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Assessing the Potential to Sequester Carbon within State Highway Rights-of-Way in New Mexico

Phase 2: Development of a Right-of-Way Carbon Sequestration Program

Prepared by:
New Mexico Department of Transportation
Research Bureau
7500B Pan American Freeway NE
Albuquerque, NM 87109

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Assessing the Potential to Sequester Carbon within State Highway Rights-of-Way in New Mexico

Phase 2: Development of a Right-of-Way Carbon Sequestration Program

Final Report
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Prepared for:
New Mexico Department of Transportation
Research Bureau
7500B Pan American Freeway NE
Albuquerque, New Mexico 87199-4690
(505) 841-9145

Prepared by:
Douglas Romig, CPSS, MSc
Cameron McNaughton, Ph.D, P.E.
John Kern, Ph.D

Golder Associates Inc.
5200 Pasadena NE, Suite C
Albuquerque, New Mexico 87113

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14. Abstract

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High Mow subplots showed a trend of increased aboveground biomass and canopy cover at the end of the growing season compared to Low Mow. Aboveground biomass and canopy cover responses to Imprinting compared to the Natural subplots were varied and insignificant. Differences in soil carbon stock among managed and natural zone treatments were generally insignificant and equivocal in response. Continuous measurements of soil temperature and moisture did not identify any significant differences between treatments in either managed or natural ROW zones.

Unmowed summertime net ecosystem exchange (NEE) was negative, indicating net sequestration of atmospheric CO_2 by photosynthetic plants. After mowing, daytime NEE were either positive for Low Mow or less negative for High Mow treatments. Low Mow nighttime fluxes were also positive after mowing and exceeded NEE observed in High Mow and Control subplots. This response to mowing is consistent with the reduction in the leaf area and increased respiration as plants replace their leaves following defoliation.

The discrete chamber-based measurements of CO_2 flux used characterized the ecosystem CO_2 dynamics at the ROW test plots where benchmarked against Ameriflux long-term NEE data from semi-arid grassland eddy covariance stations. Qualitatively, the magnitude of NEE observations at the test plots were typically within 2 standard deviations of the 10-year mean for the Kendall long-term ecological research

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Preface

The New Mexico Department of Transportation (NMDOT) was selected by the Federal Highway Administration (FHWA) to determine the feasibility of maximizing carbon sequestration within state highway rights-of-way (ROW). Golder Associates Inc. was retained by NMDOT to conduct Phase 2 of this project. Primary objectives are to: 1) determine the effectiveness of selected management practices in increasing soil organic carbon (SOC) in ROWs, and 2) develop a scientifically valid protocol for measuring net change in SOC within ROWs and present it to an appropriate carbon exchange for approval and use in marketing carbon credits.

NOTICE

DISCLAIMER

Abstract

Selected rights-of-way (ROW) vegetation management treatments were evaluated over three growing seasons to determine if they could increase soil organic carbon (SOC) along state highways in New Mexico. Eight test plots were established in north central and north eastern portions of the state along a SOC/precipitation gradient in Prairie and Lower Montane biomes. Treatments were to maintain biomass, increase soil moisture and increase available soil nitrogen. In actively managed zones of the ROW, treatments included a modified mowing regime to retain more biomass (High Mow) compared to current mowing operations (Low Mow) combined with interseeding legumes (Legume). The natural zone (ROW outside of managed areas) were treated with soil imprinting (Imprinting) and legume interseeding (Legume) compared to unmodified control (Natural). Unfortunately, the legumes broadcast seeding into established ROW plant communities was ineffective and monitoring the treatment was discontinued in the second growing season. Field measurements included SOC and nitrogen, vegetation biomass and cover, soil temperature and moisture, and carbon dioxide (CO_2) efflux. The project also considered the feasibility of a carbon offset protocol for highway ROW roadside vegetation management that could a be sold within a cap-and-trade carbon commodity market.

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The discrete chamber-based measurements of CO_2 flux used characterized the ecosystem CO_2 dynamics at the ROW test plots where benchmarked against Ameriflux long-term NEE data from semi-arid grassland eddy covariance stations. Qualitatively, the magnitude of NEE observations at the test plots were typically within 2 standard deviations of the 10-year mean for the Kendall long-term ecological research (LTER) station. Discrete NEE observations at the test plots often had a more dynamic range than the Kendall station (i.e. more negative during the day or more positive during the night).

Nonlinear relationships between NEE and physical processes (i.e. normalized difference vegetation index [NDVI], soil temperature, soil moisture and photosynthetic active radiation [PAR]) were modelled using the equation free empirical dynamic model (EDM). The EDM was trained and calibrated on thirteen years of NEE data from both the Kendall and Audubon LTER stations. The strongest predictions were obtained from the EDM using NDVI, soil temperature, and PAR with a squared correlation of 0.70.

The EDM was used to validate and predict annual NEE and mowing responses at the eight ROW test plots using site-specific data. The EDM predictions were better correlated with the discrete subplot-level measurements recorded at each test plot than with the comparison to the Kendall station mean. While the EDM predicted that all test plots were net sinks of atmospheric CO_2, Lower Montane test plots have the potential to store three or four times more carbon as the Prairie test plots and the benchmark grassland LTER stations. Predicted differences in carbon uptake between the High Mow and Low Mow treatments was approximately 5 percent across all test plots. Further refinement of the EDM

is needed to capture the full dynamic range of the CO_2 fluxes observed at the test plots and better predict treatment differences.

A framework for a proposed highway ROW roadside vegetation carbon offset protocol is presented. The protocol framework describes the requirements and expectations of North American voluntary offset programs to quantify, monitor and verify CO_2 removals from the atmosphere so that they would qualify to be sold in a cap-and-trade carbon market. Key elements of terrestrial carbon offset protocols are discussed at length including applicability, baselines, quantification, permanence, monitoring and verification, and ownership and crediting.

Preliminary estimates indicate profit associated with a NMDOT ROW offset project is low ($1.10 to $2.76/km/yr) for average annual CO_2 sequestration rates at the current market price for carbon. Returns over $50/km/yr are estimated with an increase in carbon prices and maximum NEE differences are achieved under a high mowing regime with the potential to generate an estimated $365,000 per year. Eastern portions of the U.S. as well as the Pacific Northwest have greater potential to sequester CO_2 compared to New Mexico. In these regions, modification of ROW mowing practices to either enhance or have the least impact on root growth would likely result in higher rates of carbon sequestration. In addition to the increased removal of CO_2 from the atmosphere, it is likely that mowing would also be done less frequently and thereby qualify for additional reductions of greenhouse gas emissions due to decreased equipment use. Establishing a highway ROW vegetation offset project in these wetter regions of the U.S. could produce significant financial returns and help slow global climate change.

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Abbreviations

ACR	American Carbon Registry
ARB	Air Resources Board (California)
CAR	Climate Action Reserve
CCX	Chicago Climate Exchange
CI	confidence interval
CRT	Climate Reserve Tonne
CSPP	Carbon Sequestration Pilot Project
CSR	corporate social responsibility
EDM	empirical dynamic model
FAST	Fixing America's Surface Transportation
FHWA	Federal Highway Administration
FLMA	federal land management agency
GHG	greenhouse gas(ses)
GIS	geographical information system
GPP	gross primary productivity
IPCC	Intergovernmental Panel on Climate Change
IRVM	Integrated Roadside Vegetation Management
ISO	International Organization for Standardization
kg C/m^2	kilograms per meter squared
LTER	long-term ecological research
Mg C/ha	Megagram of carbon per hectare
MT	metric tons
NDVI	normalized difference vegetation index
NEE	net ecosystem exchange
NMDOT	New Mexico Department of Transportation
OPA	offset program authority
PAR	photosynthetically active radiation
PRISM	Parameter-elevation Regressions on Independent Slopes Model (Oregon State University)
R^2	squared correlation
R_e	ecosystem respiration
RGGI	Regional Greenhouse Gas Initiative
ROW	rights-of-way

SOC	soil organic carbon
SSRs	sources, sinks, and reservoirs
$\mu mol/m^2/s$	micromoles of carbon dioxide per meter squared per second
VER	Verified or Voluntary Emissions Reduction
VCS	Verified Carbon Standard
VWC	volumetric water content
WBCSD	World Business Council for Sustainable Development
WCI	Western Climate Initiative
WRI	World Resources Institute

1 INTRODUCTION

The New Mexico Department of Transportation (NMDOT) was selected by the Federal Highway Administration (FHWA) to determine the feasibility of maximizing carbon sequestration in state highway rights-of-way (ROWs) and using the increase in soil organic carbon (SOC) to earn tradable carbon-offset credits. NMDOT developed a two-phase study to evaluate the potential to sequester atmospheric carbon in ROWs. The focus of Phase 1 was to measure SOC within state highway ROWs in a scientifically defensible manner, document current ROW management practices, and suggest new practices that might increase SOC sequestration (EMI 2013). Phase 2 was initiated in the spring of 2013 to investigate the efficacy of selected ROW management practices that could increase SOC sequestration and complete steps toward developing a ROW carbon offset protocol for a cap-and-trade greenhouse gas market.

Golder Associates Inc. (Golder) was retained by NMDOT to implement Phase 2 studies with the primary objectives to: 1) determine the effectiveness of selected ROW management practices in increasing SOC in ROWs, 2) develop a scientifically valid model for measuring net change in SOC within ROWs, and 3) determine if ROW SOC sequestration can reduce atmospheric carbon and is appropriate for approval and use in marketing carbon credits.

1.1 Background

Global climate change is arguably one of the foremost environmental challenges of our time. It is driven by increasing amounts of carbon dioxide (CO_2) and other greenhouse gases (GHGs) emitted into the atmosphere, which trap heat and raise the earth's surface temperatures. Predicted impacts of climate change include prolonged droughts, rising sea levels, and increased severity of storms, which could all be costly to society.

Solving the problem of global climate change is relatively straightforward: reduce the amount of carbon emitted into the atmosphere and increase the amount removed. The process of removing CO_2 from the atmosphere is called carbon sequestration. One way to absorb carbon from the atmosphere naturally is through photosynthesis, the process whereby plants capture CO_2 and energy from sunlight, and incorporate carbon into their roots, stems, trunks, and leaves. Ultimately, the plant dies and much of the carbon stored in its tissues is returned to the atmosphere through decomposition. Some of the plant carbon is consumed by animals (such as termites, earthworms, and rabbits) and microorganisms (such as bacteria, protozoa, and fungi) inhabiting the soil and they then transform it into soil organic matter.

1.1.1 Federal Highway Administration Carbon Sequestration Pilot Project

Beginning in 2008, the FHWA's Office of Planning, Environment, and Realty and the Volpe National Transportation Center conducted a Carbon Sequestration Pilot Program (CSPP 2010). The CSPP team sought to "assess whether a roadside carbon sequestration effort through modified maintenance and management practices is appropriate and feasible for state departments of transportation…when balanced against ecological and economic uncertainties."

The CSPP team estimated the amount of carbon that could be stored using native vegetation management on lands within the National Highway System. The team also considered the potential revenue that could be generated through the sale of carbon credits if normal vegetation management practices were modified to facilitate carbon sequestration in ROW soils and vegetation and sold cap-and-trade market (a market-based approach that provides economic incentives for achieving reductions in GHGs [Section 6]).

CSPP team determined that more than 5 million acres (2 million hectares [ha]) of ROWs are managed along the 163,000 miles (262,000 kilometers [km]) of paved and unpaved roadways nationwide. The soils and vegetation on these lands currently store an estimated 91 million metric tons (MT) of carbon and sequester carbon at an estimated rate of 3.6 million MT per year (1.06 MT per acre per year). While carbon storage occurs naturally as part of the carbon cycle, ROW management practices have the potential to incrementally increase or accelerate carbon sequestration. The CSPP team also estimated that the ROWs on the National Highway System could potentially sequester up to seven times more carbon than it currently stores (between 425 and 680 million MT).

The NMDOT was the first state transportation agency chosen to develop a carbon-assessment project for ROWs and to determine the opportunities to manage and augment vegetation and soil to increase carbon sequestration. Besides mitigating global climate change, increasing SOC within ROWs could provide funding to NMDOT through sale of carbon credits within a cap-and-trade program. FHWA selected NMDOT for the study because the state has many miles of rural roads and thus many acres of ROW to manage. It also has diverse forests and grasslands that have the potential to sequester soil carbon. In addition, New Mexico was, at the time of selection, a member of a voluntary emissions trading program to meet statewide carbon reduction goals.

1.1.2 NMDOT Phase 1 Investigation

In 2011, the NMDOT began the first phase of research building on the results of CSPP. The goals for Phase 1 were to determine the number of acres available for carbon sequestration, the amount of SOC currently in ROW soils, the environmental characteristics that affect carbon sequestration in these systems, and which vegetation management practices might increase SOC.

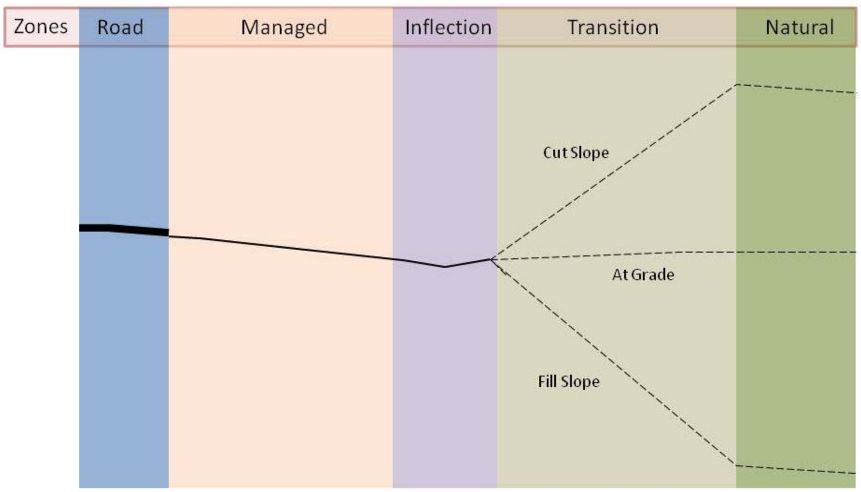
To account for the variability within ROWs, a conceptual ROW site model was developed with four zones (Figure 1.1), each with a unique history of disturbance, management, local topography, and potential soil and vegetation characteristics. The zones were:

1. managed zone, adjacent to the road and subject to frequent maintenance activities and runoff from the road;
2. inflection zone, the swale where stormwater accumulates and drains;
3. transition zone, where the soils and native plant community were initially disturbed during road construction, but have returned to natural vegetation; and
4. natural zone, areas within the ROW not disturbed by road construction and in relatively pristine condition.

The Phase 1 investigation focused on areas in the state that receive at least 14 inches (35 centimeters [cm]) of precipitation annually for three reasons. First, research (Svejcar et al. 2008) has shown that, especially during periods of drought, more arid soils become net emission sources of CO_2 rather than carbon sinks (a reservoir for storing carbon). Second, climate, not management, is the dominant driver of carbon flux in semi-arid rangelands (Haferkamp and Maencil 2004, Schuman et al. 2005). Third, aridic soils are naturally low in soil carbon and have slow sequestration rates, which make it difficult to measure absolute changes in soil carbon over time. In fact, many carbon registries like the Chicago Climate Exchange (CCX, Brown et al. 2010) originally did not offer emission offsets from drier regions that have limited capacity to sequester soil carbon.

Soil and vegetation samples were collected at 117 randomly selected sites along state highways that spanned three distinct biomes: Upper Montane (coniferous forest), Lower Montane (woodlands and shrublands), and Prairie. Mean SOC were estimated to be 57.9 mega-grams of carbon per hectare (Mg C/ha) in the Upper Montane; 36.2 Mg C/ha in the Lower Montane; 42.9 Mg C/ha in the Prairie biomes. The study found that, on average, the managed zone in the Prairie biome contained more SOC than other ROW zones, while differences in SOC by zone at the Lower Montane sites were not evident. In total, it was estimated that ROW soils contain nearly 1 million MT of SOC along 7,700 km (4,812 miles) of state highways bordered by 22,500 ha (56,250 acres).

Figure 1-1. ROW site cross section and conceptual site model



NMDOT's Highway Maintenance Management System database was also queried to examine mowing and chemical spraying, two ROW vegetation management practices most common in the Prairie transportation districts. It was found that 56 highways were mowed more frequently, and by reducing the number of visits to the district's average would result in nearly 1,900 fewer miles mowed every year.

1.2 Theoretical Basis for ROW Soil Carbon Sequestration

A key factor in understanding the potential of ROW vegetation to sequester SOC is directly related to root growth of herbaceous plants. In particular, the unique qualities of grass roots make them effective in sequestering SOC. Up to 80 percent of the total biomass of a grass plant exists as root tissues (Jackson et al. 1996), and in temperate ecosystems, nearly 50 percent of those roots die and are replaced over the course of a year (Gill and Jackson 2000). Annual senescence of grass roots directly contributes organic compounds to the soil, including easily decomposed carbohydrates and proteins to more resistant cellulose and lignin. The small diameter, fibrous grass roots have a higher rate of decomposition by soil organisms compared to the taproots of forbs, thus facilitate the formation of soil organic matter (Gill et al. 2002). Through the decomposition process, these compounds are modified to become stable organic compounds that persist for hundreds to thousands of years (Reeder et al. 2001; Schuman et al. 2005).

The principal objective of the study was to evaluate ROW vegetation management practices that could potentially increase the total above- and below-ground biomass of herbaceous plants under the premise that maintaining more photosynthetic biomass during the growing season would lead to an increase in SOC in our semi-arid environment. The primary management practices to increase biomass in the ROW plant communities include reducing defoliation by modifying the mowing regime, increasing available water, and increasing soil nitrogen.

1.2.1 Defoliation

The frequency, intensity, and timing of defoliation by grazing or mowing influences plant responses (Harris 1978). Defoliation of grasses and its impact on productivity has been intensely studied in both the laboratory and the field for the past 65 years or more. These studies have evaluated livestock grazing and simulated grazing by clipping to examine nutrient redistribution, root impacts, growth rates, compensatory regrowth, and CO_2 sequestration. Only a limited number of studies have looked at mowing in native grasslands. Thus, we focus on grass defoliation studies recognizing that clipping to a uniform height to simulate grazing may be more representative of mowing (Stroud et al. 1985). While the effects of defoliation are species-specific and modulated by a number of environmental factors (e.g., moisture availability, soil nitrogen), most studies find final aboveground biomass at the end of the growing season to be negatively affected (Ferraro and Oesterheld 2002). It is also generally accepted that removing photosynthetic tissues during the growing season leads to reallocation of energy reserves from the roots to regrow stems and leaves. As Schuster (1964) surmises, "When a grass gets grazed, it prunes its own roots to match the top."

For example, laboratory clipping of blue grama (*Bouteloua gracilis*) immediately decreased net photosynthesis by 60 percent, and new growth on the clipped plant was directed to new leaves rather than root tissues compared to unclipped plants (Detling et al. 1979). Similar observations have been made of other shortgrass prairie species (Branson 1956; Stroud et al. 1985). A single defoliation of 80 to 90 percent of shoot volume can completely halt root growth for up to 17 days (Briske 1991) and Crider (1955) found after 30 days nearly 40 percent of the roots had not recovered (not growing). A 50-percent defoliation has been shown to retard root growth in seven of eight perennial grasses for up 18 days (Troughton 1981). In some situations, repeated defoliation caused root mortality, affecting the plant's ability to draw water and nutrients from the soil and convert sunlight into carbohydrates (Crider 1955).

The reduction of root growth and mass associated with defoliation directly impacts SOC accumulation. In tallgrass prairies, changes in SOC have been found to be inversely related to grazing intensity (Leibig et al. 2005), while mowing has shown no effect on SOC (Scjzacht et al. 1996, Edwards et al. 2003) or resulted in SOC reductions (Kearney et al. 2004; Kitchen et al. 2009). Mowing effects on the soil carbon pool in shortgrass ecosystems has not been examined in the scientific literature, but in some cases SOC could be positively related to grazing. This is primarily related to the change in composition that can occur under higher grazing intensity in shortgrass and mixed-grass systems, where cool-season grasses are replaced by warm-season grasses (Schuman et al. 1999; Reeder and Schuman 2002). An increase in SOC can occur because warm-season grasses generally possess finer root systems and higher root/shoot ratios than cool-season grasses, partitioning more carbon to the roots (Derner et al. 1997 and 2006; Reeder and Schuman 2002; Reeder et al. 2004; Conant and Paustian 2002; Derner and Schuman 2007). Conversely, Schuster (1964) documented decreasing root density with depth in blue grama with increased grazing intensity.

