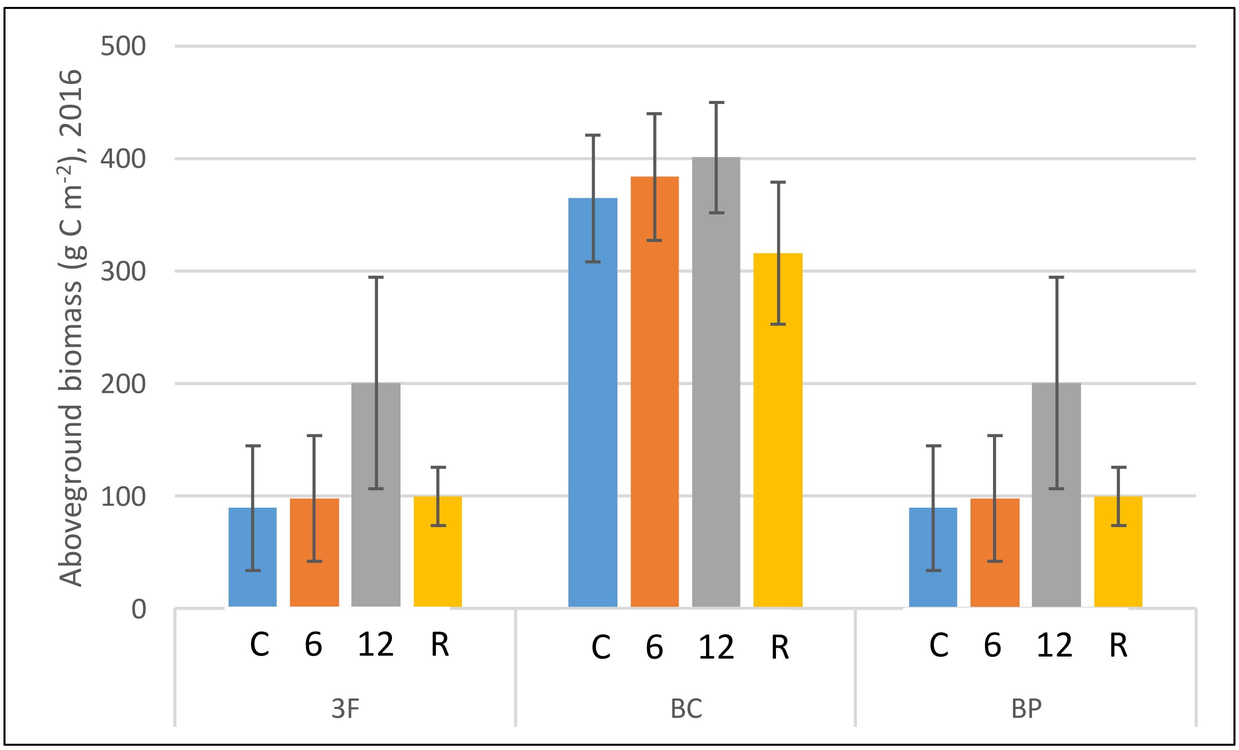


Figure 18. Summary of average (±1 SD; *n*=5) estimated aboveground biomass carbon (g m^{-2}; 2016), by site (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and treatment (C=control, 6=6 in. mow, 12=12 in. mow, and R=rabbitbrush). Estimates assume dry biomass is 50% carbon.

In 2018, as in 2016, we recorded dry biomass 20 × 50 cm (1000 cm^2) subplots for each of the treatments at each of the three sites for which there was sufficient aboveground biomass; subplots were randomly selected without replacement so as to not re-sample subplots previously harvested (in 2016). Biomass was not collected from 4 of the 18 possible combinations of treatments and sites (3F L, BP L, 3F R, BC R). Unlike in 2016, in 2018, samples were destructively harvested from all 10 replicate plots where biomass was sufficient (**Figure 19**).

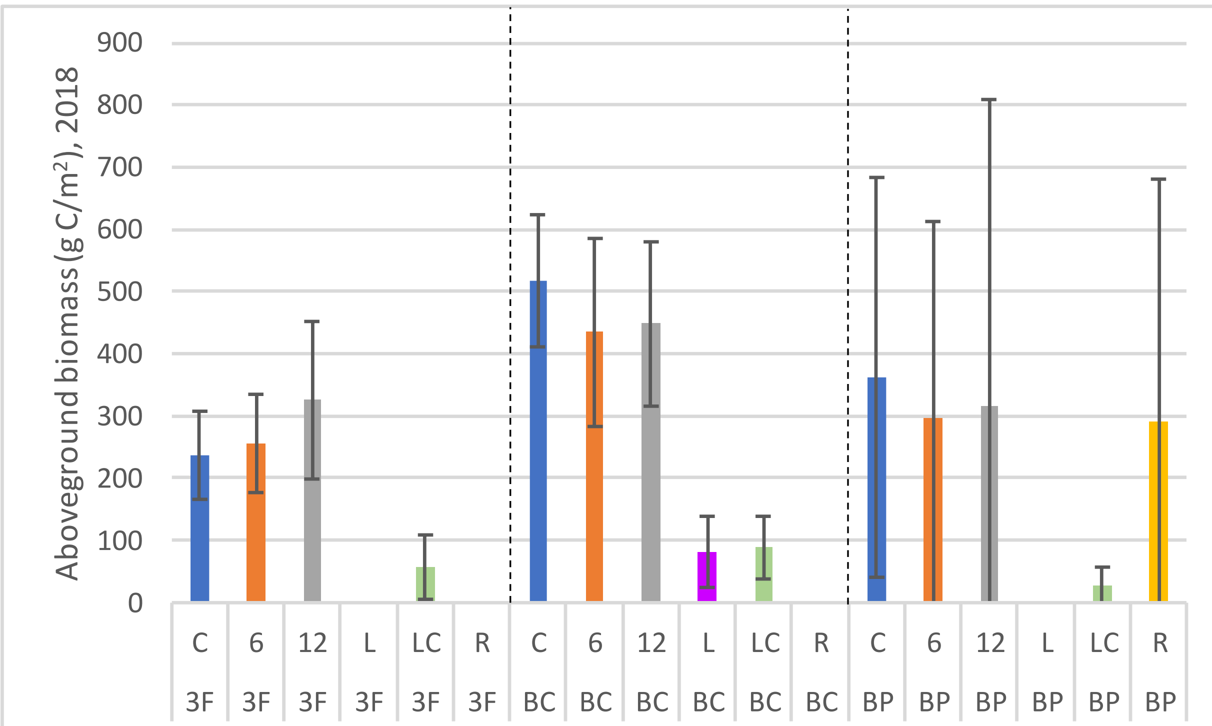


Figure 19. Summary of average (±1 SD; *n*=4–10) estimated aboveground biomass carbon (g m^{-2}; 2018), by site (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and treatment (C=control, 6=6 in. mow, 12=12 in. mow, L=legume, LC=legume "control," and R=rabbitbrush). Estimates assume dry biomass is 50% carbon.

Biomass values per 1-m^2 plot can be obtained from non-R treatments by multiplying subplot values by 10; in R treatments, rabbitbrush biomass was obtained allometrically, either using shrub breadth (Ross and Walstad 1986) or basal diameter (Brown 1976) as independent variables. Biomass results were relatively consistent using the two methods, with an R^2 of 0.55 and slope of 0.97, though biomass predicted using diameter was 25–50% greater than biomass predicted using breadth (**Figure 20**).

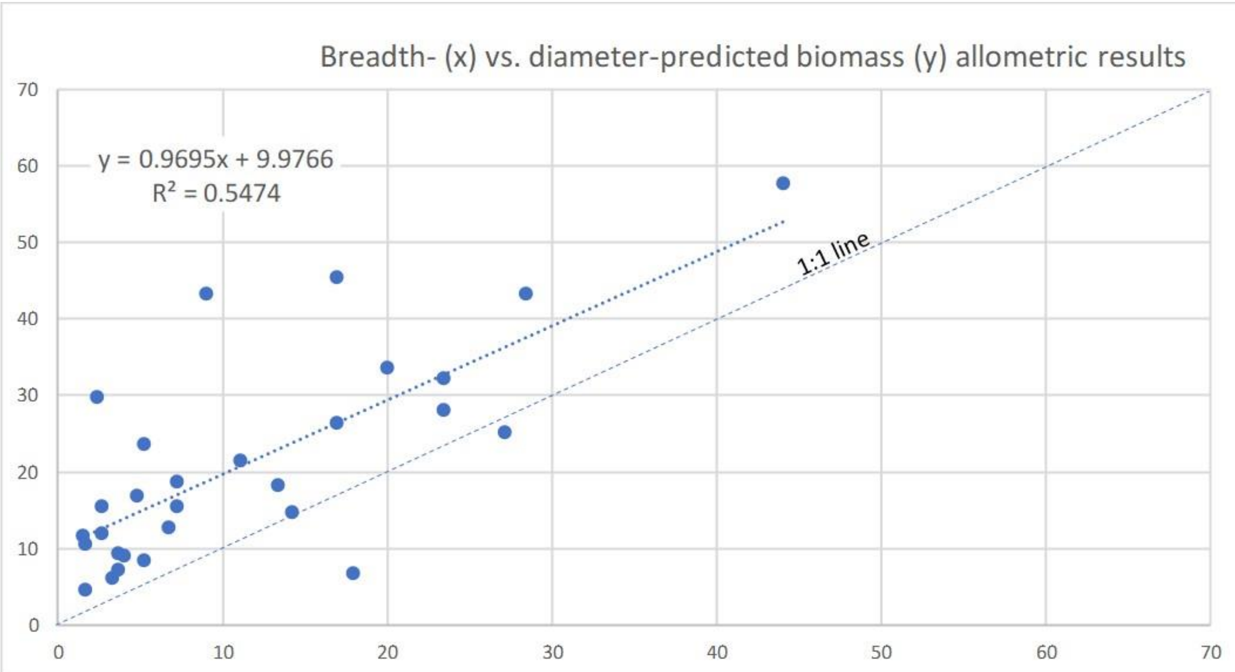


Figure 20. Comparison of predicted biomass using two approaches. X-axis shows biomass predicted with breadth measurements, and Y-axis shows biomass predicted with basal diameter measurements.

6.3 Belowground Soil Carbon Measurements

6.3.1 Soil organic matter levels

Across the 1280 samples collected and analyzed for SOM in 2016 (*n*=720) and 2018 (*n*=560; generally, 4 samples were analyzed for each 1-square-meter plot), the global average was about 5%. Assuming that SOM is ~50% carbon, this yields an estimated global average belowground SOC concentration of 2.5%. This global average, however, obscures considerable between-site variability. In 2016, for example, SOM levels at Bear Canyon, Bozeman Pass, and Three Forks averaged 7.8%, 4.2%, and 2.6%, respectively (**Figure 21**). In 2018, across all sites and all treatments, corresponding SOM levels were slightly lower (**Figure 21**). As with the biomass results, between-treatment differences in SOM were modest and not statistically significant (**Figure 21**), as might be expected at the outset of a long-term research project. Unlike the biomass results, however, soils showed less variability in 2016, with a site's average CV ranging from 0.24 (Bear Canyon) to 0.52 (Bozeman Pass).

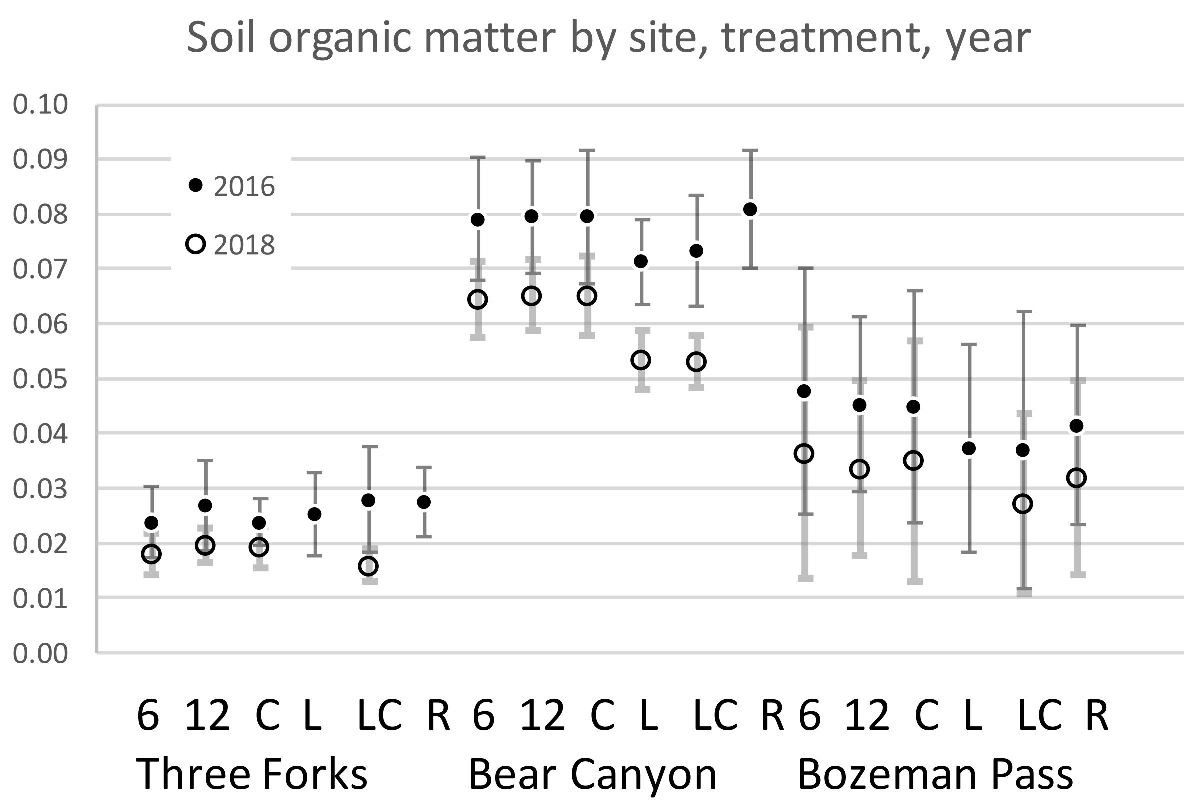


Figure 21. Average SOM (±1 SD; *n*=40) levels across sites (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and treatments (6=6 in. mow, 12=12 in. mow, C=control, L=legume, LC=legume "control," R=rabbitbrush) in 2016 and 2018. Y axis indicates the fraction of soil organic matter (0.1 = 10%). Solid symbols and black error bars correspond to 2016 results, while hollow symbols and gray bars correspond to 2018 results. Data are expressed as fractional mass; to obtain percentages, multiply by 100.

Though the overall declines in average SOM from 2016 to 2018 were unexpected, it is important to recall that soils constantly gain and lose SOC as the balance between photosynthetic gains and respiratory losses shifts. The lower average SOM values in 2018 (relative to 2016) could reflect a balance of greater losses of SOM through respiration than gains through photosynthesis. These lower average values for SOM could have resulted from an overall shift from wetter and cooler conditions to drier and warmer conditions, even though the Bozeman area received record levels of precipitation during the winter of 2017–2018, which led to a relatively wet spring. Though these SOM losses were apparent across the plots that did not receive any treatments (the controls), some of the losses were markedly greater, including at the BC L and LC plots, which dropped from an average of about 7% to 5.5%. On a percentage basis, however, the LC plots at 3F showed the greatest SOM losses (43%), dropping from an average of 2.8 to 1.6%.

