Roadside Vegetation and Soils on Federal Lands – Evaluation of the Potential for Increasing Carbon Capture and Storage and Decreasing Carbon Emissions

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16. Abstract

This study explored the roadside potential for carbon capture and storage (CCS) by eight federal land management agencies (FLMAs) in the Departments of Interior, Agriculture and Defense. The eight FLMAs collectively manage 301,588 miles (mi) (485,255 kilometers (km)) of roads of which over 70 percent are unpaved. Moreover, the eight FLMAs construct or improve an average of 1,750 miles (mi) (2,816 kilometers (km)) of roadway per year, presenting an opportunity to consider strategies to maximize CCS during roadside reclamation planning and project implementation.

Our estimate of roadside acreage available for CCS relied on the concept of the “road effect zone” (REZ), an area defined as 50 m from unpaved roads and 100 m from paved roads. Based on this definition, we estimated that there are over 17 million acres within the REZ that are available for CCS. To estimate the potential carbon uptake within this area, we relied on measurements of net carbon dioxide (CO_2) exchange from a large sample of globally distributed eddy covariance towers arrayed according to functional vegetation types. Then, for each of four FLMA case studies across four distinct biomes, we calculated the distribution of functional vegetation types within the REZ and estimated the total annual carbon flux. We then extrapolated these estimates nationally based on the total REZ area available for CCS.

We estimated that the eight FLMAs have the potential to collectively capture and store nearly 8 million metric tons of carbon each year. In reality, current carbon uptake is likely constrained within the REZ due to factors such as soil compaction, soil-nutrient limitations and pollution. Our estimates of CCS, therefore, are intended to demonstrate the potential for carbon uptake given the prospects of future enhanced roadside vegetation and soil management.

17. Key Words

carbon sequestration, roadside vegetation, greenhouse gas emissions, public roads, federal land management agency, climate change, road effect zone

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GLOSSARY

Abbreviations, Acronyms and Definitions

BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
BOR	Bureau of Reclamation
C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
CO_2E	carbon dioxide equivalent, is a measure to compare various greenhouse gases based upon their global warming potential (GWP) and are usually expressed in metric tons
CCS	carbon capture and storage = carbon sequestration
DOD	Department of Defense
DOI	Department of Interior
FHWA	federal highway administration
FLMA	federal land management agency
GHG	greenhouse gases
GIS	geographic information system
JRA	Jordan Resource Area
NEE	net CO_2 exchange
NHS	national highway system
NPS	National Park Service
REZ	roadside effected zone
ROW	right-of-way
USACE	U.S. Army Corps of Engineers
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
WMNWR	Wichita Mountains National Wildlife Refuge
YNP	Yellowstone National Park

Conversion Factors

Multipy	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 grams (10^6) = 1 metric ton (t)
1 gigagram (Gg) = 1 billion grams (10^9) = 1,000 metric tons (Mt)
1 teragram (Tg) = 1 trillion grams (10^{12}) = 1,000,000 metric tons

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EXECUTIVE SUMMARY

The increase in atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHG) has contributed to global warming and intensified the search for opportunities to reduce their concentration. One such method is the capture and storage of CO_2 by vegetation and soils, also known as terrestrial carbon sequestration. Since the transportation sector contributed nearly 27% of the United States' GHG emissions in 2010 and vehicles on roads comprised 84% of that total, it appears fitting that the present vegetation and soils along roads should be evaluated for their potential for carbon capture and storage (CCS) in the U.S.

This study adds to the assessment of the National Highway System's right-of-ways (ROWs) in 2010, by exploring the roadside potential for CCS by the eight federal land management agencies (FLMAs) – U.S. Forest Service, National Park Service, U.S. Fish and Wildlife Service, Bureau of Land Management (BLM), Bureau of Reclamation, Bureau of Indian Affairs, US Army Corps of Engineers and military installations. The eight FLMAs collectively manage 301,588 miles (mi) (485,255 kilometers (km)) of roads of which nearly 70 percent are unpaved. The FLMA road mileage is approximately 7.5 percent of the estimated 4 million mi (6.4 million km) of public roads in the United States. Within that total, the eight FLMAs construct or improve an average of 1,750 miles (mi) (2,816 kilometers (km)) of roadway per year, presenting an opportunity to consider strategies to maximize CCS during roadside reclamation planning and project implementation. This study focused primarily on FLMA roads that could be used by passenger cars, although some agency four wheel drive and other low maintenance roads were incorporated by virtue of the different methods the eight agencies use to account for their road system.

Unlike the national highway system, the FLMAs do not have ROWs. That is, most FLMA roadsides do not change to private or other ownership a fixed distance from the road's surface. Therefore, our estimate of roadside acreage available for CCS relied on the concept of the "road effect zone" (REZ), an area defined as 50 m from unpaved roads and 100 m from paved roads. Based on this definition, we estimated that there are over 17 million acres within the REZ that are available for CCS. To estimate the potential carbon uptake within this area, we relied on measurements of net CO_2 exchange from a large sample of globally distributed eddy covariance towers arrayed according to functional vegetation types. Then, for each of four FLMA case studies in a national wildlife refuge, a national park, a national forest and a BLM resource area across four distinct biomes, we calculated the distribution of functional vegetation types within the REZ and estimated the total annual carbon flux. We then extrapolated these estimates nationally based on the total REZ area available for CCS.

We estimated that the eight FLMAs have the potential to collectively capture and store over 8 million metric tons of carbon each year along their roads. That is the equivalent to the annual carbon emissions of over 6 million passenger cars or 1.6% of total annual greenhouse gas emissions from the transportation sector. In reality, current carbon uptake is likely constrained within the REZ due to factors such as soil compaction, soil-nutrient limitations, and pollution. Therefore, our estimates of CCS are intended to demonstrate the potential for carbon uptake given the prospects of enhanced roadside vegetation and soil management. The report concludes by describing opportunities to increase CCS via various management practices and also provides an appendix for managers to do simple calculations to evaluate carbon emissions created or prevented by altering their roadside vegetation management.

1. INTRODUCTION

The increase of the atmospheric concentration of greenhouse gases (GHG) over the past century has contributed to global warming and the search for opportunities to reduce the atmospheric concentration of carbon dioxide (CO_2), a major GHG. The primary methods to reduce atmospheric CO_2 concentrations are the capture and storage of CO_2 in geologic formations or terrestrially, by vegetation and soils.

The transportation sector contributed nearly 27% of the United States' GHG emissions in 2010; only the industry sector was higher at 30% (EPA 2012). In 2010, this total was 1,838.6 Tg of CO_2 equivalent (million metric tons of CO_2 eq.). Of the transportation sector's total, vehicles on roads – passenger cars (43%), light trucks (19%) and medium- and heavy-duty vehicles (22%) – accounted for 84% of the sector's total GHG emissions (EPA 2012).

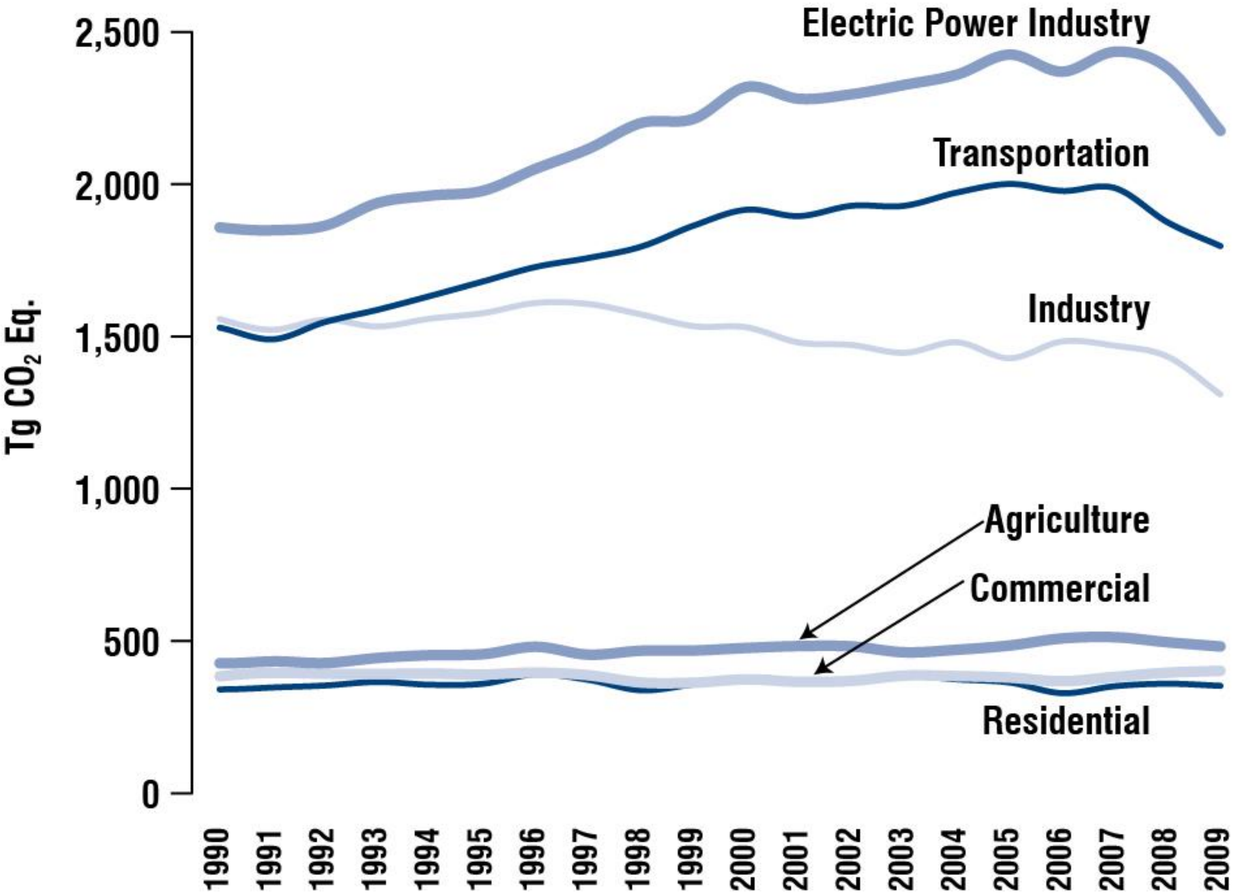


Figure 1: U.S. greenhouse gas emissions by sector. (Environmental Protection Agency 2012).

The U.S. road system is a major component of the nation's transportation infrastructure with 4,011,635 miles (6,456,101 km) of public roads managed by various entities, including federal, state, county, tribal and municipal agencies (U.S. Census Bureau 2007). This study focuses on the potential to sequester CO_2 in roadside land administered by federal agencies and reduce GHG emissions by roadside vegetation management.

Biological carbon sequestration, through the use and management of land, is a viable means of increasing the absorption of atmospheric carbon by vegetation and soil. The two major U.S. sectors addressing biological carbon sequestration are silviculture and agriculture (CBO 2007). A variety of forestry and agricultural practices have proven effective at increasing carbon sequestration (e.g., forest management, afforestation, no till cropping, changing grazing practices). The opportunity exists to enhance carbon capture and storage along road networks akin to techniques developed for silviculture and agriculture, effectively linking a major source of greenhouse gas emissions with a climate mitigation strategy.

There are estimated to be 3.4 million acres (1.4 million hectares (ha)) of unpaved land along right-of-ways (ROWs) for the 163,000 miles (262,000 km) of roads in the National Highway System (Figure 2) in the contiguous United States (FHWA 2010). This estimate covers only a small portion, approximately four percent, of the nation's public roads. The potential to capture and store carbon along other public roads, such as those of the federal land management agencies (FLMAs), could provide additional opportunities for the mitigation of climate change by capturing and storing carbon. FLMAs are agencies within the Departments of Interior, Agriculture and Defense, such as the U.S. Forest Service, National Park Service, and the Army Corps of Engineers. Collectively, FLMAs are responsible for 301,588 miles (mi) (485,255 km) of public roads (see section 2.2), which represents 7.5 percent of the public roads in the United States. In addition, proactively managing roadsides for carbon capture and storage (CCS) is compatible with many new policies and directives given to the agencies to address climate change.