Defoliation of herbaceous vegetation by mowing uniformly removes biomass from all species at regular time intervals and distributes litter across the soil surface. While litter may help retain soil moisture, it is unlikely it would contribute to SOC, as 90 percent or more will oxidize (return to the atmosphere as CO_2) in our semi-arid environment. Unlike mowing, livestock trampling of digested biomass (urine and manure) can, in theory, incorporate organic matter into the soil surface and could enhance plant growth.

1.2.2 Water Availability

Water is generally the most limited resource in semi-arid plant communities and has a direct positive relationship with vegetation productivity. This is evident along roadsides where plants immediately adjacent to the road are often more productive because runoff from the paved surface increases soil moisture in these areas. Infiltration rates are primarily determined by soil texture, though it has been shown that uneven soil surfaces slow erosion and capture water and nutrients (Marlatt and Hyder 1970). Soil imprinters (Figure 1-2) have been used to mechanically create a temporary uneven surface by stamping an array of offset indentations or divots that vary in size depending on equipment (Dixon 1990).

Due to their shape, divots harvest water and maintain soil moisture almost twice as long as ridges (Hyder and Bement 1970, Winkel et al. 1991, Winkel and Roundy 1991). The longevity of indentations primarily depends on vegetation cover, soil texture, wind, and precipitation. Marlatt and Hyder (1970) documented complete erosion of indentations after a single summer of record-setting precipitation, whereas the indentations may remain effective at capturing water for more than 3 years, even after they fill with sediment (Gaglio, 2013). In arid rangeland, where imprinting was combined with broadcast seeding, germination rates and productivity were found to be higher compared to untreated soils that were drill seeded (Haferkamp et al. 1987, Dixon 1990, Winkel et al. 1991).

Figure 1-2. Soil imprinter

1.2.3 Nitrogen Availability

Nitrogen (N) is essential to growth of vascular plants (Wallace et al. 1981) and application of N fertilizers has been shown to increase plant biomass in some grassland ecosystems (Samuel and Hart 1998, Berg and Sims 2000) and SOC (Derner and Schuman 2007). However, in semi-arid regions, native plants are adapted to inherently low soil fertility conditions (Chapin 1980) and generally have little response to increased N (Reeder and Schuman 1989; Carpenter and West 1987; Halvorson and Bauer 1984; Laurenroth et al. 1978; Reeder and McGinnies 1989). This lack of response is attributable to low genetic plasticity and lower tissue nutrient requirements (Drenovsky and Richards, 2004).

Legumes have a symbiotic relationship with rhizobial bacteria that fix atmospheric nitrogen (N_2) to ammonia (NH_3), which in turn is transformed into nitrate (NO_3) to be absorbed by the host plants (Smith 1996). Nitrogen generally becomes available to adjacent plants upon death of the legume roots or the entire legume plant (Burity et al. 1989). Interseeding with legumes in intensely-grazed shortgrass pastures has been shown to increase grass productivity (Burity et al. 1989) and SOC (Mortenson et al. 2004). Legumes are typically less than 2 percent of a grassland community (Schuman et al. 1999, Reeder et al. 2004) and modest increases in the proportion of legumes may enhance the productivity of grazed grasses (Sheehy 1989).

2 MATERIALS AND METHODS

2.1 Study Design

Golder used a before-after-control-impact experimental design to compare potential highway ROW management practices (or treatments) and to determine if they can enhance SOC sequestration. The experimental design combined the Phase 1 managed/inflection zones into a managed zone (M Zone) immediately adjacent to the road shoulder, approximately 4 to 5 meters (m) wide. The transition/natural zones were combined into a natural zone (N Zone) typically 4 to 6 m wide.

Three treatments, modified mowing, soil imprinting, and interseeding legumes, were initially tested. These treatments were selected because they have a reasonable probability of increasing SOC and they could be applied to most highway ROWs. Treatments for the M Zones included: 1) modification of the mowing regime to increase stubble height of herbaceous plants and retain more live biomass (High Mow), and 2) interseeding into established vegetation with a native legume, white prairie clover (*Dalea candida*), to determine if soil nitrogen availability can be increased. Treatments for the N Zones included: 1) imprinting soils to better capture water and nutrients, and 2) interseeding with white prairie clover. Safety concerns precluded imprinting soils in the M Zones as the operation might create a rough or soft highway shoulder. One control and three treated subplots were established for each zone in a two-by-two factorial experimental design (Figure 2-1). These test plots were arranged pairwise along the highway ROWs.

The ROW test plots were selected from Phase 1 sampling sites, which spanned the range of SOC along a precipitation gradient (Figure 2-2; EMI 2013). Because the treatments being tested primarily focused on modifying grass and forb composition in the ROWs, test plots were limited to Prairie and Lower Montane biomes dominated by herbaceous and limited shrub vegetation rather than forest plant communities.

Test plots were established at eight Phase 1 ROW sites the week of June 24, 2013 across north central and northeastern portions of the state (Figure 2-3). Due to time and distance constraints, certain monitoring activities (particularly discrete CO_2 flux measurements) were focused on three primary test plots, 104-79, 469-39, and 555-12. Five secondary test plots were monitored in less detail with a lower intensity, shorter duration, and less frequency of discrete CO_2 flux measurements (test plots 021-15, 120-30, 469-02, 472-07, and 538-43).

Figure 2-1. Original test plot design

Managed Zone	**CONTROL** Current (Low) Mowing (15 cm high) [M1]	Current Mowing (15 cm) Interseed Legumes [M2]	Higher Mowing Height (25-30 cm) Interseed Legumes [M3]	Higher Mowing Height (25-30 cm) No Legumes [M4]	↑ 5 m ↓
Natural Zone	**CONTROL** No Mowing [N1]	No Mowing Interseed Legumes [N2]	No Mowing Interseed Legumes and Imprint [N3]	No Mowing Imprint Only [N4]	↑ 5 m ↓
	← 100 m →	← 100 m →	← 100 m →	← 100 m →	

Figure 2-2. Precipitation and SOC gradient for Phase 1 Montane and Prairie sites and Phase 2 ROW test plots

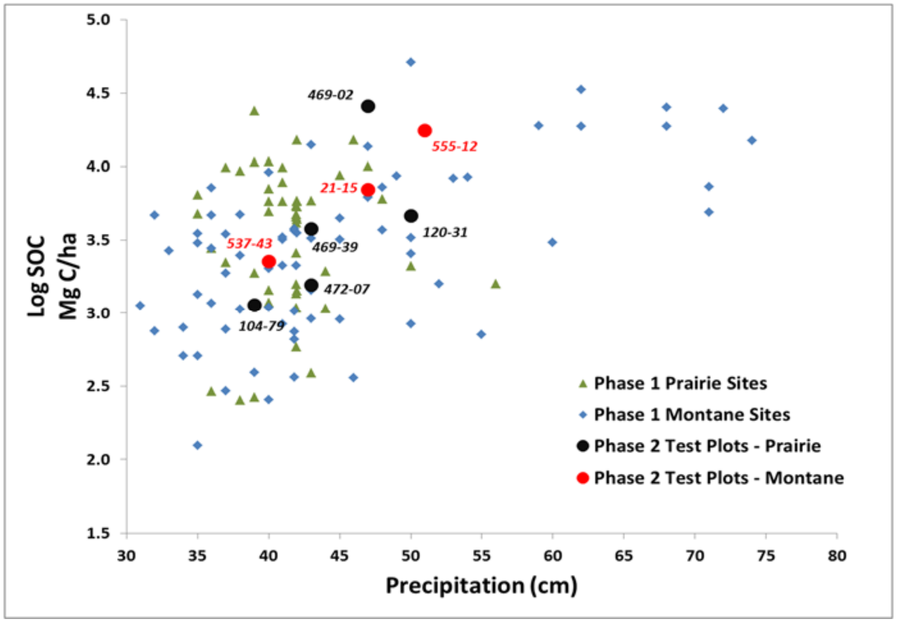
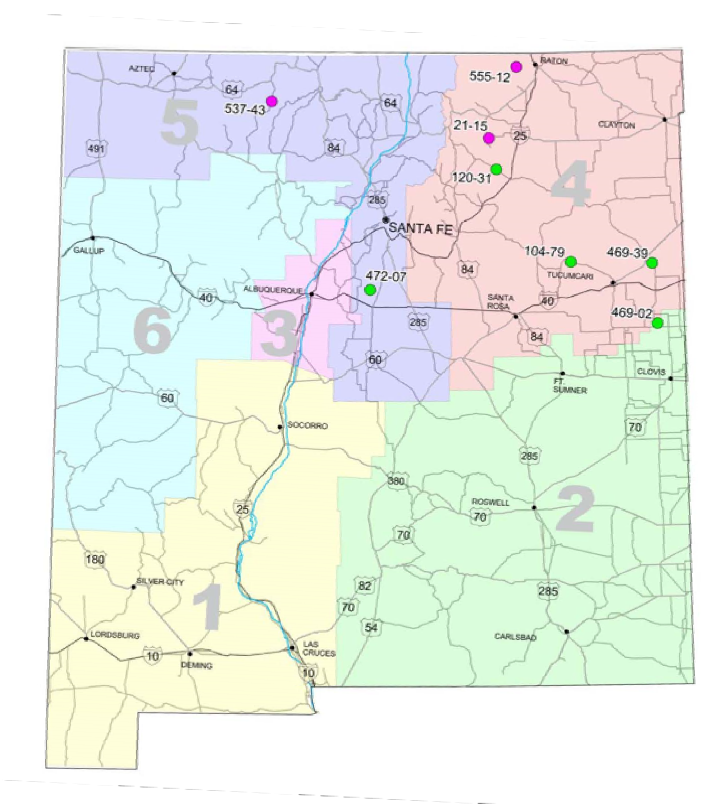


Figure 2-3. ROW test plots by highway mile marker (green = Prairie; pink = Lower Montane) and NMDOT transportation districts



2.2 Test Plot Installation

Eight test plots were established the week of June 24, 2013. All test plots were in the northern half of New Mexico, five in the Prairie biome and three within the Lower Montane biome (Figure 2-2). In some cases, ROWs did not have sufficient length to accommodate four 100-m subplots, but they met all the other selection criteria. Therefore, plots were shortened or, in the case of test plot 021-15, the subplots were installed on both sides of the road. General characteristics of the test plots are summarized in Table 2-1.

High Desert Native Plants, LLC, performed the imprinting and seeding. Imprinting was accomplished using a 6-foot-wide Dixon Land Imprinter™ in the two N Zones of each test plot. The land imprinter created an array of offset divots on the soil surface. Due to existing vegetation, the imprinting required two passes to achieve the desired surface conditions. Dimensions of an individual divot were approximately 30 by 30 centimeters (cm) and 15 cm deep. At each test plot, two M Zones and two N Zones were interseeded with white prairie clover mixed with an inert filler to achieve a seeding density of five seeds per square foot (0.8 lbs pure live seed/acre) using broadcast seeding.

Unfortunately, the 2014 summer monitoring found no evidence of the interseeded legume established in either the M or N Zones at any of the eight test plots. In consultation with the Technical Panel, it was agreed to discontinue the monitoring of the legume treatments and focus on the ROW treatments where observation indicated significant effects. Therefore, each test plot was consolidated into two M and two N Zones (Figure 2-4), with the investigation of treatments reduced to the effects of high versus low mowing in the M Zone, and imprinted versus control in the N Zone.

Figure 2-4. Revised test plot design

Managed Zone	**CONTROL** Current [Low] Mowing (15 cm high) [M1]	**TREATED** Higher Mowing Height (25-30 cm) [M3]	↑ 5 m ↓
Natural Zone	**CONTROL** No Mowing [N1]	**TREATED** Imprinting [N3]	↑ 5 m ↓
	← 200 m →	← 200 m →	

Table 2-1. General characteristics of ROW test plots

Test Plot	Precipitation (cm/year)	Temperature (° C)		Elevation (m)	Soil Texture	Ecosystem	Dominant Plant Species		
		Min	Max				Grasses	Forbs	Shrubs
Lower Montane Biome									
021-15	46.7	-9.4	29.1	1964	Clay Loam	Pinyon-Juniper Woodland	Western wheatgrass, Cane bluestem, Alkali sacaton, Sand dropseed	Bindweed, Sunflower	none
537-43	40.7	-12.2	29.1	2226	Sandy Clay Loam	Sagebrush/ Mixed conifer forest	Western wheatgrass, Blue grama, Smooth brome	Bindweed, Sweetclover, Trailing fleabane	Sagebrush, Fringed sage, Rubber rabbitbrush
555-12	49.2	-8.9	27.4	2189	Loam	Mixed conifer forest	Little bluestem, Western wheatgrass, Switchgrass, Blue grama, Smooth brome	Mullen, Sweetclover Bindweed	none
Prairie Biome									
104-79	38.6	-4.3	24.7	1257	Sandy Loam	Shortgrass Prairie	Blue/Sideoats/Black gramas, Galleta, Sand dropseed, Bristlegrass	Globemallow, Desert zinnia,	Honey mesquite, Yucca, Snakeweed
120-31	49.3	-9.4	28.2	2082	Loam	Shortgrass Prairie	Blue grama, Cane bluestem, Mat muhly, Sand dropseed	Kochia, Buffalo gourd, Goosefoot, Sunflower	Fringed sage
469-02	46.6	-4.6	32.3	1418	Sandy Loam	Shortgrass Prairie	Blue grama, Sand dropseed, Western wheatgrass, Cane bluestem	Bindweed, Kochia, Nightshade	none
469-39	42.3	-5.0	34.3	1212	Loam	Shortgrass Prairie	Blue/Sideoats gramas, Cane bluestem, 3-awn, Plains lovegrass, Sand dropseed, Vine mesquite	Tumbleweed, Ragweed, Scurfpea, Bullthistle	Snakeweed, Yucca
472-07	37.6	-7.3	30.7	1926	Sandy Loam	Shortgrass Prairie	Blue grama, Mat muhly, Sand dropseed, Cane bluestem, Needlegrass	Kochia, Ragweed, Tumbleweed, Globemallow	Winterfat, Prickly pear

2.3 Monitoring Activities and Methods

Because of the inherent challenges in measuring changes in SOC in a semi-arid climate and the natural variation of carbon in soils, the study was designed to use multiple lines of evidence to ascertain CO_2 sequestration rates from the two management treatments (Golder 2013a). A specific concern was the ability to statistically detect changes in SOC under different treatments in a relatively short study period that might otherwise be detected over a longer study and/or in a wetter climate.

To evaluate the effectiveness of ROW treatments, we measured conventional biometric data (plant canopy cover, aboveground biomass of live plant material and litter, soil moisture and temperature, SOC, etc.) that is comparable with other ecological and/or soil research projects investigating carbon dynamics. Additionally, we recorded discrete and continuous chamber-based CO_2 flux measurements to be integrated with net ecosystem carbon exchange data from regional eddy-covariance flux networks to develop a model to understand the relationships between ecosystem respiration and the carbon uptake by vegetation in the ROW. Details of the monitoring activities for the test plots are described in the following subsections.

2.3.1 Climate and Remotely-Sensed Data

Monthly temperature (minimum, maximum, and mean) and precipitation data for each test plot were assembled from 4-km spatial climate datasets provided by the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate group at the Oregon State University (2016). Remotely-sensed data resources Photosynthetically Active Radiation (PAR) and Normalized Difference Vegetation Index (NDVI) were obtained from the National Aeronautics and Space Administration ([NASA] 2016a and b).

2.3.2 Soil Sampling and Analysis

Soil conditions were characterized at the start and completion of the investigation by systematically collecting surface soil samples (surface to 20 cm deep) within each subplot using a hand auger. Two separate soil samples were collected for laboratory total soil carbon and nitrogen analyses; each sample was comprised of five subsamples that were bulked in the field. Soil bulk density samples were also collected using a cylindrical metal coring tool of known volume driven into the soil approximately 10 cm deep. Samples were dried at 105^{o} C and weighed to determine bulk density of site soils.

The fine earthen material (<2 mm size fraction) of each bulk sample was thoroughly mixed and a 100-g subsample was sent to the Soil, Water, and Forage Analytical Laboratory at Oklahoma State University for analysis of carbon and nitrogen. At the laboratory, a 0.5-g subsample was burned at 1000^{o} C in a LECO CN2000™ furnace. Following Rabenhorst (1988), a second 0.5-g subsample was burned at 575^{o} C. The first ignition was to measure total carbon and nitrogen, and the second ignition was to measure organic carbon. Inorganic carbon was calculated as the difference between total (1000^{o} C) and organic (575^{o} C) carbon. Detection and reporting limits were 0.02 and 0.1 percent, respectively (Zhang 2013). For comparison, SOC results (percent mass) were normalized to a soil carbon stock or density, reported as kilograms of carbon per square meter (kg C/m^2), for the 20-cm soil surface interval using the soil bulk density from each test plot.

Composite soil samples collected from each ROW test plot in 2013 were also sent to Energy Laboratory in Billings, Montana, to characterize soil pH, saturation percent, and particle size (texture).

Table 2-2. Summary of soil and vegetation variables monitored during ROW study

Variable	Method/Data Source	Frequency
Soils		
Total soil C and N	LECO C/N analyzer	Q2 2013 and Q3 2015
Soil bulk density	Cylindrical core	Q2 2013 and Q3 2015
Soil pH	pH meter - saturated paste	Q2 2013
Soil texture	Hydrometer method	Q2 2013
Saturation percent	Gravimetric	Q2 2013
Soil temperature	Automated in-situ sensor	Continuous at 30-minute intervals
Soil moisture	Automated in-situ sensor	Continuous at 30-minute intervals
Soil CO_2 flux	Infrared gas analysis	Quarterly – discrete and continuous
Vegetation		
Plant cover Species composition	5 to 10 ¼-m^2 quadrats/treatment	May, July, and September/October
Aboveground production	5 ¼-m^2 quadrats/treatment	September/October
Remotely-Sensed Data		
Precipitation	PRISM data	Monthly
Photosynthetic radiation	fAPAR data	Weekly

2.3.3 Vegetation

Vegetative canopy and basal cover were monitored throughout the growing season from all test plots. Monitoring vegetation cover varied by season, with more intensive monitoring during the fall. Transects were placed randomly within each test plot. Five to ten ¼-square-meter (m^2) quadrats were placed systematically along the transect during the three growing season monitoring events (May, July, and September/October). Quantitative vegetation data (e.g., canopy and basal cover) were measured by growth-form (i.e., grass, forb, shrub) and the dominant species within each quadrat was recorded. Amounts of canopy cover, basal cover, surface litter, rock fragments, and bare soil were estimated visually. All cover estimates were made in 0.1-percent increments and percent area cards were used to increase the accuracy and consistency of the cover estimates.

Aboveground plant production was measured at the end of the growing season, in late September or early October. In each test plot, herbaceous vegetation in five quadrats was clipped at the ground surface and all litter was collected to measure aboveground biomass. Herbaceous vegetation was bagged by growth form (grass, forb, or shrub), and along with litter, dried at 60° C for 24 hours and then weighed.

2.3.4 Soil Moisture and Temperature

Soil moisture was measured using Decagon EC-5 H_2O™ probes (capacitance probes) and soil temperature was measured using Pace Scientific™ solid-state temperature probes (thermistors). The sensors were installed approximately 10 cm below the ground surface and were connected to a Pace Scientific XR5-SE™ datalogger in a waterproof housing. Probes were installed in each subplot approximately 1 month after the test plots were established. In-situ soil moisture and temperature were measured automatically every 30 minutes. Data were downloaded quarterly during the regular monitoring events.

Responses of the soil moisture sensors were calibrated to known water content to understand site-specific soil/water relationships using the thermogravimetric method, where known gravimetric and volumetric water contents (VWC) in soil samples were related to sensor responses in volts (White et al. 1994). Four-point calibration curves for sensor voltages were developed from soil samples of a known volume and water content for each ROW site (Golder 2013b).

2.3.5 Surface CO_2 Flux Measurements

To quantify the effects of the treatments on ecosystem carbon dynamics and soil carbon, Golder recorded discrete measurements of in-situ soil temperature, soil VWC, and the exchange of CO_2 gas between the ground surface and the atmosphere (i.e., CO_2 flux).

At the ecosystem level, the net rate of exchange of CO_2 between the atmosphere and terrestrial ecosystems represents the sum of CO_2 sinks (negative CO_2 flux with respect to the atmosphere) and CO_2 sources (positive CO_2 flux). Sinks can include plant photosynthesis and microbial autotrophy; sources can include plant respiration, microbial respiration, and root respiration. The strength of each source/sink term is controlled by abiotic factors such as incident solar radiation, soil temperature, soil moisture, and by the presence of soil microbes, plants, and fungi.