The somewhat greater losses associated with these specific treatments are consistent with the loss of carbon that can accompany disturbance, and these were the treatments with the greatest soil disturbance. Another possible explanation for the year-to-year declines could be that samples were collected to slightly different depths (e.g., 7 cm in 2018 vs. 5 cm in 2016), which could have led to the systematic, but artifactual, incorporation of slightly less SOM-rich material into the samples characterized, reducing overall sample SOM levels. This possibility is not well-supported, however, for two reasons: it would have required (i) a remarkably consistent shift in sampling procedures (always shallower in 2016, always deeper in 2018) across the nearly 1300 samples that were collected; and (ii) a remarkably consistent shift from higher SOM at the shallower depths to lower SOM at just slightly greater depths across all sites and treatments.

Taken together then, these project findings imply that treatments intended to build SOM and SOC could be associated, as they appear to be here with these three roadside sites, with decreased SOM levels as the treatments take effect. The extent to which this might have been a transient effect will require further investigation. Taller rabbitbrush seedlings due to growth, for example, could lead to a wetter, cooler microclimate in those plots, which in turn could shift the balance of photosynthetic inputs and respiratory losses to the extent that we can detect increased SOM and SOC. At this time, and not unexpectedly after only little more than 2 years since treatment installations, none of the treatments appear to have resulted in increased SOM and SOC.

6.3.2 Estimated soil organic carbon inventories

We can convert these SOM concentrations to SOC concentrations, and from these values, obtain estimates of SOC inventories, expressed on a unit volume (such as 1 m^3, or unit area [such as 1 m^2] after fixing a depth) basis. Any conversion of mass-based estimates of soil properties to volume-based estimates requires bulk densities. We obtained estimated bulk densities for soils using a Google Map-based interface to Natural Resources Conservation Service SSURGO map unit data (https://casoilresource.lawr.ucdavis.edu/gmap/). For the Three Forks, Bear Canyon, and Bozeman Pass sites, we estimated surface bulk density to be 1.4, 1.2, and 1.5 g cm^{-3} (for the Chinook, Straw, and Billman soil series, respectively). We acknowledge uncertainty with these estimates, since road material is unlikely to match pre-construction soil properties. For a constant density, greater depths translate to greater volumes, and therefore greater mass.

As a worked example, for Bear Canyon Plot #1 (“control”), our four samples averaged (±1 SD, n=4) SOM of 9.1 ± 0.6% in 2016. (This same 1 m^2 plot in 2018, again with four samples, averaged 7.1 ± 0.5%.) With our estimated SOM:SOC ratio of 2, this would yield a SOC concentration of 4.55%, or 0.0455 g of SOC per gram of soil. With our estimated soil bulk density of 1.2 g cm^{-3}, and fixing a soil depth of 5 cm, we can estimate the volumetric SOC as a simple product of these three terms, along with a conversion factor from square centimeters to square meters: 0.0455 g SOC (g soil)$^{-1}$ * 1.2 g soil cm^{-3} * 5 cm * 10^4 cm^2 m^{-2} = 2730 g C m^{-2} (to 5 cm depth).

Expressed to a 10 cm depth, and assuming density and SOC are constant for this second depth interval, would yield an inventory of 5460 g C m^{-2} (to 10 cm depth). Over the upper foot (30 cm), again with assumptions about SOC levels as well as densities, this single plot would contain 16,380 g C m^{-2} (to 30 cm depth). These calculations assume 0% coarse fragments, which is justified (Fay et al. 2018) based on a related study in which samples were sieved (2 mm; data not shown). These types of "inventory" estimates are summarized here for 2016 (Table 8) as well as 2018 (Table 9).

Table 8. Average estimated belowground SOC inventories to 30 cm (*n*=40; grams SOC per 1 m^2 plot) by site (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and by treatment (C=control, 6=6 in. mow, 12=12 in. mow, R=rabbitbrush, LC=control, no legumes in seed mix, L= legumes in seed mix) in 2016.

Treatment	3F	BC	BP
C	5040	14220	10125
6	4998	14220	10800
12	5670	14220	10125
R	5880	14400	9225
LC	5880	13680	8325
L	5250	13680	8325

Table 9. Average estimated belowground SOC inventories to 30 cm (*n*=40; grams SOC per 1 m^2 plot) by site (3F=Three Forks, BC=Bear Canyon, BP=Bozeman Pass) and by treatment (C=control, 6=6 in. mow, 12=12 in. mow, R=rabbitbrush, LC=control, no legumes in seed mix, L= legumes in seed mix) in 2018. Missing values represent unsuccessful treatments.

Treatment	3F	BC	BP
C	3493	11707	6306
6	3239	11617	6565
12	3537	11742	6054
R			5730
LC	2864	9560	4893
L		9625	

For BC, all treatments averaged 14,070 g SOC m^{-2} to 30 cm in 2016, but only 10,850 g m^{-2} to 30 cm in 2018, a 23% reduction. Although these estimated SOC inventories to 30 cm rely on a number of assumptions, the most important may be the assumption that SOC values we recorded only for the surface-most 5 cm of soil in each plot are representative of SOC to 30 cm. Soil organic carbon usually declines exponentially with depth (Jobbagy and Jackson 2000).

6.3.3 Soil respiration rates

We measured soil respiration rates during two intensive field campaigns (July, November) in 2016 at the Bear Canyon site (**Figure 22**). In 2017 and 2018, measurements were obtained from all three sites, excluding the unsuccessful treatments.

As outlined in the Methods section, our typical procedures were to record a pair of measurements before the addition of 500 ml of water to the soil respiration ring and a pair of measurements after the water addition. The water addition was expected to help index the stimulatory effect of a growing season precipitation event. While the general response of soil respiration rates to temperature has been well understood for decades (e.g., Kirschbaum 1995), the response of soil respiration to the dual and interactive environmental conditions of temperature and moisture is far less clear. For example, a Boston-area field study determined that warming only increased heterotrophic soil respiration (that attributable only to microbial populations as roots were excluded) in early spring when soil moistures were between approximately 15% and 26% (Suseela et al. 2012); both drier and wetter conditions yielded lower respiration rates with warming and wetting vs. drying within the optimum moisture range appeared to show a hysteretic response. Li et al. (2017) reported that experimental warming (+3°C) coupled with elevated precipitation (+30%) for Korean pines (*Pinus densiflora*) led to increased soil respiration (+60%) relative to control plots, but the same experimental warming and decreased precipitation (-30%) led to decreased soil respiration (-20%).

Because of the uncertainties in how soil temperatures and moistures interact to influence soil respiration rates, we combined pre-watering rates (across all sites and treatments, these rates were lower) with post-watering rates to have a more generalizable estimate of “typical” soil respiration rates. We acknowledge that the ideal characterization would include continuous and simultaneous measurements of soil temperatures, soil moistures, and soil respiration rates across the three project sites and all replicated treatment plots, but such a set of measurements would be prohibitively expensive, both in equipment and trouble-shooting labor.

To our knowledge, whether these types of patterns identified for northeastern North American forests and Korean pines hold for different vegetation communities or more arid systems, such as those typical of Montana, let alone roadside grassland-dominated communities, has never been investigated.

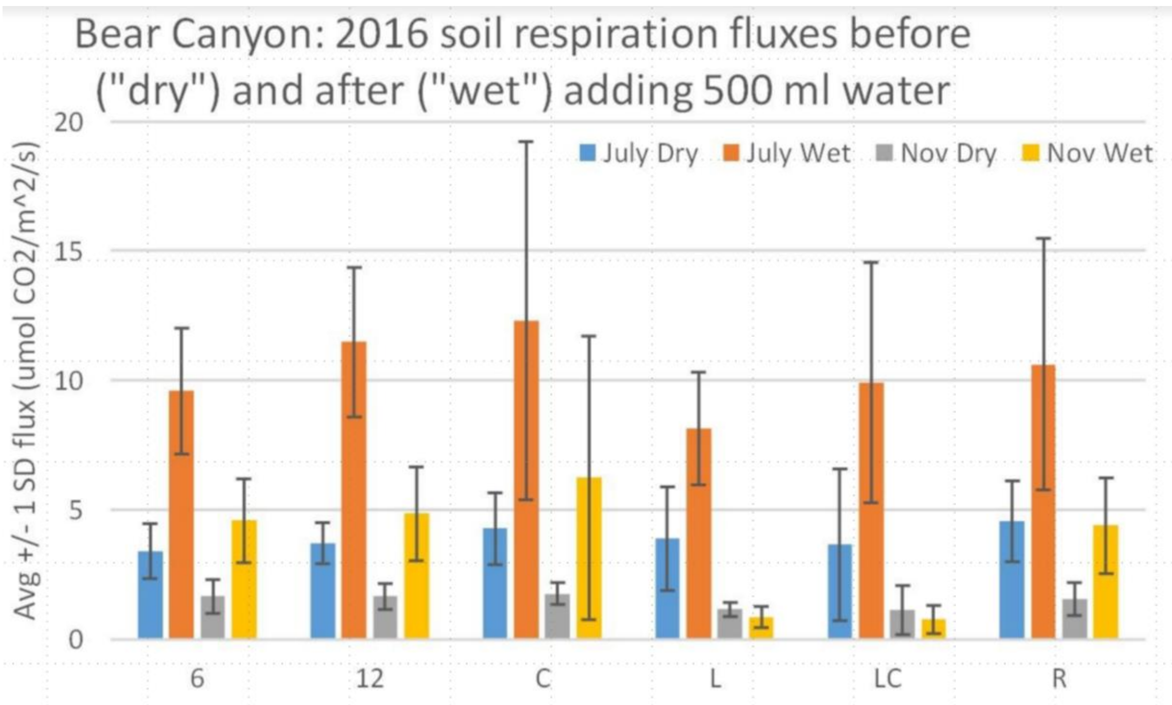


Figure 22. Summary of Year 1 average (±1 SD; *n*=10 duplicate readings) soil respiration rates (µmoles CO_2 m^{-2} s^{-1}; 2016) at BC, by treatment (6=6 in. mow, 12=12 in. mow, C=control, L=cleared+legume, LC=cleared-legume, R=rabbitbrush).

These Year 1 BC soil respiration results yielded four initial insights:

1. The results clearly show a pronounced stimulatory effect of the water additions, though the effect is less dramatic in November when soil temperatures are much cooler.

2. The results also show no clear treatment differences, as might be expected at the outset of a long-term experiment.

3. The results point to clear seasonal differences, both before and after water additions, with much higher flux values in summer than in late fall. In fact, July post-watering values (~9 µmol CO_2 m^{-2} s^{-1}) were about triple the July pre-watering levels and double the November post-watering values.

4. Finally, not all treatments at Bear Canyon yielded increased trends in post-watering soil respiration rates, implying potentially important treatment-by-season interactions. For example, while four treatments showed the expected increases in soil respiration rates following the water addition (6, 12, C, R) in both July and November, both the L and LC treatments showed decreased soil respiration following water additions—but only in November. Importantly, between replicate plot variances were very large, and these differences are not statistically significant.

These Year 1 measurements were followed by additional measurements in Years 2 and 3, some of which are highlighted in **Figure 23** and **Figure 24**.

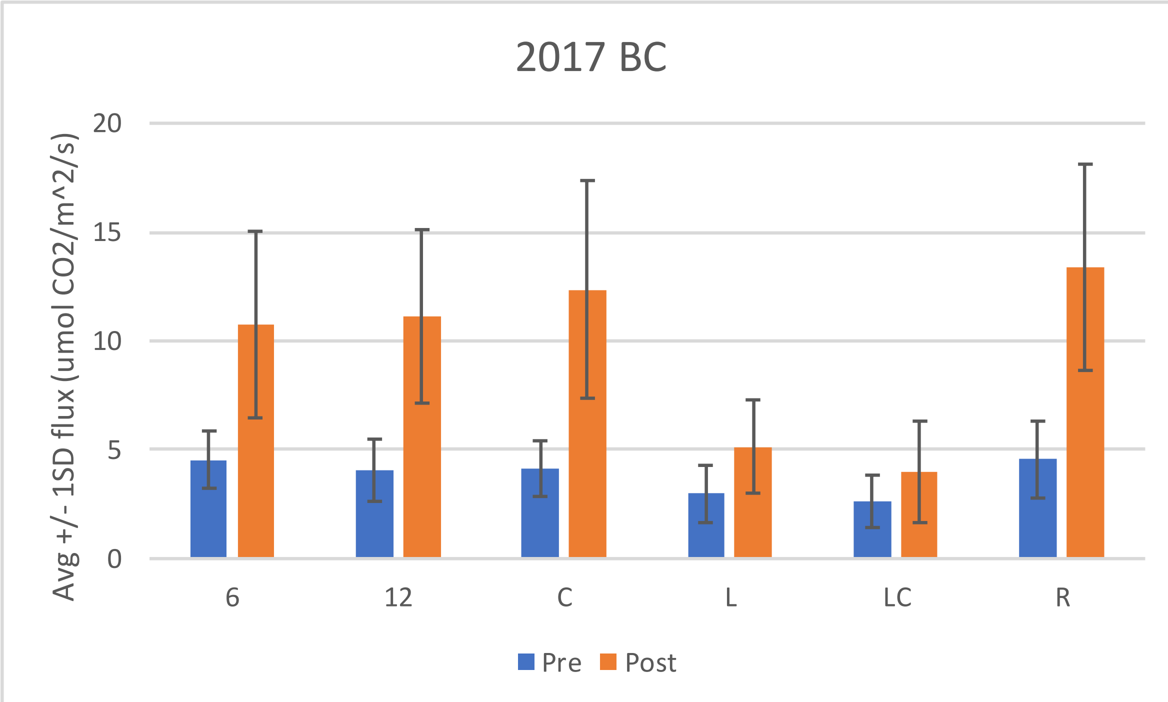


Figure 23. Summary of Year 2 average (±1 SD; *n*=10 duplicate readings) soil respiration rates (µmoles CO_2 m^{-2} s^{-1}; 2016) at BC, by treatment (6=6 in. mow, 12=12 in. mow, C=control, L=cleared+legume, LC=cleared-legume, R=rabbitbrush).

Our soil respiration measurements at BC in 2017 demonstrated support for our initial findings in 2016, that the response to our water addition was sharply muted in the L and LC plots. This may have reflected the direct and indirect reduction of soil carbon inventories following disturbance (Table 8) and/or the residual effects of disturbance on the soil microbial communities at these plots.