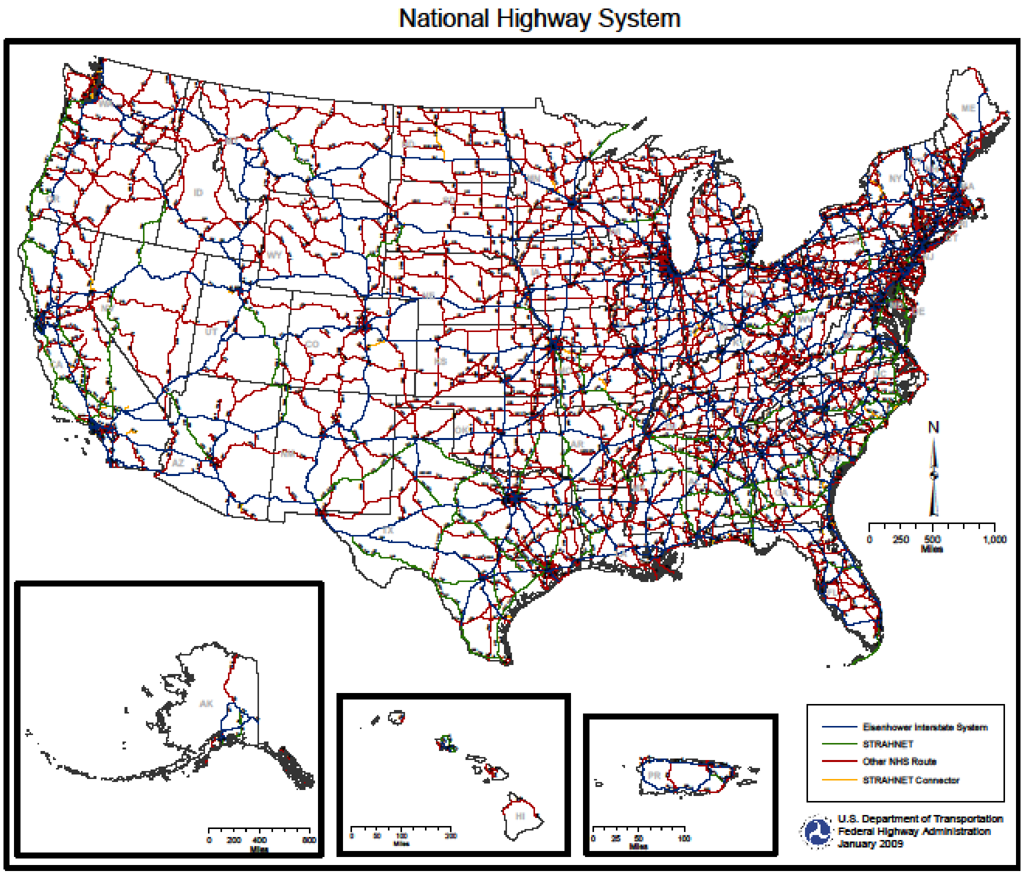


Figure 2: Map of the national highway system. (Source: Federal Highway Administration.)

The aim of this study is to provide a framework for estimating the current and future potential to capture and store carbon in the millions of acres of roadside vegetation and soil along the U.S. public roads within the lands administered by federal land management agencies. It also includes options to estimate the potential reductions in carbon emissions resulting from roadside vegetation management activities.

This report is focused on the federal land management agencies (FLMAs) and the public roads for which they have primary responsibility. The eight FLMAs of particular interest are in the following three administrative departments:

1. Department of Interior
    - National Park Service (NPS)
    - U.S. Fish and Wildlife Service (USFWS)
    - Bureau of Land Management (BLM)
    - Bureau of Reclamation (BOR)
    - Bureau of Indian Affairs (BIA)

2. Department of Agriculture
    - U.S. Forest Service (USFS)

3. Department of Defense (DOD)
    - Military installations
    - US Army Corps of Engineers (USACE)

This project seeks to help managers and policy makers evaluate the potential role that roadside soils and vegetation can contribute to the overall reduction of U.S. contributions to greenhouse gases. It also seeks to demonstrate, through a series of case studies, that roadside vegetation and soils could be embraced as an asset in the search for solutions to increase carbon capture and storage in the United States. To do so, we highlight four individual FLMA management units (Yellowstone National Park, Wichita Mountains National Wildlife Refuge, the BLM's Jordan Resource Area, and the Okanogan-Wenatchee National Forest) to demonstrate a simple, yet effective technique to estimate both roadside acreage available for CCS, as well as the potential uptake of carbon. It explores various roadside vegetation management actions that could lead to increased CCS. Lastly, it has an appendix for managers to do simple calculations to evaluate carbon emissions created or prevented by roadside vegetation management activities and product use (i.e., herbicides, different types of mowers).

2. A FRAMEWORK FOR CAPTURING AND STORING CARBON ALONG ROADSIDES

2.1. Roadside CCS Implements a Variety of FLMA Policies and Strategies

Since 2009, there have been a series of new federal policies, strategies and direction to encourage federal land management agencies to address climate change through their management, programs and research. A brief review of these policies illustrates that the development of roadside management of vegetation and soils for carbon capture and storage is consistent with emerging federal direction relative to climate change mitigation.

2.1.1. Presidential policy

President Obama signed an Executive Order in October 2009 giving direction to the federal government to create a clean energy economy (Executive Order 13514). Executive Order 13514 included direction to federal agencies to "reduce their greenhouse gas emissions from direct and indirect activities" and to "[c]onsider and account for sequestration and emissions of greenhouse gases resulting from federal land management practices".

2.1.2. Departmental policy

On February 22, 2010, Secretary Ken Salazar, signed a Secretarial Order for the Department of the Interior (DOI) to address the impacts of climate change on America's water, land and other resources (Secretarial Order 3289). Updating related DOI Orders dating back to 2001, this Order established a Department-wide approach for applying scientific tools to increase the understanding of climate change and to coordinate an effective response.

In its purpose section, Interior agencies were directed to continue their work to quantify the amount of carbon stored in U.S. forests, wetlands and grasslands. Section 4 establishes the DOI's Carbon Storage Project that is to, in part, establish methodologies and develop partners to enhance carbon storage in plants and soils.

The Department of Agriculture issued its strategic plan to address climate change in 2010 (USDA 2010). A key element of the USDA's plan focused on mitigation and included strategies to increase carbon sequestration through research, the application of risk management paradigms, conservation planning, and program management.

2.1.3. Federal land management agency strategies and direction

The USDA Forest Service developed a response to address climate change, which they published in July of 2010 (USDA Forest Service 2010). Included in the agency's report is their research strategy that includes "[i]ncrease carbon sequestration and reduce emissions (mitigation)."

Similarly, the National Park Service (NPS) published their response to climate change using both mitigation and adaptation strategies in September of 2010 (National Park Service 2010). In their mitigation strategy the NPS proposed to promote land management that enhances carbon storage and assess the potential for biological carbon sequestration (within soil and vegetation) to mitigate greenhouse gas emissions.

The U.S. Fish and Wildlife Service also developed a strategic plan to address climate change, which includes mitigation strategies (U.S. Fish and Wildlife Service 2011). Their plan contains a goal to "conserve and restore fish and wildlife habitats at landscape scales while simultaneously sequestering atmospheric greenhouse gases" and includes working "with partners to implement carbon sequestration projects in strategic locations."

Throughout the federal government, the emphasis on implementing strategies to address climate change has increased substantially in the past few years. Conducting an assessment to describe the potential for FLMA programs to take advantage of its roadside vegetation and soils to capture and store carbon is a practical approach to meet these new directives. Evaluating options for roadside vegetation management strategies that reduce GHG emissions may produce benefits at both the agency level and at the for individual unit level.

2.2. FLMA Roads System

As previously stated, the eight federal land management agencies collectively manage 301,588 miles (mi) (485,358 kilometers (km)) of roads that are paved, gravel or graded earth surface (Table 1). This amount is approximately 7.5 percent of the estimated 4 million miles (6.4 million km) of public roads in the United States. FLMAs and their roads system offer considerable potential for roadside carbon management. Of the eight FLMAs that we focus on in this report, the Bureau of Indian Affairs manages the largest amount of roads with a total of 90,731 mi (146,017 km) while the Bureau of Reclamation manages the least amount of roads with 1,863 mi

(2,998 km) (Table 1). Due to the different missions, policies and enabling legislation of each of the FLMAs, it is acknowledged that roadside vegetation and the distance from the road that soils and plants to be managed for carbon capture and storage may not be treated identically. It is apparent that tribal lands, National Parks, multiple use-sustained yield lands and military installations each have different priorities and practices. Therefore, if roadside carbon capture and storage policy and practice is advanced, it may be necessary for policy makers, administrators or legislators to either re-align or change the existing policy and practices of the FLMAs.

Table 1: Miles of road, paved and unpaved,on federal and Indian lands (FHWA 2008).

Federal Land Management Agency	Paved Road Length[1] Miles (Kilometers)	Total Road Length[1] Miles (Kilometers)
U.S. Forest Service (USFS)	31,400 (50,533)	99,100 (159,486)
National Park Service (NPS)	5,450 (8,771)	9,550 (15,369)
Bureau of Indian Affairs (BIA)	36,883 (59,357)	90,731 (146,017)
U.S. Fish and Wildlife Service (FWS)	415 (668)	4,900 (7,886)
Bureau of Land Management (BLM)	N/A	68, 880 (110,872)
Bureau of Reclamation (BOR)	1,082 (1,741)	1,863 ((2,998)
Military Installations	14,400 (23,175)	14,400 (23,175)
U.S. Army Corps of Engineers (USACE)	6,996 (11,259)	12,164 (19,576)
Total	**96,626 (155,504)**	**301,588 (485,358)**

[1] FHWA. 2008. Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance, Transportation Serving Federal and Indian Lands (Chapter 12). FHWA, Washington, D.C. Data from Exhibit 12-3. [http://www.fhwa.dot.gov/policy/2008cpr/chap12.htm#body]

2.3. Carbon Capture and Storage Background

Carbon capture and storage (CCS; also called carbon sequestration) refers to a collection of approaches that seek to transfer CO_2 from the atmosphere into other long-lived carbon pools, typically geologic formations (Lal 2008). Most CCS approaches seek to actively remove CO_2 from the atmosphere using engineering techniques. Biological carbon sequestration efforts seek to improve the ability of the biosphere to remove CO_2 from the atmosphere; at present, terrestrial vegetation removes approximately 28% of anthropogenic CO_2 emissions from the atmosphere on an average, annual basis (Le Quéré et al. 2013).

Observing ecosystem CO_2 uptake can be done by measuring the changes in stocks of carbon in vegetation and soils over time, or by directly measuring the flux between the atmosphere and the biosphere using chamber techniques, inverse methods that attribute observations of atmospheric CO_2 concentrations to source areas, or eddy covariance measurements from flux towers. From the perspective of observing the net flux of CO_2 between the biosphere and the atmosphere at the plot scale (tens of meters to kilometers), the eddy covariance technique offers a number of advantages including: non-invasive observations, the ability to measure flux continuously at high temporal resolution (typically half-hourly) over long time scales (decades), and the ability to synthesize multiple measurement sites into global databases (Baldocchi 2008). We build upon these advantages here and explore measurements of the net ecosystem exchange of CO_2 (NEE, i.e. the net exchange of CO_2 between the surface and atmosphere) from eddy covariance towers in the FLUXNET network for different vegetation classes that are likely candidates for CCS efforts along roadsides in the U.S.

2.4. Carbon Capture and Storage in a Roadside Context

To date, the federal lands roadside revegetation manuals and reports have focused very little, or not at all, on techniques that could be beneficial to CCS (i.e., Steinfield et al. 2007a, Steinfield et al. 2007b, Armstrong et al. 2011). Therefore, CCS as a short term climate mitigation strategy, and techniques that could be used to implement the strategy, are worthy of exploration.

The unpaved areas adjacent to FLMA roadways are ideal places to consider CCS strategies for two primary reasons. First, these areas are easily accessible by managers. Second, the FLMAs' road systems are constantly being maintained, improved, and expanded. In this context, CCS can be viewed as an ancillary byproduct of successful roadside reclamation and management, with numerous positive benefits beyond safety and efficiency, including broader ecological functions such as wildlife habitat, plant communities, and water quality. In other words, CCS follows directly from prudent management of vegetation along roadways.

So what is a roadside in the context of CCS? From a technical management standpoint, a roadside "refers to any area of disturbance associated with road maintenance, modification, or construction, including waste areas and source pits associated with construction" (Steinfeld et al. 2007a). Such areas are often highly disturbed environments, with compacted soil, altered microbial communities, and often deficient in soil nutrients and organic matter such that conditions for plant growth are less than ideal (Steinfeld et al. 2007a).