Net ecosystem exchange (NEE) is defined as the net exchange of CO_2 between the ecosystem and the atmosphere. Gross primary productivity (GPP) is the total amount of atmospheric carbon fixed into organic carbon by plants via photosynthesis, and ecosystem respiration (R_e) is defined as sum of heterotrophic (soil organisms) and autotrophic (plant) respiration. These three terms are related by the following equation:

$$NEE = GPP + R_e$$

Since respiration always releases carbon to the soil pore spaces or atmosphere, R_e is always positive. Negative values for NEE indicate drawdown of atmospheric CO_2 via photosynthesis (GPP) exceeding ecosystem respiration. Since GPP only occurs during the day (i.e., GPP_{light} = negative; GPP_{dark} = 0), nighttime measures of NEE are equivalent to nighttime ecosystem respiration ($NEE_{dark} = R_{e\text{-}dark}$) (Randerson et al. 2002).

The exchange of carbon between the atmosphere and terrestrial ecosystems can be measured by several methods, including eddy-covariance and various chamber-based systems, each with their own advantages and disadvantages (Norman et al. 1997; Liang et al. 2003). The eddy-covariance measurements analyzed as part of this study are described in Section 4.4.

Soil CO_2 flux measured using chambers has also been used independently from eddy-covariance data to determine the carbon budget of grasslands (Frank et al. 2002; Bremer et al. 1998) and prairie restoration treatments (Cahill et al. 2009). Ryan and Law (2005) observed that less sample-frequency chamber data can result in high variance, but if these data were regressed with soil temperature and water content, the variance of aggregate estimates was reduced.

Chamber-based flux measurements using short opaque collars, placed on a homogenous surface type, effectively measure R_e directly. For heterogeneous surfaces (patchy vegetation), separate bare soil and short vegetation flux measurements were combined in an area-weighted fashion to accurately estimate R_e. NEE measurements using chamber-based systems were feasible using tall clear-acrylic collars placed over short vegetation (e.g., grasses, forbs).

Surface CO_2 flux was measured using a portable LiCor Model 8100A™ survey CO_2 flux chamber system. Two separate instruments were used for the study, one owned by Golder and one rented from LiCor. Both instruments were calibrated regularly by the manufacturer. The instrument consists of a bowlshaped chamber connected via pneumatic hoses and electronic cables to an infrared gas analyzer housed inside a durable Pelican™ case. A soil moisture probe and a soil temperature probe were connected through an analog-to-digital input/output circuit. First, the instrument was placed on 20-cm diameter collars, which were installed approximately 24 hours before. Measurements over bare soil were conducted using short opaque acrylic collars, while measurements over vegetation used tall clear-acrylic collars. Clear acrylic collars were selected as industry data indicated Plexiglas™ transmits 92 percent of the incident solar radiation (Altuglas International 2016).

The LiCor 8100A™ instrument was controlled wirelessly using an application installed on an Apple iPod™. The flux chamber began in an elevated position and was purged by ambient air currents for 1 minute. The chamber was then closed for 2 minutes. While closed, the infrared gas analyzer continuously measured the concentrations of CO_2 and water vapor (H_2O) as a small pump circulated air from the chamber into the gas analyzer and back into the sealed chamber. Positive increases in the concentrations of CO_2 over time indicated a positive flux to the atmosphere; reductions in the concentrations of CO_2 indicated a negative flux.

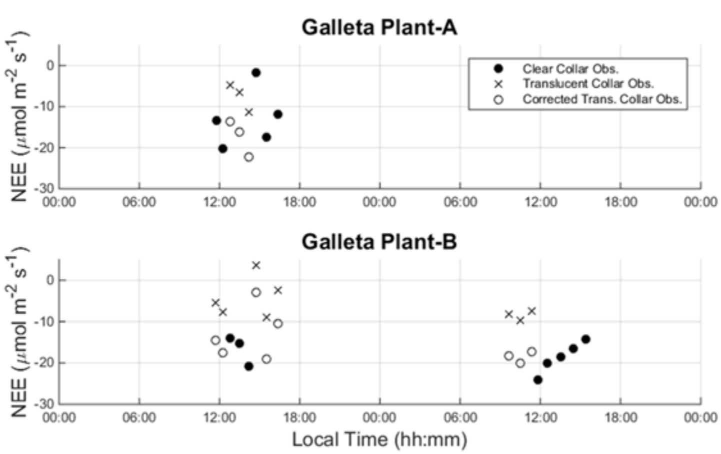
Flux measurements were recorded at different times over the 2-year study. During discrete plot-level monitoring, a minimum of five 3-minute-long replicate measurements (1-minute purge, 2-minute sample) were recorded at each soil collar. Longer measurements were also recorded to observe diurnal patterns in NEE. These longer measurements often included replicate measurements every 15 minutes (N = 4/hour) for 8 to 12 hours.

2.3.6 Correcting for Differing Opacity of Acrylic Collars

During separate field seasons, one of two acrylic collars was used and one of two LiCor flux chambers was used. In summer 2015, both collars and both LiCor units were deployed simultaneously to increase the intensity of the CO_2 flux measurements. When the acrylic collars were placed side by side, field technicians noted that one collar was visibly clearer than the other.

Over 3 days, a controlled test of the effects of this differing light transmission was conducted to determine whether or not it could affect daytime NEE measurements. Results of the test indicated that an empirical correction factor of 1.31 should be applied to daytime NEE measurements when the translucent collar was used (Figure 2-5). All chamber-based measurements of NEE during the study that were recorded when using the translucent collar have been corrected using this factor. Future studies should obtain as transparent as possible acrylic collars for chamber-based flux measurements of daytime NEE. A small-scale evaluation of differing acrylic products may be needed.

Figure 2-5. Effects of collar transparency on NEE measurements



3 ECOSYSTEM MODELING

3.1 Methods

The objective of this analysis was to develop a predictive model to infer average and annual NEE over a large area with similar physiographic characteristics for approximately 1 week. Prediction of mean or equivalently total weekly NEE within the NMDOT ROWs over large geographic areas would be a way to predict the potential effects of various land use and management practices (treatments). Two types of time series models were developed: 1) fitting a series of trigonometric polynomials termed Fourier expansion, and 2) using a technique developed from modern "big data" methods known as empirical dynamic modeling (EDM). The Fourier expansion approach was based solely on NEE time series, whereas the second method predicted NEE as a function of soil temperature, soil moisture, above-ground biomass and photosynthetically active radiation (PAR).

3.1.1 Fourier Expansion

With modest assumptions, discrete time series can be decomposed into the sum of sine and cosine functions:

$$NEE(t) \cong a_0 + \sum_{n=1}^{N} \left(a_n \cos\frac{n\pi t}{L} + b_n \sin\frac{n\pi t}{L} \right)$$

with amplitudes a_n and b_n and frequency $L/n\pi$. Time series composed of a small number of periodic forcing functions can be well approximated with sine and cosine functions evaluated at a small number of frequencies. In such situations, forecasting would proceed based on the fitted Fourier expansion. Conversely, when a large number of periodic functions are required to develop a satisfying description of the time series, forecasts based on the fitted models are likely to be less reliable.

The number of periodic components (N) needed to reproduce important characteristics of the NEE time series was diagnosed by finding the number of such components required to explain a large proportion (i.e. 80 to 90 percent) of the variance in the initial time series.

The variance of the of the time series is given by the sum of squared amplitudes, and the contribution of the i^{th} frequency to total variance is proportional to $a_i^2 + b_i^2$. To investigate the presence and number of periodic forcing functions that may drive patterns in the time series, these Fourier amplitudes were estimated and plotted against frequency.

3.1.2 Empirical Dynamic Model

Whereas the Fourier expansion method based predictions solely on the past patterns measured in the NEE time series, directly incorporating related physical process variables should improve predictive power. Predictions could be improved by incorporating covariates such as soil temperature and moisture or above-ground biomass. These covariates can be incorporated through linear regression and time series analyses, although both approaches require that covariate relationships remain constant in time, which are referred to as linear dynamics. However, relationships between covariates can vary temporally; NEE could respond differently to variations in soil moisture depending on the amount of biomass present. Such complex dynamics cannot be accommodated by linear time series analyses based on equations that remain constant through time.

Recent developments based on the theory of chaotic dynamical systems (Sugihara 1994; Ye et al. 2015) accommodate the difficulties of using simple equations to describe nonlinear interactions among natural processes. They instead rely upon a computer intensive empirical method identifying sets of conditions wherein the dependent variable can be forecast from the underlying process variables based on empirical patterns. Known as empirical dynamic modeling (EDM), it is an equation-free method that reveals dynamic relationships between physical processes as they evolve over time.

The EDM provides an approach to model the relationships between NEE and physical processes (i.e. NDVI, soil temperature, soil moisture, and PAR) that may vary nonlinearly. Nonlinear variation is exhibited when process relationships vary temporally and in concert with other processes. For example, an increase in PAR signals the potential for photosynthesis, although this potential photosynthesis is only realized when soil temperatures are in a certain range, and when biomass is present, as signaled by NDVI. Because of these obvious interactions, one would not expect NEE to vary linearly with these processes, although they are clearly among the key factors driving NEE. For these reasons, the EDM was selected over Fourier Expansion as a promising candidate for modeling and predicting NEE.

3.1.3 Model Selection

To test the model's potential to extrapolate in time and space, we combined time series from the Kendall and Audubon long-term ecological research (LTER) stations (Section 4.4.1) in a cross validation approach, fitted the EDM to all but one station-year combination, and then forecasted NEE for the deleted station-year. This process is known as cross validation.

The basic approach was to:

1. select a candidate set of predictor variables;
2. fit the EDM to all but one station-year with the selected predictor variables;
3. predict the omitted time series;
4. calculate mean monthly NEE for observed and predicted values;
5. store the paired observed and predicted monthly means;
6. repeat steps 2 through 5; and
7. calculate the squared correlation between observed and predicted monthly mean values.

This squared correlation represents the predictive quality of the selected model. This approach was used for a set of 14 candidate models, which were then compared based on the squared correlation between monthly mean flux measurements.

Quantifying model quality by predicting out-of-sample observations guards against over-fitting, because overly complex models that agree with idiosyncratic features of the training dataset generally do not extrapolate well to out-of-sample observations. This is a fundamental principal of machine learning algorithms that set apart from traditional parametric statistical methods that rely upon statistical theory and diagnostics for selecting parsimonious models (Burnham and Anderson, 1998).

3.2 Model Validation/Calibration/Extrapolation

The selected best model was calibrated to the full dataset from both the Kendall and Audubon stations, which provided the best predictions conditioned on the available recorded data. The calibrated model was applied to covariate measurements (NDVI, soil temperature, soil moisture, and PAR) at the eight NMDOT ROW test plots to predict NEE. NEE was also measured directly at these test plots, which provided the observed pair of values based on 3-hour averaging periods. Covariate time series were lengthy, so NEE could be predicted over approximately a 2-year time period, although actual monitoring was generally restricted to 1 day in the spring, summer, and fall. Observed and predicted values were compared in two ways: 1) predicted NEE was plotted against time with the observed values overlaid for comparison, and 2) predicted NEE was plotted against observed NEE with a 1-to-1 line, as well as a fitted geometric mean regression line. The coefficient of determination and equation of the fitted line were included on the plots. These comparisons provide understanding of how well the fitted model can be extrapolated spatially to locations that were not used for model training.

3.3 Predicting Annual Net Ecosystem Exchange and Effects of Mowing

Predicted NEE time series at each of the eight ROW test plots were integrated from January 2014 through December 31, 2014, to predict the annual change in soil carbon. Test plots with fewer than 320 days of measurements were excluded from the analysis. To simulate mowing regimes, NDVI was modified to reflect the changes in total canopy cover of the natural (control) subplot and three mowing treatments (low, high, and deferred) were developed using spring, summer, and fall cover data averaged across all ROW test plots (Figure 3-1). Canopy cover was interpolated to determine monthly data from three seasonal monitoring events in conjunction with NEE patterns observed at Sevilleta and Kendall LTER stations and modeled leaf area index used in regional soil-atmosphere models (Romig et al. 2006). Table 3-1 provides model inputs for canopy cover reductions and delays in plant recovery associated with mowing treatments and are based on observations made by Briske (1991) and Crider (1955), and were designated as low-mow, high-mow, deferred mowing, and natural treatments.

Figure 3-1. Canopy cover annual time series for natural (control) and low-, high-, and deferred mowing

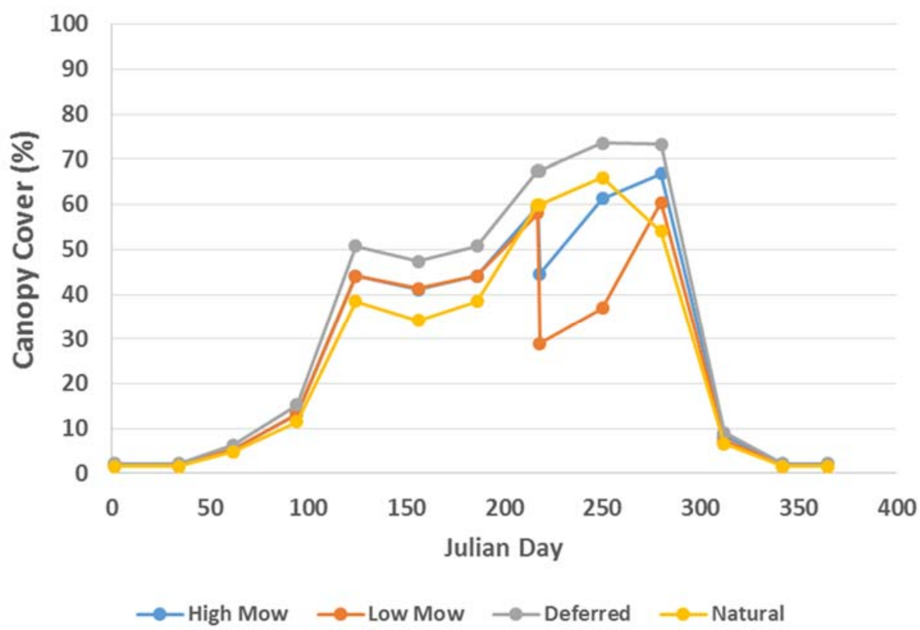
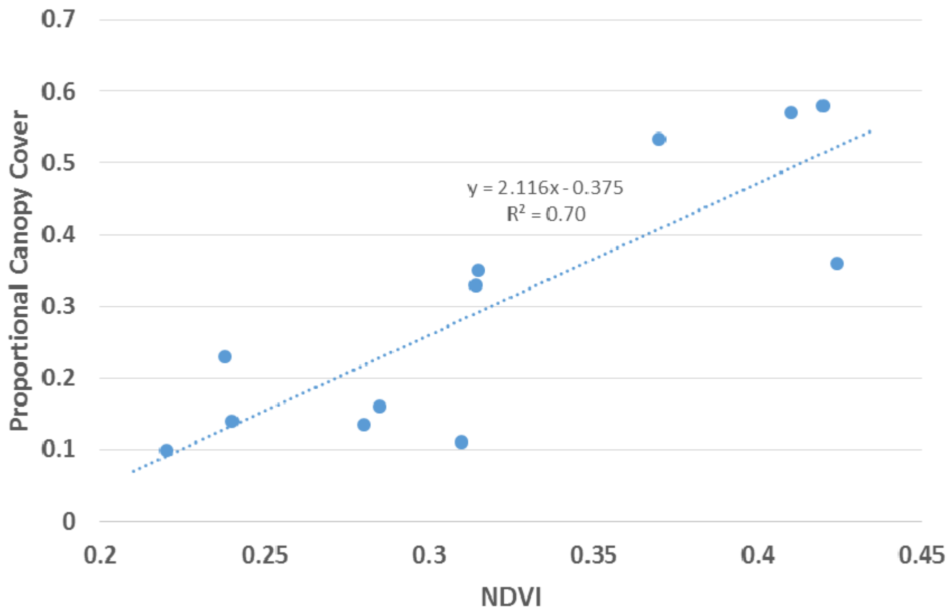


Table 3-1. Assumptions for the time series for canopy cover

Treatment	Canopy Reduction	Growth Response
High-Mow	-25%	1 week delay
Low-Mow	-50%	3 week delay
Deferred	+5%	NA
Natural	NA	NA

Canopy cover values were then converted to an NDVI using a linear correlation between proportional canopy cover and NDVI developed at the Kendall station (Figure 3-2; Lanteri et al. 2004). The model was applied to modified NDVI values to predict NEE associated with No-Mow, Low-Mow, and High-Mow treatments. The predicted NEE was plotted against time and compared to the predictions under the No-Mow scenario. These predicted NEE time series representing the mowing treatments were integrated through 2014 to compare with the total annual NEE under No Mow, so that the net effect of mowing relative to un-mowed conditions could be predicted.

Figure 3-2. Relationship between proportional canopy cover and NDVI at the Kendall station



4 RESULTS AND DISCUSSION

4.1 Climate

Monthly data for precipitation and temperature (minimum, mean, and maximum) were obtained from PRISM (2016) for May 2013 through October 2015 and compared to 30-year average (1980 through 2010). Monthly climate data were also summarized for each test plot (Table 4-1).

4.1.1 Precipitation

Growing season precipitation (May through October) during the study was near the 30-year average at the Lower Montane test plots in 2013, but 20 to 30 percent below average in 2014 and 2015 (Figure 4-1). Prairie sites had more varied precipitation during the growing season (Figure 4-2) compared to Lower Montane sites. Test plot 472-07 had average to above average rainfall for all three years. Test plots 469-39 and 104-79 had below normal precipitation in 2013 and 2014, while near average to slightly above average in 2015. Test plot 469-02 had below average rainfall during the growing season for all three years, while test plot 120-31 had above average precipitation in 2013.

According to the National Weather Service, all of the test plots experienced some drought during early summer of 2013 and throughout much of 2014, ranging from abnormally dry to extreme drought conditions. In 2015, statewide precipitation was above average in May and June, relieving drought conditions, but precipitation later in the growing season was below average, particularly at the Lower Montane test plots as well as 120-31 and 469-02.

4.1.2 Temperature

Monthly maximum, minimum, and mean temperatures at the Lower Montane and Prairie test plots (Figures 4-3 and 4-4, respectively) averaged over the study period did not differ substantially from 30-year averages. Slightly higher minimum temperatures were estimated across the three Lower Montane test plots in January and February during the study, and again in August through October (Figure 4-3). Prairie test plots had slightly lower maximum temperatures in October and November and marginally higher minimum temperatures in September compared to the 30-year average (Figure 4-4).