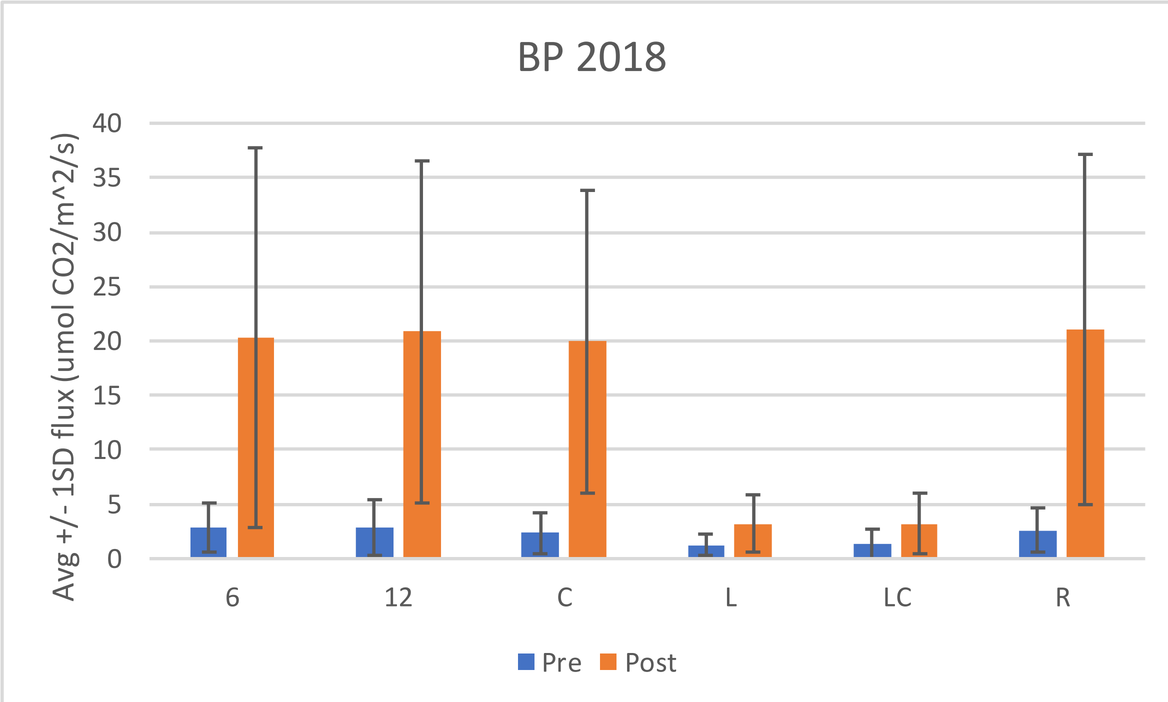


Figure 24. Summary of Year 3 average (±1 SD; *n*=10 duplicate readings) soil respiration rates (µmoles CO_2 m^{-2} s^{-1}; 2016) at BP, by treatment (6=6 in. mow, 12=12 in. mow, C=control, L=cleared+legume, LC=cleared-legume, R=rabbitbrush).

Our soil respiration results from BP were broadly consistent with those from BC, with the exception that the post-watering rates at BP (ignoring the L and LC treatments) were nearly double (~20 µmol CO_2 m^{-2} s^{-1}) the post-watering rates at BC (again ignoring the L and LC treatments; 10.8–13.4 µmol CO_2 m^{-2} s^{-1}). The BP post-watering soil respiration rates were also much more variable (BP non-L treatments, post-watering CV range: 70–86%; BC non-L treatments, post-watering CV range: 36–41%). As at the BC site, our L and LC treatments at BP showed lower soil respiration rates than other treatments, both before and after watering; post-watering CVs were 82% and 88%, respectively. These patterns highlight the heterogeneity of soil respiration rates apparent even across plots with the same treatment. For example, within BP control plots, pre-watering soil respiration rates ranged from 0.4–5.5 µmol CO_2 m^{-2} s^{-1} (CV 82%), and post-watering soil respiration rates ranged from 4.3–40.8 µmol CO_2 m^{-2} s^{-1} (CV 90%). Finally, we monitored soil respiration rates at our lowest-elevation site, Three Forks, in June 2018. These results are summarized in **Figure 25**.

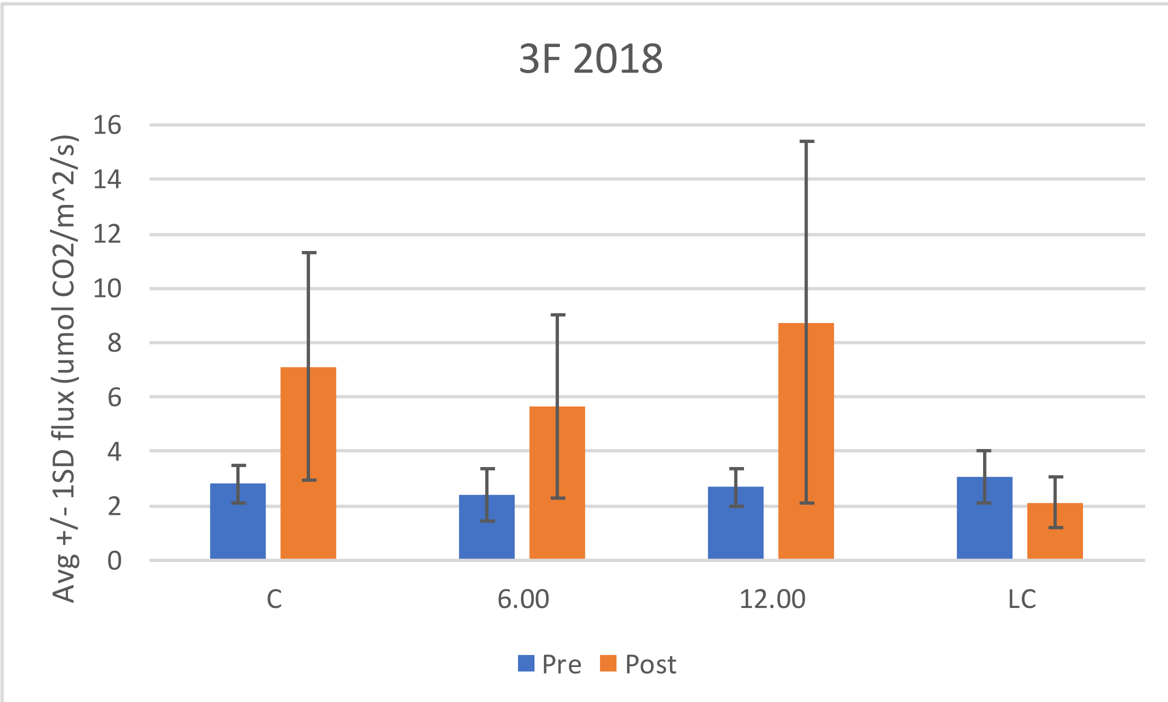


Figure 25. Summary of average soil respiration rates (SD; *n*=10 duplicate readings; umoles CO^2 m^{-2} s^-1) at 3F, by treatment (6=6 in. mow, 12=12 in. mow, C=control, LC=cleared-legume).

At 3F, soil respiration rates were quite low relative to those recorded at BC and BP. For example, pre-watering average soil respiration rates ranged from 2.4 to 3.1 µmol CO_2 m^{-2} s^{-1} across the four treatments where data were collected (we excluded L and R treatment plots), while post-watering average soil respiration rates ranged from 2.1 to 8.7 µmol CO_2 m^{-2} s^{-1}.

Framed more generally, in 2017 and 2018 pre-watering soil respiration rates for non-L treatments averaged 2.2 to 2.6 to 4.3 µmol CO_2 m^{-2} s^{-1} for the BP, 3F, and BC sites, respectively. Corresponding non-L treatment, post-watering soil respiration rates averaged 15.8, 7.2, and 11.9 µmol CO_2 m^{-2} s^{-1} for the BP, 3F, and BC sites, respectively. Taken together, this indicates that BP non-L soils were most responsive to the addition of water (post-watering to pre-watering [post/pre] ratio of 7.2), perhaps a reflection of the site's greater effective precipitation. The 3F and BC sites both showed much lower responsiveness to the addition of water, with post-watering/pre-watering ratios of ~2.7. Though their respiratory responses were comparable, it is important to note that BC measurements in 2017 were taken about a year after the fall 2016 measurements, after air temperatures had cooled, while 3F measurements were taken during much warmer, though potentially droughty, conditions.

For context on this range of post-watering/pre-watering ratios, we can re-examine the 2016 set of measurements from the BC site (Figure 23). These results show a post-watering/pre-watering July ratio of ~3, but a post/pre-November ratio of ~2. These findings are broadly consistent with those outlined by Suseela et al. (2012) in that the stimulatory effect of additional water was greater in July than in November. For reference purposes, the addition of 500 ml to the 20 cm diameter rings translates to a simulated, extremely high-intensity precipitation event of approximately 1.6 cm or 0.6 in. Apart from the intensities used, we note that both smaller and larger volume additions might have led to smaller post-watering/pre-watering ratios, though how water-stimulated respiration rates interact with plant communities, soil textures, and soil temperatures (as well as antecedent soil moisture) remains to be more fully investigated.

We note that climate modeling (RCP 8.5) associated with the 2017 Montana Climate Assessment (Whitlock et al. 2017; www.montanaclimate.org) projects indicates that some parts of Montana could warm by 5.4°C (9.8°F) by 2100, while precipitation could increase in winter, spring, and fall, but decline in summer (pages xxvi–xxviii). While these types of projections could help inform future roadside management options, additional research will be required to clarify how such climatic shifts might interact with the differing vegetative communities, soils, and climates that roadsides encompass.

6.3.4 Estimated soil carbon turnover times

To estimate soil carbon turnover times as the quotient of volumetric carbon (to 30 cm, see Section 6.3.2 and Table 10) and annualized soil respiration rates, we first must convert daily measures of soil respiration into annualized soil respiration rates.

To do this for Bear Canyon, we simply averaged July and November pre-water respiration rates, and converted these umol CO_2 m^{-2} s^{-1} values into units of g CO_2-C m^{-2} y^{-1}, since 1 umol of CO_2 contains 1 umol of CO_2-C, every umol of CO_2-C weighs 12 ug, and there are ~$3.15 \cdot 10^7$ seconds per year. An example of converted flux values is presented in **Table 10**; a measured flux of 10 umol CO_2 m^{-2} s^{-1} yields a corresponding, annualized flux of 3780 g C m^{-2} y^{-1}.

Table 10. Conversion of a range of raw *u*mol CO^{2} m-2 s-1 values into annualized values that help set up estimates of soil carbon turnover times (g C m-2 y-1).

umol CO2/m2/s	umol C/m2/s	umol C/m2/y	ug C/m2/y	g C/m2/y
1	1	31500000	378000000	378
10	10	315000000	3.78E+09	3780
100	100	3150000000	3.78E+10	37800

Recalling our prior estimate of volumetric carbon for one project plot in 2016 (see Section 6.3.2; 16,380 g SOC m^{-2} [to 30 cm depth]), we can set up the following quotient to estimate bulk SOC residence or turnover time as 4.3 y.

$$\frac{16{,}380\ g\ SOC\ m^{-2}}{3780\ g\ C\ m^{-2}\ y^{-1}} = 4.3\ y$$

Notice that any combination of larger annualized soil respiration rates in the denominator and smaller volumetric SOC estimates in the numerator will yield *shorter* residence times. Conversely, smaller annualized soil respiration rates in the denominator and/or larger volumetric SOC estimates in the numerator will yield *longer* residence times.

It is only longer residence times that are likely to contribute to long-term terrestrial carbon sequestration, independent of the setting; short residence times imply that any buildup of SOC is probably short-lived, with the SOC being respired to the atmosphere.

Estimates of soil carbon residence times based on first-year measurements are in Table 11. These estimates ranged from 19 to 32 years for control and cleared (legume) plots, respectively. Estimated carbon residence times were not uniformly variable: rabbitbrush (R) plots had CVs nearly five-fold greater than the variability recorded for reclamation seed mix with legume (L) plots. The smaller estimated soil carbon inventories for 2018 (Table 9) would yield even shorter residence times.

Table 11. Summary of average soil carbon residence times (SCaRT; in years) and variability in SCaRT (expressed as a coefficient of variation [CV]) for six treatments at Bear Canyon site in 2016: C=control, 6=6 in. mow, 12=12 in. mow, R=rabbitbrush, LC=cleared-legume, L=cleared+legume). SCaRT were estimated as the quotient of SOM-derived volumetric SOC estimates to 30 cm (g SOC m^{-2}) and annualized soil respiration rates (SRR; units g C m^{-2} y^{-1}).

Treatment	SOM	g SOC30/m^2	Average Soil Respiration Rates (SRR) (umol) $CO_2/m^2/s$)	g C/m^2/y	SCaRT (y)	SCaRT (CV)
C	0.079	11787	1.75	662	19	0.31
6	0.079	11871	1.66	626	22	0.42
12	0.079	11795	1.64	621	21	0.40
R	0.083	12449	1.54	582	31	1.03
LC	0.072	10842	1.25	471	32	0.63
L	0.072	10792	1.17	442	25	0.21

Our estimates of ~ 23% smaller SOC at BC in 2018 (vs. 2016) would lead to a corresponding lowering of SCaRT. Note that our use of pre-watering soil respiration rate averages would likely *overestimate* annual residence times, since our post-watering/pre-watering ratios for the stimulatory effect of added water ranged from 2 to >7. As soil respiration rates increase, including through the stimulation that can reasonably be inferred to occur during summer thunderstorms or frontal rain events, our estimated soil carbon residence times will be shorter still.

To summarize, Table 12 lists estimated residence times drawn from the average SOC stocks in 2018 as well as average pre-watering soil respiration rates, annualized according to the step-wise procedures in Table 9.

Table 12. Summary of average soil carbon residence times (SCaRT; in years) our three project sites using 2018 estimates of SOC and 2017–2018 soil respiration rates, mostly drawn from control plots. SCaRT were estimated as the quotient of SOM-derived volumetric SOC estimates to 30 cm (g SOC m^{-2}) and annualized soil respiration rates (SRR; units g C m^{-2} y^{-1}).

Site	g SOC_{30}/m^2	Pre-watering Soil Respiration Rates (umol $CO_2/m^2/s$)	Estimated annual Soil Respiration (g $C/m^2/y$)	SCaRT (y)
3F	3500	2.6	983	3.6
BC	11700	4.3	1625	7.2
BP	6300	2.2	832	7.6

Our results, and these types of estimates they have made possible, are drawn from replicated field trials. We investigated, after three growing seasons, whether increased mowing height (from 6 to 12 in.) could result in either increased aboveground biomass (not a statistically significant increase [Figure 20]) or increased SOC (12 in. treatments resulted in similar or lower SOC than controls). We also investigated whether planting shrubs could result in increased aboveground biomass (the only plots with surviving shrubs were at our BP site, and these showed lower biomass than the controls) or increased SOC (R treatments showed declines from 2016 to 2018 comparable to those observed at control plots). We also investigated how integrating legumes into post-construction rehabilitation schemes might influence aboveground biomass (the only surviving legumes were observed at our BC site, and biomass in these plots was about 5-fold lower than control plots) or SOC (legume plots showed some of the largest absolute decreases in SOC). The sharpest reductions in SOC (~43%) were observed in the legume-control (LC) plots at our 3F site. Together our findings emphasize the need for expanded investigation of future management options that can increase roadside soil carbon stores.