For the purposes of this report, we characterize the unpaved areas along FLMA roadways in a broader management context than traditional definitions of "roadside" or "right-of-way." The National Highway System (NHS) highways usually have fenced right-of-ways that separate lands under the jurisdictions of the federal, state and metropolitan transportation authorities from adjacent roadside owners. However, on FLMA roads the ownership is primarily that of the FLMA. Therefore, there is little or no fencing since an ownership demarcation is unneeded.

Given the lack of "hard boundaries" along FLMA roads, we borrow the term ecological "road-effect zone" (REZ) from the scientific literature (Forman 2000), which was originally defined as a broad area along roadways that had wide-ranging and measureable impacts on a variety of ecological processes including habitat fragmentation, wildlife mortality, noise and chemical pollution, dust, disruption of hydrologic cycles and water quality, soil erosion, and introduction of noxious weeds. While this definition includes many processes that are beyond the scope of this report, the concept and bounds of the REZ are relevant to the discussion of CCS. Hence, based on assumptions in Forman (2000), we opted to characterize the REZ in FLMAs according to two basic categories of roadways. For paved roads, the REZ was assumed to be 109 yards (100 m) on either side of the roadway. For unpaved roads (including gravel and bare earth), the REZ was assumed to be 55 yards (50 m) on either side of the roadway. The rationale for broadening the definition of roadside is that the REZ is an easily accessible area along roadways that offers opportunities for enhancing vegetation and soils management for CCS. It is acknowledged that this definition may not apply along all roadways within FLMAs, such as on Indian reservations and other locales where private lands abound.

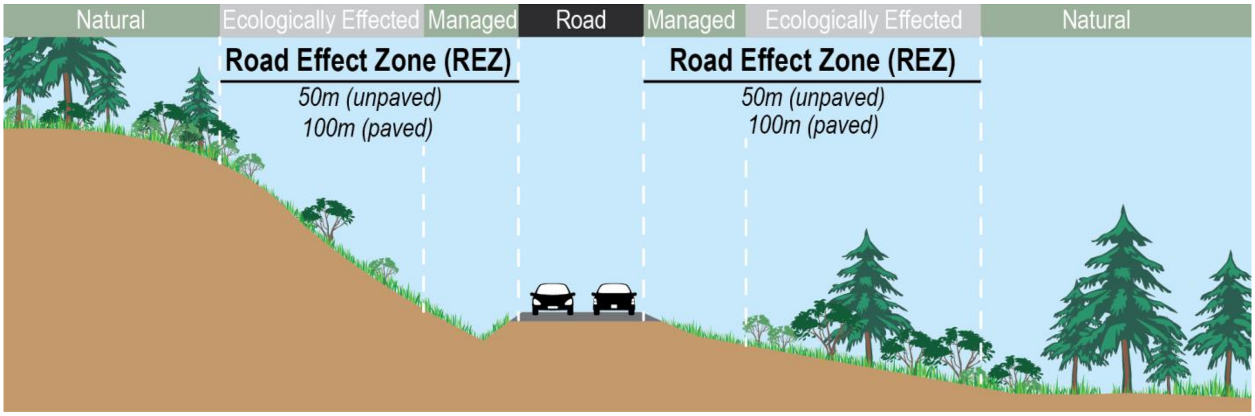


Figure 3: Stylized cross-section of typical roadside zones described for carbon sequestration including road effect zones (Forman 2000).

2.5. Considering CCS after FLMA Road Construction and Re-construction

The FLMAs' road systems are constantly being maintained, improved, and even expanded in some locales. Annual road construction and reconstruction programs provide an ideal opportunity to consider carbon capture and storage as part of the reclamation of roadsides after construction or resurfacing of roads. Not all the mileage reported for reconstruction projects necessarily disturbs adjacent roadside soils and vegetation, but the projects do create an opportunity to consider adjacent roadsides for CCS management. Based on the FHWA - Federal Lands Highways' annual reports, the eight FLMAs constructed or improved more than 8,750 mi (14,081 km) of their roads in the five-year period of 2007-2011 (Table 2). This is an average of 1,750 mi (2,816 km) per year of road improvements for which opportunities exist to consider strategies to maximize carbon capture and storage during roadside reclamation planning and project implementation. Assuming 10 m of soil disturbance on either side of the roadway, or if not disturbed, at least that could be considered for CCS management, this equates to approximately 13,917 acres (5,632 ha) per year ,collectively. Road construction and reconstruction projects offer the FLMA sample opportunities to incorporate CCS management into tens of thousands of acres of roadsides each year.

Table 2: Summary of the length in miles (km) of road construction and improvement based on the FHWA (Federal Highway Administration), Federal Lands Highway Division's annual reports (FHWA 2007, FHWA 2008, FHWA 2009, FHWA 2010, FHWA 2011).

Federal Lands Highways Programs	Lane Miles (km) Constructed/Improved by Fiscal Year					
	2007	2008	2009	2009-2010 (Recovery Act[1])	2010	2011 [2]
FLH – Indian Reservation Roads	0	0	0	0	0	2106 (3,389)
FLH – Park Roads and Parkways	378 (608)	203 (327)	92 (148)	225 (362)	77 (124)	1275 (2,052)
FLH - Forest Highways	238 (383)	220 (354)	166 (267)	95 (153)	96 (154)	0
FLH – Public Lands Discretionary	11 (18)	2 (3)	0	95 (153)	1 (2)	0
FLH- Forest Highways and Public Lands Discretionary	0	0	0	0	0	425 (684)
FLH - Emergency Relief for Federally Owned Roads	0	3 (5)	135 (217)	0	29 (47)	0
FLH – Refuge Road Program	56 (90)	31 (50)	43 (69)	36 (58)	61 (98)	65 (105)
Recovery Act - Using Funds from Other Agencies	0	0	0	1524 (2,453)	0	0
Total Other Programs	35 (56)	68 (109)	205 (330)	466 (750)	105 (169)	184 (296)
Total Lane Miles Constructed/Improved	718 (1,156)	527 (848)	641 (1,032)	2441 (3,928)	369 (594)	4055 (6,526)

[1] Recovery Act is the American Recovery and Reinvestment Act of 2009

[2] Annual report didn't differentiate between the Recovery Act and the Annual Program

3. ESTIMATION OF ACREAGE AND CARBON CAPTURE AND STORAGE POTENTIAL ALONG FLMA ROADSIDES

3.1. Introduction

A previous study estimated the amount of carbon sequestered along unpaved right-of-way of the national highway system (NHS). It was estimated that there are over 3.4 million acres of unpaved right-of-way along the 164,000 mi (km) of highways of the NHS (FHWA 2010). Approximately 3.6 million metric tons of carbon is sequestered per year for this acreage, an amount equivalent to the annual carbon dioxide emissions of approximately 2.6 million passenger cars (FHWA 2010). This estimate was developed from analysis of land cover types within a random sample of 1,000 polygons across the conterminous U.S. highways. The sampled land cover distributions provided the basis for extrapolating average carbon sequestration rates for basic vegetation physiognomic groups (e.g. deciduous, coniferous, mixed, grasses, shrubs).

To date, there has been no systematic estimate of the CCS potential along the 301,588 miles (485,359 km) of roads managed by the eight FLMAs.

3.2. Methodology

We selected individual management units from four different FLMAs to conduct a series of case studies for estimating roadside acreage and CCS potential. The management units we selected are a National Park, a National Wildlife Refuge, a BLM Resource Area, and a National Forest. We adopted the case-study approach to demonstrate a simple and effective method for managers and policy makers to estimate the roadside acreage available for CCS and the potential uptake of carbon.

We chose four individual FLMA management units on the basis of prior knowledge of roads management, as well as the desire to represent a variety of environmental and biophysical conditions. Thus, we selected a representative location from the Pacific Northwest, the Great Basin, the Rocky Mountains and the Great Plains (Figure 4). For each of these case studies, we compiled the most current and comprehensive GIS roads data available. These data were either acquired directly from agency personnel or from the agency's official website. From these data, we classified the FLMA roadways according to broad functional road types (paved versus unpaved) and then applied the appropriate REZ buffer (200 m for paved roads; 100 m for unpaved roads). The road length multiplied by the REZ width enabled estimation of the total REZ acreage within each FLMA case study.

Figure 4: Location of the four case study projects. Locations include a National Park, a Bureau of Land Management Resource Area, a National Wildlife Refuge, and a National Forest.

To estimate potential carbon capture within the REZ, it was necessary to first characterize the vegetation along FLMA roadways. For this we used geographic information system (GIS) datasets acquired from LANDFIRE (http://www.landfire.gov) that characterized vegetation according to broad, functional type (physiognomic class – e.g. evergreen v. deciduous). LANDFIRE data products are designed to facilitate national and regional strategic planning of management activities, and have a 30 m grid spatial resolution. We intersected the LANDFIRE vegetation layer with the REZ buffers and calculated the acreage of each physiognomic class within the REZ buffers.

Finally, to estimate potential carbon capture within the REZ, we utilized empirical observations of net CO_2 exchange (NEE) from a global network of eddy covariance towers (Figure 5) arrayed according to functional vegetation types.

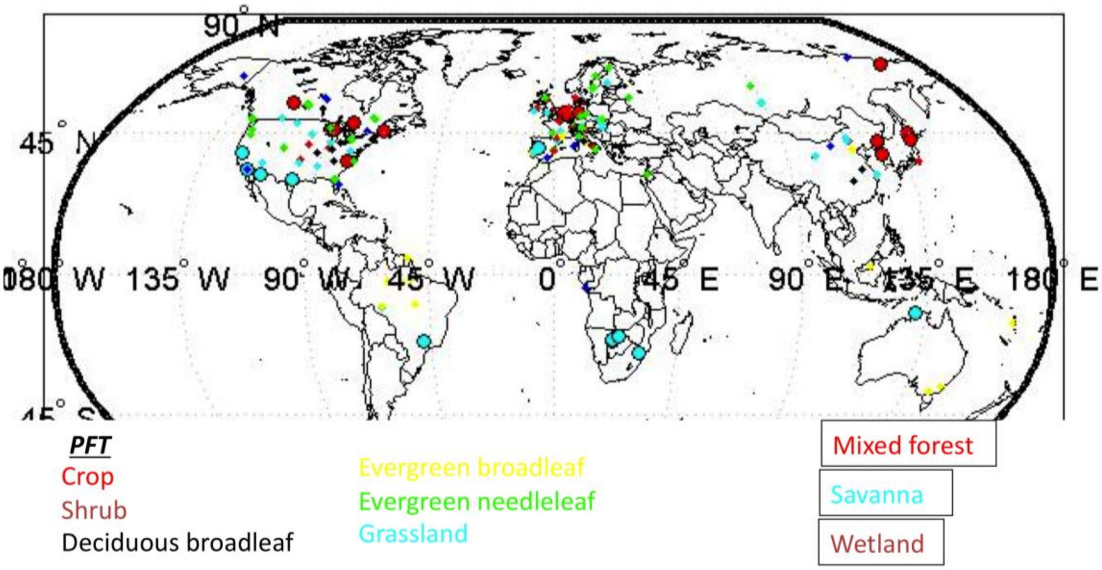


Figure 5: International flux tower network.