Figure 4-1. Growing season (May-October) precipitation at Lower Montane test plots

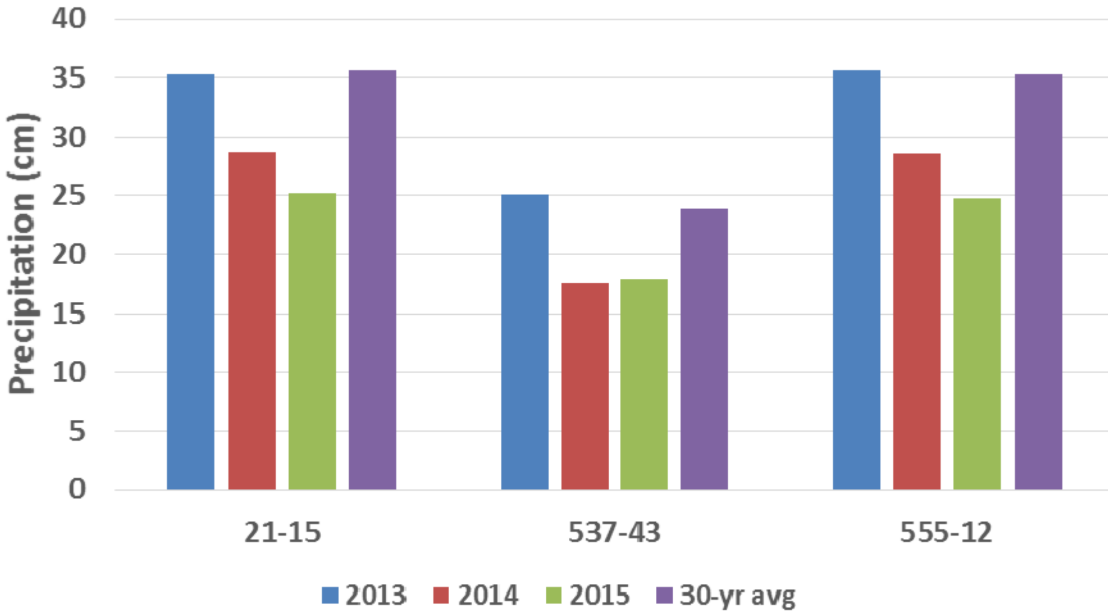


Figure 4-2. Growing season (May-October) precipitation at Prairie test plots

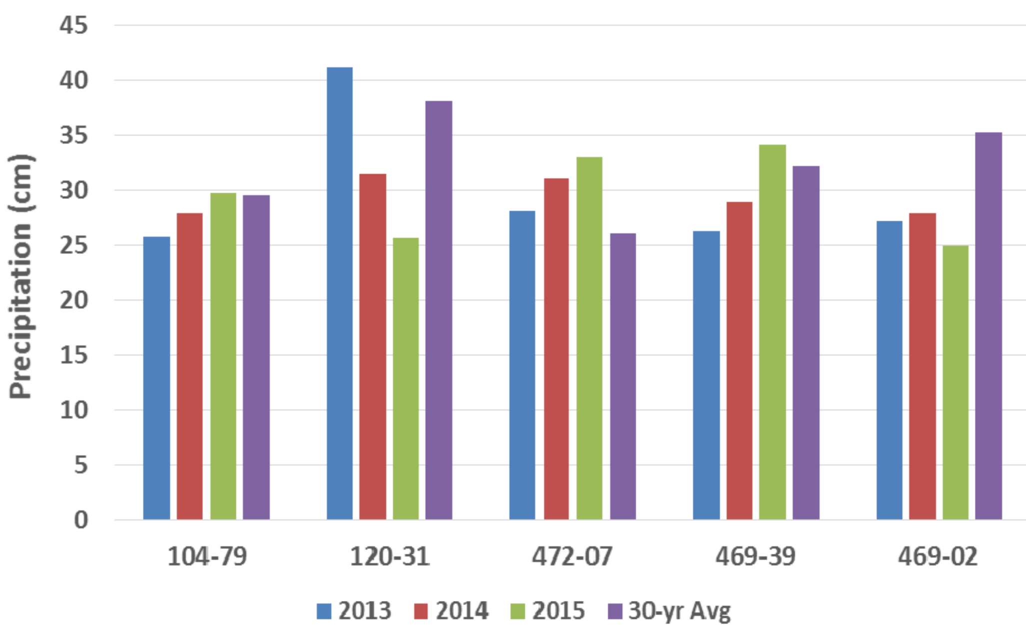


Figure 4-3. Lower Montane test plot mean, maximum, and minimum temperatures average during study compared to 30-year averages

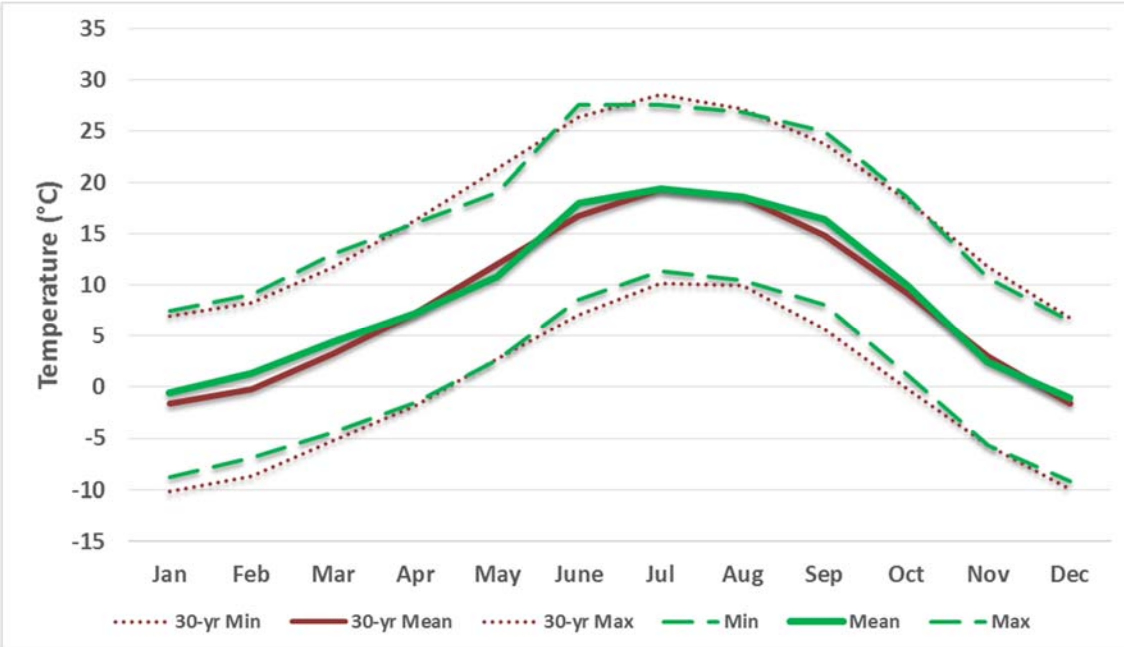


Figure 4-4. Prairie test plot mean, maximum, and minimum temperatures average during study compared to 30-year averages

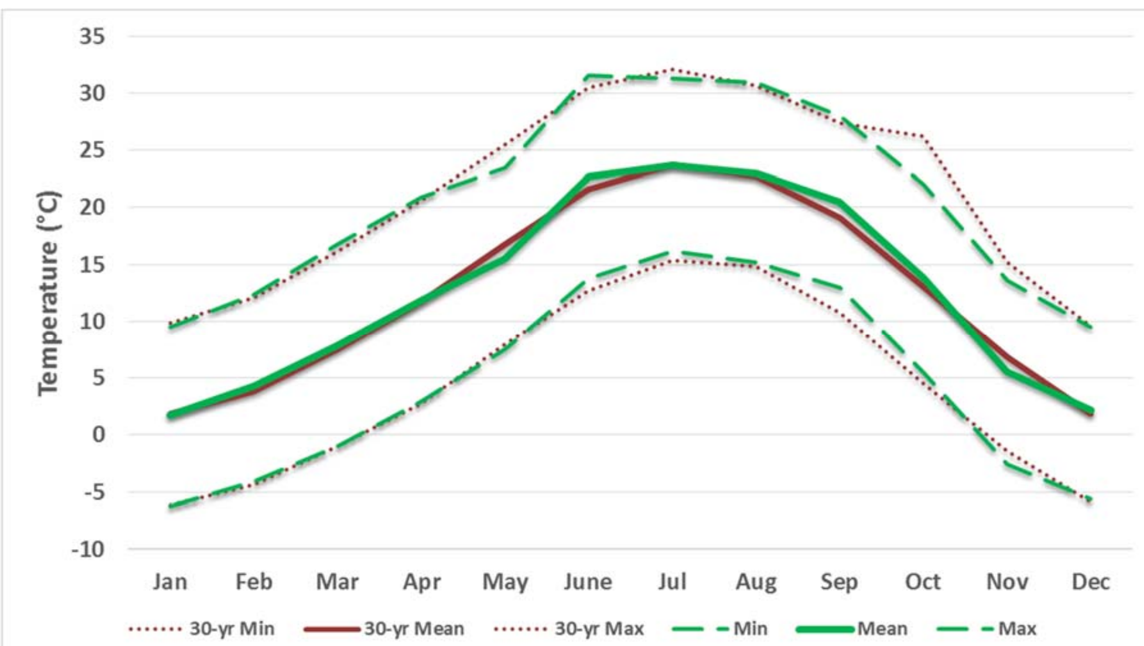


Table 4-1. Monthly precipitation and mean, maximum, and minimum temperatures at ROW test plots

Site	2013								2014											
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Precipitation (cm)																				
021-15	0.7	2.4	11.0	5.8	12.4	2.9	3.6	0.4	0.1	0.5	1.3	2.9	5.3	1.8	9.6	7.5	3.1	1.4	2.1	2.2
537-43	0.0	0.2	6.9	6.9	9.0	2.1	4.3	0.7	0.1	1.2	2.4	1.1	2.0	0.1	7.2	3.6	2.8	2.0	2.1	2.9
555-12	2.6	2.6	10.0	7.8	9.8	2.8	1.9	0.5	0.5	0.7	2.2	3.5	3.8	2.3	10.5	5.9	3.8	2.2	1.9	2.1
104-79	1.7	3.1	6.6	4.2	9.4	0.8	2.3	0.4	0.0	0.1	0.4	1.1	6.0	4.4	6.5	3.9	5.9	1.1	1.5	0.8
120-31	1.1	2.8	10.7	5.5	18.8	2.2	4.0	0.5	0.1	0.4	1.0	2.2	5.6	1.8	10.6	8.1	4.1	1.3	2.1	2.2
472-07	0.1	0.6	9.0	4.0	13.2	1.2	4.3	1.3	0.0	0.5	1.5	0.6	3.1	6.9	8.0	2.5	9.4	1.2	0.9	0.7
469-39	1.8	4.9	5.5	3.2	10.5	0.3	1.4	0.6	0.0	0.2	0.3	0.3	6.6	5.6	7.2	2.3	5.9	1.3	1.0	0.8
469-02	1.2	6.6	6.9	4.6	7.0	0.8	1.5	0.7	0.0	0.5	0.4	0.6	6.8	0.5	8.4	8.8	2.0	1.4	1.8	2.6
Mean Temperature (°C)																				
021-15	13.5	20.3	20.1	19.6	16.9	9.1	3.9	-0.2	0.8	2.7	5.3	8.4	12.0	18.6	20.5	18.3	17.2	12.2	3.1	0.7
537-43	9.7	17.6	19.5	18.7	14.7	5.5	0.7	-5.6	-3.7	-0.9	1.9	5.0	9.9	16.0	19.8	17.2	16.1	9.1	1.6	-1.8
555-12	12.2	19.4	19.5	19.2	16.5	8.9	3.5	0.0	0.2	1.3	3.9	7.0	11.4	17.6	18.9	17.6	16.3	10.9	2.1	0.4
104-79	20.9	26.6	26.5	26.3	23.3	15.0	8.2	3.2	3.9	5.4	9.7	14.6	19.2	25.4	26.8	26.4	21.8	17.6	7.5	4.7
120-31	3.6	19.8	19.5	19.2	16.4	8.7	3.8	-0.2	0.8	2.5	5.1	8.0	11.6	18.0	19.9	17.8	16.6	11.6	3.1	0.7
472-07	14.3	21.4	21.4	20.3	17.1	8.9	2.9	-1.5	0.2	3.8	5.5	8.8	12.6	23.2	24.3	23.7	19.8	15.7	5.8	4.1
469-39	19.7	25.4	25.3	26.1	23.5	14.9	7.7	2.7	3.2	4.7	9.2	14.1	19.4	24.9	26.4	26.6	21.8	16.8	6.8	4.4
469-02	18.4	24.5	23.9	23.9	21.4	13.4	6.6	2.3	2.7	4.3	8.4	12.7	17.4	20.3	22.0	19.0	17.7	12.2	3.4	1.1
Maximum Temperature (°C)																				
021-15	22.9	30.2	27.7	27.8	24.5	18.5	12.1	8.1	10.0	11.0	14.7	17.4	20.8	28.1	28.8	26.2	25.7	21.6	11.8	8.3
537-43	21.1	29.4	28.9	27.5	23.5	16.0	9.6	3.7	6.5	8.0	11.3	15.4	19.5	27.6	29.4	26.3	25.7	19.0	10.2	5.1
555-12	20.2	27.9	26.4	26.1	23.0	16.4	10.6	7.0	8.0	8.8	12.1	14.9	19.2	25.8	26.3	24.8	23.6	18.9	9.9	6.5
104-79	28.3	35.4	33.1	33.9	29.9	23.6	15.5	10.6	13.1	13.6	18.7	23.2	27.3	33.4	34.1	33.4	27.7	25.8	15.2	11.8
120-31	22.7	29.7	27.0	27.2	23.7	17.8	12.1	8.1	10.0	10.9	14.7	16.8	20.2	27.6	28.1	25.7	24.7	21.1	12.1	8.5
472-07	24.3	32.2	29.3	29.0	24.9	18.6	10.6	5.4	9.0	11.9	14.8	18.5	22.3	31.3	31.6	31.3	25.3	23.4	13.5	10.6
469-39	28.7	34.5	32.7	33.7	30.8	24.3	15.5	10.8	12.7	13.4	18.8	23.3	28.1	33.1	33.8	34.9	28.4	25.5	15.6	11.1
469-02	27.3	33.1	31.0	31.4	28.5	21.9	13.7	9.5	11.6	12.7	17.8	22.2	26.0	30.9	30.3	26.8	25.8	21.5	12.0	8.2
Minimum Temperature (°C)																				
021-15	4.2	10.5	12.4	11.4	9.3	-0.4	-4.2	-8.5	-8.4	-5.6	-4.2	-0.6	3.2	9.1	12.2	10.4	8.8	2.2	-5.7	-8.2
537-43	-1.7	5.9	10.1	9.9	5.8	-5.0	-8.1	-14.9	-13.9	-9.9	-7.5	-5.4	0.3	4.4	10.1	8.2	6.1	-0.9	-7.3	-9.6
555-12	4.2	10.9	12.6	12.3	9.9	1.3	-3.6	-6.9	-7.6	-6.2	-4.3	-0.9	3.6	9.4	11.6	10.3	9.8	3.7	-5.2	-6.9
104-79	13.4	17.9	19.9	18.7	16.7	6.3	0.9	-4.3	-5.2	-2.8	0.6	6.0	11.0	17.4	19.6	19.4	15.8	9.2	-0.4	-2.8
120-31	13.1	9.9	12.0	11.1	9.1	-0.3	-4.5	-8.5	-8.5	-5.9	-4.5	-0.9	3.0	8.4	11.7	9.8	8.6	1.9	-6.1	-8.2
472-07	4.4	10.6	13.4	11.6	9.4	-0.7	-4.8	-8.4	-8.5	-4.3	-3.8	-1.0	2.9	15.1	17.0	16.1	13.7	7.3	-2.5	-3.6
469-39	10.6	16.3	17.9	18.4	16.2	5.6	-0.1	-5.4	-6.2	-3.9	-0.3	4.9	10.7	16.7	19.0	18.2	14.9	7.8	-2.0	-3.9
469-02	9.5	15.8	16.8	16.5	14.4	4.8	-0.6	-4.9	-6.2	-4.0	-0.9	3.3	8.8	9.7	13.7	11.1	9.5	2.8	-5.6	-6.1

Site	2015										30-year Average												
	J	F	M	A	M	J	J	A	S	O	J	F	M	A	M	J	J	A	S	O	N	D	Total
Precipitation (cm)																							
021-15	2.7	3.3	2.2	2.6	11.6	4.1	3.5	2.1	0.9	2.9	1.4	1.4	2.4	3.0	5.0	5.8	7.6	9.0	5.0	3.2	1.6	1.4	46.7
537-43	4.3	3.5	2.2	1.7	7.6	1.8	3.0	2.2	1.5	1.8	2.7	2.7	3.2	2.9	2.5	2.1	5.1	6.7	4.1	3.3	2.8	2.7	40.7
555-12	2.1	4.3	1.9	4.2	11.7	3.3	3.8	2.3	1.0	2.7	1.6	1.5	3.4	3.5	5.4	5.8	7.5	9.0	4.4	3.2	2.1	1.7	49.2
104-79	3.3	2.3	1.0	2.5	12.6	2.8	5.1	3.4	1.0	4.8	0.8	1.0	2.2	2.2	3.9	5.2	6.3	7.0	3.9	3.2	1.6	1.2	38.5
120-31	2.7	3.0	2.5	2.1	11.4	4.0	4.5	2.2	0.1	3.5	1.5	1.3	2.3	2.7	4.9	6.3	8.4	9.2	6.1	3.1	1.8	1.5	49.3
472-07	4.5	2.0	0.9	3.5	18.0	1.2	7.4	1.8	1.2	3.3	1.5	1.6	2.1	1.9	3.0	2.6	5.6	6.8	4.6	3.5	2.1	2.3	37.5
469-39	3.9	2.2	0.8	3.6	13.0	2.9	8.4	3.6	2.8	3.4	1.1	1.1	2.3	2.5	4.8	5.9	6.2	7.2	4.6	3.5	1.6	1.4	42.3
469-02	2.5	2.1	1.2	1.7	7.7	3.6	5.9	1.5	1.3	5.0	1.3	1.4	2.6	2.5	4.7	6.4	6.5	8.4	5.1	4.2	1.9	1.7	46.6
Mean Temperature (°C)																							
021-15	1.1	2.1	6.2	8.8	11.6	18.5	19.6	19.4	17.8	12.3	-0.4	1.1	4.4	8.5	13.3	17.9	20.1	19.3	15.9	10.3	4.2	-0.5	9.5
537-43	-2.2	1.2	4.3	6.2	9.4	16.9	18.2	18.5	15.7	10.4	-3.7	-1.9	2.0	6.1	10.8	15.7	18.9	18.2	14.0	8.0	1.4	-3.6	7.2
555-12	0.7	1.5	5.1	8.1	10.9	17.3	18.4	18.8	16.9	11.9	-0.7	0.3	3.5	7.3	12.1	16.6	19.0	18.3	14.7	9.4	3.5	-0.8	8.6
104-79	2.9	6.4	10.0	15.6	18.2	24.8	27.7	26.4	24.9	16.9	3.9	5.9	9.9	14.3	19.5	24.5	26.7	25.7	21.7	15.4	9.1	3.8	15.0
120-31	0.8	2.1	6.0	8.4	11.1	18.1	19.2	19.1	17.4	11.8	-0.6	0.9	4.2	7.9	12.7	17.3	19.4	18.6	15.2	9.8	4.1	-0.5	9.1
472-07	1.1	5.0	8.4	12.9	15.8	20.1	20.9	21.1	18.6	11.9	0.0	2.2	5.7	9.6	14.6	19.5	21.8	20.8	17.2	11.0	4.9	0.0	10.6
469-39	1.9	5.8	9.6	14.8	17.4	24.9	26.8	25.6	24.4	16.7	3.3	5.5	9.4	14.0	19.1	24.1	26.3	25.3	21.4	15.1	8.4	3.2	14.6
469-02	-0.7	2.8	6.7	9.0	12.2	22.6	24.7	23.7	22.6	15.3	2.9	4.8	8.8	12.6	17.9	22.7	24.4	23.3	19.8	14.0	7.8	2.8	13.5
Maximum Temperature (°C)																							
021-15	8.5	10.4	14.8	17.6	19.3	27.1	27.4	28.2	27.2	20.8	8.6	10.0	13.3	17.8	22.5	27.1	29.1	27.7	24.9	24.9	13.1	8.2	18.9
537-43	5.1	8.7	13.3	15.6	17.8	27.0	26.9	27.9	25.4	19.2	4.8	6.6	10.6	15.5	20.9	26.5	29.1	27.5	24.0	24.0	10.3	5.0	17.1
555-12	6.7	7.8	12.2	15.3	17.4	24.7	25.5	26.7	25.7	17.9	7.5	8.4	11.5	15.7	20.6	25.3	27.4	26.2	23.3	23.3	11.8	7.1	17.4
104-79	9.1	13.5	17.9	23.4	24.2	32.6	34.8	33.6	32.4	23.0	12.0	14.1	18.3	22.9	27.8	32.8	34.7	33.4	29.6	29.6	17.3	11.4	23.7
120-31	8.3	10.1	14.7	16.9	18.6	26.6	27.1	27.5	26.6	19.9	8.2	9.5	13.0	17.0	21.7	26.5	28.2	27.0	24.1	24.1	13.1	8.0	18.4
472-07	6.2	12.4	16.3	21.9	22.9	29.7	29.0	29.9	28.1	19.8	7.3	9.9	14.3	18.8	24.0	29.5	30.7	29.1	26.1	26.1	13.0	7.3	19.7
469-39	8.7	13.9	18.4	24.0	24.5	32.8	34.7	33.6	32.6	23.7	11.6	14.0	18.1	23.0	27.7	32.6	34.3	32.9	29.5	29.5	17.0	11.1	23.4
469-02	6.2	11.2	16.1	18.7	20.2	30.3	32.4	31.9	30.6	21.2	10.4	12.8	17.1	21.6	26.4	31.1	32.3	30.8	27.5	27.5	15.6	10.1	21.9
Minimum Temperature (°C)																							
021-15	-7.4	-6.9	-2.9	0.0	3.8	10.1	11.9	11.3	8.8	3.8	-9.4	-7.8	-4.5	-0.9	4.2	8.6	11.1	10.8	6.9	0.8	-4.8	-9.2	0.5
537-43	-9.9	-7.4	-4.4	-3.1	1.0	6.8	9.6	8.9	5.9	1.7	-12.2	-10.3	-6.5	-3.4	0.6	4.8	8.8	8.8	4.0	-1.9	-7.5	-12.1	-2.2
555-12	-5.7	-5.6	-3.1	0.8	4.4	9.9	11.7	11.3	8.7	5.0	-8.9	-7.8	-4.5	-1.2	3.7	7.9	10.5	10.4	6.2	0.8	-4.8	-8.8	0.3
104-79	-3.8	-1.6	2.6	7.7	12.2	17.0	20.9	19.4	17.7	10.8	-4.3	-2.3	1.5	5.8	11.2	16.1	18.7	18.0	13.9	7.2	0.8	-3.9	6.9
120-31	-7.7	-7.0	-3.2	-0.1	3.6	9.6	11.4	10.8	8.3	3.7	-9.4	-7.8	-4.6	-1.1	3.7	8.0	10.5	10.3	6.4	0.4	-4.9	-9.0	0.2
472-07	-4.9	-3.4	0.4	3.9	8.8	10.4	12.8	12.3	8.9	4.1	-7.3	-5.5	-2.8	0.4	5.2	9.6	12.8	12.4	8.4	2.2	-3.2	-7.3	2.1
469-39	-4.6	-2.9	1.7	5.6	10.3	16.9	19.0	17.9	16.6	9.7	-5.0	-3.1	0.6	5.0	10.5	15.7	18.3	17.6	13.2	6.5	-0.2	-4.7	6.2
469-02	-7.1	-5.4	-2.5	-0.4	4.2	15.2	17.3	16.3	15.2	8.9	-4.6	-3.2	0.4	3.7	9.4	14.2	16.5	15.9	12.1	6.1	0.1	-4.4	5.5

4.2 Soils

Table 4-2 summarizes the soil characteristics for each test plot. Prairie test plots are moderately coarse- to medium-textured with sandy loams and loams. Lower Montane test plots tended to be more fine-textured with increased clay and silt content. Soils are generally neutral to slightly alkaline in reaction with saturated paste, with pH ranging from 6.8 to 7.6. Soil bulk density was measured at each site to assist with soil-water calibrations and used to calculate soil carbon stock or carbon density (discussed below). Bulk density ranged from 1.20 to 1.44 g/cm^3 in 2013 and from 1.34 to 1.72 g/cm^3 in 2015. Saturation percent is a function of soil texture and pore space and is used to quantify the soil water content of a saturated soil, as well as estimate the amount of water available to plants. Saturation percent ranged from 27.8 percent for the moderately-coarse soil at test plot 469-39 to 47.2 percent at test plot 021-15, where soils are moderately fine-textured.