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APPENDIX A: CHRIS COTE'S PROFESSIONAL PAPER

TERRESTRIAL CARBON SEQUESTRATION POTENTIAL WITHIN MONTANA ROADSIDE RIGHT OF WAY CORRIDORS

by

Christopher A. Cote

A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

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1.0 EXECUTIVE SUMMARY

The transportation sector is one of the largest contributors to greenhouse gas (GHG) emissions in the United States (U.S.) and as such, can reasonably expect that future climate change policy will mandate that the transportation sector reduce its overall carbon footprint. State and Federal Departments of Transportation (DOTs) are beginning to evaluate cost effective means to reduce or offset carbon emissions through options such as increasing terrestrial carbon sequestration in right of way (ROW) lands owned adjacent to roadways. This study provides an estimate of the ROW acreage by vegetation type, owned by the Montana DOT, and an estimate of the annual carbon sequestration occurring in the entire ROW owned by the Montana DOT. Additionally, this study evaluates options for developing a carbon sequestration program at Montana DOT, potential land management options to increase carbon sequestration, and the potential value of a carbon sequestration program.

Estimates of total ROW acreage owned by Montana DOT were obtained through Geographic Information System (GIS) analysis and combined with Montana vegetation data in order to determine acreage estimates according to vegetation type. Estimates of annual carbon sequestration from a network of global carbon measurement sites were applied to vegetation classes and used to estimate annual carbon sequestration. It was found that ROW owned by Montana DOT consists of 70% grasslands and sequesters 75,292 metric tons of carbon per year.

Options to increase carbon sequestration within two zones of the ROW, the active and managed zone, and the passive unmanaged zone are evaluated. In the active ROW zone, decreasing frequency of vegetation management or using a seed mix with greater biomass production can augment carbon sequestration. In the passive zone of the ROW, revegetation of grasslands with shrubs is found to increase carbon sequestration by 16,200 metric tons of carbon per year. This is equivalent to the removal of 12,505 passenger vehicles from the road per year or the energy use of 5420 homes per year (EPA, 2014b).

A carbon sequestration program is shown to offer potential as an option for Montana DOT to reduce its GHG emissions and to generate revenue through trading or selling of carbon credits in an exchange market. Potential value of revegetating passive ROW from grasslands to shrubs is estimated between $356,400 and $2,197,800 U.S. dollars based on future carbon market pricing.

2.0 RESEARCH OBJECTIVES AND STUDY PURPOSE

The intent of this study is to provide a means to estimate carbon sequestration within Montana Department of Transportation (DOT) roadside right of way (ROW) corridors and evaluate additional carbon sequestration potential through modified roadside best management practices. This study provides additional benefit by allowing right of way acreage estimates classified by functional ecosystem type to be further analyzed for their economic value relative to the services they provide in regard to metrics such as surface water runoff prevention, insect pollination, invasive species resistance, or aesthetics. This study builds upon several other studies conducted at state and federal levels to estimate roadside ROW acreage and carbon sequestration potential of these lands, as described in Section 4.0.

This study seeks to contribute to an ongoing study of carbon sequestration potential within Montana DOT ROW funded by the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) and implemented by staff at the Western Transportation Institute (WTI) and the Montana State University Land Resources and Environmental Science department (MSU LRES). This ongoing study seeks to estimate the carbon sequestration within Montana DOT

ROWs (Task 1), evaluate the potential to enhance carbon sequestration in ROWs (Task 2), and evaluate the effect of revised vegetation management including: increasing vegetation mowing height, addition of native woody shrubs into grass dominated ROWs, and modifying native grass-dominated seed mixes to include native legumes (Task 3). This paper and study seeks to complete Task 1 and contribute to Task 2 of the ongoing study funded by CESTiCC.

3.0 BACKGROUND

3.1 Carbon cycle, increase in atmospheric GHGs, Climate Change

Global climate change from anthropogenic greenhouse gas (GHG) emissions poses significant risk to people and ecosystems through severe and irreversible changes in all components of the climate system. Greenhouse gas may be defined as any compound in the atmosphere that traps heat resulting in warming of the climate, including compounds such as CO_2, CH_4, or N_20. The recent warming of the atmosphere and ocean is unequivocal, with changes since the 1950s nearly unprecedented over millennia (IPCC, 2014). Anthropogenic GHG emissions have continually increased since the preindustrial era and have led to current atmospheric concentrations of GHGs at their highest concentration in the past 800,000 years with concentrations of CO_2, CH_4, or N_20 above pre-industrial era concentrations by 43, 152, and 20 percent, respectively (IPCC, 2014). It is extremely likely that the anthropogenic increase in GHG emissions is the dominant cause of observed warming since the 1950s (IPCC, 2014). Under all current and future emissions scenarios, over the 21st century average global surface temperature is projected to rise between 2° F and 11° F with a high likelihood of more frequent heat waves, extreme precipitation events, warming ocean temperatures, and sea level rise between 7 inches and 4 feet possible (dependent on sea ice melt models) (IPCC, 2014). In order to limit global warming between 3.6 and 4.3° F, global GHG emissions must be reduced to 50 to 85 percent below year 2000 levels by 2050 (IPCC, 2014).

Carbon released to the atmosphere as GHGs is predominantly responsible for the climate change observed since the 1950s (EPA, 2014a). Carbon is exchanged, or cycled in many forms among Earth's oceans, atmosphere, ecosystems, and terrestrial geosphere, commonly referred to as the carbon cycle (see figure 1). Globally, the carbon cycle is characterized by carbon fluxes among reservoirs of carbon storage. These reservoirs can be referred to as sinks if they accept more carbon than they release, and sources if they release more carbon than they accept. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (sinks in most circumstances) and are emitted to the atmosphere annually through natural processes (e.g., volcanic eruptions, decay of wood products, forest fire, etc.) and anthropogenic activities (e.g., fossil fuel combustion). When in equilibrium, carbon fluxes between these various reservoirs are roughly balanced. However, since the Industrial Revolution began in the 1750s anthropogenic combustion of fossil fuels has shifted the balance of carbon fluxes toward the atmosphere, resulting in a global atmospheric CO_2 increase of approximately 43% (EPA, 2014a). In the United States, fossil fuel combustion accounted for 93.7% of CO_2 emissions in 2013, with this total accounting for approximately 16% of global CO_2 emissions (EPA, 2014a).

Figure 1- A simplified depiction of the global carbon cycle. Carbon pools shown in blue represent carbon storage in petagrams (Pg) of carbon. Fluxes shown in red represent Pg per year. Source: http://globecarboncycle.unh.edu/CarbonCycleBackground.pdf. (Cited December 2015, created 2011)

3.2 Transportation's role in reducing greenhouse gas emissions causing climate change

In 2013, total U.S. greenhouse gas emissions were 6,643 million metric tons (MMT), representing an increase of 5.9% between 1990 and 2013 (EPA, 2014a). The transportation sector is one of the largest contributors to GHG emissions in the United States, representing 27% of total GHG emissions, with emissions from vehicles attributable to 84% of this total in 2010 (EPA, 2012). Primary GHGs produced by the transportation sector are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFC), with CO_2 accounting for 95% of transportation GHG emissions in the United States (EPA, 2012). Transportation GHG emissions have been growing steadily in recent decades, with GHG emissions increasing 27% from 1990 to 2006 alone, representing nearly one-half of the increase in total U.S. GHG emissions for this period (USDOT, 2010). GHG emissions from the transportation sector are predominantly attributable to exhaust emissions from passenger and commercial vehicle miles traveled, and fuel use across transportation modes (EPA, 2014a). Due to the overall high contribution of the transportation sector to GHG emissions, it seems necessary that this sector will have to play a significant role in U.S. attempts to reduce GHG emissions and mitigate effects of future climate change.

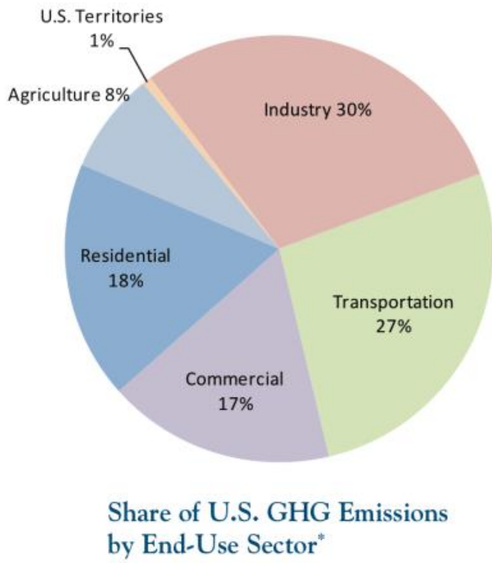

Figure 2 – United States GHG Emissions by end-use sector (EPA, 2012)

State Departments of Transportation (DOTs) are facing the challenges of meeting environmental goals for reduction of greenhouse gas (GHG) emissions and declining budgets for transportation programs and infrastructure, with limited ability to raise additional revenue (Storey et al., 2012). Recently action has been taken at both the federal and state level in public transportation to study various ways by which the sector can help reduce GHG emissions attributable to transportation.

Section 1101(c) of the Energy Independence and Security Act of 2007 authorized the formation of the U.S. Department of Transportation (USDOT) Center for Climate Change and Environmental Forecasting. This government agency implements strategic research, policy analysis, partnerships, and outreach with the goal of reducing transportation related GHGs and mitigating the effects of global climate change on the transportation network. The Center for

Climate Change and Environmental Forecasting produced a 2010 report, *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions*: *Volume 1*, on the impact of the nation's transportation system on climate change and evaluating strategies to reduce transportation sector GHG emissions.

The study evaluated four types of strategies to reduce transportation GHG emissions including: introducing low carbon fuels, increasing vehicle economy, improving transportation system efficiency, and reducing carbon-intensive travel activity. The study also evaluated the policy strategies of aligning transportation and planning investments to achieve GHG reduction objectives and pricing carbon (this is discussed in Section 3.4 in regard to potential carbon cap and trade policy) (USDOT, 2010). The study concludes with a commitment from the USDOT to reduce the impact of the U.S. transportation system on climate change. The report notes that some actions and partnerships such as the Sustainable Communities Partnership with the Environmental Protection Agency (EPA) and the department of Housing and Urban Development (HUD) support low carbon transportation options. The report also notes that the Energy Independence and Security Act of 2007 gave the USDOT statutory authority to create a fuel efficiency program for medium and heavy duty vehicles and work trucks.

In 2008 the Federal Highway Administration (FHWA) established the Carbon Sequestration Pilot Program (CSPP) to study whether roadside carbon sequestration through modified maintenance and management practices is appropriate and feasible for state DOTs (FHWA, 2010). The CSPP produced an estimate of carbon sequestration along Federal Aid Highways, including major routes and the interstate system, which is discussed further in Section 2.5. The FHWA also published a handbook titled "A Performance-Based Approach to Addressing Greenhouse Gas Emissions through Transportation Planning" as a resource for State DOTs to integrate GHG performance measures into transportation decision-making (FHWA, 2013). This handbook predominantly addresses GHG emission reduction through goals of achieving fewer vehicle miles traveled on roadways.

At the state level, several recently completed and ongoing studies have evaluated the potential for state DOTs to offset GHG emissions through terrestrial carbon sequestration in roadside right of way corridors (these studies are discussed in more detail in Section 4.0, while carbon sequestration is discussed in Section 3.3). The Florida DOT recently conducted an inventory of the roadside ROW along state highway systems and concluded that Florida's ROW represents substantial value in regards to ecosystem services, and a large offset of carbon emissions from transportation (Harrison, 2014). The Texas DOT recently conducted a brief review of state ROW available for carbon sequestration, and an experiment regarding the quantification of carbon sequestered by soils and vegetation in the ROW (Storey et al., 2012). The New Mexico DOT completed the first of a three phase study to evaluate the potential for ROW soils to sequester carbon along New Mexico state highways. New Mexico's study involves the quantification of ROW area and field sampling to evaluate carbon storage potential in various ecosystem types, under different vegetation management strategies (Dunn, 2013).

State level GHG emissions policies also exist in California. California's Global Warming Solutions Act of 2006 (AB 32), Sustainable Communities and Climate Protection Act (SB 375), and Executive Order S-14-08 direct the California DOT (Caltrans) to develop actions to reduce GHGs (Caltrans, 2010). Caltrans is currently evaluating roadside management strategies to reduce GHG emissions associated with transportation.

In general, state and federal transportation departments are now acknowledging the substantial role that transportation plays in U.S. GHG emissions and are beginning to take voluntary and policy directed steps to reduce the overall GHG emissions from the sector. State

DOTs are seeking GHG reductions through policy changes, roadside right of way carbon sequestration, transportation system efficiencies, and vehicle fuel efficiency standards.

3.3 Terrestrial Carbon Sequestration

Prior to a discussion of policies regarding carbon emissions and the use of a national cap and trade carbon economy (Section 3.4), it is important to first describe terrestrial carbon sequestration, a means by which carbon may be deliberately removed from the atmosphere and stored in plants and soils. Terrestrial carbon sequestration differs from geologic carbon sequestration in that carbon is stored in near surface terrestrial stocks, rather than deep geologic layers. Terrestrial carbon sequestration potentially provides a means for DOTs to offset emissions from transportation networks by increasing the removal of carbon from the atmosphere and storage of this carbon in vegetation and soil organic matter (SOM) within vegetated roadside ROWs.

Historically, terrestrial carbon sequestration has typically been assessed from an agricultural or forestry perspective. Only recently has the land owned by the transportation sector been considered in regard to carbon sequestration, and carbon credits (Section 3.4). Roadway systems have substantial acreage supporting vegetation within their ROWs, typically consisting of various combinations of grasses, shrubs, and trees. This vegetation has historically been overlooked, or viewed as a maintenance liability for DOTs, however recent GHG emissions reduction policies and goals have spurred the incentive for DOTs to re-evaluate ROWs in terms of their potential to sequester C and subsequently provide economic benefits (Storey et al., 2012).

There are three ways to reduce GHG emissions from the transportation sector while maintaining the same level of transportation services: achieve the same production using less energy through increased efficiency and conservation (such as increasing fuel efficiency standards of vehicles or streamlining transportation routes); utilize carbonless energy sources; or promote carbon sequestration (Litynski et al., 2006). The first two items refer to ways to reduce emissions of carbon at their sources; the third item refers to terrestrial carbon sequestration. Terrestrial carbon sequestration presents an alternate or additional strategy to reducing emissions to reduce the amount of anthropogenic-released carbon in the atmosphere.

The photosynthetic process is the biochemical transformation of carbon (C) from CO_2 into carbohydrates necessary for plant growth and structure. When photosynthesis exceeds the rate of plant respiration, carbon from the atmosphere is sequestered in plant biomass. Most of the sequestered C eventually cycles back to the atmosphere through decomposition of the plant material, but a fraction is retained in soils when the decomposition rate is slower than the rate that biomass is added to the soil (figure 3). In this scenario, vegetation growth results in terrestrial carbon sequestration in near surface soils.

Vegetation and soils are widely recognized as large C pools, with the global terrestrial biosphere estimated to absorb roughly 1 Gt of C annually, an amount equal to one-sixth of all anthropogenic C emissions. In the near term, carbon sequestration in terrestrial ecosystems offers a low-cost means to reduce C emissions with additional benefits of restored habitat for plants and wildlife, enhanced biomass production, reduced surface water runoff, restored soil quality, and increased agricultural production (Lal, 2004). Terrestrial C sequestration may serve a strategic role in offsetting C emissions from vehicles. By increasing the amount of C stored in the terrestrial ecosystem (carbon sequestration) anthropogenic C emissions can be partially offset (Litynski et al., 2006).