These flux tower networks (e.g., AmeriFlux, Agriflux) (Figure 6) have provided continuous data collection of ecosystem exchanges of carbon (e.g., net ecosystem exchange), between terrestrial ecosystems and the atmosphere since 1992 (Baldocchi et al. 2001). Thus, for each of the vegetation physiognomic classes, we averaged the annual NEE from 253 globally-distributed towers and applied this estimate to the REZ within each FLMA (Table 3). NEE (the sum of all photosynthetic inputs of carbon from atmosphere to biosphere minus all respiratory losses of carbon from biosphere to atmosphere) varies by approximately a factor of two for the primary

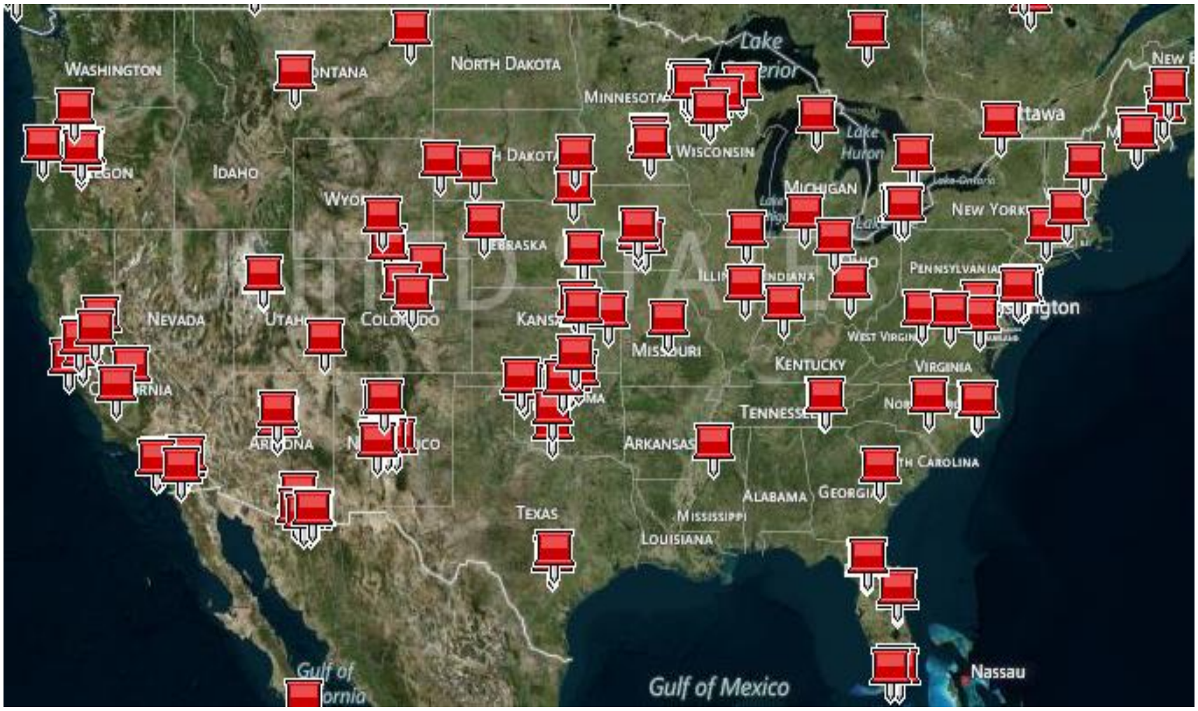


Figure 6: Screen capture of Ameriflux tower locations in the conterminous United States and adjacent lands (Source: http://bwc.berkeley.edu/Amflux/MapsComp/).

physiognomic vegetation types, from a low of 0.40 metric tons of C/acre/yr^{-1} for grassland communities to a high of 0.90 metric tons of C/acre/yr^{-1} for deciduous broadleaf forest. This approach of estimating net carbon uptake by physiognomic class is an improved methodology relative to previous approaches (FHWA 2010) that did not include heterotrophic respiration in the flux estimate, because it draws directly on empirical observations from a broad network of flux towers and reports whole ecosystem carbon balance (NEE), which is a more realistic portrayal of dynamic carbon flux processes.

Table 3: The net ecosystem exchange of CO2 (NEE) by major vegetation physiognomic groupings. Positive fluxes represent uptake of CO2 from the atmosphere by the biosphere.

Vegetation Physiognomic Class	**Carbon Flux (NEE) (metric tons C/acre yr^{-1})**	**Standard Deviation Carbon Flux (NEE) (metric tons C/acre yr^{-1})**	**Number of measurement sites**
Evergreen needleleaf forest	**0.55**	**0.89**	**69**
Deciduous broadleaf forest	**0.90**	**1.01**	**32**
Mixed evergreen-deciduous forest	**0.43**	**0.68**	**16**
Grassland	**0.40**	**0.53**	**45**
Shrubland	**0.54**	**0.50**	**16**
Wetland	**0.87**	**0.65**	**11**
Crop	**0.69**	**0.74**	**30**

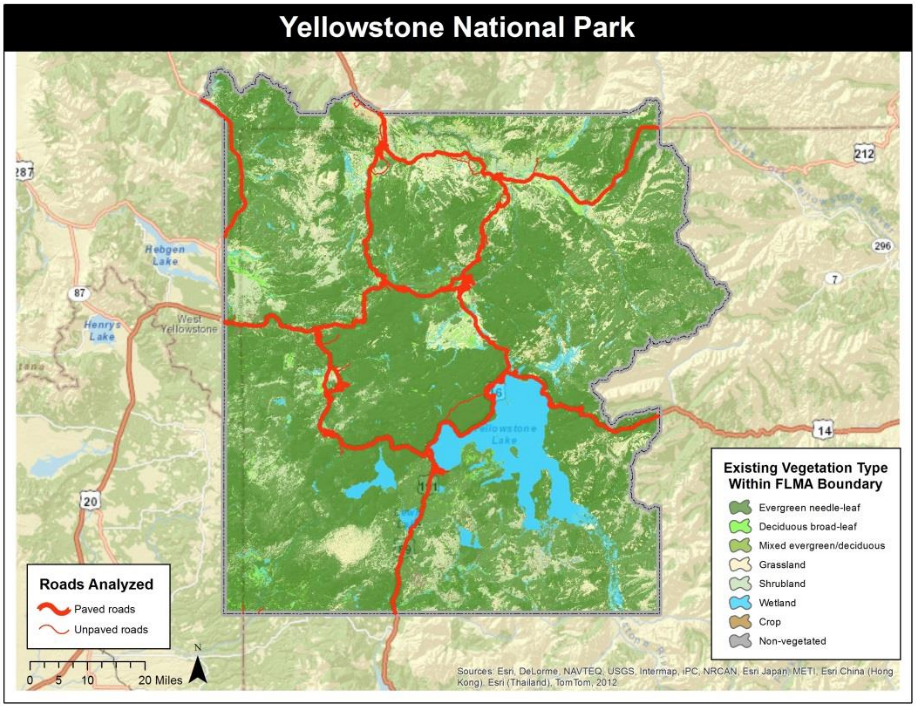
By focusing our estimates of carbon capture on the current vegetation physiognomic class within the REZ, we make no assumption about disturbance history or age-structure, but rather assume that these are integrated across the flux tower observations (Figure 5). The broad estimates of standard deviation of NEE around the mean reflect this assumption, as nearly all of the physiognomic types have the potential to be either net carbon “sources” or “sinks” given disturbance history and age-structure (Amiro et al. 2010). In this context, the mean carbon flux for each physiognomic class reflects a baseline expectation of typical flux in a given environment in the absence of factors that might constrain carbon uptake. Given the assumption that carbon uptake might be constrained in a roadside context due to factors such as soil compaction, soil-nutrient limitations, and pollution, our estimates of mean physiognomic class carbon flux are intended to demonstrate the potential for carbon uptake given enhanced management (Section 4).

From these four case studies, we extrapolated nationally to estimate annual carbon uptake along all FLMA roads. In order to do this, we made some simplifying assumptions. Since the distribution of vegetation physiognomic classes was unknown across the FLMAs nationally, we assumed a constant rate of carbon uptake based on the mean observed carbon uptake rates within each of the FLMA case studies. Hence, national extrapolation for each FLMA was simply a function of the length of roads and the area within the REZ. Therefore, the national estimate assumes that the carbon uptake rates observed in our case studies are representative of the national rates, and is intended to provide a rough estimate of the carbon sequestration potential for each of the four FLMAs.

3.3. Case Studies of Federal Lands Management Agencies – Estimations of Carbon Capture and Storage Potential

3.3.1. National Park Service System – Yellowstone National Park, Wyoming, Montana, and Idaho

Yellowstone National Park (YNP), which encompasses parts of Wyoming, Montana, and Idaho, is located in the heart of the Rocky Mountains (Figure 7). YNP contains 390 miles of roadway, which is approximately 4% of the total National Park Service road network. Over 80% of the road network in YNP is paved, and there are nearly 30,000 acres within the REZ (Table 4).



Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Figure 7: Map of Yellowstone National Park and its roads.

Table 4: Yellowstone National Park (YNP) road length and road effect zone (REZ) area.

Agency	Paved Road Length Miles (km)	Paved Road Effect Zone Acres (ha)	Unpaved Road Length Miles (km)	Unpaved Road Effect Zone Acres (ha)	Total Road Length Miles (km)	Total Road Effect Zone Acres (ha)
YNP	320 (515)	25,427 (10,290)	70 (113)	2,790 (1,129)	390 (627)	28,216 (11,419)

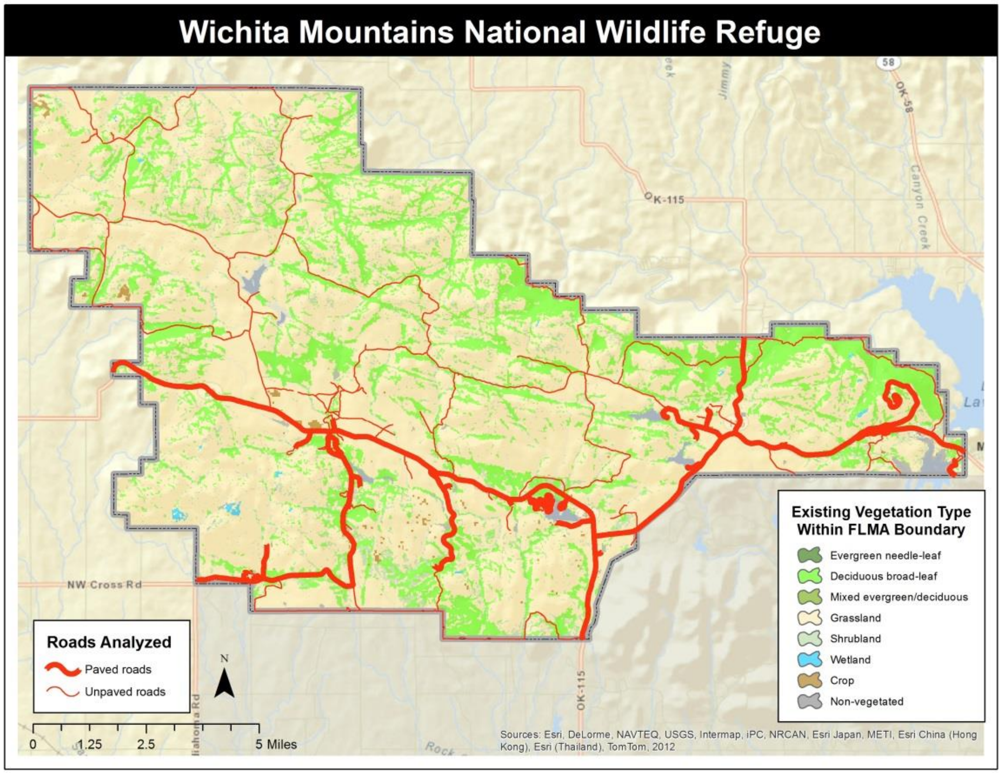
The roadside vegetation in YNP is dominated by evergreen needleleaf forest interspersed with grassland and shrubland communities. Evergreen needleleaf forest contributes to more than 60% of the roadside carbon uptake in YNP (Table 5). Deciduous broadleaf forest, mixed forest, and wetland comprise minor roadside vegetation components of the park. Across all roadside vegetation types in YNP, the annual uptake of carbon amounts to nearly 13,000 metric tons along park roads.

Table 5: Yellowstone National Park (YNP) road effect zone (REZ) areas and associated annual carbon uptake by vegetation physiognomic class.

Physiognomic Class	Paved Road Effect Zone Acres (ha)	Unpaved Road Effect Zone Acres (ha)	Total Annual Carbon Flux (metric tons C)
Evergreen needleleaf forest	**12,728 (5,151)**	**1,386 (561)**	**7,763**
Deciduous broadleaf forest	**583 (236)**	**94 (38)**	**609**
Mixed evergreen-deciduous forest	**845 (342)**	**54 (22)**	**387**
Grassland	**4,171 (1,688)**	**941 (381)**	**2,045**
Shrubland	**2,441 (988)**	**208 (84)**	**1,430**
Wetland	**625 (253)**	**27 (11)**	**568**
Non-vegetated	**4,033 (1,632)**	**79 (32)**	**0**
Total	**25,427 (10,290)**	**2,790 (1,129)**	**12,802**

3.3.2. National Wildlife Refuge System - Wichita Mountains National Wildlife Refuge, Oklahoma

The Wichita Mountains National Wildlife Refuge (WMNWR) is located in southwest Oklahoma (Figure 8) and has 118 total miles of roadway, the majority of which is unpaved. The total REZ for the refuge is over 6,000 acres, fairly evenly split between paved and unpaved roads (Table 6).



Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Figure 8: Map of the roads on the Wichita Mountains National Wildlife Refuge.

Table 6: Wichita Mountains National Wildlife Refuge (WMNWR) road length and road effect zone (REZ) area.

Agency	**Paved Road Length Miles (km)**	**Paved Road Effect Zone Acres (ha)**	**Unpaved Road Length Miles (km)**	**Unpaved Road Effect Zone Acres (ha)**	**Total Road Length Miles (km)**	**Total Road Effect Zone Acres (ha)**
WMNWR	39 (63)	3,096 (1,253)	79 (128)	3,153 (1,276)	118 (190)	6,249 (2,529)

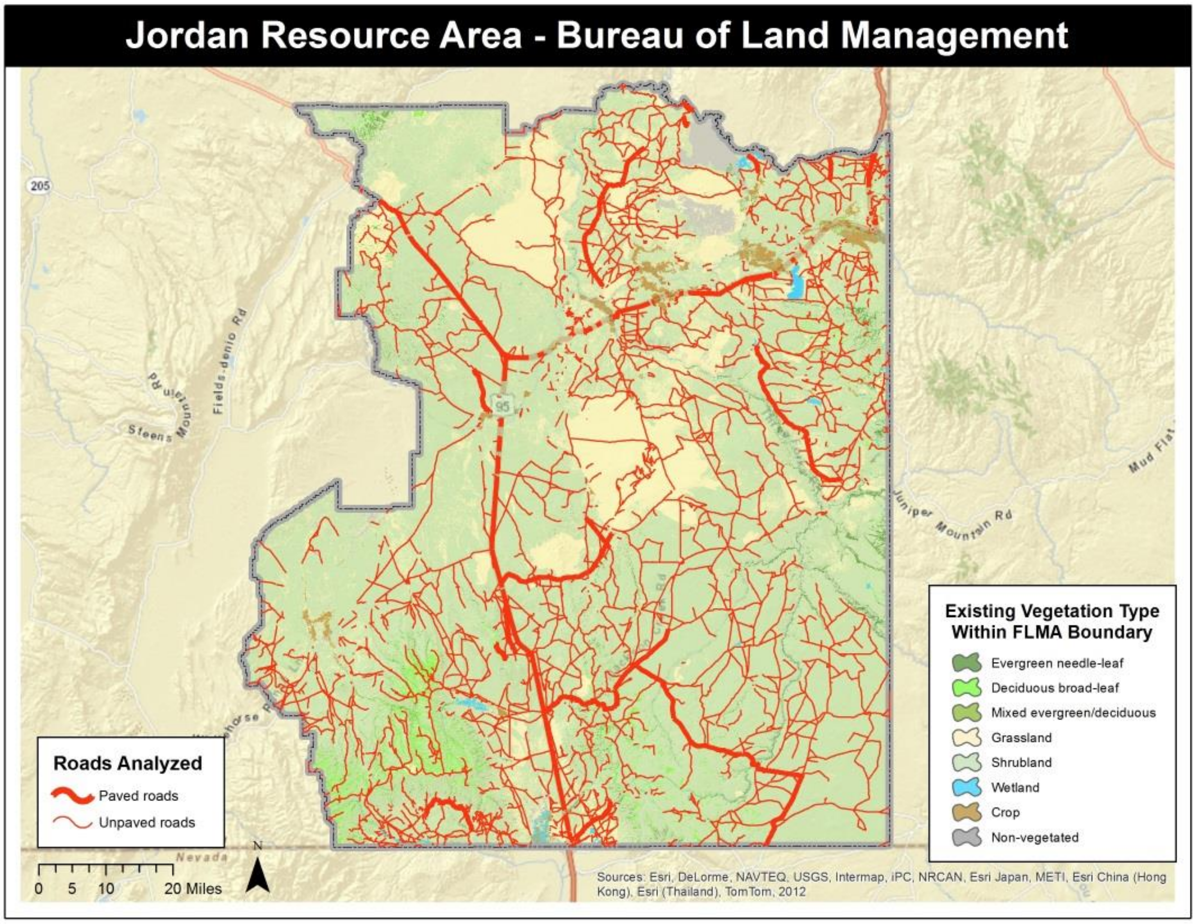
The roadside vegetation in the WMNWR is dominated by grassland and deciduous broadleaf forest, and annual carbon uptake is evenly split between these vegetation types. Across all roadside vegetation types in WMNWR, the annual uptake of carbon amounts to over 3,000 metric tons (Table 7).

Table 7: Wichita Mountains National Wildlife Refuge road effect zone (REZ) areas and associated annual carbon uptake by vegetation physiognomic class.

Physiognomic Class	Paved Road Effect Zone Acres (ha)	Unpaved Road Effect Zone Acres (ha)	Total Annual Carbon Flux (metric tons C)
Evergreen needleleaf forest	**7 (3)**	**0 (0)**	**4**
Deciduous broadleaf forest	**739 (299)**	**907 (367)**	**1,481**
Mixed evergreen-deciduous forest	**5 (2)**	**0 (0)**	**2**
Grassland	**1,532 (620)**	**2,009 (813)**	**1,416**
Shrubland	**319 (129)**	**215 (87)**	**288**
Wetland	**5 (2)**	**0 (0)**	**4**
Crop	**15 (6)**	**5 (2)**	**14**
Non-vegetated	**474 (192)**	**17 (7)**	**0**
Total	**3,096 (1,253)**	**3,153 (1,276)**	**3,210**

3.3.3. Bureau of Land Management – Jordan Resource Area, Oregon

The Jordan Resource Area (JRA), located in the southeast corner of Oregon (Figure 9), contains over 3,500 miles of roads, the vast majority of which are unpaved (Table 8). The total REZ for the JRA is over 150,000 acres.



Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Figure 9: Map of the Jordan Resource Area of the Bureau of Land Management in southeast Oregon and its roads.

Table 8: Jordan Resource Area (JRA) and Bureau of Land Management (BLM) road lengths and road effect zone (REZ) areas.

Agency	Paved Road Length Miles (km)	Paved Road Effect Zone Acres (ha)	Unpaved Road Length Miles (km)	Unpaved Road Effect Zone Acres (ha)	Total Road Length Miles (km)	Total Road Effect Zone Acres (ha)
JRA	250 (402)	19,877 (8,044)	3,420 (5,508)	136,103 (55,080)	3,670 (5,910)	155,979 (63,124)

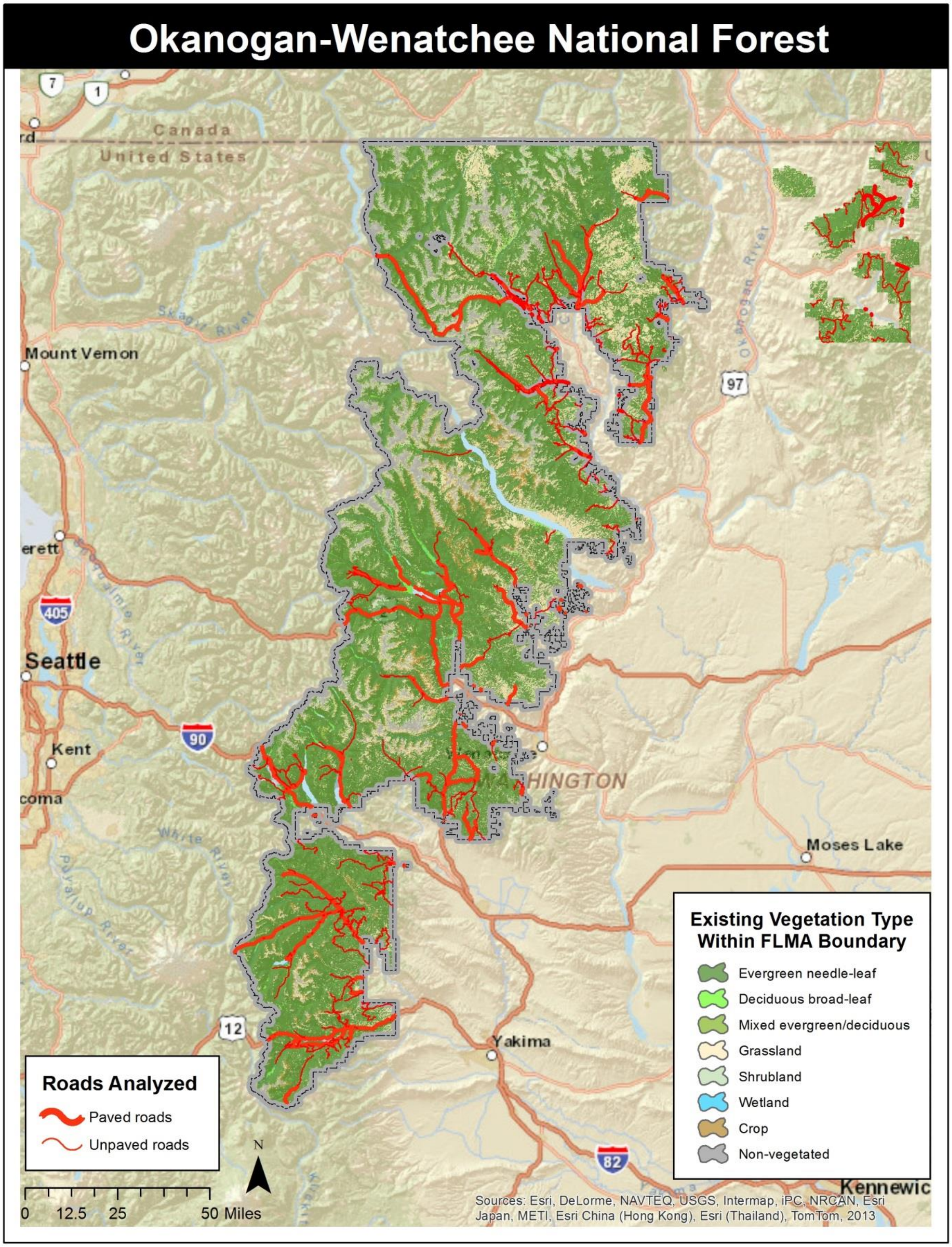
The roadside vegetation in the JRA is primarily grassland and shrubland, and annual carbon uptake is fairly evenly split between these vegetation types. The average annual uptake of carbon is over 70,000 metric tons (Table 9) along the roadsides of the JRA.

Table 9: Jordan Resource Area (JRA) road effect zone (REZ) areas and associated annual carbon uptake by vegetation physiognomic class.

Physiognomic Class	**Paved Road Effect Zone Area (ha)**	**Unpaved Road Effect Zone Area (ha)**	**Total Annual Carbon Flux (Mg C)**
Evergreen needleleaf forest	**37 (15)**	**306 (124)**	**189**
Deciduous broadleaf forest	**783 (317)**	**1,072 (434)**	**1670**
Mixed evergreen-deciduous forest	**141 (57)**	**1,483 (600)**	**698**
Grassland	**9,027 (3,653)**	**83,384 (33,745)**	**36,964**
Shrubland	**8,283 (3,352)**	**48,770 (19,737)**	**30,809**
Wetland	**2 (1)**	**86 (35)**	**77**
Non-vegetated	**1,604 (649)**	**1,001 (405)**	**0**
Total	**19,877 (8,044)**	**136,103 (55,080)**	**70,407**

3.3.4. National Forest and Grassland System – Wenatchee-Okanogan National Forest, Washington

The Okanogan-Wenatchee National Forest (OWNF) in central Washington contains over 1,500 miles of roadways, the majority of which are unpaved (Table 10). The forest lies east of the hydrologic divide, or the crest of the Cascade Mountains, and thus is drier than the forests west of the Cascade crest that are closer to the Pacific ocean (Figure 10). There are over 80,000 acres of REZ in the OWNF.



Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2013

Figure 10: Map of the roads on the Okanogan-Wenatchee National Forest in Washington state. Note: due to the scale of the image, roads may appear more dense than in actuality.

Table 10: Okanogoan-Wenatchee National Forest (OWNF) and U.S. Forest Service (USFS) road lengths and road effect zone (REZ) areas.