Table 4-2. General soil characteristics at test plots

Test Plot	Particle Size Distribution (%)			Textural Class	pH, sat. paste	Saturation Percent (%)	Bulk Density (g/cm^3)	
	Sand	Silt	Clay				2013	2015
Lower Montane Biome								
021-15	24	40	36	CL	7.5	47.2	1.20	1.34
537-43	50	26	24	SCL	7.5	39.7	1.29	1.72
555-12	47	29	24	L	6.8	38.4	1.42	1.58
Prairie Biome								
104-79	60	23	17	SL	7.6	30.2	1.44	1.38
120-31	38	40	22	L	7.4	43.2	1.21	1.41
469-02	52	28	20	L	7.4	32.8	1.38	1.36
469-39	71	15	14	SL	7.6	27.8	1.22	1.66
472-07	65	22	13	SL	7.5	30.8	1.34	1.40

Soil samples for laboratory carbon analyses were collected in June 2013, when the test plots were established, and in September or October of 2015, during the last monitoring event. Table 4-3 lists measured values for SOC as percent mass. Organic carbon data were used to calculate soil carbon on a unit/area basis (carbon stock or density) based on the soil bulk density at each test plot. Because of differences in bulk density at test plots in 2013 and 2015 (Table 4-2), comparisons are made on an equivalent soil mass basis (Ellert and Bettany 1995). Extremely high SOC in both treated subplots M3 and N3 of test plot 555-12 in 2013 and 2015 (Table 4-3) is now believed to be associated with an oxidized coal seam present near the surface in this section of ROW. Because of this, test plot 555-12 was not included in the analysis of SOC responses to treatments.

Initial (2013) and final (2015) carbon stock for the 20-cm surface interval for M and N Zones at each ROW test plot are plotted in Figures 4-5 and 4-6, respectively. These data represent arithmetic means bracketed by the 90-percent confidence intervals (90% CI). As shown, M Zones have higher SOC compared to N Zones, except for test plot 537-43. The M Zone of test plot 537-43 is an embankment fill on top of the original ground surface.

For most test plots, comparison of carbon stock between treatments (Figure 4-5) showed no consistent response among initial (solid bars) and final (hatched bars) values. Whereas the final M3 (High Mow) SOC was lower at test plots 537-43 and 472-07, the other test plots had higher carbons stock compared to M1 (Low Mow). Significantly more carbon stocks, on 90% CI, was measured at test plots 104-79 and 469-39, with the High Mow treatment compared to the Low Mow, but was significantly less at test plots 472-07 and 537-43 (Figure 4-5). Treatment effects on carbon stocks also varied within the N Zone at a plot level (Figure 4-6). Significantly different carbon stock was measured at test plot 021-15 with Imprinting (N3) relative to the Control (N1); yet at test plot 472-07, the Control subplot had significantly higher carbon stocks.

Figure 4-7 illustrates pooled carbon stock (density) by treatment for all test plots assuming an equivalent soil mass (Ellert and Bettany 1995). No significant differences between treatments in 2013 and 2015 carbon stocks are evident, based on the 90% CI, for either M or N Zone. Figure 4-7 suggests relative changes in carbon stock within treatments during the 3-year study, with the High Mow (M3) showing the largest relative increase. However, annual sequestration rates by treatment (Table 4-3) have substantial variability between test plots and affirms the inherent challenges to detect changes in SOC given our semi-arid climate, the natural variation of carbon in our soils, and the relatively short study.

Table 4-3. Percent organic carbon and carbon stock in ROW test plots in 2013 and 2015

Test Plot	Treatment	Subplot	Organic Carbon (%)		Carbon Stock (kg C/m^2)		Sequestration Rate[2] (kg C/m^2/yr)
			2013	2015	2013	2015[1]	
Lower Montane							
021-15	Low Mow	M1	1.98	2.19	4.43	5.25	0.16
	High Mow	M3	1.76	2.87	4.17	6.88	0.88
	Control	N1	1.75	1.46	4.19	3.50	-0.23
	Imprint	N3	1.66	1.56	3.99	3.74	-0.08
537-43	Low Mow	M1	0.77	0.83	1.98	2.15	0.06
	High Mow	M3	0.75	0.38	1.87	0.99	-0.32
	Control	N1	1.03	0.84	2.65	2.16	-0.16
	Imprint	N3	1.07	1.09	2.71	2.82	0.02
555-12	Low Mow	M1	2.11	2.35	6.00	6.67	0.23
	High Mow	M3	4.64	10.78	13.19	30.63	5.81
	Control	N1	2.11	2.06	6.00	5.86	-0.05
	Imprint	N3	3.66	5.29	10.39	15.01	1.54
Prairie							
104-79	Low Mow	M1	1.47	1.02	4.22	2.93	-0.43
	High Mow	M3	1.35	1.24	3.81	3.57	-0.11
	Control	N1	0.76	0.74	2.18	2.13	-0.02
	Imprint	N3	0.74	0.78	2.05	2.25	0.04
120-31	Low Mow	M1	1.50	1.71	3.62	4.15	0.18
	High Mow	M3	1.46	1.71	3.53	4.14	0.21
	Control	N1	1.41	1.44	3.41	3.47	0.02
	Imprint	N3	1.51	1.59	3.65	3.85	0.07
469-02	Low Mow	M1	1.44	1.67	3.99	4.60	0.20
	High Mow	M3	1.79	2.01	4.94	5.55	0.20
	Control	N1	0.81	1.37	2.23	3.77	0.51
	Imprint	N3	1.15	1.31	3.18	3.61	0.15
469-39	Low Mow	M1	0.90	1.01	2.20	2.46	0.09
	High Mow	M3	0.99	1.28	2.42	3.12	0.23
	Control	N1	0.62	0.61	1.50	1.48	-0.01
	Imprint	N3	0.63	0.63	1.53	1.54	0.00
472-07	Low Mow	M1	1.23	1.19	3.30	3.18	-0.04
	High Mow	M3	0.94	0.50	2.52	1.34	-0.39
	Control	N1	0.82	0.76	2.19	2.05	-0.05
	Imprint	N3	0.64	0.69	1.73	1.85	0.04

Notes: 1 = carbon stock calculated on an equivalent soil mass using 2013 bulk density (Table 4-2)
2 = annual carbon sequestration rate is based on the difference between 2015 and 2013 carbon stock, positive values indicate increase in SOC

Figure 4-5. Initial (i) and final (f) average carbon stock (± 90% CI) for M Zones at test plots (M1 = Low Mow, M3 = High Mow)

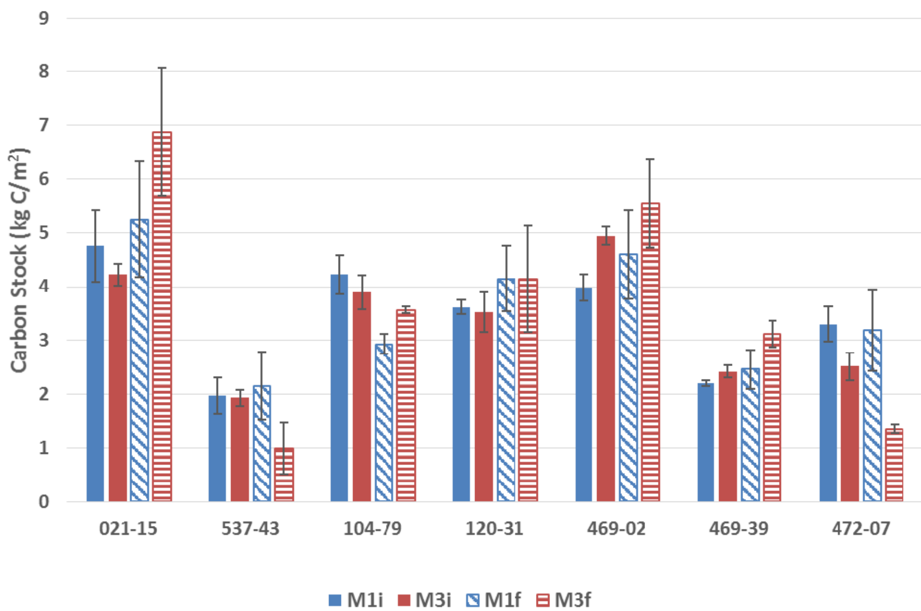


Figure 4-6. Initial (i) and final (f) average carbon stock (± 90% CI) for N Zones at test plots (N1 = Control, N3 = Imprinted)

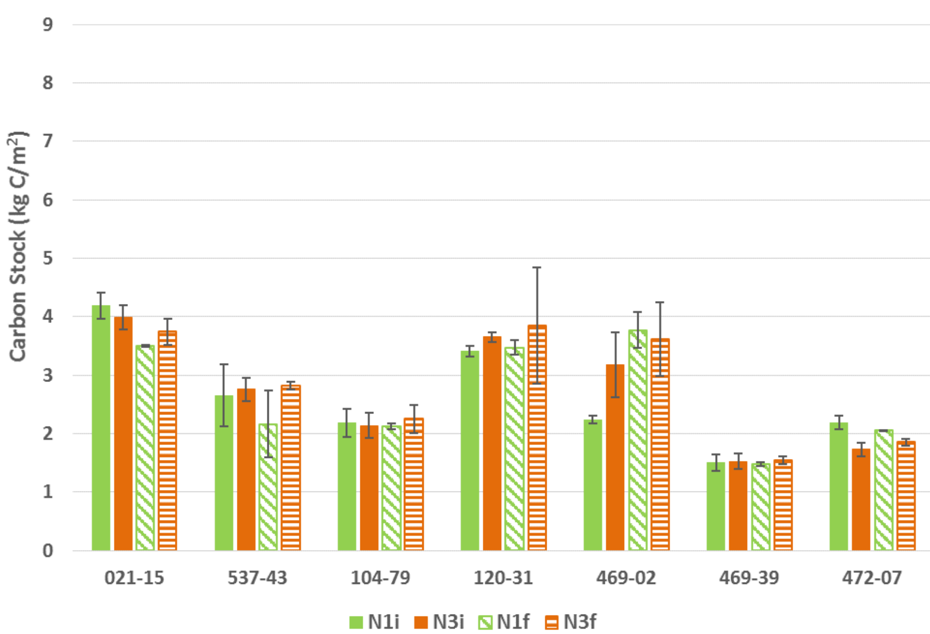
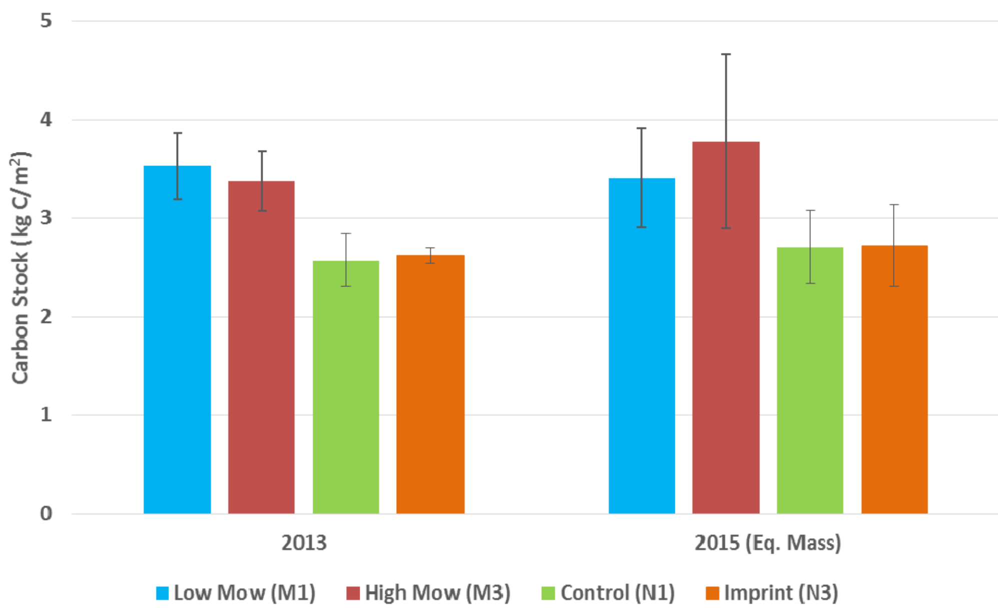


Figure 4-7. Initial (2013), final (2015) and equivalent mass carbon stock (± 90% CI) for ROW treatments



4.3 Vegetation

Field observations in the fall of 2013 discovered that mowing had only been performed at test plot 120-31 in accordance with the study protocol. To ensure mowing was implemented correctly in 2014 and 2015, we installed better signage, communicated more consistently with NMDOT maintenance supervisors, and provided direct field oversight of the mowing. Supervised mowing occurred within a 3-week period centered around August 1 in 2014 and 2015 (Table 4-4). High and low mowing treatments were done according to study protocols at six test plots in 2014 and seven test plots in 2015. Low Mow was to approximately 15 cm (6 inches) high. High Mow was accomplished by lifting the rotary mower to its maximum height, between 25-30 cm (10-12 inches), depending on specific equipment.

Because of the improper mowing, M Zone data from test plots 472-07 and 537-43 were excluded from the analysis of vegetation cover and biomass data. Comparisons of the N Zone subplots, Control and Imprinting, were based on 3 years of data from all test plots.

4.3.1 Aboveground Biomass

Figure 4-8 shows the aboveground biomass production by M Zone treatments for total, grass, forb and litter at the test plots for 2014 and 2015. These data represent arithmetic means bracketed by the 90% CI. While the High Mow treatment consistently had more total biomass compared to Low Mow, the only significant increase associated with the High Mow treatment was measured at Prairie test plots, based on the 90% CI (Figure 4-8a). Grasses were the most dominant component of standing biomass in both Prairie and Lower Montane test plots, but treatment effects were varied and not significant (Figure 4-8b). Forb biomass was relatively low in comparison to grasses, and consistently higher in the High Mow treatment compared to the Low Mow, but no significant differences were evident based on overlapping 90% CI, even in 2015 when higher forb biomass (likely a result of more spring precipitation) was observed at Prairie test plots (Figure 4-8c). Prairie test plot High Mow treatments had more litter biomass than Low Mow treatments, while the Lower Montane test plots showed the opposite (Figure 4-8d).

Table 4-4. Mowing treatments at ROW test plots

Test Plot	Year		
	2013	2014	2015
021-15	Not mowed	July 31	August 5
104-79	Not mowed	August 6	July 22
120-31	Unknown date	July 29	August 6
472-07	Not mowed	June - Entire plot mowed to 6” August 13 - Treatment mowing	July 29 - Low mow July 30 – High mow
469-39	Not mowed	August 5	July 21
469-02	Not mowed	August 5	July 21
537-43	Not mowed	August 14 August 30 - High mow to 6”	July 28
555-12	Not mowed	July 30	August 4

Figure 4-9 shows the total, grass, forb, and litter aboveground biomass produced at treated N Zones at the test plots for 2013 through 2015. Total standing biomass in Control and Imprinting treatments have varied responses from year to year (Figure 4-9a). The large increases in total biomass at both Prairie and Lower Montane test plots in 2015, particularly within the Control subplot, appears to be a direct result of higher forb biomass (Figure 4-9c). No significant or consistent trends in grass or forb biomass were observed over the 3-year study for the two N Zone subplots in either biome (Figures 4-9b and c). There was generally more litter biomass in 2014 and 2015 in the N Zones for the Imprinting treatment, but these differences are not significant based on the 90% CI compared to the Control(Figure 4-9d).

4.3.2 Canopy Cover

Canopy cover by M Zone treatments for total, grass, forb, and litter measured during the fall monitoring events in 2014 and 2015 are shown in Figure 4-10. Total canopy cover was higher from High Mow treatments compared to Low Mow at Lower Montane test plots in 2015 and at Prairie test plots for both 2014 and 2015 (Figure 4-10a). These differences, however, are not significant based on the 90% CI. As with biomass, grasses were the dominant component of canopy cover at both Prairie and Lower Montane test plots, but treatment effects were varied and not significant (Figure 4-10b). Similarly, only varied and insignificant responses in forb cover were observed between treatments (Figure 4-10c). Litter cover from High Mow subplots was less at both Prairie and Lower Montane test plots compared to Low Mow, but again, no significant differences based on the 90% CI (Figure 4-10d).

Figure 4-11 shows fall canopy cover in N Zones for total, grass, forb, and litter from 2013 through 2015. While total canopy cover increased over the 3-year study in both Control and Imprinting subplots, responses varied and were not significantly different in any given year in either biome (Figure 4-11a). No significant or consistent trends in grass canopy cover were observed over the 3-year study for the two N Zone subplots in either biome (Figure 4-11b). Forb cover at Lower Montane test plots, while not significant, was consistently greater in the Imprinted subplots than the Control during the whole study (Figure 4-11c). Forb cover at Prairie test plots did not follow that pattern. Litter cover was generally greater in the Imprinted subplots compared to the Control in both biomes. Based on the 90% CI, litter in the Imprint subplots was significantly greater in both the Prairie and Lower Montane test plots in 2015 (Figure 4-11d).