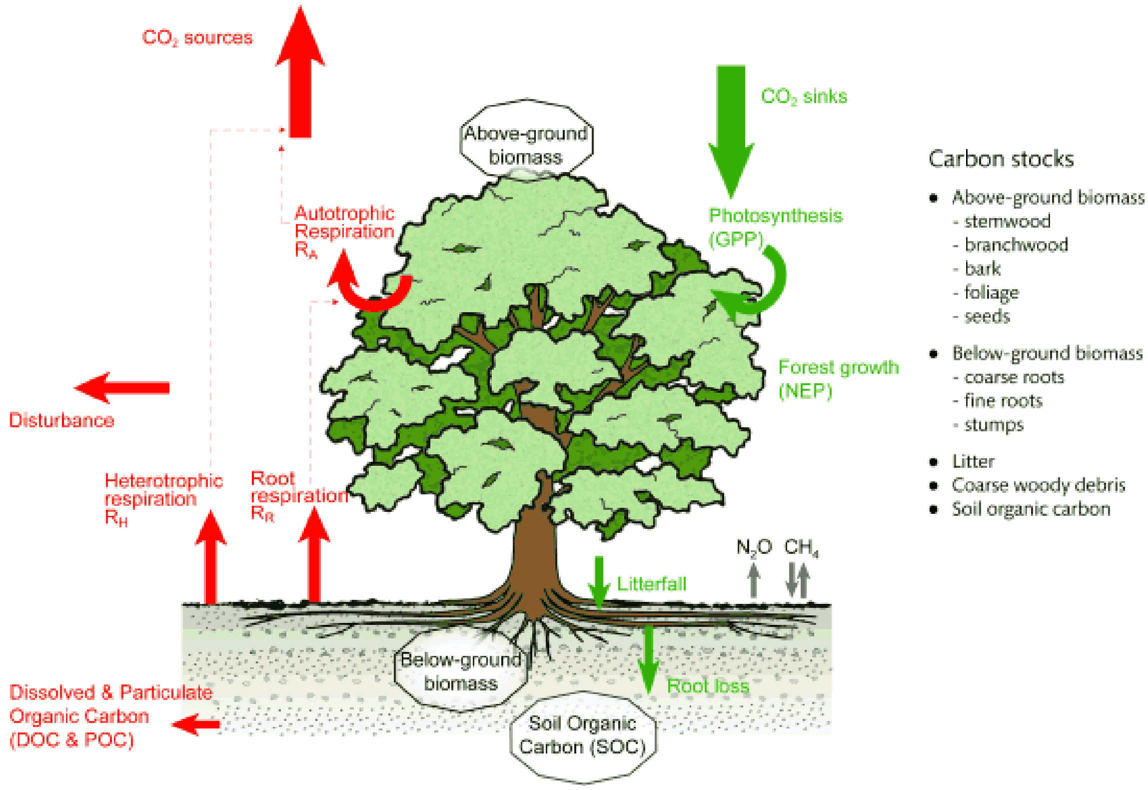

Figure 3 – Terrestrial Carbon sequestration diagram.

Source: http://www.forestry.gov.uk/website/forestresearch.nsf/ByUnique/INFD-62NBUH. (Cited December 2015, created 2009).

As figure 3 illustrates, the removal of C from the atmosphere and storage of C as SOM or soil organic carbon (SOC) is the ultimate goal of terrestrial carbon sequestration. Lal (2004) notes that the depletion of the SOC pool through anthropogenic activities mainly relating to land use change such as deforestation or conversion of natural to agricultural ecosystems has contributed 78 +/- 12 Pg of C to the atmosphere since the industrial revolution. Fortunately however, anthropogenic activities also have the potential to increase C sequestration in soils through restorative land uses and land management practices. Globally, the potential of terrestrial C sequestration through land management practices is estimated at 0.9 +/- 0.3 Pg C/year, which could off-set one-fourth to one-third of the annual increase in atmospheric CO2 concentrations (Lal, 2004).

Many studies have demonstrated the potential for anthropogenic increases in terrestrial C sequestration in grasslands and agro-ecosystems for both the subtropics and temperate regions. Carbon sequestration in many grasslands can be increased by reduction of biomass burning, raising the nutrient status of the soil, and introducing improved grasses and legumes (Batjes, 1998).

3.4 Recent GHG Emissions Policies and Regulations, GHG Cap and Trade

Since 2009, there have been numerous new federal policies, strategies, and direction provided to encourage land management agencies to address climate change. U.S. President Obama signed Executive Order 13514 in October 2009 giving direction to the federal government to create a clean energy economy. Additionally this order instructs federal agencies to "Reduce their greenhouse gas emissions from direct and indirect activities," and to "consider and account for sequestration and emissions of greenhouse gases resulting from federal land management practices." In 2010, Department of Interior (DOI) Secretary Ken Salazar signed Secretarial Order 3289, establishing a Department-wide approach for applying scientific tools to understand and respond to climate change. The DOI issued a strategic plan to address climate change in 2010 including strategies to increase carbon sequestration (USDA, 2010).

The Departments of Agriculture, National Park Service, and U.S. Fish and Wildlife service have all developed plans to respond to climate change per the direction of the DOI. All of these plans (USDA Forest Service 2010, NPS 2010, and USFWS 2011) contain provisions for land management activities to increase terrestrial carbon sequestration. The stated approaches to reducing GHG emissions and increasing terrestrial C sequestration from these federal land management agencies are congruent with those presented in USDOT, 2010.

All of the aforementioned national policy documents utilize terrestrial carbon sequestration as a major strategy for reducing GHG emissions from their respective sectors. Terrestrial carbon sequestration not only provides benefit in terms of mitigating the impact of GHG emissions, it also presents potential substantial value to DOTs through sale of carbon credits within a cap-and-trade program (Dunn, 2013). Carbon footprints, carbon credits, and associated carbon sequestration techniques are rapidly becoming a critical part of how environmental mitigation business is conducted globally. State DOTs are beginning to evaluate roadside right of ways as an opportunity for carbon sequestration and biomass production for alternative fuels (Storey et al., 2012).

A carbon cap and trade program may be defined as an environmental policy tool that achieves GHG reductions by setting a limit on emissions (cap) and allowing flexibility in how entities comply (trade). A national program such as this would set limits on GHG emissions allowed by state or sector, but allow flexibility in the accounting method to calculate emissions and emission reductions. In this respect, entities may be allowed to trade or sell carbon emissions credits based on reductions in allowable emissions, and generate carbon credits through increases in carbon sequestration. EPA currently administers several cap and trade programs with regard to other air quality parameters (such as SO_2 and NO_x) including the Clean Air Interstate Rule, Clean Air Visibility Rule, and the Acid Rain Program (described further at http://www3.epa.gov/captrade/programs.html).

Emerging carbon regulations in the U.S. are developing under the Regional Greenhouse Gas Initiative (RGGI) in the northeast, the Western Climate Initiative, and the Midwestern Greenhouse Gas Reduction Accord. To achieve GHG reductions, the regional initiatives plan to implement carbon cap-and-trade programs (Bird et al., 2008). In 2015, EPA published a final rule (FRL-9930-65-OAR) in the Federal Register (Federal Register, 2015) establishing final emission guidelines for states to follow in developing plans to reduce GHG from existing fossil fuel powered electric generating plants. This rule will become effective on December 22, 2015 and represents the first U.S. national regulation specifically targeted to reduce GHG emissions (specifically CO_2 emissions) that cause climate change. This regulation provides a precedent for regulation that could one day require the transportation industry to reduce GHG emissions and result in a national carbon cap and trade policy.

Carbon credits and offsets are a relatively new form of trade in the global marketplace and are rapidly becoming a viable commodity as well as the most common way to regulate GHG emissions. The basic unit of carbon trade is 1 metric ton of CO_2 or equivalent (tCO_2e). The carbon market trades emissions under cap-and-trade scenarios, with the basic concept that members have set caps or limits on allowable GHG emissions. Members exceeding their set goal for GHG emissions can purchase credits, while members with surplus credits (through GHG emissions reductions) can sell or trade those credits. Participation can be made mandatory or voluntary (Storey et al., 2012).

The Chicago Climate Exchange (CCX) is a North American greenhouse gas emission reduction program. From 2003 through 2010 CCX operated as a comprehensive cap and trade program with an offsets component. In 2011 CCX transformed into the Chicago Climate Exchange Offsets Registry Program, a voluntary program to register verified emission reductions based on a comprehensive set of established protocols (ICE, 2015). Although participants in the current Offsets Registry Program no longer have mandatory emission reduction commitments, the CCX provides a framework of a market based emissions credit exchange likely to evolve under federal or state cap and trade regulation.

The CCX developed the only carbon sequestration offset protocols resulting in emissions credit exchanges in the United States (CCX, 2009a,b,c). The CCX was launched in 2003 and had more than 300 members from all sectors of the global economy. The CCX trades carbon credits through Carbon Financial Instrument (CFI) contracts, with each contract representing 100 tCO_2e (Caltrans, 2010). In order to join the CCX, an entity was required to become a member of the trading group, then demonstrate baseline GHG emission levels and have GHG offset projects reviewed and approved by the CCX. Due to the ecosystem types typically present in right of ways, and management options for this land, three CCX general offset protocols are most applicable to DOT ROW carbon sequestration projects: *Forestry Carbon Sequestration Project Protocol*, *Continuous Conservation Tillage and Conversion to Grassland Soil Carbon Sequestration Offset Project Protocol*, and *Sustainably Managed Rangeland Soil Carbon Sequestration Offset Project Protocol* (CCX, 2009a,b,c).

Through documentation of current carbon sequestration quantity within DOT ROWs, then implementation of revised vegetation management practices, or other action to increase terrestrial carbon sequestration, DOTs could join a market similar to CCX then begin to trade or sell carbon credits on the market, providing an economic gain to DOTs along with the benefit of reducing GHG emissions from the sector. The carbon market in the U.S. is currently voluntary. However, if a mandatory national cap and trade system is established in the U.S., then participation in a carbon exchange market such as the CCX, would likely be required for all state DOTs given the contribution of the transportation sector to GHG emissions in the U.S.

3.5 Montana DOT ROW Management and GHG policy

Neither Montana DOT nor the state of Montana currently has any directive towards reducing GHG emissions from state level policy or regulation. All ROW management undertaken by

Montana DOT is directed towards the goals of maintaining roadways/roadside for safety, protecting the environment, and maintaining pleasing aesthetics in a functional manner. Vegetation management is stated to have the goal of producing and maintaining low-maintenance, self-sustaining roadsides by encouraging beneficial vegetation (MDT, 2002). It may be noted that these goals are congruent with goals of a roadside carbon sequestration management program, should one be implemented in the future.

Montana DOT Maintenance Division implements the Roadway/Roadside Maintenance Program including maintaining drainage facilities, maintaining roadway slopes, controlling vegetation in the ROW, maintaining ROW landscaped areas, and maintaining livestock and wildlife controls (MDT, 2002). Sections 5.6 – 5.9 of Montana DOT's Maintenance Manual (MDT, 2002) outline the vegetation management practices undertaken in the ROW. Montana DOT treats the ROW as two separate zones with regard to vegetation management. An "Active Zone" is defined as the area within 15 feet of the paved road shoulder and the "Passive Zone" is defined as the area 15 feet from the paved road shoulder to the boundary of the ROW. The Active Zone is maintained and controlled for vegetation growth, invasive species removal, and large woody vegetation removal (only when necessary for safety). The Passive Zone is not managed unless special circumstances warrant, such as for a weed control plan, or to reduce snow drifting (MDT, 2002).

4.0 LITERATURE REVIEW

In 2010, the Federal Highway Administration (FHWA) published the results of the Carbon Sequestration Pilot Program (CSPP). The purpose of the CSPP is to assess whether roadside carbon sequestration on the National Highway System (NHS) through modified maintenance and management practices would be appropriate and feasible for state DOTs when balanced against economic and ecological uncertainties (FHWA, 2010). Specific goals of this pilot program included: estimating revenue DOTs could earn if carbon sequestration management efforts are undertaken using native vegetation; determining the cost-effectiveness of such a program nationally; and creating decision support tools that state DOTs can use to determine if carbon sequestration programs may be effective in their states. The FHWA, 2010 study determined that there are approximately 5.05 million acres of ROW available in the NHS nationwide, with a likely range of 1.4 to 8.7 million acres. Of this acreage, approximately 3.4 million acres are unpaved, with the unpaved acreage classified and quantified according to the ecosystem types of grassland, woody vegetation, grassland/woody vegetation mix, and shrub as presented below in Table 1.

NHS ROW Acreage	U.S. Estimate (in 1000s of acres)
Total	1,400 – 8700, likely ~5,000
Unpaved	400 – 6,400, likely ~3,400
Grassland	200 - 2,800, likely 2,200
Woody vegetation	30 – 460, likely 360
Grassland/woody vegetation mix	26 – 600, likely ~470
Shrub	30 – 500, likely ~390

Table 1 - Estimated NHS ROW Acreage by ecosystem classification (FHWA, 2010)

From this ROW acreage and ecosystem type quantification, the FHWA estimates that approximately 91 million metric tons (MMT) of carbon is currently sequestered in vegetation and soils within NHS ROW and vegetation in NHS ROW currently sequesters 3.6 MMT of carbon per year. The FHWA CSPP also produced a Highway Carbon Sequestration Estimator tool to help DOTs assess the return on investment under various carbon sequestration scenarios, as revenue generated from biological carbon sequestration is concluded to vary greatly from state to state based on carbon prices, management techniques, and ecological variability (FHWA, 2010). The FHWA Carbon Sequestration Estimator tool was utilized for assessing the economic feasibility of carbon sequestration in Montana and is discussed further in Section 7.2.

The Florida DOT published a study in 2014 (Harrison, 2014), evaluating the economic value of ecosystem services provided by vegetated ROW within Florida's State Highway System (SHS). Harrison estimated that approximately half of Florida's estimated 186,121 acres of SHS ROW is vegetated, and applied the same ecosystem percentages found in FHWA, 2010 to this area. The economic value of runoff prevention, carbon sequestration, pollination and other insect services, air quality, invasive species resistance, and aesthetics of this land was estimated at 500 million dollars, an amount vastly exceeding the estimated 33.5 million dollar annual cost to manage ROW vegetation. The annual value of carbon sequestration alone of vegetated ROW was estimated at 39 million dollars, with this amount estimated to nearly double to 56 million dollars if sustainable ROW vegetation management practices (50% reduction in mowing, elimination of chemical weed control and fertilization) are employed. Harrison notes that Kalbli, 2009 evaluated the potential of the Florida DOT becoming a provider (seller) of carbon credits under a national cap and trade carbon plan. Kalbli, 2009 concluded that this would potentially be possible for the Florida DOT by using native vegetation management practices in state owned ROW, however the Florida DOT would have to provide baseline criteria for measuring carbon sequestration to be evaluated by a third party designated by a carbon credit trading group (Kalbli, 2009). The Harrison study provides a means for Florida to provide a baseline estimate of carbon sequestration within its SHS ROW, and to potentially modify vegetation management practices in order to become a provider, or seller of carbon credits on a cap and trade market.