Agency	Paved Road Length Miles (km)	Paved Road Effect Zone Acres (ha)	Unpaved Road Length Miles (km)	Unpaved Road Effect Zone Acres (ha)	Total Road Length Miles (km)	Total Road Effect Zone Acres (ha)
OWNF	546 (879)	43,453 (17,585)	1,000 (1,610)	39,786 (16,101)	1,546 (2,489)	82,239 (33,686)

The vegetation in the OWNF is composed primarily of evergreen needleleaf forest, which accounts for approximately 82% of the annual carbon uptake along the REZ in the OWNF. The total estimated annual uptake of carbon in the OWNF is nearly 40,000 metric tons (Table 11).

Table 11: Okanagon-Wenatchee National Forest (OWNF) road effect zone (REZ) areas and associated annual carbon uptake by vegetation physiognomic class.

Physiognomic Class	Paved Road Effect Zone Acres (ha)	Unpaved Road Effect Zone Acres (ha)	Total Annual Carbon Flux (metric tons C)
Evergreen needleleaf forest	**28,214 (11,418)**	**30,055 (12,163)**	**32,048**
Deciduous broadleaf forest	**707 (286)**	**138 (56)**	**761**
Mixed evergreen-deciduous forest	**4,112 (1,664)**	**1,552 (628)**	**2,435**
Grassland	**3,566 (1,443)**	**4,156 (1,678)**	**3,085**
Shrubland	**667 (270)**	**230 93)**	**484**
Wetland	**198 (80)**	**44 (18)**	**211**
Crop	**215 (87)**	**1 (0.3)**	**149**
Non-vegetated	**5,775 (2,337)**	**3,620 (1,465)**	**0**
Total	**43,453 (17,585)**	**39,786 (16,101)**	**39,172**

3.3.5. Summary of the four FLMA case studies and extrapolation of CCS for roadside vegetation to the national level.

The four FLMA case studies demonstrate a simple, yet effective way to estimate roadside area available for CCS and potential carbon uptake. The REZ area and potential carbon uptake varied significantly among the four case studies, driven by the length of the road network within each case study, the ratio of paved versus unpaved roads, and the distribution of vegetation physiognomic classes. The highest rates of carbon uptake were observed in the Wichita Mountains National Wildlife Refuge, due to the dominance of broadleaf deciduous forests. However, with a small road network and associated REZ, the potential annual carbon uptake in this refuge is relatively minor. Conversely, the lowest rates of carbon uptake were observed in the Jordan Resource Area and Yellowstone National Park. In the Jordan Resource Area, the REZ is dominated by grassland communities. However, with a vast road network and associated REZ, the potential annual carbon uptake across this Resource Area is of significance.

Extrapolation from these case studies to the national level is hampered by the lack of available, consistent geospatial roads data for each FLMA. This presents a serious obstacle to a national-level assessment and is an important research and management challenge. We can, however, via these case studies, assess the carbon uptake potential of the eight FLMAs with some simplifying assumptions. By utilizing mean rates of carbon uptake derived from each FLMA case study as a surrogate for national-level flux rates, we extrapolated carbon flux nationally across each FLMA’s road network. For FLMAs that lacked a case study (BIA, BOR, Military Installations, and the USACE), we assumed the mean carbon flux rate from the four case studies.

Across the road network of all 8 FLMAs, there are over 17 million acres within the REZ available for CCS (Table 12). Within that area, there is the potential to sequester over 8 million metric tons of carbon on an annual basis. From this basic approach, we see that the estimated mean rates of carbon flux exhibit little variation among FLMAs (from 0.45 metric tons C/acre yr^{-1} to 0.51 metric tons C/acre yr^{-1}). Here, the length of the road network and the associated area within the REZ drive the differences among FLMAs. The USFS, BIA, and BLM manage the largest roadside areas for potential CCS.

There are approximately 50% more miles of roads in the 8 FLMAs as there are in the National Highway System (FHWA 2010). Using a broader definition of “roadside” in this study, we estimated that there is approximately four times the roadside acreage available for carbon capture and storage along FLMA roads as along the National Highway System. The estimation of over 8 million metric tons of carbon per year (~29 million metric tons CO_2E) is the equivalent of annual carbon dioxide emissions from over six million passenger cars. In other terms, this amount of carbon uptake is approximately 1.6% of the total annual greenhouse gas emissions from the entire transportation sector.

Table 12: FLMA road lengths and REZ area with estimated total annual carbon flux

FLMA	Paved Roads miles (km)	Road Length miles (km)	Total REZ acres (ha)	C Flux (metric tons C/acre yr^{-1})	Total Annual C Flux (metric tons)
USFS	31,400 (50,523)	99,100 (159,452)	5,188,470 (2,099,745)	0.47[b]	2,438,581
NPS	5,450 (8,769)	9,550 (15,366)	596,376 (241,350)	0.45[c]	268,369
BIA	36,883 (59,345)	90,731 (145,986)	5,073,727 (2,053,309)	0.48[d]	2,435,389
FWS	415 (668)	4,900 (7,884)	211,316 (85,518)	0.51[e]	107,771
BLM	N/A	68,880 (110,828)	4,107,837[a] (1,662,419)	0.45[f]	1,848,527
BOR	1,082 (1,741)	1,863 (2,998)	117,088 (47,385)	0.48[d]	56,202
Military	14,400 (23,170)	14,400 (23,170)	1,145,042 (463,392)	0.48[d]	549,620
USACE	6,996 (11,257)	12,164 (19,572)	761,771 (308,284)	0.48[d]	365,650
Total	**74,705 (120,200)**	**258,282 (415,576)**	**17,201,626 (6,961,403)**		**8,070,109**

[a] For the BLM, we assumed that 50% of their road length was paved, therefore, we used a 150 m REZ buffer to estimate the total REZ.

[b] The USFS estimate of C flux is based on the average estimated C flux in the Okanogan-Wenatchee National Forest (OWNF). We calculated the average OWNF carbon uptake as 0.47 metric tons C/acre yr^{-1} (mean C flux for OWNF = 39,172 metric tons C/83,239 acres).

[c] The NPS estimate of C flux is based on the average estimated C flux in Yellowstone National Park (YNP). We calculated the average YNP carbon uptake as 0.45 metric tons C/acre yr^{-1} (mean C flux for YNP = 12,802 metric tons C/28,216 acres).

[d] The BIA, BOR, Military Installations, and the USACE estimates of C flux was calculated as the mean estimated C flux in YNP, WMWR, JRA, and OWNF.

[e] The FWS estimate of C flux is based on the average estimated C flux in the Wichita Mountains Wildlife Refuge (WMWR). We calculated the average WMWR carbon uptake as 0.51 metric tons C/acre yr^{-1} (mean C flux for WMWR = 3,210 metric tons C/6,249 acres).

[f] The BLM estimate of C flux is based on the average estimated C flux in the Jordan Resource Area (JRA). We calculated the average JRA carbon uptake as 0.45 metric tons C/acre yr^{-1} (mean C flux for JRA = 70,407 metric tons C/155,979 acres).

4. VEGETATION AND SOIL MANAGEMENT IN RIGHT-OF-WAYS TO INCREASE CARBON CAPTURE AND STORAGE

There are a variety of strategies to consider when making decisions for plantings, seedings or other types of roadside vegetation management in the context of maximizing carbon capture and storage. The ideal time for considering these approaches is immediately after there is disturbance in the road verges. Thus, strategies for maximizing CCS could be incorporated into post-construction reclamation plans for roadside soils and vegetation. At other times, it may be in a more truncated time frame when roadside reclamation is needed immediately after natural disturbances such as wild fires, avalanches, floods or mudslides. For managers interested in addressing CCS for roadsides, it would be advantageous to evaluate the various potential CCS strategies that are appropriate for each particular federal land management unit and have pre-selected those strategies that can be incorporated into post-construction and post-disturbance reclamation plans and projects.

Implementation of CCS projects along roadsides present a unique challenge due to the number of limiting factors for plant growth, and hence carbon capture and storage (Steinfeld et al. 2007a). Roadsides are typically hostile environments for plants, with limitations on water input and water storage. Often roadsides have compromised surface stability and slope stability, and are generally vectors for weeds and pests. Furthermore, following road construction projects, roadside soils are generally lacking in soil organic matter.

Although not all practices used on highways are appropriate for FLMA roadsides, new information is being developed on CCS for the national highway system. For example, the New Mexico Department of Transportation is exploring ways to increase CCS in their state highway right-of ways. Their approach is to inventory soil organic carbon across the state highway system, as well as evaluate roadside vegetation and soil management practices with the potential to advance CCS (Dunn 2013a). Nine management practices were evaluated from the inventory, including adding mycorrhizal fungi, increasing water availability, establishing various types of plant species, imprinting offset divots in the soil and changing mowing times, frequency and heights (Dunn 2013b). Current research is investigating the most promising of these practices that have the potential to increase soil organic carbon: inter-seeding legumes, imprinting soils and reducing mowing (Dunn et al. 2013).

The remainder of this section presents practices that relate to design, plant selection, maintenance, reducing adverse of operations and other considerations that can enhance the carbon sequestration potential of roadside vegetation.

4.1. Roadside Soils

Carbon pools in vegetation are often short-lived (< 100 years) depending on species and management type. As a consequence, CCS efforts often focus on increasing soil carbon pools (Schlesinger 1999). In the agricultural sector, conservation tillage, including no-till practices, have long been recognized as exemplary strategies for soil carbon sequestration in agricultural systems (Kern & Johnson, 1993). Coupled with the observation that carbon sequestration also tends to decrease following natural or anthropogenic disturbance (Baldocchi, 2008), any CCS strategy for roadsides should seek to minimize soil disturbance.

It is important to note that the use of fertilizer can increase CCS in the area where the fertilizer is applied, but CO_2 emissions from the Haber-Bosch process that is used to produce most nitrogen-based fertilizers results in a likely situation of no net carbon gain (Schlesinger, 1999) and therefore fertilization is not recommended for roadside CCS management.

4.2. Roadside Re-vegetation Practices that have the Potential to Increase CCS

Good roadside reclamation practices are good for CCS. Therefore, roadside reclamation plans that seek to maximize slope stability, plant establishment and vegetative aerial cover, while at the same time minimize erosion and surface runoff are beneficial for CCS. However, where a federal land management unit is located, and the types of natural ecosystems that are available, matter. Ecosystems with longer growing seasons, rather than large maximum canopy photosynthesis, tend to exhibit larger NEE on an annual basis (Baldocchi, 2008). In addition, wetlands have higher mean NEE than grasslands (Table 3). So, for example, if a road project is located in a southeast U.S. hardwood forest and also requires reclamation of wetlands, it has the potential for higher levels of CSS than a road running through a dry grassland in the northern plains. Given the constraints of growing season and native ecosystems, planting species that are likely to establish and grow given the unique microenvironment of roadsides is likely the most successful strategy.

It is also important to note for the purposes of roadside CCS that recently disturbed ecosystems tend to lose carbon to the atmosphere on an annual basis (Amiro 2010), and efforts to minimize disturbance when designing or repairing roads may be just as important as strategies designed to maximize CCS after road alteration.

4.2.1. Physiognomic classes

As a general rule, managing for different physiognomic classes along FLMA roadsides may result in the potential to increase or decrease CCS for roadside areas. Not all physiognomic classes are the same, for example, deciduous broadleaf forests had the highest carbon uptake rates at 0.9 metric tons C/acre year^{-1} compared to 0.4 C/acre year^{-1} for grasslands based on the measurements of the flux towers (Table 3). However, the standard deviation across all categories was often as high as the average flux per physiognomic class.

Roadside reclamation plans must take in to account successful revegetation seed mixes and plantings for the sites and also must assure driver safety, so that trees or large diameter shrubs are not located too close to the pavement or in clear zones. However, given these and other reclamation considerations such as cost and effectiveness, it may be useful to consider the physiognomic types that could help increase roadside CCS during the development of roadside reclamation planning. For example, planting trees and shrubs on roadsides that lie behind guard rails or other safety barriers could increase carbon uptake but not pose any safety threat to motorists.

4.2.2. Living fences

In northern climates, managing snow and protecting roads from snow and ice in the winter months is an important facet of daily operations. Many locations along public roads have received fencing treatments for controlling drifting and blowing snow to reduce snow plowing and to assure safer roads for motorists. In a study on Interstate 80 in Wyoming, it was demonstrated that structural snow fences reduced snow removal costs by more than one-third (Tabler 1991). One alternative to structural fences is the use of vegetation plantings such as twin rows of shrubs, community shelterbelts of trees or windbreaks using trees (Johnson 2008). Current design criteria for living snow fences can realize a snow trapping efficiency of 79% when applied to a real world situation (Blanken 2009). Thus, living fences not only protect roads from blowing and drifting snow, they diversify habitat for wildlife and have the potential additional advantage of increasing CCS. CCS is improved due to the planting of woody species (particularly if multi-strata living fences are used), the localized increase in moisture availability and the reduction of desiccation on the leeward side of the living fences. Unfortunately, there has been no quantification of the amount of carbon flux produced by living fences published at this time, and it is important to note that woody encroachment in grassland areas often results in reduced soil C storage.