Figure 4-8. M Zone biomass measured during the fall monitoring events at test plots (± 90% CI)

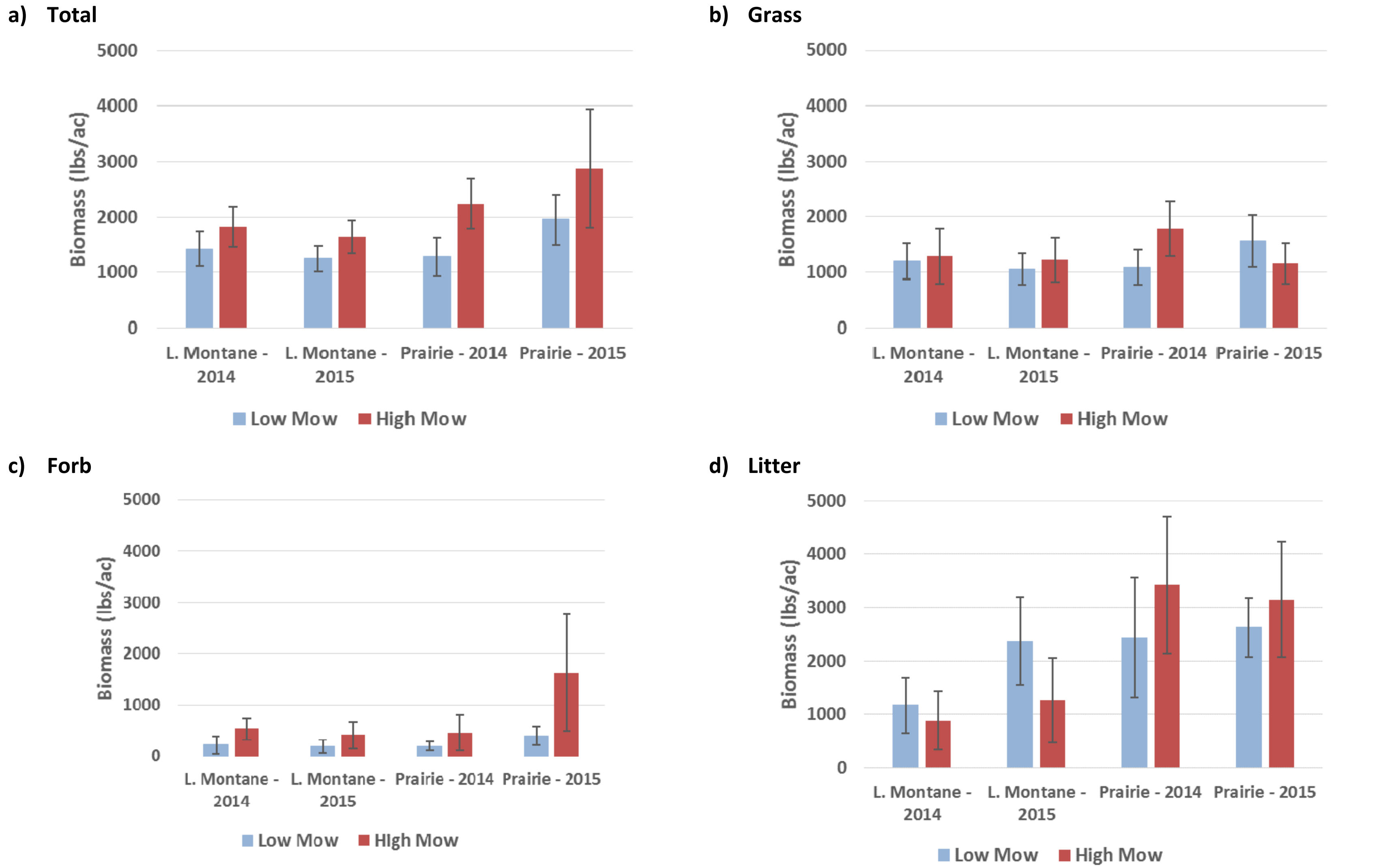


Figure 4-9. N Zone biomass at test plots (± 90% CI)

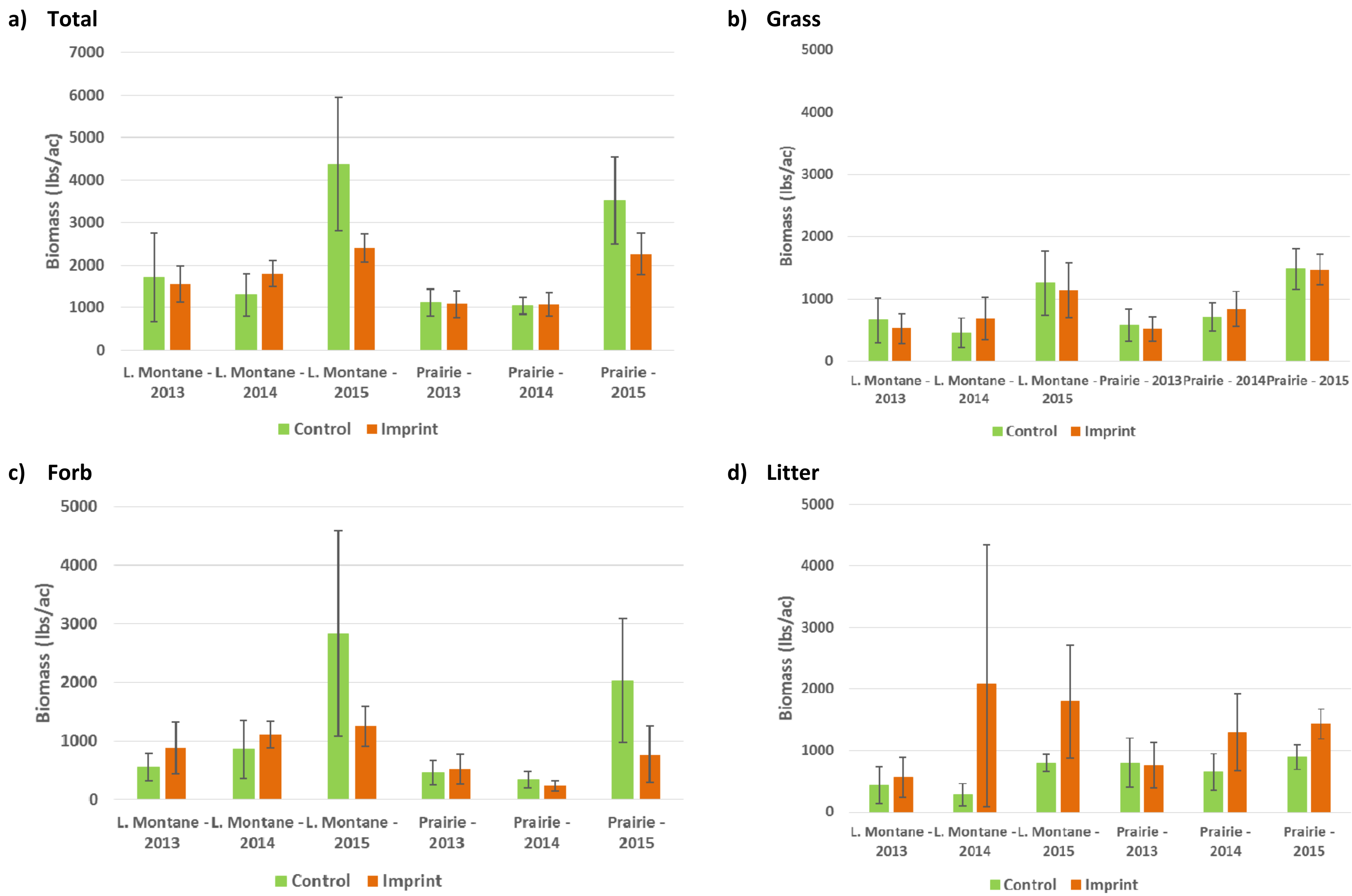
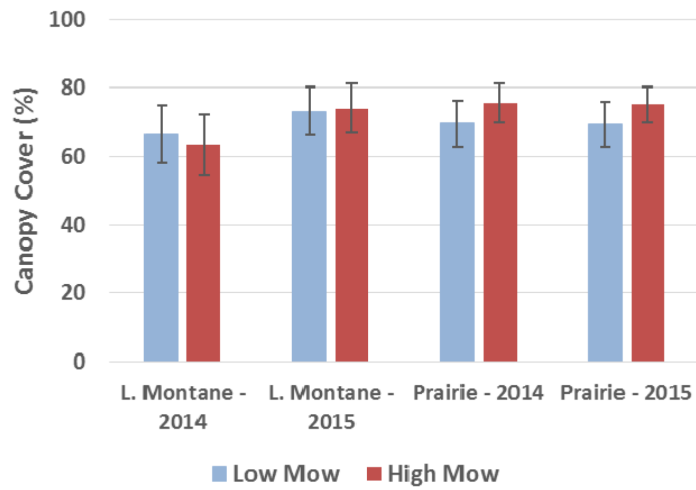
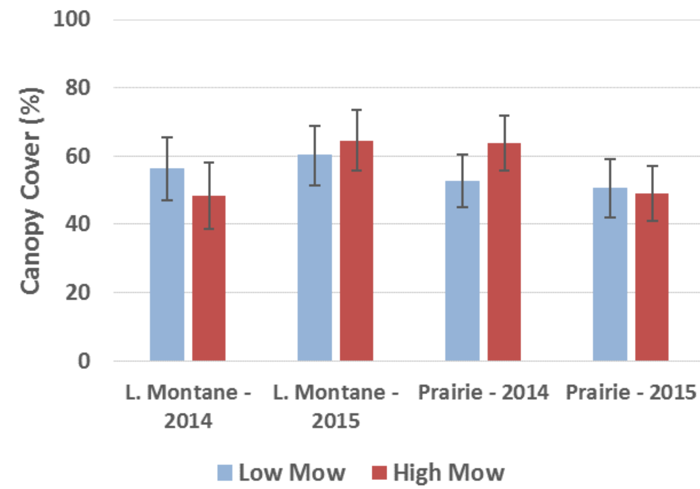


Figure 4-10. M Zone canopy cover at test plots (± 90% CI)

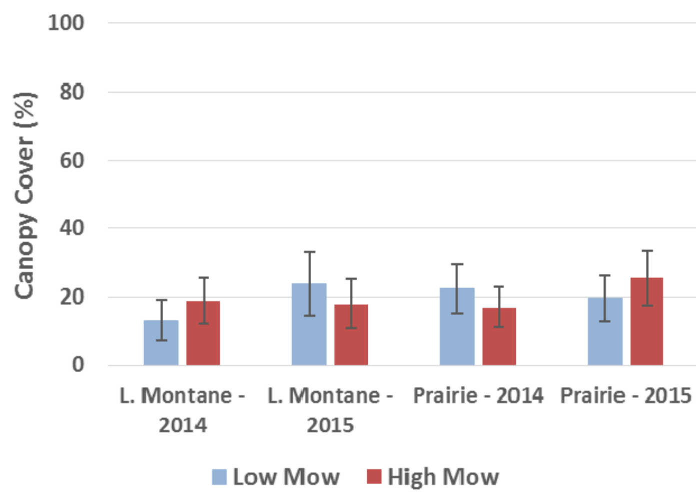
a) Total



b) Grass



c) Forb



d) Litter

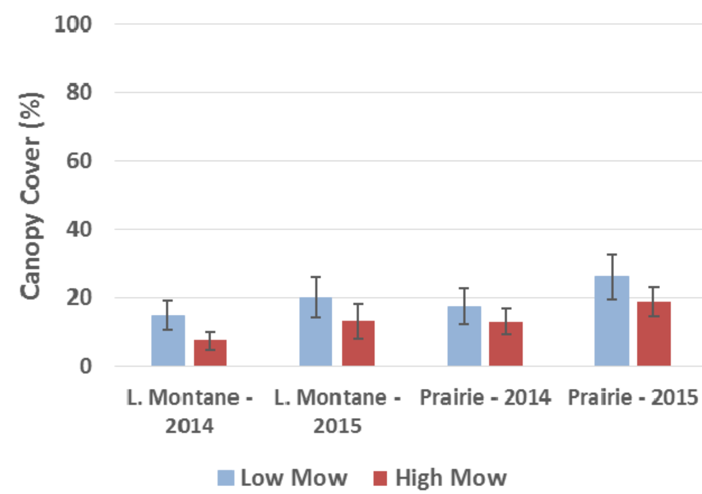
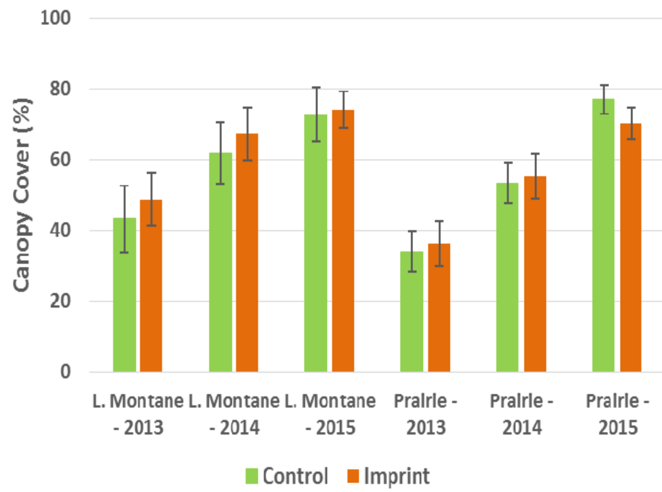
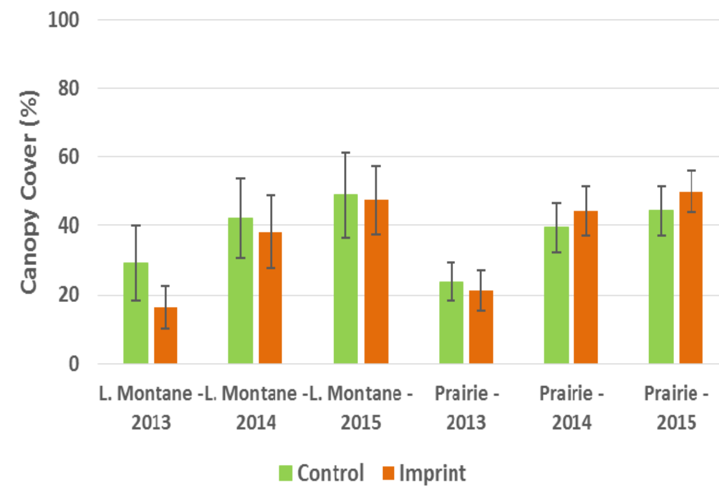


Figure 4-11. N Zone canopy cover at test plots (± 90% CI)

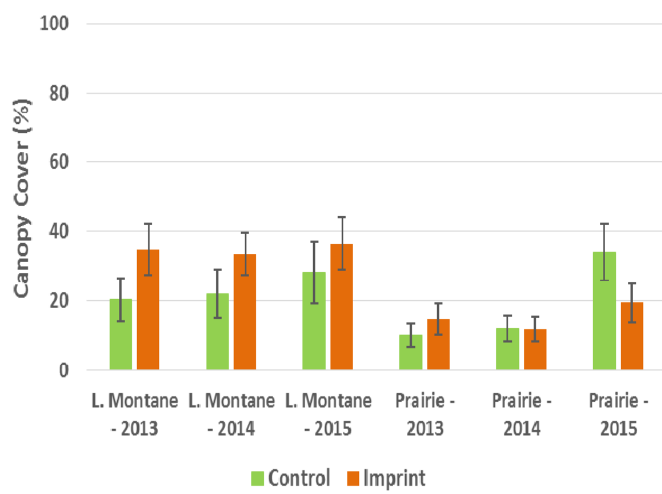
a) Total



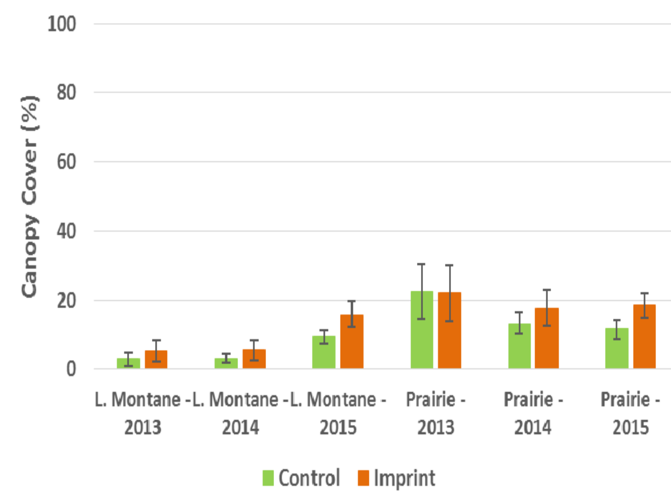
b) Grass



c) Forb



d) Litter



4.4 Surface CO_2 Flux

Golder's discrete measurements of surface CO_2 fluxes over bare soil and vegetation at the test plots indicate diurnal and seasonal differences in daytime soil respiration, nighttime soil respiration, nighttime soil plus plant respiration, as well as daytime net exchange of CO_2 (soil plus plant respiration, minus photosynthesis). The CO_2 flux data, along with the continuous (every 30 minutes) soil temperature and moisture measurements, show seasonal differences as well as inter-site and inter-plot variability.

To put the discrete CO_2 flux measurements into context, this section presents the following:

- An analysis of the LTER station data.
- A summary of the test plot soil temperature and moisture recordings.
- A summary of the ecosystem modeling results.
- A comparison of LTER station data to test plot data.
- A comparison of ecosystem modeling results to test plot data.
- A quantitative and qualitative analysis of the surface CO_2 flux modeling.
- An analysis of the effects of mowing on soil carbon.

4.4.1 Analysis of Long-Term Ecological Research Data

Discrete chamber-based measurements of CO_2 flux characterized the ecosystem CO_2 dynamics at the ROW test plots. However, these discrete data cannot be used to measure or predict annual net carbon stored by each M or N Zone at the test plots. Golder's approach was to benchmark the discrete seasonal measurements for M and N Zone subplots against LTER station data available from the Ameriflux network (Lawrence Berkeley National Laboratory 2016). Long-term, global, and ecosystem-level measurement programs such as Ameriflux, FLUXNET-Canada (Margolis et al. 2006), and ChinaFLUX (Yu et al. 2006) contribute to the following scientific objectives (Baldocchi et al. 2001):

- Quantify the spatial differences in carbon dioxide and water vapor exchange rates that may be experienced within and across natural ecosystems and climatic gradients;
- Quantify temporal dynamics and variability (seasonal, interannual) of carbon, water, and energy flux densities. These data allow us to examine the influences of phenology, droughts, heat spells, El Niño, length of growing season, and presence or absence of snow on canopy-scale fluxes; and
- Quantify the variations of carbon dioxide and water vapor fluxes due to changes in insolation, temperature, soil moisture, photosynthetic capacity, nutrition, canopy structure, and ecosystem functional type.

Eddy-covariance systems measure NEE directly, but require significant data processing and use thermodynamic variables (i.e., soil temperature and moisture) to parameterize daytime R_e. GPP can be estimated by subtracting the parameterized values of R_e from the NEE measurements. In many CO_2 flux studies, partitioning of NEE into its components, R_e and GPP, starts with the estimate of R_e from nighttime chamber-based flux measurements (Reichstein et al. 2005). Reichstein and others recommended the use of diurnal chamber-flux measurements to establish short-term relationships between temperature and R_e for eddy-covariance data interpretation. Lavigne and others (1997) used chamber-flux measurements to find that nighttime R_e emits 30 to 100 percent of daytime net photosynthetic carbon uptake, stressing the importance of understanding nighttime carbon flux for determining NEE.

4.4.1.1 Data Quality and Completeness

Initially, Golder identified the Sevilleta Desert Grasslands LTER station (Sevilleta) as the most appropriate data to serve as the baseline to develop a statistical, empirical model to predict land-atmosphere carbon dynamics at the test plots. However, analysis of the Sevilleta data indicated that it is incomplete, containing only 3 years of complete data. In addition, the 2012 soil temperature and VWC data were averaged every 24 hours, not every 30 minutes. This impeded Golder's ability to constrain relationships between soil temperature, soil moisture, and NEE. Two alternate LTER stations were located, their data downloaded and evaluated for completeness, the Audubon Research Ranch (Audubon) and the Walnut Gulch Kendall Grassland (Kendall). Both alternate stations are in Arizona (Figure 4-12), but have comparable biophysical characteristics to the Sevilleta station (Table 4-5). Table 4-6 summarizes the data completeness for all years of record for all three stations. Inclusion of the Audubon and Kendall data in the analysis increased the data completeness from 2 years to approximately 18 years.