A study was conducted for the Texas DOT with the goal of developing a testing method to quantify the ability of vegetation and soil to sequester carbon in a full-scale, controlled laboratory environment (Storey et al., 2012). This study discusses the need to accurately quantify plant and soil carbon sequestration capabilities in order to accurately determine the amount of carbon sequestered within Texas SHS ROW. The study estimates 1.1 million acres of ROW within the Texas SHS with the majority available for terrestrial carbon sequestration, though the calculation of Texas DOT ROW acreage and carbon sequestration potential was not the direct focus of this study. The study was ultimately inconclusive with regard to the carbon sequestration capabilities of various plants occurring within Texas SHS ROW due to plant injury occurring from (deliberate) exposure to vehicle exhaust, however the study provides valuable insight as to field testing methods available to provide accurate estimates of carbon sequestration by plant species type. This information is valuable to land managers seeking to maximize carbon sequestration potential through vegetation management within ROWs. This study provides additional discussion regarding the potential value of carbon sequestration within ROWs in a carbon cap and trade policy scenario.

In 2011, the New Mexico Department of Transportation (NMDOT) initiated a project selected by FHWA to determine the feasibility of maximizing carbon sequestration within SHS ROWs. The first of three phases of this project have been completed, and results are summarized in (Dunn, 2013). The objectives of the first phase of this project were to determine the amount of carbon currently sequestered with the SHS ROW, document current ROW management practices, and provide recommendations as to ROW management practices to increase sequestration of carbon (Dunn, 2013). The Dunn, 2013 study provides an estimate of current sequestration of carbon in NMDOT SHS ROW based on the collection of soil and vegetation samples from 117 randomly selected study sites across three biomes representative of the state (upper montane, lower montane, and prairie). Soil Organic Carbon (SOC) concentrations were determined for each biome, with variation in SOC between study sites mainly attributable to differences in precipitation, clay, litter, and grass in the ROW. This study additionally evaluated current ROW management practices such as mowing and weed spraying and recommended new management strategies that may meet fiscal and staffing budgets of NMDOT, maintain safety and environmental standards, and result in a net increase in carbon sequestered in ROW soils. Phase II of this project, which is not yet completed, involves testing new ROW vegetation management practices in sites previously sampled during Phase I in order to provide an accurate pre and post revised management strategy calculation of carbon sequestered in ROW soils. These management strategies include inter-seeding legumes, imprinting soils, and reducing mowing frequency (Dunn, 2013). This ongoing study appears to have the potential to provide a defensible framework by which NMDOT may accurately estimate the current carbon sequestration within its ROWs and potentially sell carbon credits by employing new ROW management strategies. The relative precision of the mean SOC calculated from this study was 7.7% across the study area, and 11-12% for individual biomes, within and close to the value of 10% precision required by the CCX for trading or selling carbon credits (Dunn, 2013).

A study of the amount of carbon sequestered by lands adjacent to roadways owned by eight federal land management agencies (FLMAs) and the potential to increase carbon capture and storage (CCS) during road construction and improvement projects was completed in 2014 (Ament et al., 2014). This study relied on the concept of a road effect zone (REZ) of 50 meters from unpaved roads and 100 meters from paved roads, as FLMAs typically include continuous land ownership and management surrounding their roadways rather than narrow ROW areas typically owned by state DOTs. This study estimated that the eight FMLAs include a REZ of 17 million acres. This acreage was further evaluated through an analysis of functional vegetation type within the REZ, and then measurements of carbon flux potential from a large sample of globally distributed eddy covariance towers were applied to each representative vegetation type. The study determined that the eight FMLAs studied have the potential to capture and store over 8 MMT of carbon each year within their REZs. As an average of 1,750 miles of road are improved or reconstructed annually between the eight FMLAs, the study suggests several revegetation practices in conjunction with road projects that could increase carbon sequestration with REZs including planting particular physiognomic classes of vegetation, the use of living fences as a means of snow and ice protection for roadways, reducing the effects of dust and salt, and abandoned road reclamation. Additionally, the study provides a means for land managers to estimate the reduction in carbon emissions through a reduced vegetation-moving schedule which may result in greater terrestrial carbon sequestration.

5.0 METHODS

This section presents the methodology to calculate ROW acreage owned by the Montana DOT, the quantification of ROW acreage by landscape type, evaluation of these estimates through sampling, and estimation of terrestrial carbon sequestration according to acreage of landscape types within ROW. This methodology is consistent with the approach utilized by (FHWA, 2010) and (Ament et al., 2014) to classify landscape types within ROW corridors or REZ areas and to estimate the amount of terrestrial carbon sequestration occurring.

5.1 Calculation of ROW acreage owned by Montana DOT

The researcher obtained estimates of ROW acreage owned by Montana DOT utilizing Geographic Information System (GIS) software ArcMap version 10.3.1., road centerline layers provided by Montana DOT Mapping Division, and the MDT document *Montana Department of Transportation: Statewide Integrated Roadside Vegetation Management Plan: 2012-2018* (MDOT, 2012).

The Montana DOT Mapping Division provided GIS layers representing the centerlines of Interstate National Highway System (NHS) Routes, Non-NHS highways, Primary routes, and Secondary routes. Urban Montana DOT routes were excluded from this evaluation as ROW in urban areas typically consists of non-vegetated surfaces (such as sidewalks). The centerlines of the four types of Montana roadways were imported into ArcMap as individual layers as well as a Montana State border layer, which confines the study boundary (figure 4).

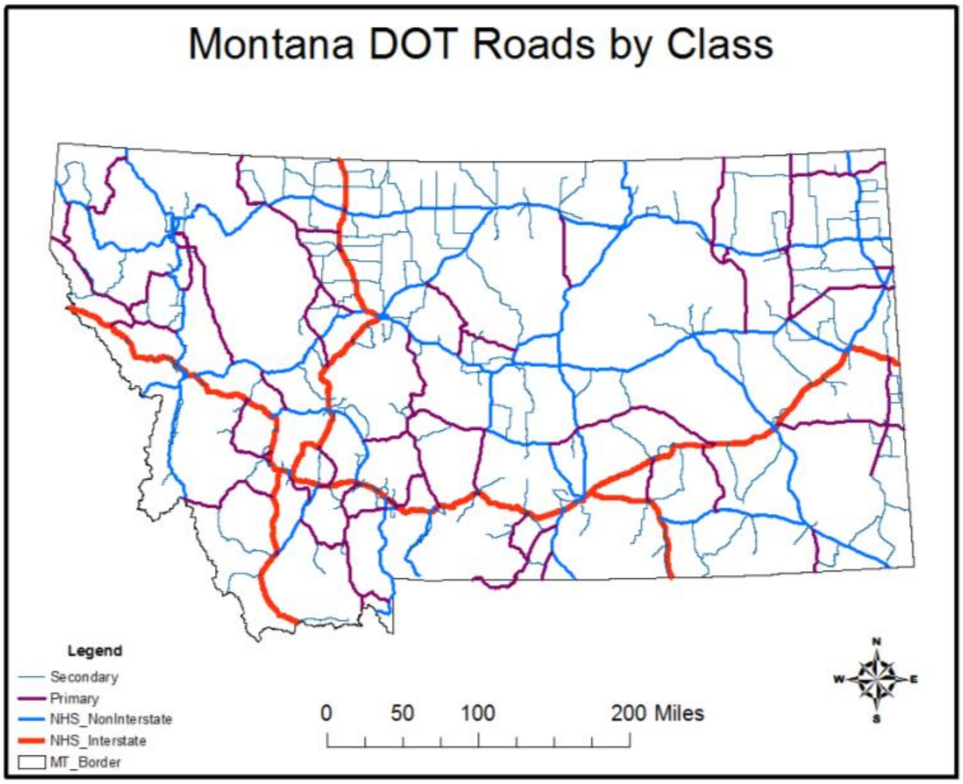

Figure 4 – Montana DOT interstate and non-interstate highway, primary, and secondary routes

Montana DOT does not have consolidated statewide information available as to the exact boundaries of land owned by the department and no GIS layer depicting right of way ownership exists. Therefore, MDOT (2012) was utilized to calculate the amount of ROW acreage associated with each road type according to the generic road construction information provided in this document. Appendix C of this document provides very useful information regarding the amount of ROW acquisition required for each road type, and the acreage of ROW present per centerline road mile. For example, typical total width of a primary highway is 160 feet, with 32 feet of road surface, and 128 feet of non-roadway ROW (MDT, 2012).

These estimates were used to create buffers on either side of roadway centerlines, to encompass the typical expected width of the roadway and its ROW. The calculation of ROW acres per centerline mile were later used to remove the area of constructed road from estimates. The

ROW adjacent to the roadway was treated as a continuous unit and the active and passive zones of the ROW were not differentiated in this part of the analysis, as discussed further in Section 7.1. MDT, 2012's listed total roadway widths including ROW of 260', 160', and 120' were applied to interstate and state highways, primary routes, and secondary routes, respectively and used to create new GIS layers using the "Buffer" tool within ArcMap. The buffered roadway layers were further simplified by MDT corridor name, dissolving unnecessary boundaries between segments of the same roadway using the "Dissolve Buffer" tool in ArcMap. The end result of this process was to produce (4) unique GIS layers representing total width of roads and associated ROW for the road types evaluated in this study. The total acreage encompassed by both the roadways and ROWs was calculated for each layer using the "Calculate Geometry" tool within each layer's attribute table.

5.2 Calculation of ROW acreage by landscape type

In order to calculate acres of ROW by landscape type, a Montana state-wide landscape vegetation classification GIS layer was required. Three potential such layers were identified including: LANDFIRE vegetation layers through the Landscape Fire and Resource Management Planning Program (www.landfire.gov), United States Geologic Survey National Gap Analysis Program (www.gapanalysis.usgs.gov), and a Montana State specific dataset (Montana Climax Vegetation) provided by the U.S. Soil Conservation Service, and hosted by the Montana State Library (http://mslapps.mt.gov/). After evaluating each dataset, it was determined that the Montana Climax Vegetation dataset best served the needs of this study due to its simplified, but descriptive landscape vegetation classification, and the fact that this dataset did not attempt to identify paved road surfaces (an issue found with the other datasets where much of the ROW was depicted as being "developed/paved" due to the adjacent roadway). The Montana Climax Vegetation dataset classifies the landscape of Montana according to seven vegetation descriptions: montane forest, intermountain grassland, riparian, shrub grassland, plains grassland, plains forest, and water (figure 5).

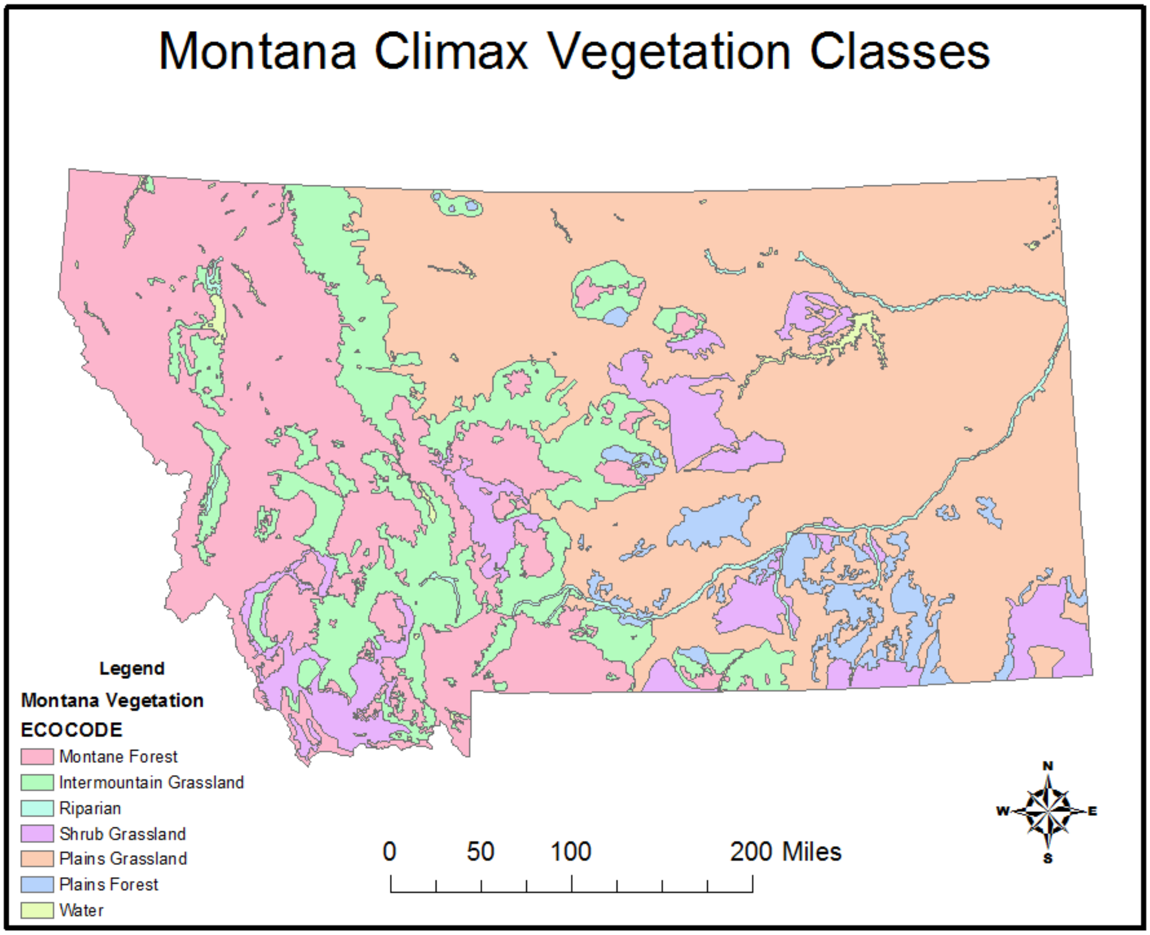

Figure 5 – Montana Climax Vegetation dataset. Different colors correspond to different landscape level vegetation classifications

In order to calculate the acreage of the landscape types present in MDOT ROW, this vegetation layer was combined with each road buffer layer using the ArcMap "Clip" tool. The clip tool is used in ArcMap to extract the data from one feature class using the features from another class. In other words, the clip tool was used to extract only the elements from the vegetation layer that are found within MDOT's ROW. This is illustrated in figure 6. New layers for each type of roadway clipped to the data from the vegetation layer were created and saved. Attribute tables from each layer were exported into Microsoft Excel format to allow for summation of total ROW acreage by landscape vegetation type, as provided in Section 6.1.