4.2.3. Shrubs as arrestors for errant vehicles

There is relatively little information available about the effect of vegetation on slowing errant vehicles from roadside impacts. One exception is Laker (1966) who investigated the option of using thick vegetation as a barrier to vehicle penetration by a 20 ft (6.1 m) thick rose, *Rosa spp.*, hedge. Tests showed vehicles were slowed by the hedge. More research will need to be conducted on the benefits of CCS and improving safety for errant vehicles by increasing relatively small-stemmed woody shrubs adjacent to roads. Developing shrubby areas adjacent to the roads may be problematic in some locales with certain species, for example, willow thickets, *Salix spp.,* that attract moose, *Alces alces* in Alaska (Rea 2002).

4.3. Biofuel Cropping

Many efforts to plant specific species for the purpose of CCS focus on exotic C4 perennials, especially *Miscanthus giganteus* for biofuel cropping (Heaton, Dohleman, & Long, 2008), largely to offset fossil fuel emissions rather than to result in CCS in and of itself. *M. giganteus* often yields over 250% of the typical biomass of corn, and over 4 times the amount of ethanol fuel. However, widespread *M. giganteus* planting may alter regional hydrology by enhancing evapotranspiration (Vanloocke, Bernacchi, & Twine 2010), and planting an exotic species is not likely a desirable management strategy across FLMA management units.

Short rotation coppice, commonly of alder (*Alnus spp.*), willow (*Salix spp.*), poplar (*Populus spp.*) or other native species amenable to coppicing, may be a preferred management strategy depending on ease of harvest from the roadside and marketability of woody material. Short rotation coppice systems tend to be highly productive (Deckmyn, Muys, Garcia Quijano, & Ceulemans, 2004), and disturbance to soil is minimal in the root stock. It should be noted that the encroachment of woody vegetation to grass-dominated ecosystems may result in reduced soil carbon stocks despite likely greater vegetation biomass (Jackson, Banner, Jobbagy, Pockman, & Wall, 2002).

4.4. Reducing the Effects of Road Salt

Chloride salts are the most commonly used chemicals for winter road maintenance applications and sodium chloride has been shown to affect soil within 15 feet (4.6 m) of roadways (Fay and Shi 2012). Sodium accumulation in roadside soils can reduce soil permeability and fertility, which can in turn reduce plant growth (TRB 1991). High levels of road salt can extirpate roadside woody plants; it has been reported that many woody plant species exposed to road salts are no longer present along the road (Environment Canada 2004). Thus, the effects of winter operations and road salt on adjacent soils and vegetation has the potential to adversely impact CCS. If plant growth and soil fertility are below optimal conditions, their potential for CCS along roadsides is reduced. Therefore, road managers seeking to increase CCS in areas where winter operations are depositing chloride salts on a seasonal basis should pursue actions that minimize concentrations of these salts in roadside soils.

4.5. Reducing the Adverse Effects of Dust

The eight FLMAs have an estimated 183,577 miles (295,376 km) of unpaved roads which is over seventy percent of their collective road mileage (Table 1). Since untreated unpaved roads can be a source of high levels of dust, the management of particulate emissions from roads is an important issue for FLMA road managers. Concentrations of the smaller sized components of dust, particulate matter of ten micrometers (0.0004 inches) or less (PM-10), were found to decrease as a function of the distance to the road. PM-10 emissions were found to mainly not exceed a distance of 45m (49.2 yards) from gravel roads (Edvardsson and Magnusson 2009). Larger sized dust particles fall out even closer to the road. Dust has both a physical and chemical impact, so dust that falls on adjacent roadside vegetation can reduce gas exchange, photosynthesis, transpiration, vegetative growth, reproductive growth and may affect other physical and biochemical processes (Thompson et al. 1984, Farmer 1991, Prusty et al. 2005). For road managers seeking to increase roadside CCS, reducing dust emissions will benefit existing vegetation as far as 45 m from the road by reducing the adverse effects of dust on plants' ability to capture and store carbon.

4.6. Road Reclamation

Road reclamation, such as actions that either abandon or re-contour roads, is another opportunity with the potential to capture and store carbon on federal lands. There are many benefits from the removal of roads for hydrological and geomorphological restoration as well as to improve fish and wildlife habitat (Switalski et al. 2004). The benefits that accrue for CCS are just beginning to be evaluated. Results of one study on US Forest Service and Nez Perce tribal lands in Idaho showed that the re-contouring technique increased total carbon (TC) pools to levels similar to never-roaded sites while the abandoned road technique was not as effective in elevating TC pools to non-roaded conditions (Lloyd et al. 2013). As this area of research is developed and expanded, more information will be available to FLMA road and vegetation managers on the CCS costs and benefits of road bed reclamation.

5. POTENTIAL CARBON EMISSION REDUCTIONS VIA CURRENT ROADSIDE MANAGEMENT PRACTICES

In addition to practices that enhance the CCS potential of federal land roadside vegetation, managers also have an opportunity to pursue strategies that reduce the amount of carbon emissions produced within their units. Two important activities for managing roadside vegetation are to: 1) control plant growth for road safety and infrastructure protection and, 2) prevent the establishment and expansion of noxious weeds and other exotic plants. Both activities contribute to carbon emissions and there may be opportunities for roadside vegetation managers on federal lands to adjust effective operations that may at the same time reduce the amount of carbon dioxide and other GHG emissions.

There are various carbon analysis and calculation tools available for the transportation sector. For example, more than fifteen of these tools that help transportation managers evaluate projects and programs were evaluated for the Transportation Research Board and the American Association of State Highway and Transportation Officials (ICF Consulting 2006). They range in type from calculating vehicle fleet emissions using EPA’s MOBILE 6.2 modeling software (online at www.epa.gov/oms/m6.htm) to forecasting energy consumption. Many of these are sophisticated, but they are not transparent, so users do not know the derivation of the amounts and values for various sources of carbon emissions used in the calculator.

Appendix A consists of three sections that give FLMA managers direct information to help them evaluate the levels of carbon emissions that result from various roadside vegetation management activities. At this time there is no comprehensive web-based carbon emission calculator for roadside vegetation management for the transportation sector. The information in Appendix A will give carbon emissions for what are the most common roadside vegetation activities and products. This will allow managers to calculate some simple carbon emission estimates under existing roadside operations and protocols and should allow for a relatively simple estimation of the reductions in emissions that could result by modifying current operations and practices. Appendix A addresses the most common roadside vegetation activities: mowing, pesticide applications, and general consumption of fuel by all vehicles and diesel/gas powered machines used for roadside vegetation management.

6. CONCLUSIONS AND RECOMMENDATIONS

As part of their adherence to Executive Order 13514 and other federal strategies and direction, FLMAs should consider the potential to increase carbon sequestration and decrease greenhouse gas emissions as part of their roadside vegetation operations and management activities. If successfully developed and implemented across the 258,282 miles (415,576 km) of FLMA roads, such climate-smart activities have the potential to increase carbon capture and storage while at the same time allowing for the reduction of carbon emissions.

The following recommendations are proposed to promote and encourage enhanced CCS strategies in FLMA units:

1. Based on the methodologies presented for the four case studies in this report, each FLMA management unit can estimate the current CCS along its roads.

This report used a standard of 55 yards (50 m) for unpaved roads and 109 yards (100 m) for paved roads as the distance away from both sides of the road to demarcate the road effect zone (REZs), but individual FLMA management units could fine tune the REZ based on finer scale, local information and analysis.

2. Road construction and reconstruction plans and projects should seek to minimize disturbance to existing soil and plant communities. The first, best CCS strategy is to leave roadside soils and vegetation undisturbed.

3. Roadside revegetation and reclamation manuals, plans and projects should have sections devoted to CCS calculations and considerations for both plant and soil management sensitive to CCS strategies.

4. Roadside managers should consider opportunities where increasing physiognomic complexity may have the potential to increase CCS along roadsides.

An analysis of opportunities to increase woody species, for example, multiple stories of plants along existing roadsides that currently are simple strata, such as grasslands, has the potential to increase CCS.

5. Consideration of living snow fences, shrub arrestors and other opportunities to increase CCS should be incorporated into roadside vegetation management plans.

6. Modifying road operations to reduce the adverse effects of dust and salt on the ability of roadside plants to photosynthesize and capture and store carbon should be considered in a CCS strategy.

7. Federal land managers could conduct calculations of current carbon emissions from roadside vegetation maintenance and operations, based on fuel consumption, mowing practices, pesticide spraying and pesticide consumption.

Based on simple calculations from numbers provided in this report’s Appendix A, a simple handheld calculator will allow managers to identify the current level of carbon emissions from the primary sources of GHG emissions for roadside vegetation management. Then, if scenarios for reductions are considered, additional calculations will provide estimates of potential carbon emission reductions. If these simple calculations of carbon emission reductions are large enough, a more thorough and expert plan and analysis should be conducted.

7. REFERENCES

Amiro, B.D. and A. G. Barr, J. G. Barr, T. A. Black, R. Bracho, M. Brown, J. Chen, K. L. Clark, K. J. Davis, A. R. Desai, S. Dore, V. Engel, J. D. Fuentes, A. H. Goldstein, M. L. Goulden, T. E. Kolb, M. B. Lavigne, B. E. Law, H. A. Margolis, T. Martin, J. H. McCaughey, L. Misson, M. Montes-Helu, A. Noormets, J. T. Randerson, G. Starr, J. Xiao. 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America, Journal of Geophysical Research: Biogeosciences ,Volume 115, Issue G4.

Armstrong, A., Roberts, T.C. and R. Christians. 2011. Current and innovative solutions to roadside revegetation using native plants, A domestic scan report. FHWA-WFL/TD-11-001, Federal Highway Administration, Western Federal Lands Highway Division, Vancouver, WA.

Baldocchi D. 2008. Turner Review No. 15. 'Breathing' of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. Australian Journal of Botany **56**, 1–26.

Baldocchi D, Falge E, Gu L, Olson R, Hollinger D, Running S, Anthoni P, Bernhofer C, Davis K, Evans R, Fuentes J, Goldstein A, Katul G, Law B, Lee X, Malhi Y, Meyers T, Munger W, Oechel W, Paw KT, Pilegaard K, Schmid HP, Valentini R, Verma S, Vesala T, Wilson K, Wofsyn, S. 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull Am Meteorol. Soc, 82(11):2415–2434.

Bartlett, M.D. and I.T. James. 2011. A model of greenhouse gas emissions from the management of turf on two golf courses. Science of Total Environment, 409 (2011), 1357-1367.

Blanken, P.D. 2009. Designing a living snow fence for snow drift control. Arctic, Antarctic and Alpine Res., 41(4): 418-425.

Congressional Budget Office (CBO). 2007. The Potential for Carbon Sequestration in the United States. The Congress of the United States, CBO, Washington, D.C.

Deckmyn, G., Muys, B., Garcia Quijano, J. and Ceulemans, R. 2004. Carbon sequestration following afforestation of agricultural soils: comparing oak/beech forest to short-rotation poplar coppice combining a process and a carbon accounting model. Global Change Biology, 10: 1482–1491.

Dunn, W.C. 2013a. Assessing the potential to sequester carbon within State highway rights-of way in New Mexico Phase I: Inventory of soil organic carbon and current management practices, Report No. NM10ENV-01, New Mexico Department of Transportation, Albuquerque, NM.

Dunn, W.C. 2013b. The path forward: An implementation plan for Phase 1 of the project, "Assessing the potential to sequester carbon within State highway rights-of way in New Mexico". Report No. NM10ENV-01, New Mexico Department of Transportation, Albuquerque, NM.

Dunn, B., Romig, D., Estelle, A. and R. Wessel. 2013. Can highway rights-of-way slow down climate change? Poster presented at the 2013 International Conference on Ecology & Transportation, June 23-27, 2013, Scottsdale, AZ.

Edvardsson, K. and R. Magnusson. 2009. Monitoring of dust emission on gravel roads: Development of a mobile methodology and examination of horizontal diffusion. Atmos.Env., 43(2009): 889-896.