Table 4-5. Eddy-covariance long-term ecological research station characteristics

Station	Sevilleta	Audubon	Kendall
Latitude	34.3623	31.5907	31.7365
Longitude	-106.7020	-110.5092	-109.9419
Altitude (m)	1589	1466	1524
Soil Type	Calciargids/Haplocalcids	Ustic Calciargids/ Haplargids	Ustollic Haplargids
Climate Type	BSk - Arid Steppe cold	BSk - Arid Steppe cold	BSk - Arid Steppe cold
Grassland	Black grama Sand dropseed Galleta	Sideoats/blue grama Plains lovegrass Cane bluestem	Lehman's lovegrass Black/Hairy gramas Curly mesquite

Figure 4-12. Locations of eddy-covariance long-term ecological research stations

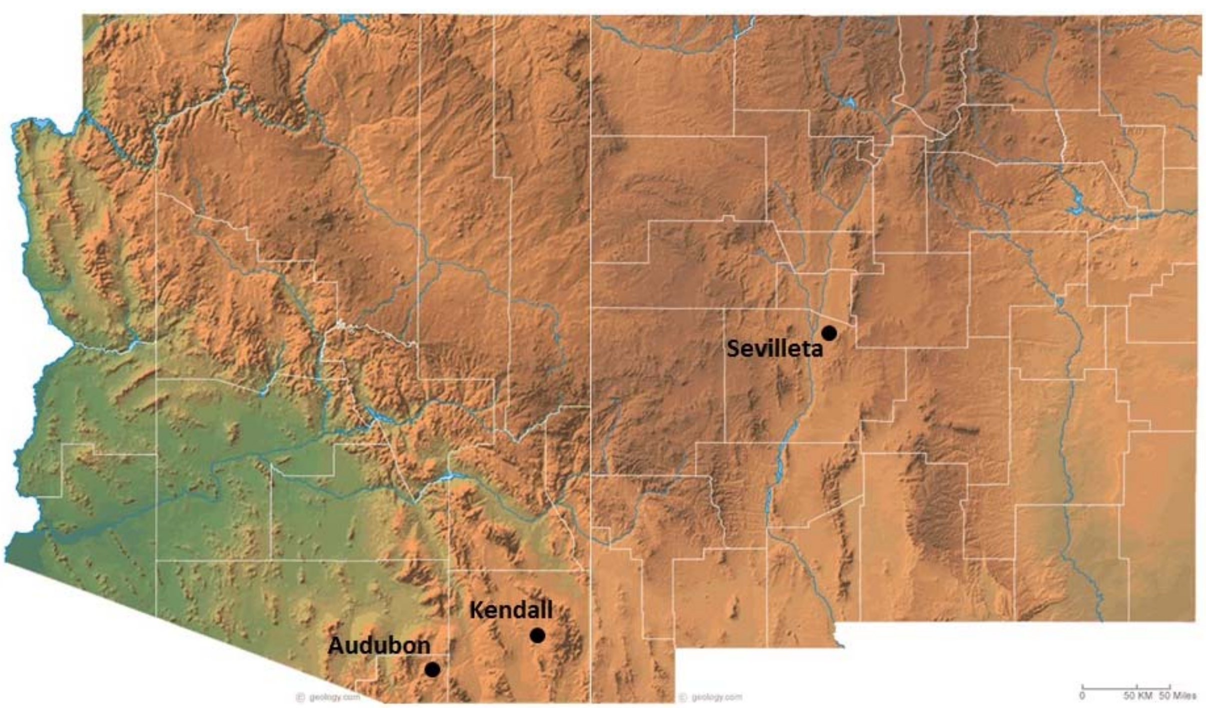


Table 4-6. Assessment of data completeness (values in percent)

Station	Parameter	Year											
		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Sevilleta	NEE									100	100	100	100
	SWC1									80.6	99.9	100[a]	0.0
	TS1									100	100.0	100[a]	0.0
Audubon	NEE	83.8	51.5	86.5	88.3	81.7	73.9	76.1	77.8	35.7	92.1		
	SWC1	96.1	83.1	100	100	100	99.8	51.9	0.0	0.0	0.0		
	TS1	100	100	100	99.8	100	94.3	99.7	91.5	92.6	96.7		
Kendall	NEE			0.0	39.8	41.8	86.1	85.5	81.6	89.2	89.3	88.8	87.2
	SWC1			99.6	100	99.7	99.7	95.7	100	100	99.9	99.6	99.9
	TS1			99.6	100	99.7	99.0	95.7	100	100	99.9	99.6	99.9

Notes: Shaded areas = data not available; a = Data were averaged every 24 hours, not every 30 minutes; NEE = net ecosystem exchange; SWC1 = soil water content depth 1; TS1 = soil temperature depth 1

4.4.1.2 LTER Data Processing

Measurements at each of the LTER stations were recorded every 30 minutes. Instrument noise, environmental variability on short-time scales (especially for NEE), and occasional data gaps were challenging while performing the temporal analysis of the LTER data. For this reason, the data from all three stations were averaged and binned into 3-hour intervals (i.e., 00:00 to 03:00, 03:00 to 06:00, etc.).

Figures 4-13 through 4-15 plot all available 30-minute Sevilleta, Audubon, and Kendall time series data, respectively. The top panel shows the raw NEE values (green line) in micromoles of carbon dioxide per meter squared per second (μmol m^{-2} s^{-1}) and the values after binning into 3-hour averages (black line). The middle and bottom panels resulted from the same binning, except for soil temperature (red) and VWC (blue). As expected, high-frequency noise in the NEE data are smoothed using bin averaging. This had a smaller effect on temperature, tending to smooth peak daily values. VWC can change quickly during rainfall events, but is generally a parameter that changes slowly over time (days to weeks). As a result, bin averaging did not result in much smoothing of the VWC data.

Figure 4-16 highlights ecosystem behavior in 2010 by focusing on the May 1 through September 1 data from the Kendall station. In May, soil temperatures below 30^{o} C led to CO_2 uptake by plants. Higher temperatures in June led to plant dormancy (low daytime NEE), and depleted VWC. With the onset of the monsoon season in mid-July, soil temperatures decreased, VWC was replenished, and NEE reached both its maximum daytime value (i.e., maximum GPP) and nighttime values (i.e., respiration associated with plant, root, and microbial growth).

Figure 4-13. Time series of raw and binned NEE, soil temperature, and VWC data from the Sevilleta station

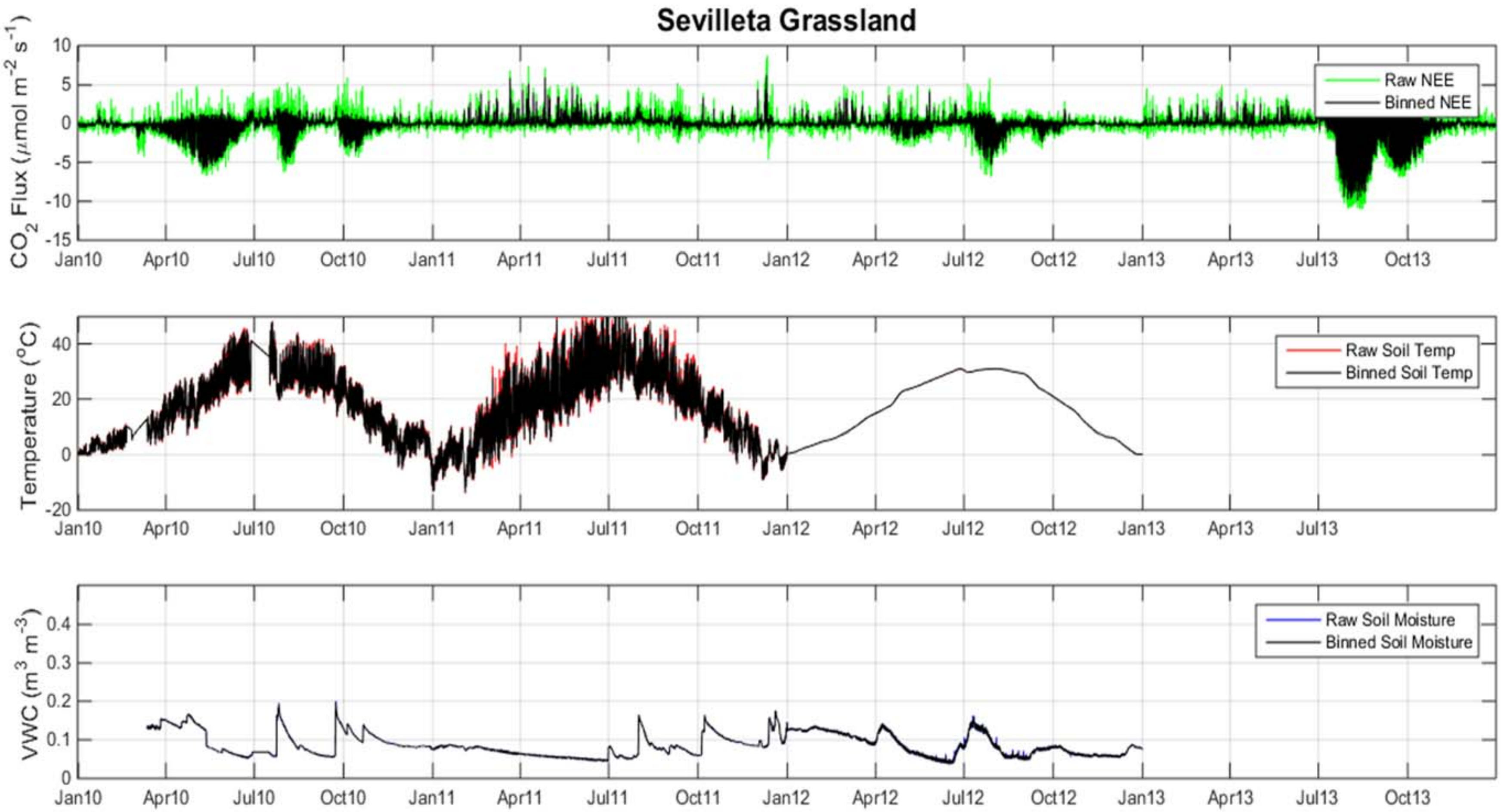


Figure 4-14. Time series of raw and binned NEE, soil temperature, and VWC data from the Audubon station

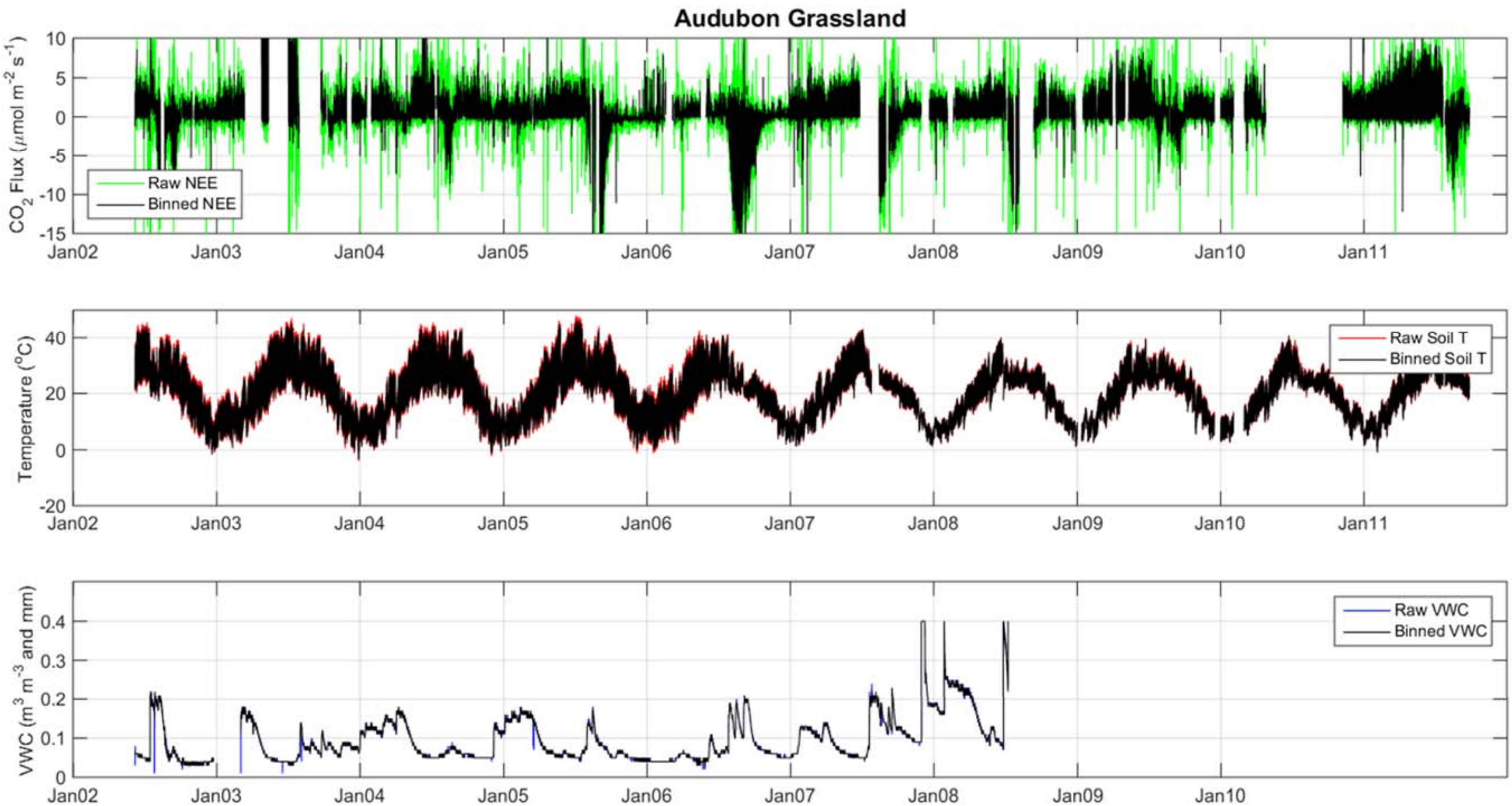


Figure 4-15. Time series of raw and binned NEE, soil temperature, and VWC data from the Kendall station

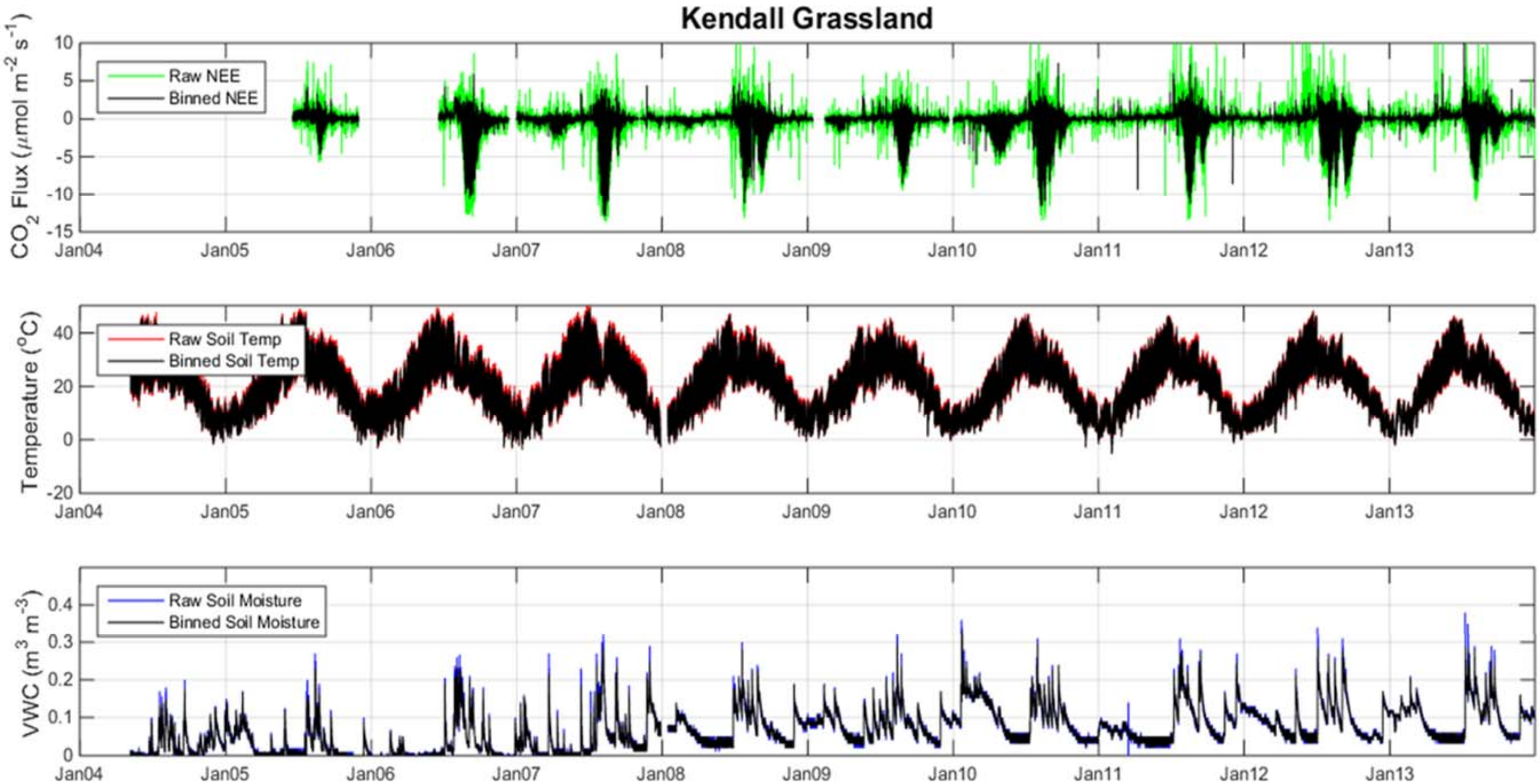
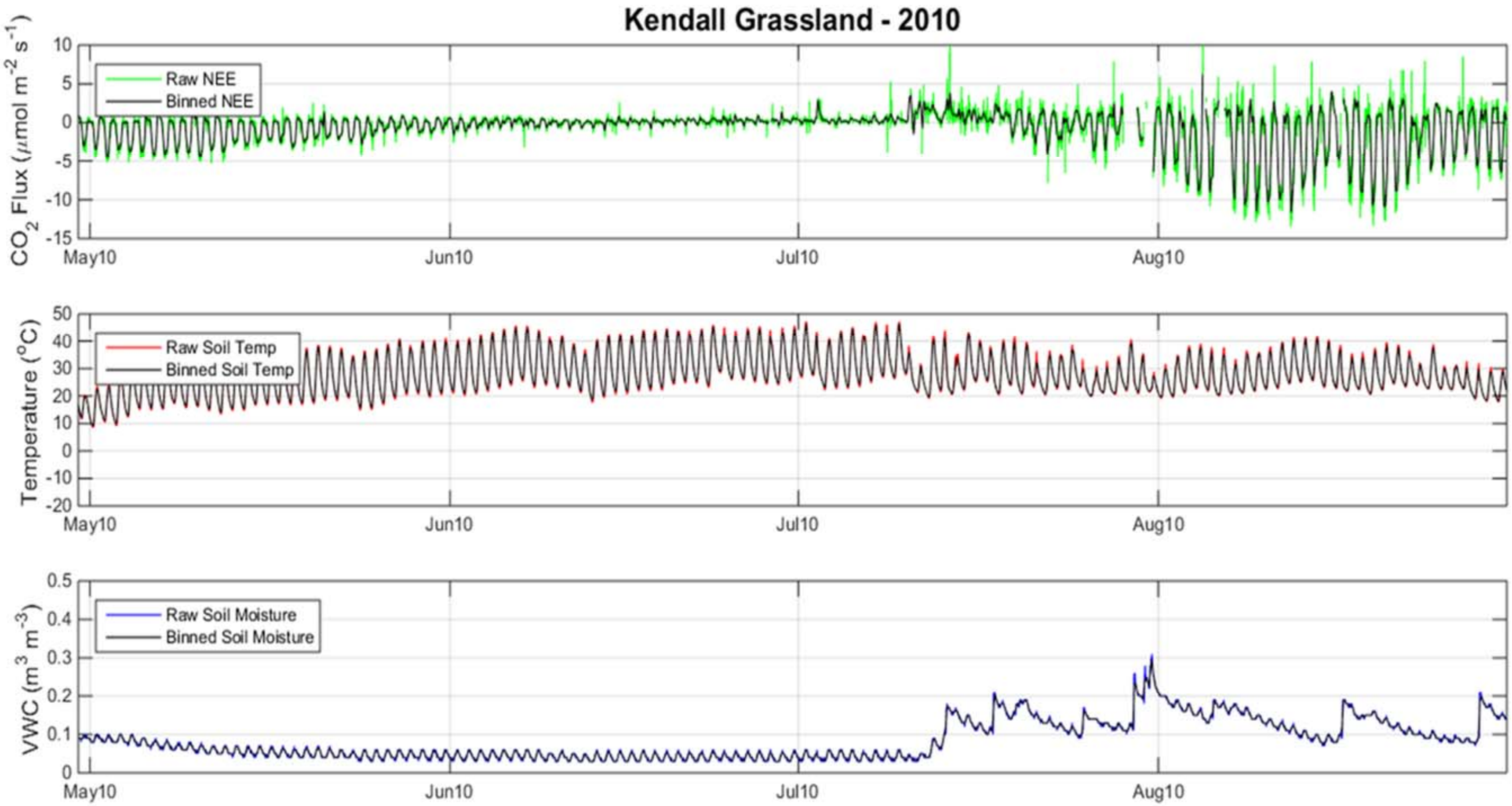


Figure 4-16. Summer 2010 time series of raw and binned NEE, soil temperature, and VWC for the Kendall station



4.4.1.3 Averaging and Intersite Comparison

Figures 4-17 through 4-19 combine the multi-year 30-minute data from each LTER station for an annual average of NEE, soil temperature, and VWC, respectively. The figures illustrate seasonal cycles that are common to these three LTER stations in Arizona and New Mexico's "Arid Steppe Cold" ecosystems. These seasonal cycles are summarized below.

- In late fall through early spring, NEE tends to be slightly positive, indicating net loss of CO_2 from the land surface to the atmosphere.
- In late spring through early fall, daytime NEE is typically negative, indicating uptake of CO_2 by plants; nighttime NEE is higher, indicative of enhanced plant/root/microbial respiration during the growing season.
- A notable feature of these ecosystems is the dual peak in spring/summer NEE. Early in the growing season there is more CO_2 exchange when soil temperature is moderate, VWC is high, and plants are active. Near the summer solstice, soil temperatures peak at 40 to 50^o C and daytime GPP is suppressed with no corresponding decrease in R_e. These observation likely indicate plants are experiencing heat stress.
- With the onset of the monsoon season in mid-July, daytime soil temperatures decrease down to 10^o C and VWC is replenished by precipitation. It is during the monsoon season that peak CO_2 uptake by plants occurs during the daytime, and peak CO_2 release from plant/root/microbial respiration occurs at night.