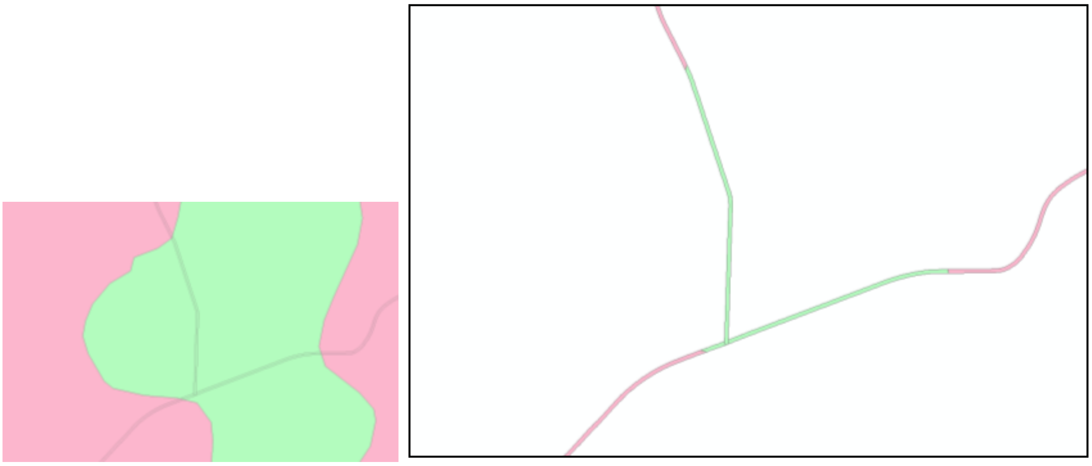

Figure 6 – Left: Vegetation data layer displayed over roadway buffers. Right: Same area, clipped vegetation data to ROW boundary showing no data outside of roadway ROWs and transition from Montane forest (pink) to Intermontane Grassland (green) occuring within the ROW.

5.3 Calculation of Terrestrial Carbon Sequestration in Montana DOT ROW

Once ROW acreage by landscape vegetation type was determined, potential terrestrial carbon capture and sequestration was estimated according to empirical observations of net CO_2 exchange (NEE) from a global network of eddy covariance towers arrayed according to functional vegetation types. The same approach to estimate carbon sequestration relying on averages of eddy covariance tower empirical data by ecosystem type was utilized in Ament et al., 2014. The eddy covariance tower estimates of carbon sequestration by ecosystem type are derived from numerous measurement sites across the globe and arranged in networks measuring long-term carbon and energy fluxes in contrasting ecosystems and climates in networks such as FLUXNET (Wilson et al., 2000). These global networks of micrometeorological flux measurement sites measure the exchanges of carbon dioxide, water vapor, and energy between the biosphere and atmosphere. Vegetation classes evaluated by these global network of measurement sites include temperate conifer and broadleaved forests, tropical and boreal forests, crops, grasslands, chaparral, wetlands, and tundra. Sites exist on five continents and their latitudinal distribution ranges from 70° N to 30° S. The global proliferation of long-term eddy covariance sites measuring carbon and energy fluxes provides a unique contribution to the study of the environmental, biological, and climatological controls over carbon exchange between vegetation and the atmosphere (Baldocchi et al., 2001). Table 2 identifies the annual Carbon Sequestration potential provided in Ament et al., 2014 and shows the ecosystem types applied to the vegetation classes in this study. Flux tower equivalent ecosystems were selected based on expected dominant plant species present (e.g., Montana montane forest consists of predominantly evergreen needleleaf tree species) and applied to each of the Montana climax vegetation classes identified in this study.

GIS Code	Montana Climax Vegetation Ecosystem Type	Flux Tower Equivalent Ecosystem	Carbon Flux (NEE) (metric tons C/acre per year)	Standard Deviation Carbon Flux (NEE) (metric tons C/acre per year)	Number of measurement sites
1	Montane Forest	Evergreen needleleaf forest	0.55	0.89	69
2	Intermountain Grassland	Grassland	0.40	0.53	45
3	Riparian	Deciduous broadleaf forest	0.90	1.01	32
4	Shrub Grassland	Shrubland	0.54	0.5	16
5	Plains Grassland	Grassland	0.40	0.53	45
6	Plains Forest	Mixed evergreen-deciduous forest	0.43	0.68	16
7	Water	NONE	0	0	0

Table 2 – Annual Carbon Sequestration Estimates from Ament et al., 2014 applied to Montana Climax Vegetation Ecosystem type in this study.

Using the Carbon Flux estimates per acre of vegetation type, it is a simple calculation to multiply by the total estimates of acres of each vegetation type identified in Montana DOT ROW in order to obtain estimated values of metric tons of carbon sequestered in the total land area per year. The results of these calculations are provided in Section 6.2.

5.4 GIS Sampling Verification

In order to evaluate the accuracy of the ROW acres by vegetation type determined by these methods, a sampling strategy was employed to evaluate the results of the GIS analysis through visual review of aerial and roadway images. In order to establish reference points in ArcMap for review, a Montana DOT GIS layer containing roadway mile markers (Reference Markers) was imported into ArcMap as well as a layer of aerial imagery (National Agriculture Imagery Program (NAIP), 2013). Thirty sampling locations were selected across the study area at random, corresponding to reference marker locations distributed between the four types of routes included in the study. At each sampling location, the aerial imagery was reviewed to determine if the ROW boundary drawn in ArcMap appeared to be accurate. Physical markers such as adjacent county routes, private property, transition to cropland, or fence lines often provided clear evidence of this, though in some landscape types such as Montane Forest, it can be difficult to determine where the ROW property boundary ownership may terminate due to the continuous vegetation. Images of the roadway at the reference marker were reviewed in Google Maps Street Viewer in order to determine if the landscape vegetation in the ROW matched the GIS analysis for the roadway and if an active ROW management strip appeared to be present.

Figure 7- NAIP imagery and an Interstate route sampling location. Montana DOT Vegetation layer off (left) and on (right). Layer ROW boundaries match fence lines and transition from prairie grassland to cultivated cropland outside ROW boundary.

Figure 8 – Three sampling locations top to bottom representing Montane Forest, Plains Forest, and Intermountain Grassland. Samples demonstrate characterized vegetation types are accurate and active ROW management strips are present.

Road Name	Reference Marker	Route Type	Climax Vegetation Characterization	Vegetation Accurate?	ROW distance from road accurate?	Active ROW Vegetation Management Strip?	Comments
I-15	387	Interstate HWY	Plains Grassland	Yes	Yes	Yes	
I-15	3	Interstate HWY	Shrub Grassland	No	Yes	Yes	Grassland in ROW. Shrub Grassland outside ROW
US-94	65	Interstate HWY	Plains Forest	Yes	Yes	Yes	
US-90	369	Interstate HWY	Riparian	Yes	Yes	Yes	Center median is grassland
I-90	63	Interstate HWY	Montane Forest	Yes	Yes	Yes	Center median is grassland
I-90	545	Interstate HWY	Plains Grassland	Yes	No	Yes	More ROW than expected. Large center median.
I-15	109	Interstate HWY	Shrubs Grassland	Yes	Yes	Yes	Vegetation could also be described as intermountain grassland
US-87	106	Non-interstate HWY	Plains Grassland	Yes	Yes	Yes	
US-12	3	Non-interstate HWY	Montane Forest	Yes	Yes	Yes	
MT-200	138	Non-interstate HWY	Plains Grassland	Yes	No	Yes	ROW confined by private property and river adjacent to road
US-191	97	Non-interstate HWY	Shrub Grassland	Yes	Yes	Yes	
US-287	104	Non-interstate HWY	Intermountain Grassland	Yes	Yes	Yes	
MT-16	52	Non-interstate HWY	Plains Grassland	Yes	Yes	Yes	
MT-191	33	Non-interstate HWY	Plains Grassland	Yes	Yes	Yes	
MT-212	85	Non-interstate HWY	Plains Grassland	Yes	Yes	Yes	
MT-83	25	Primary	Montane Forest	Yes	Yes	Yes	
US-89	8	Primary	Intermountain Grassland	Yes	Yes	Yes	
MT-43	17	Primary	Shrub Grassland	Yes	Yes	Yes	
MT-141	14	Primary	Intermountain Grassland	Yes	Yes	Yes	
US-87	7	Primary	Intermountain Grassland	Yes	Yes	Yes	

Road Name	Reference Marker	Route Type	Climax Vegetation Characterization	Vegetation Accurate?	ROW distance from road accurate?	Active ROW Vegetation Management Strip?	Comments
MT-69	17	Primary	Intermountain Grassland	Yes	Yes	Yes	
US-89	31	Primary	Montane Forest	Yes	Yes	Yes	One side of roadway is a mostly bare soil slope, but does have conifers growing
MT-1	57	Primary	Intermountain Grassland	Yes	Yes	Yes	
S-254	2	Secondary	Plains Grassland	Yes	Yes	Yes	
Pipe Creek Road	13	Secondary	Montane Forest	Yes	Yes	Yes	
S-323	56	Secondary	Shrub Grassland	Yes	Yes	Yes	
S-258	11	Secondary	Plains Grassland	Yes	Yes	Yes	
S-308	5	Secondary	Plains Grassland	Yes	Yes	Yes	
Brusett Road	1	Secondary	Plains Grassland	Yes	Yes	Yes	
S-464	33	Secondary	Montane Forest	Yes	Yes	Yes	
Helmville Road	2	Secondary	Intermountain Grassland	Yes	Yes	Yes	

Table 3 – Sampling results of ArcMap layer of Vegetation in Montana DOT ROW

6.0 RESULTS

The results of this study provide an estimate of the ROW ownership of Montana DOT and the C sequestration potential of these lands. Section 7.0 provides additional discussion as to the potential to augment terrestrial carbon sequestration with various management strategies and Section 8.0 discusses limitations of the estimates.

6.1 ROW acreage by vegetation classification

Table 4 below presents total acreage of Montana DOT right of way by road class and vegetation type.

Route Type	Montane Forest	Intermountain Grassland	Riparian	Shrub Grassland	Plains Grassland	Plains Forest	Water	Total ROW Acres
NHS Interstate	4,682	7,181	3,696	3,187	8,333	818	28	27,925
NSH Non-interstate	8,051	10,404	1,498	2,616	22,827	891	201	46,488
Primary	8,783	11,555	526	3,054	14,680	844	609	40,051
Secondary	3424	11,227	1,662	4,345	29,508	972	227	51,365

Route Type	Montane Forest	Intermountain Grassland	Riparian	Shrub Grassland	Plains Grassland	Plains Forest	Water	Total ROW Acres
TOTALS	24,940	40,367	7,382	13,202	75,348	3,525	1,065	165,829

Table 4 – Total Montana DOT ROW acreage by road class and vegetation type

In terms of ROW acreage, this study finds that most of the ROW acreage owned by Montana DOT occurs on non-interstate roads, with the largest ROW land ownership occurring on the smallest class of Montana state roads, the secondary routes and the least total ROW land ownership occurring along the National Highway System (NHS) Interstate routes.

Grasslands (plains and intermountain grasslands) represent the vast majority of vegetation in Montana DOT ROW, with a total of 115,715 acres or 70% of the entirety of ROW vegetation. The next most common landscape type is montane forest, representing 15% of the ROW vegetation types. Shrub grasslands represent 8% of the ROW vegetation and riparian zones, plains forest, and water all represent relatively small percentages of ROW vegetation with the three groups totaling 7% of the acreage all-together.

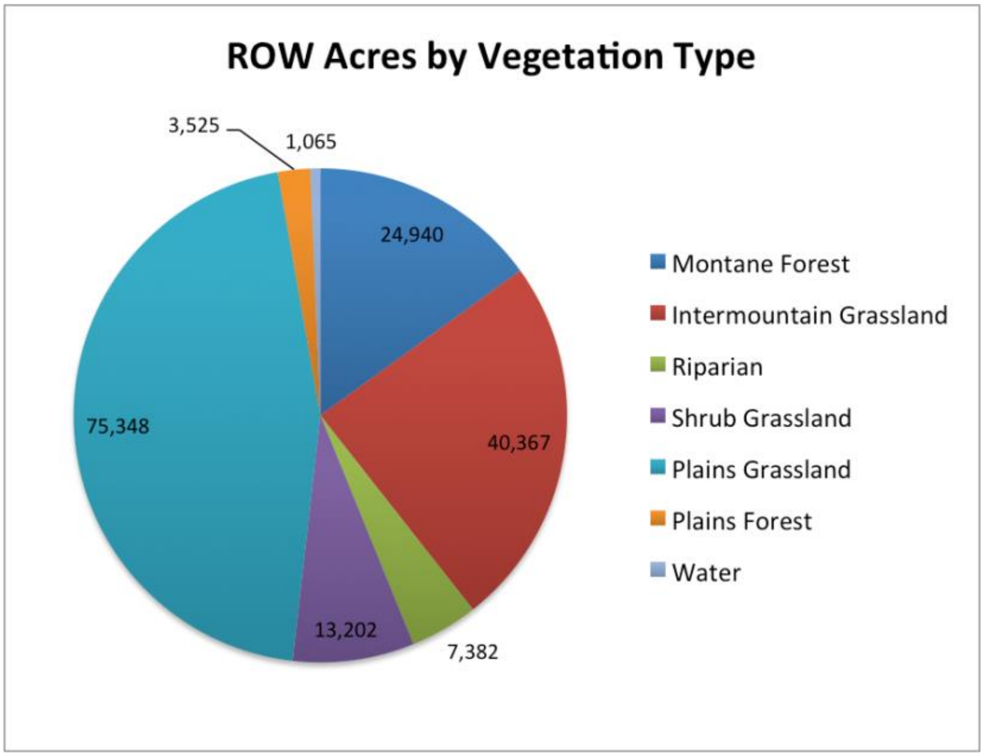

Figure 9 – Distribution of Montana DOT ROW acres according to dominant vegetation type

6.2 Potential Maximum Current Terrestrial Carbon Sequestration in Montana DOT ROW

By applying the annual carbon sequestration values per landscape vegetation class from Table 2, one is able to determine an estimate for annual terrestrial carbon sequestration occurring on Montana DOT ROW lands.

Landscape Vegetation Type	Total Acres	Carbon Flux (NEE) (metric tons C/acre per year)	Total C Sequestration (metric tons of C per year)
Montane Forest	24,940	0.55	13,717
Intermountain Grassland	40,367	0.40	16,147
Riparian	7,382	0.90	6,644
Shrub Grassland	13,202	0.54	7,129
Plains Grassland	75,348	0.40	30,139
Plains Forest	3,525	0.43	1,516
Water	1,065	0	0
Total Carbon Sequestration in ROW			**75,292**

Table 5 – Estimate of Annual Carbon Sequestration Occurring in Montana DOT ROW lands

This study finds that the maximum annual terrestrial carbon sequestration occurring in Montana DOT ROW is 75,292 metric tons of carbon per year. This is the estimated annual C flux occurring in Montana DOT ROW based on the vegetation types that currently exist in the ROW, and without any vegetation management conducted by Montana DOT.

In terms of values in a carbon cap and trade market, the annual carbon flux occurring in Montana DOT ROW represents 276,071 tCO_2e units in the Chicago Climate Exchange Offsets Registry Program (though the annual carbon flux is not the potential economic value of Montana DOT implementing a GHG emissions reduction program, as discussed further in Section 7.0). This value is obtained by converting the annual estimated carbon flux reported in metric tons of carbon to carbon dioxide equivalent (the standard unit traded in climate exchanges) by using the ratio of the atomic mass of a carbon dioxide molecule (44) to the atomic mass of a carbon atom (12) (EPA, 2005). Therefore, 75,292 metric tons C * (44/12) = 276,071 tCO_2e.

6.3 Accuracy Evaluation of Estimates

Section 6.2 provides an estimate of 75,292 metric tons of C that may be taken up by vegetation and soils within Montana DOT ROW based on flux tower estimates of carbon sequestration according to landscape vegetation type. This value relies on the accuracy of the ROW acreage estimates by landscape vegetation class as well as the flux tower carbon sequestration estimates applied to these areas.