EPA (Environmental Protection Agency). 2012. Fast facts: U.S. Transportation sector greenhouse gas emissions, 1990-2010. EPA-420-F-12-063, U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Washington, DC.

EPA (Environmental Protection Administration). 2011. Greenhouse gas emissions from a typical passenger vehicle. Office of Transportation and Air Quality, EPA-420-F-11-041, December 2011, Washington, D.C.

EPA (Environmental Protection Administration). 2008. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2006. EPA 430-R-08-005, U.S. Environmental Protection Agency, Washington, D.C.

Executive Order 13514. Federal leadership in environmental, energy and economic performance. 74 Federal Register 52117 (October 8, 2009).

Farmer, A.M. 1993. The effects of dust on vegetation – a review. Env.Pollution, 79(1993): 63-75.

Fay, L. and X. Shi**.** 2012, Environmental impacts of chemicals for snow and ice control: State of the knowledge. Water, Air and Soil Pollutions, 223: 2751–2770.

FHWA (Federal Highway Administration). 2007. Activities, accomplishments and trend analyses. Federal Lands Highway Program. U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway, Washington, DC.

FHWA (Federal Highway Administration). 2008a. Activities, accomplishments and trend analyses. Federal Lands Highway Program. U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway, Washington, DC.

FHWA (Federal Highway Administration). 2008b. Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance, Transportation Serving Federal and Indian Lands (Chapter 12). FHWA, Washington, D.C. Online at: www.fhwa.dot.gov/policy/2008cpr/chap12.htm#body

FHWA (Federal Highway Administration). 2009. The year in review, activities, accomplishments & trend analyses. Federal Lands Highway Program. U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway, Washington, DC.

FHWA (Federal Highway Administration). 2010a. The federal lands highway program, 2010, the year in review. U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway, Washington, D.C.

FHWA (Federal Highway Administration). 2010b. FHWA, Office of Planning, Environment and Realty and the John A. Volpe National Transportation Systems Center. 2010b. Carbon sequestration pilot program. Online at: www.fhwa.dot.gov/hep/climate/carbon_sequestration/index.htm

FHWA (Federal Highway Administration). 2011. The federal lands highway program, 2011, the year in review. U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway, Washington, DC.

Forman, R.T.T. 2000. Estimate of the area affected ecologically by the road system in the United States. *Conservation Biology* 14: 31-35.

Gao, H., Sonntag, D., and P. Morse. 2010. Air quality and energy impacts of NYSDOT Highway ROW Management. Research Project C-07-13, prepared for NYSDOT. School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, USA.

Gucinski, H., Furniss, M.J., Ziemer, R.R., and M.H. Brooks, eds. 2001. Forest Roads: A Synthesis of Scientific Information. General Technical Report, PNW-GTR-509, USDA-Forest Service, Pacific Northwest Research Station, Corvallis, OR.

Heaton, E.A., Dohleman, F.G. and Long, S. P. 2008. Meeting US biofuel goals with less land: the potential of Miscanthus. Global Change Biology, 14: 2000–2014.

ICF Consulting. 2006. Assessment of greenhouse gas analysis techniques for transportation projects. NCHRP Project 25-25, Task 17, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Johnson, A.M. 2008. Best practices handbook for roadside vegetation management. Report MN/RC 2008-20, Minnesota Department of Transportation, Office of Research Services, St. Paul, MN.

Kern, J.S. and Johnson, M.G. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J., 57: 200–210.

Laker, I.B. 1966. Vehicle impact tests on a hedge of rosa multiflora japonica. RRL Report No 3., Road Research Laboratory, Crowthorne, Berkshire, U.K.

Lal, R. 2008. Carbon sequestration. Phil. Trans. R. Soc. B, 363(no. 1492): 815-830.

Le Quéré, C. and R. Andres, T. Boden, T. Conway, R. Houghton, J. House, G. Marland, G. Peters, G. van der Werf, A. Ahlström, R. Andrew, L. Bopp, J. Canadell, P. Ciais, S. Doney, C. Enright, P. Friedlingstein, C. Huntingford, A. Jain, C. Jourdain, E. Kato, R. Keeling, K. Klein Goldewijk, S. Levis, P. Levy, M. Lomas, B. Poulter, M. Raupach, J. Schwinger, S. Sitch, B. Stocker, N. Viovy, S. Zaehle and N. Zeng (2012), "The Global Carbon Budget 1959–2011", Earth System Science Data Discussions (in review), http://www.earth-syst-sci-data-discuss.net/5/1107/2012.

Lloyd, R.A., Lohse, K.A. and T.P.A. Ferre. 2013. Influence of road reclamation techniques on forest ecosystem recovery.

National Park Service. 2010. Climate Change Response Strategy. National Park Service, U.S. Department of the Interior, Washington, D.C.

Prusty, B.A.K., Mishra, P.C. and P.A. Azeez. 2005. Dust accumulation and leaf pigment content in vegetation near the national highway of Sambalpur, Orissa, India. Ecotox. Env.Safety, 60(2005):228-235.

Rea, R.V. 2003. Modifying roadside vegetation management practices to reduce vehicular collisions with moose *Alces alces*, Wildl. Biol, 9: 81-91.

Schlesinger, W.H. 1999. Carbon and Agriculture: Carbon sequestration in soils. Science, 284 (no. 5423), 2095.

Secretarial Order 3289, Amendment No. 1. 2010. Addressing the Impacts of Climate Change on America's Water, Land and Other Natural and Cultural Resources. U.S. Department of the Interior, Washington, D.C.

Steinfield, D.E., Riley, S.A., Wilkinson, K.M., Landis, T.D. and L.E. Riley. 2007a. Roadside Revegetation: An Integrated Approach To Establishing Native Plants, FHWA-WFL/TD-07-005 Federal Highway Administration, Western Federal Lands Highway Division, Vancouver, WA.

Steinfield, D.E., Riley, S.A., Wilkinson, K.M., Landis, T.D. and L.E. Riley. 2007b. A Manager's Guide to Roadside Revegetation Using Native Plants, FHWA-WFL/TD-07-006, Federal Highway Administration, Western Federal Lands Highway Division, Vancouver, WA.

Switalski, T.A., Bissonette, J.A., DeLuca, T.H. and M.A. Madej. 2004. Benefits and impacts of road removal. Front Ecol Environ, 2(1): 21-28.

Tabler, R.D. 1991. Snow fence guide. Report SHRP-W/FR-91-106. Strategic Highway Research Program, National Research Council, Washington, D.C.

Thompson, J.R., Mueller, P.W., Fluckiger, W. and A.J. Rutter. 1984. The effect of dust on photosynthesis and its significance for roadside plants. EnvPollution (Series A) 34(1984):171-190.

TRB. 1991. Highway deicing, comparing salt and calcium magnesium acetate, Special Report 235, Transportation Research Board, National Research Council, Washington, DC.

U.S. Census Bureau. 2007. The 2007 Statistical Abstract. U.S. Census Bureau, Administrative and Customer Services Division, Statistical Compendia Branch, Washington, D.C. [http://www.census.gov/compendia/statab/transportation/ highway_infrastructure_and_use/]

USDA Forest Service 2013. Personal Communication, Leslie Doak, Assistant National Road System Operations and Maintenance Engineer, Arlington, VA.

USDA Forest Service. 2012. Guidelines for road maintenance levels. USDA, Forest Service, National Technology and Development Program, 7700-Transportation Management, 1177 1811-SDTDC, Washington, DC.

USDA Forest Service. 2010. National Roadmap for Responding to Climate Change. U.S. Forest Service, U.S. Department of Agriculture, Washington, D.C.

U.S. Fish and Wildlife Service. 2011. Rising to the Urgent Challenge, Strategic Plan to Respond to Accelerating Climate Change. USFWS, U.S. Department of the Interior, Washington, D.C.

Vanloocke, A., Bernacchi, C. J. and Twine, T. E. 2010. The impacts of *Miscanthus*×*giganteus* production on the Midwest US hydrologic cycle. GCB Bioenergy, 2: 180–191.

APPENDIX A: CALCULATING CARBON EMISSIONS

Using carbon emission data that is available for mowing, spraying and consuming pesticides, as well as general fuel consumption by vegetation management vehicles and machines, allows roadside managers to calculate a rough estimate of their current carbon emissions. Developing scenarios that reduce roadside vegetation management activities or increases efficiencies of fleet and machine consumption of fuel and pesticides will give managers an initial estimate of the potential to reduce carbon emissions. If carbon emissions are significant and reducing carbon emissions is a priority, further development of a more detailed and sophisticated carbon emissions reduction plan for roadside vegetation management could be justified.

Carbon emissions from roadside mowing operations.

Gao and others (2010) calculated real world greenhouse gas emissions from a variety of diesel tractors, mower equipment and herbicide applicators used for roadside vegetation management by the New York State Department of Transportation. A few examples from the study are displayed in Table 13, which shows carbon emissions by mower type or for a light truck with a herbicide applicator in its box. Table 13 only shows some of the makes and models of mowers in the report; the full report provided data for more mower types, which varied between 5.2 to 36.5 kilograms (kg) CO/mile of emissions and 3.6 to 75.2 kg CO$_2$/acre of emissions.

Table 13: Examples of carbon emissions produce by various vegetation management equipment (from Goa et al. 2010).

Operation Type	Make and Model	Distance Treated		Acres Treated	
		CO^2 (kg/mile)	CO (g/mile)	CO^2 (kg/acre)	CO (g/acre)
Mowers					
Sickle bar	Ford 2910	7.2	94.6	7.1	93.5
Flail	John Deere 401B	6	56.8	4.1	38.5
Batwing	Ford 5610	7.9	64.3	4.4	35.4
Over the Rail	New Holland TL90A	36.5	63	75.2	129.9
Herbicide Applicator					
Light duty truck	N/A	1.4	3.5	2.9	7.3

Based on data from Table 13 and by using other information from Goa et al. (2010) it is a relatively straight forward calculation to estimate the level of carbon emissions under current operations and to identify how future vegetation management could contribute to a reduction in carbon emissions for roadside vegetation operations. Although Goa et al. (2012) did not cover all types of mowers and herbicide applicators, enough information is available to FLMA managers to complete estimations using some caveats. For example, carbon emission reductions could result from cutbacks in the frequency or mileage of roadside mowing or the amount and frequency of applications of herbicide. More judicious use of both vegetation management practices could further increase the impact, amounting to significant carbon emission reductions across each of the FLMAs each year.

Carbon emissions for fuel consumption used in vegetation management

Overall, management of fuel efficiency for fleets of vehicles used for roadside vegetation maintenance and operations can help reduce overall GHG emissions. Managers can either increase the fuel efficiency of individual vehicles or convert from traditional diesel/gas vehicles to hybrid, electric or other alternative fuel vehicles. Either of these actions will help reduce tailpipe emissions resulting from roadside vegetation management activities. The Environmental Protection Agency (EPA 2011) uses the following average carbon emissions for vehicles consuming a gallon of fuel:

a) 8,887 grams CO_2 / gallon of gasoline

b) 10,180 grams CO_2 / gallon of diesel

FLMA managers, knowing how many gallons of fuel they consume each year for roadside management, can use the EPA's standard emissions for gas and diesel to calculate carbon emissions for the annual operations of their vehicles based solely on fuels. They also can calculate reductions in carbon emissions as they make changes to their fleets or reduce the amount of fuel consumed to manage roadside operations.

Carbon emissions for pesticide production used in roadside management

The use of the herbicide applicator truck in Table 13 did not include the carbon emissions from the production of pesticides that would be sprayed along the roadsides used by the power applicator. Bartlett and James (2011) used calculations of carbon emissions for the production of herbicides, insecticides and fungicides in a model that measured the carbon emissions of two different types of golf courses. Assuming many of the pesticides used for turf management at golf courses are the same or similar to those used for roadside management; road managers can use the following carbon emissions for their calculations in treating noxious weeds and other unwelcome vegetation, fungi or insect pests. For each kilogram of active ingredient, the following carbon dioxide equivalent emissions (CO_2E) are estimated (Bartlett and James 2011):

Herbicide production:	18.25 +/- 8.71 kg CO_2E kg^{-1}
Insecticide production:	14.79 +/- 11/44 kg CO_2E kg^{-1}
Fungicide production:	11.94 +/- 10.35 kg CO_2E kg^{-1}

The pesticides used for roadside management do not result in relatively large amounts of carbon emissions compared to mowing or overall fuel consumption, but it is worthwhile to have data that does account for such use.