As the sampling conducted on this dataset illustrated, the ROW acreage was qualitatively determined to be representative in 28 of 30 samples, with one sample showing less ROW than expected and one sample showing more ROW than expected. While not quantifiable due to a lack of a broad scale ROW ownership dataset available from Montana DOT, it appears that the ROW estimates based on road construction requirements should be accurate across the study area for the purpose of estimating carbon sequestration based on the sampling results.

The verification sampling produced similar results in terms of landscape vegetation classification accuracy, with 29 of 30 samples appearing to correctly represent the anticipated vegetation type. Deviations from landscape classification type were minor and were attributed to minor distinctions between classes, such as shrub grassland and prairie grassland. Overall it does appear that the landscape vegetation classification reported in this study is accurate.

Finally, the flux tower estimate approach utilized in this study mirrors that of Ament et al., 2014. The authors in this study state that this approach of estimating net carbon uptake by physiognomic class is an improved methodology to previous approaches, such as FHWA, 2010, that did not include heterotrophic respiration in carbon flux estimates. By using the average flux tower network estimates by landscape vegetation class, this study draws directly on empirical observations from a broad network of monitoring equipment and applies these values to equivalent landscapes in Montana DOT ROW based on the predominant vegetation present. This presents a more realistic portrayal of dynamic carbon flux processes as Ament et al., 2014 noted in their study.

7.0 DISCUSSION

7.1 Influence of Active and Passive ROW Zones on Estimates

While seemingly a reliable value, the total annual carbon sequestration estimate does not take into account the active management zones that Montana DOT maintains within its ROW for safety purposes. As discussed in Section 3.5, Montana DOT Maintenance division implements a roadside vegetation management policy that includes vegetation growth control and woody vegetation removal from the ROW active zone, the area within fifteen feet of the paved road shoulder. This active zone was visually identified in all 30 of 30 samples evaluated from ArcMap and Google Earth datasets, indicating that it is likely a dominant feature of the ROW across the state.

It is unlikely that the active zone management strongly influences the overall C sequestration estimate, as over 70% of the ROW acreage is comprised of grassland-dominated vegetation, which is the expected vegetation type found within the active zone. While the active zone is mowed and sprayed by Montana DOT to control vegetation growth, the nature of the flux tower C sequestration estimates are such that disturbances such as these are already accounted for in the annual C flux estimates, as discussed in Section 6.3. Thus, even the 22% of ROW acreage calculated to consist of montane forest, riparian, or plains forest is still well represented by the flux tower estimates applied to the ROW acreage. For the purpose of a Montana DOT ROW statewide C sequestration estimate, there does not appear to be a need to adjust the C sequestration value based on vegetation management occurring in the active zone.

Future studies of true C flux occurring in the active and passive zones (discussed further in Sections 7.2 and 7.3) will provide the empirical data necessary to revise the estimates provided in this study based on field measured values of C flux occurring within each zone of the ROW and within each landscape vegetation type. Revised vegetation management of the ROW active and passive zones presents the simplest and most cost effective means for Montana DOT to increase C sequestration in the ROW and therefore warrants additional discussion in Section 7.2 and 7.3.

7.2 Active Vegetation Management ROW Zone and C Sequestration Potential

The active zone of the ROW extends 15 feet from the edge of the paved roadway. Interstate highways will have four of these zones occurring at the same reference location due to travel lanes separated by a vegetated center median, while all other routes have two active zones at any reference location, one on either side of the roadway. Based on the total width of the active zones and length of centerline miles for each route type, the total acreage of the Active Zone of the ROW was calculated (Table 6).

After obtaining ROW active zone acreage, in order to provide an estimate as to the amount of carbon that this area has the potential to sequester annually, the flux tower annual C flux estimate of 0.40 metric tons of carbon per acre of grasslands was applied. Ascribing the carbon flux tower estimates for grassland vegetated landscapes to the active zone is appropriate as Montana DOT's Maintenance manual specifies that vegetation in the active zone is to be mowed as necessary and large woody vegetation is removed as necessary for safety from the active zone. Table 6 below summarizes the results of this evaluation.

Route Type	Total Road Centerline Miles	ROW Active Management Strip Area (Acres)	Grassland Carbon Flux (NEE) (metric tons C/acre per year)	Total Annual C Sequestration by ROW Active Management Strip (metric tons C)
NHS Interstate	1,280	9,892	0.40	3,957
NHS Non-interstate	2,995	10,900	0.40	4,360
Primary	2,581	9,392	0.40	3,757
Secondary	4,607	16,766	0.40	6,706
Total Active Management ROW Strip Potential C Sequestration				18,780

Table 6 – Active Zone ROW Management Area Potential C Sequestration

The value of 18,780 metric tons of carbon sequestered by the Active Zone of the ROW represents the quantity of C sequestered by this landscape per year as natural grasslands based on flux tower estimated landscape values. In terms of the value of this estimate on a carbon exchange market, this represents 68,860 tCO_2e in a market such as the CCX based on conversion from metric tons of C to metric tons of CO_2. Additionally, this value is approximately equal to the emissions from 14,497 passenger vehicles driven for a year, or the emissions associated with providing electricity to 9,471 homes for an entire year (EPA, 2014b). The most accurate estimate of carbon sequestered in the active zone of the ROW may be achieved through collection of the actual carbon flux occurring in the active zone under current management strategies through field collection. This approach could provide an empirically measured value to replace the estimate used in Table 6. New Mexico DOT's ongoing carbon sequestration study provides a good model for conducting this data collection effort. This field study could also include testing of other vegetation management strategies such as reduced vegetation mowing of the active zone or the addition of leafy plant species into the native grassland vegetation within the active zone. Some species of plants are known for biomass production efficiency due to their minimal water needs and fixation of relatively large amounts of carbon including maize, sugar cane, millet, or sorghum (Storey et al., 2012). A seed mix including species of plant such as these may demonstrate opportunity to augment ROW carbon sequestration. By revegetating the active zone of the ROW following typical road construction projects with a seed mix that includes more efficient carbon fixing plants that can be managed without any additional cost in the disturbed ROW, the overall carbon sequestration can be increased. In order to measure this increase, one must measure the current C flux in the active zone under current active zone ROW management strategies, and also the C flux occurring in the active zone under proposed new vegetation seed mixes and management strategies. Task 3 of the ongoing study funded by CESTiCC may accomplish this goal through experimentation.

Another strategy for reducing GHG emissions through revised ROW vegetation management in the active zone is to reduce the GHG emissions associated with the management itself. FHWA provides a Highway Right of Way Carbon Sequestration Estimator Tool with their 2010 study. This tool calculates carbon emissions generated by vegetation management activities such as mowing or herbicide/pesticide application. By reducing the frequency of these activities, one not only potentially increases the amount of aboveground carbon stocks in vegetation, but also reduces the GHG emissions required to manage the vegetation, which may be accounted for when determining the additional carbon sequestered by a revised vegetation management plan. As Montana DOT's Maintenance Manual is somewhat vague with regard to the frequency and means of vegetation control in the active zone, this document should first be revised to provide clear guidance as to the recommended frequency of vegetation mowing and maximum allowable height of vegetation in the active zone in order to provide a clear baseline with which to compare a revised vegetation management plan.

7.3 Passive Vegetation Management ROW Zone and C Sequestration Potential

As discussed in Section 3.5, the passive zone of the ROW begins 15 feet from the edge of pavement and continues to the boundary of ROW property ownership. The passive zone is not managed by Montana DOT unless special circumstances warrant, such as woody vegetation posing a risk to the roadway or a need to control drifting snow. The passive zone of the ROW includes 118,878 acres, or 72% of the total ROW. Therefore, vegetation management in the passive zone may represent the greatest potential for Montana DOT to increase C sequestration within its ROW and at the lowest annual cost due to minimal management efforts directed at this area of the ROW.

As there is no vegetation management by Montana DOT occurring in the passive zone, one of the best options to increase C sequestration without any additional management needs is to convert the passive zone of the ROW to vegetation types that have the potential for greater annual C uptake. The revegetation of the passive zone could be systematically conducted in coordination with normal road construction projects in order to minimize costs to Montana DOT.

This strategy will likely be most effective in grassland landscape types. It is unlikely that greater C sequestration could be accomplished in the landscape types identified as riparian, montane forest, shrub grassland, or plains forest, without additional vegetation management by Montana DOT. This is because these landscape types already include large woody vegetation and are likely already sequestering the maximum amount of C possible. Fortunately, these landscape types represent a combined total of 30% of Montana DOT ROW, while grasslands make up the remaining 70% of the ROW.

One can estimate the potential to increase annual C sequestration in the passive zone of the ROW in grassland landscapes. As Table 2 shows, the flux tower estimate of grasslands carbon sequestration is 0.40 metric tons of carbon per acre, per year, while shrublands sequester 0.54 metric tons of carbon per acre, per year. Thus, by converting all grasslands to shrublands over a long period of time through purposeful revegetation of these lands, Montana DOT could document an increase in carbon sequestration of approximately 35%. Intermountain and plains grasslands represent 115,715 ROW acres and are found to sequester 46,286 metric tons of carbon per year. These lands would be estimated to sequester 62,486 metric tons of carbon as shrublands, an increase of 16,200 metric tons of carbon sequestration. In a carbon exchange such as the CCX, this represents a value of 59,400 tCO_2e that Montana DOT would be able to sell or trade on this market by converting all passive zones of ROW from grasslands to shrublands. The additional 16,200 metric tons of carbon sequestration is approximately equal to removing 12,505 passenger vehicles from the road for one year, or the annual energy use of 5420 homes (EPA, 2014b).

7.4 Ability of Montana DOT to Sell or Trade Carbon Credits

Carbon sequestration projects that request listing on the Chicago Climate Exchange Offsets Registry Program must demonstrate the ability of new land management practices to sequester more carbon than previous land management techniques. Thus, for Montana DOT to register carbon credits on a market such as the CCX, the baseline carbon sequestration estimates in Montana ROW must be accurately documented as well as the change in carbon sequestration under revised management practices. The baseline carbon sequestration estimates in this study provide a starting point for establishing a defensible and accurate assessment of carbon sequestration occurring in Montana DOT ROW. By conducting field investigations to empirically measure current carbon sequestration in the active and passive ROW zones and potential carbon sequestration under various new active zone management strategies and passive zone vegetation re-planting, one is able to determine the net difference in sequestration due to revised land management practices, which is necessary to become eligible to sell carbon credits in an exchange market.

Between 2005 and 2009, more than 15,000 farmers, ranchers, and foresters participated in the CCX due to carbon mitigation practices conducted on more than 25 million acres of land (Ritten et al., 2012). Trading volume on the CCX peaked in 2008, but has slowed dramatically since, especially following the expiration of the voluntary cap and trade program offered through the CCX in 2010, however, the CCX is still a functioning registry for the over the counter carbon credit market. In addition, there are other international affiliates to the CCX, such as the Montreal

Climate Exchange (Canada), Tianjin Climate Exchange (China), EnVex (Australia) and the European Climate Exchange (Ritten et al., 2012).

Carbon prices on the various exchanges have fluctuated significantly since their inceptions, with a high value of over seven U.S. dollars per metric ton of CO_2 sequestered, with recent lows well under one U.S. dollar per metric ton (Ritten et al., 2012). However, the value of carbon in exchange markets is predicted to greatly increase in the future as demand for the service increases. Ritten et al. (2012) provide the lowest predicted price of metric ton of CO_2 sequestered in the year 2020 as six U.S. dollars per metric ton and the highest value as thirty-seven U.S. dollars per metric ton. These values were obtained from an American Electric Power 2004 study (AEP, 2004) that evaluated the impact of various GHG regulations on the price of carbon in exchange markets. For the example given in Section 7.3 (Montana DOT revegetating the passive zone of grasslands ROW with shrubland vegetation), the quantity of 59,400 tCO_2e has a low economic value of $356,400 U.S. dollars and a high economic value of $2,197,800 U.S. dollars. Clearly the price of carbon in exchange markets strongly influences the economic value of a carbon sequestration program for Montana DOT.

8.0 STUDY LIMITATIONS

The values provided in this study are estimates based on the best available data. The exact ROW acreage owned by Montana DOT and the ROW acreage according to landscape vegetation type are likely to vary somewhat from the values reported in this study. However, as the sampling effort demonstrated, the data do appear to be accurate based on a manual verification of selected aerial and roadway imagery. The values of carbon sequestered annually per acre of landscape vegetation type are estimates derived from numerous empirical measurements. As such, they are expected to accurately represent these landscape vegetation types, however empirically measured data collected from these vegetation types in the ROW would provide a more accurate estimate of the carbon sequestration occurring in Montana DOT ROWs.

9.0 CONCLUSIONS

It is found that Montana DOT ROW includes approximately 165,829 acres, over 70% of which is characterized by a variety of grassland vegetation. The estimated carbon sequestration potential of these lands based on their predominant vegetation types is 75,292 metric tons of carbon per year. Montana DOT maintains an active zone of the ROW for roadside safety purposes totaling 46,951 acres and with a carbon sequestration potential of 18,780 metric tons of carbon per year as a natural grassland landscape. The passive zone of the ROW includes 118,878 acres, of which approximately 70% is grasslands vegetation. Converting the grassland passive ROW zones to shrubland represents an increase of 16,200 metric tons of annual carbon sequestration with a maximum estimated value of nearly 2.2 million dollars on carbon exchange markets and represents the annual removal of approximately 12,505 passenger vehicles from the road in terms of overall emissions reduction (EPA, 2014b).

In order for Montana DOT to augment the carbon sequestration in its ROW for the purpose of meeting future GHG emission standards or to generate revenue by selling carbon credits, Montana DOT may document current carbon sequestration occurring in the active and passive zones of the ROW through field measurement of carbon flux, and field measurements of carbon flux under revised vegetation management practices tested within the active zone and replanting of the passive zone. By revising Montana DOT's Maintenance Manual to describe the former and revised vegetation management practices, Montana DOT would then provide the documentation to quantify and describe the change in carbon sequestration occurring in the ROW.

The use of the ROW in Montana to provide a potential GHG emission offset from the transportation sector appears to be promising. Sequestration of C in terrestrial ecosystems offers a low-cost means of reducing net C emissions with significant collateral benefits: restored habitat for plants and wildlife, reduced water runoff, and increased production of agricultural and forest products (Litynski et al., 2006). If national or state level policy one day mandates that state transportation departments take action to reduce the overall GHG emissions, terrestrial carbon sequestration in roadside ROWs provides perhaps the easiest means to offset emissions. Terrestrial carbon sequestration could serve a strategic role in offsetting GHG emissions from the transportation sector in the future. A carbon sequestration program for Montana DOT should include a defensible quantification of current annual carbon sequestration occurring in Montana DOT ROW, a plan to systematically revegetate the passive zone of grasslands ROW in conjunction with road construction projects, and should revise Sections 5.6 – 5.9 of Montana DOT's Maintenance Manual to describe former and revised vegetation management practices in the active zone of the ROW. By implementing a program such as this, Montana DOT is prepared for future GHG regulations, contributes to national goals of reducing GHG emissions, gains additional value from improved ecosystem services in its ROW, and may produce an additional revenue stream through trading or selling carbon credits in a cap and trade carbon exchange market.

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