Figure 4-20 highlights ecosystem behavior focusing on May 1 through September 1 annual average climate data from the Kendall station.

Figure 4-17. Binned annual average of 2010 to 2013 Sevilleta station data

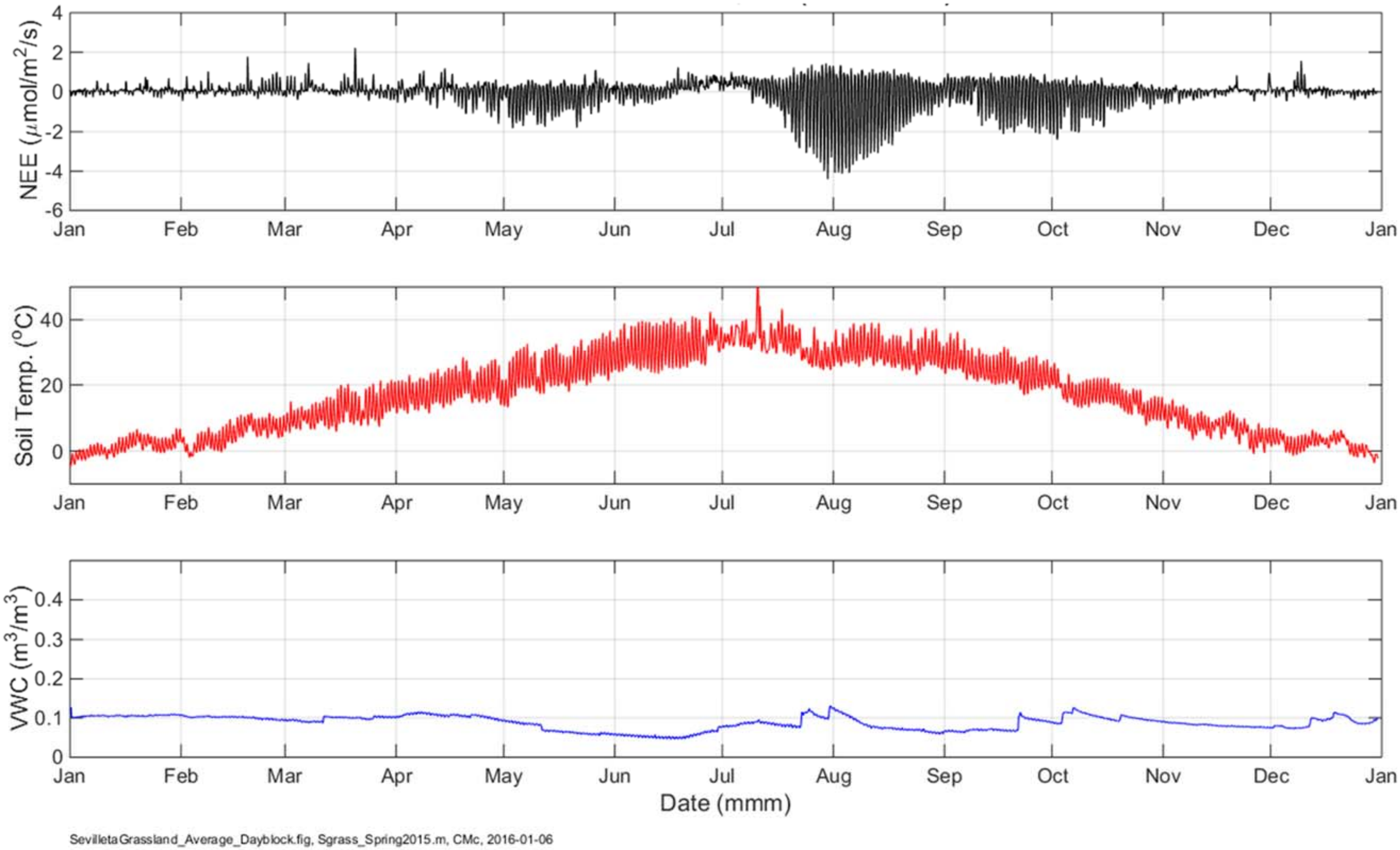


Figure 4-18. Binned annual average of 2010 to 2013 Audubon station data

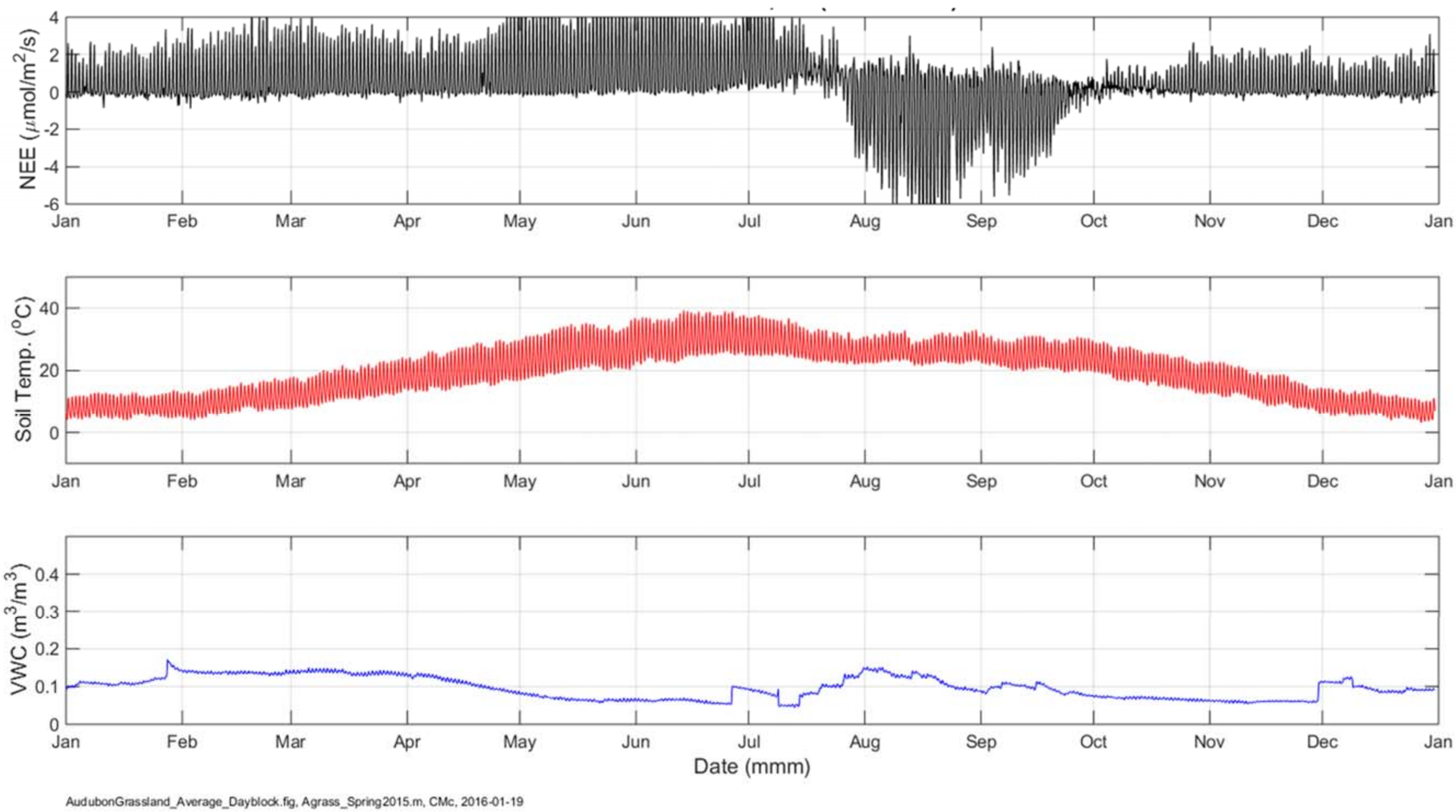


Figure 4-19. Binned annual average of 2010 to 2013 Kendall station data

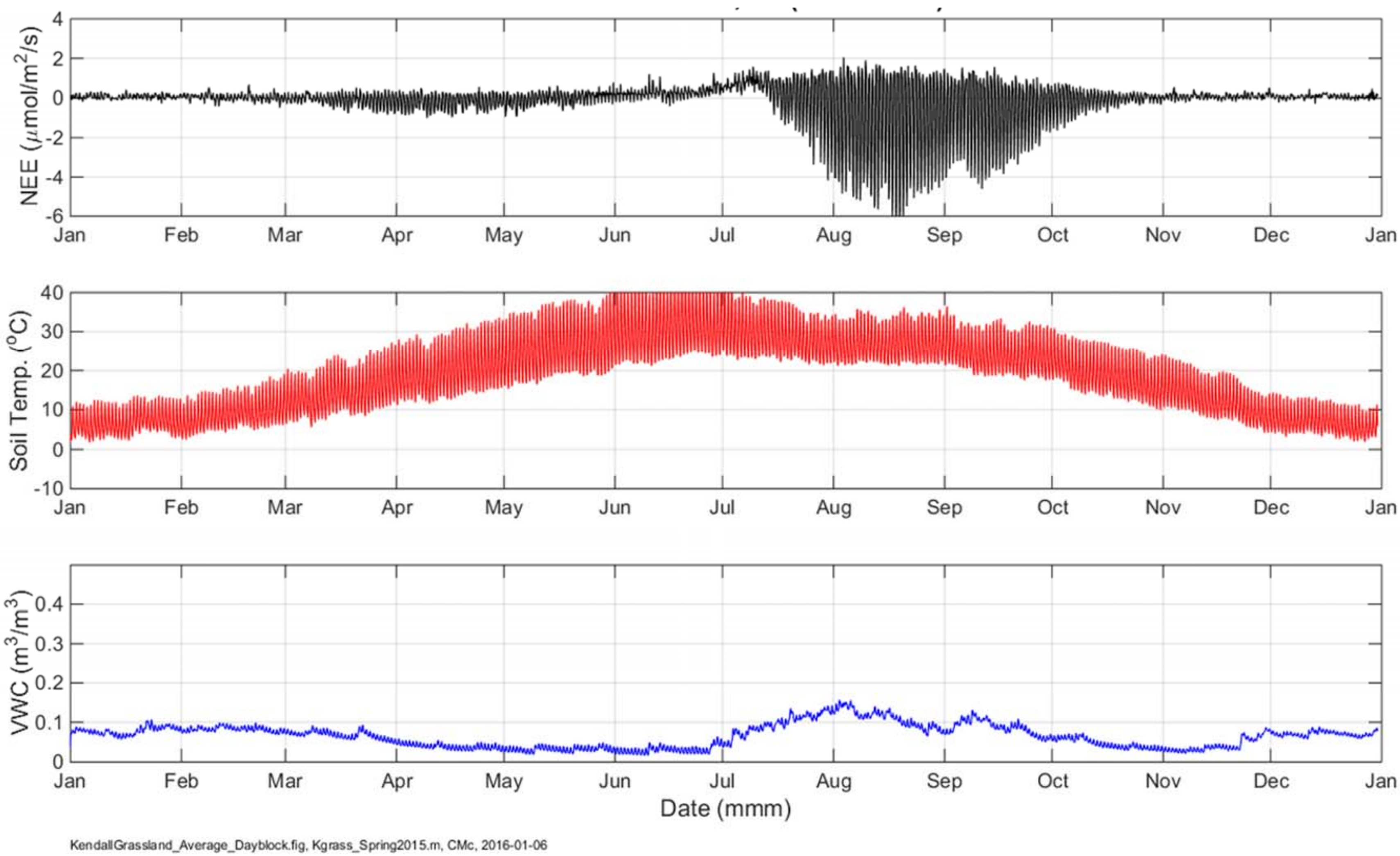
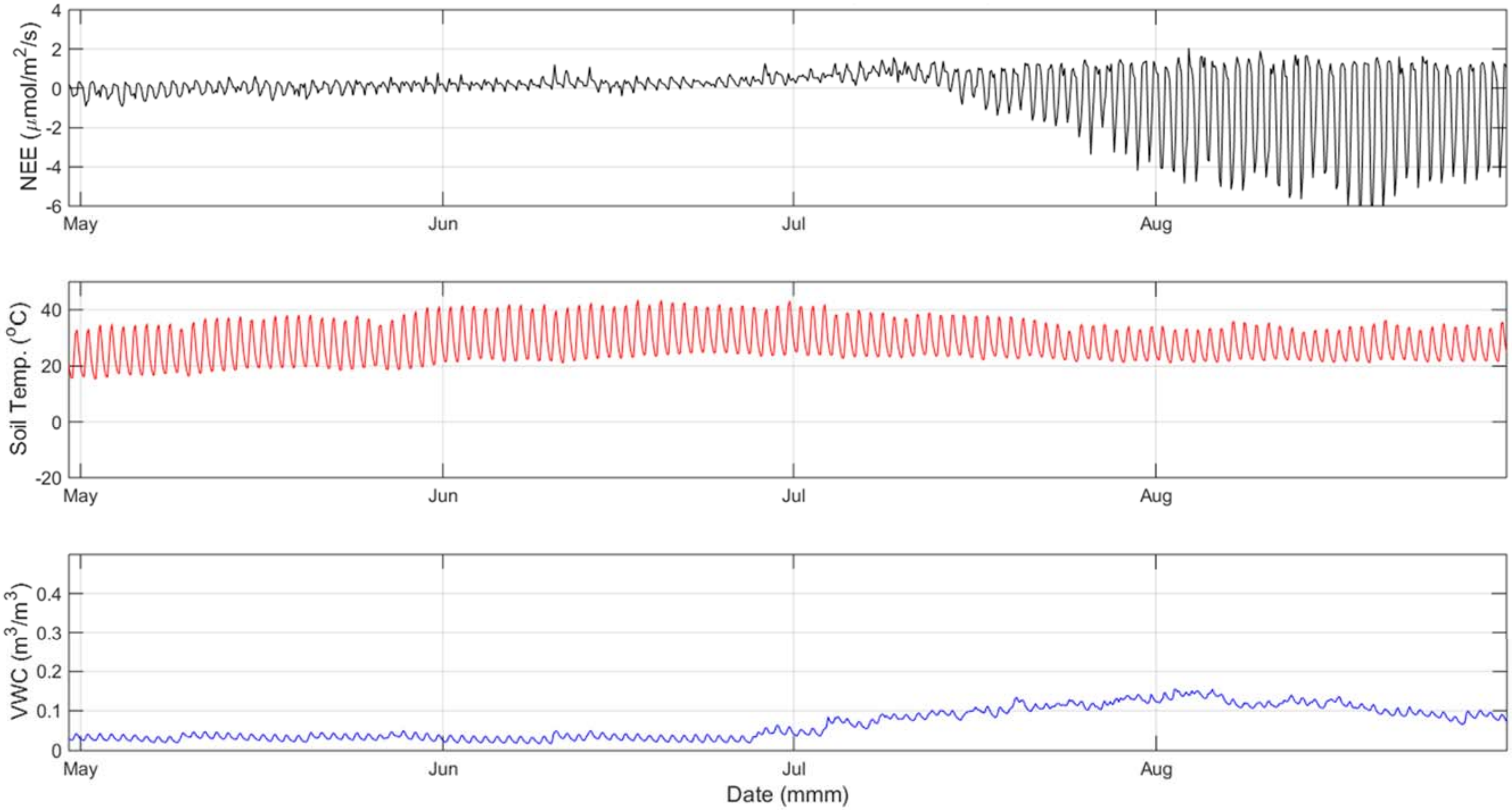


Figure 4-20. Summer monsoon season for the annual average of 2010 to 2013 Kendall station data



4.4.2 Continuous Measurements of Soil Temperature and Moisture

Soil temperature and moisture probes were installed at each subplot at each test plot in August 2013. The last measurements were recorded in October 2015, providing more than 2 years of continuous measurements.

There were occasional data gaps in the measurements for individual test plots. However, after combining the eight original subplots into four subplots, there are few instances when at least one soil temperature or moisture probe were not collecting data every 30 minutes. Table 4-7 summarizes the data completeness for the M1, M3, N1, and N3 subplots for each ROW test plot. Completeness ranged from 72 to 98 percent, with the majority of the test plot probes recording data more than 90 percent of the time.

Table 4-8 summarizes the statistics associated with all soil temperature and VWC data recorded at each ROW test plot. Table 4-9 combines these results for the Prairie and Lower Montane test plots separately. Figures 4-21 through 4-25 summarize the time series of soil temperature and VWC recorded at ROW test plots 104-79 and 555-12 from August 2013 until October 2015. Graphs of these data for all ROW test plots are in Appendix A.

The bottom panel of each figure are the average soil temperature and VWC data for the M1, M3, N1, and N3 subplots. Subplot differences (e.g., 104-79-M1 versus 104-79-N1) in soil temperature are generally small, as are inter-plot differences in soil temperature (e.g., 104-79-M1 versus 555-12-M1). Inter-plot and inter-site differences in VWC are greater. For example, there are significant differences in VWC measured between the M Zone subplots and the N Zone subplots at test plot 104-79. The M1 and N1 subplot VWC data were recorded by one set of sensors and datalogger, whereas the M3 and N3 subplot VWC data were recorded by a separate suite of sensors and datalogger. Therefore, instrument-related causes can be ruled out as the difference between VWC measured between the M and N Zones at test plot 104-79; i.e., at 104-79 the N Zone is typically drier than the M Zone.

As expected, Prairie test plots were warmer and drier than the Lower Montane test plots (Table 4-9). Figure 4-21 and Table 4-9 show that summer soil temperatures at test plot 104-79, in the Prairie, are above 25^{o} C, and that minimum winter soil temperatures are near 0^{o} C. At test plot 555-12, in the Lower Montane biome, the summer peak in soil temperature is less than 25^{o} C and the winter minimum is typically below 0^{o} C (Figure 4-22 and Table 4-9). Figure 4-23 and Table 4-8 show that summer VWC at test plot 104-79 are typically between 0.15 and 0.25 m^3/m^3 prior to the summer monsoon, when precipitation causes increases of up to 0.40 m^3/m^3. At test plot 555-12, summer VWC are typically between 0.20 and 0.35 m^3/m^3 prior to the summer monsoon, then increase up to 0.40 m^3/m^3.

The continuous thermodynamic data from each test plot were complete and of high quality for this study. This makes them suitable for input to the EDM to predict carbon dynamics at the inter-plot level (M1, M3, N1, and N3) for each test plot.

Table 4-7. Data recovery summary by test plot (values in percent)

Plot	120-31	104-79	469-02	469-39	472-07	021-15	537-43	555-12
M1	94	90	97	82	96	76	72	74
M3	93	96	87	97	98	94	94	95
N1	94	90	97	82	98	76	72	74
N3	93	96	87	97	98	94	94	95

Table 4-8. Summary of ROW thermodynamics by test plot

	Parameter	number	mean	median	st dev	min	max
Prairie Test Plots							
120-31	Soil T	24,598	12.8	13	8.4	-2.5	33.4
	VWC	24,598	0.25	0.25	0.06	0.11	0.42
104-79	Soil T	24,404	17.2	18	9.1	-1.3	37.9
	VWC	24,404	0.23	0.23	0.06	0.11	0.42
469-02	Soil T	24,217	15.4	15.8	9	-2.4	36.2
	VWC	24,087	0.17	0.16	0.07	0.01	0.4
469-39	Soil T	23,606	17.6	18.5	9.7	-3.8	39.2
	VWC	23,600	0.14	0.12	0.06	0.06	0.36
472-07	Soil T	25,590	14.4	15.1	8.9	-4.8	33.5
	VWC	25,486	0.17	0.17	0.05	0.06	0.36
Lower Montane Test Plots							
021-15	Soil T	22,416	12	12.3	7.7	-4.5	32.8
	VWC	22,442	0.27	0.26	0.05	0.16	0.51
537-43	Soil T	21,928	12.6	12.8	9	-6.4	34.1
	VWC	21,821	0.29	0.28	0.09	0.11	0.61
555-12	Soil T	22,137	12	13	8	-4.1	28.7
	VWC	22,138	0.3	0.3	0.05	0.2	0.44

Notes: Soil T = soil temperature in °C; VMC = volumetric water content in m^3/m^3

Table 4-9. Summary of Prairie versus Lower Montane test plot thermodynamics

Parameter	Prairie		Lower Montane	
	Soil T	VWC	Soil T	VWC
mean	15.5	0.19	12.2	0.29
median	16.1	0.19	12.7	0.28
min	-3.0	0.07	-5.0	0.16
max	36.0	0.39	31.9	0.52

Figure 4-21. Test plot 104-79 soil temperature

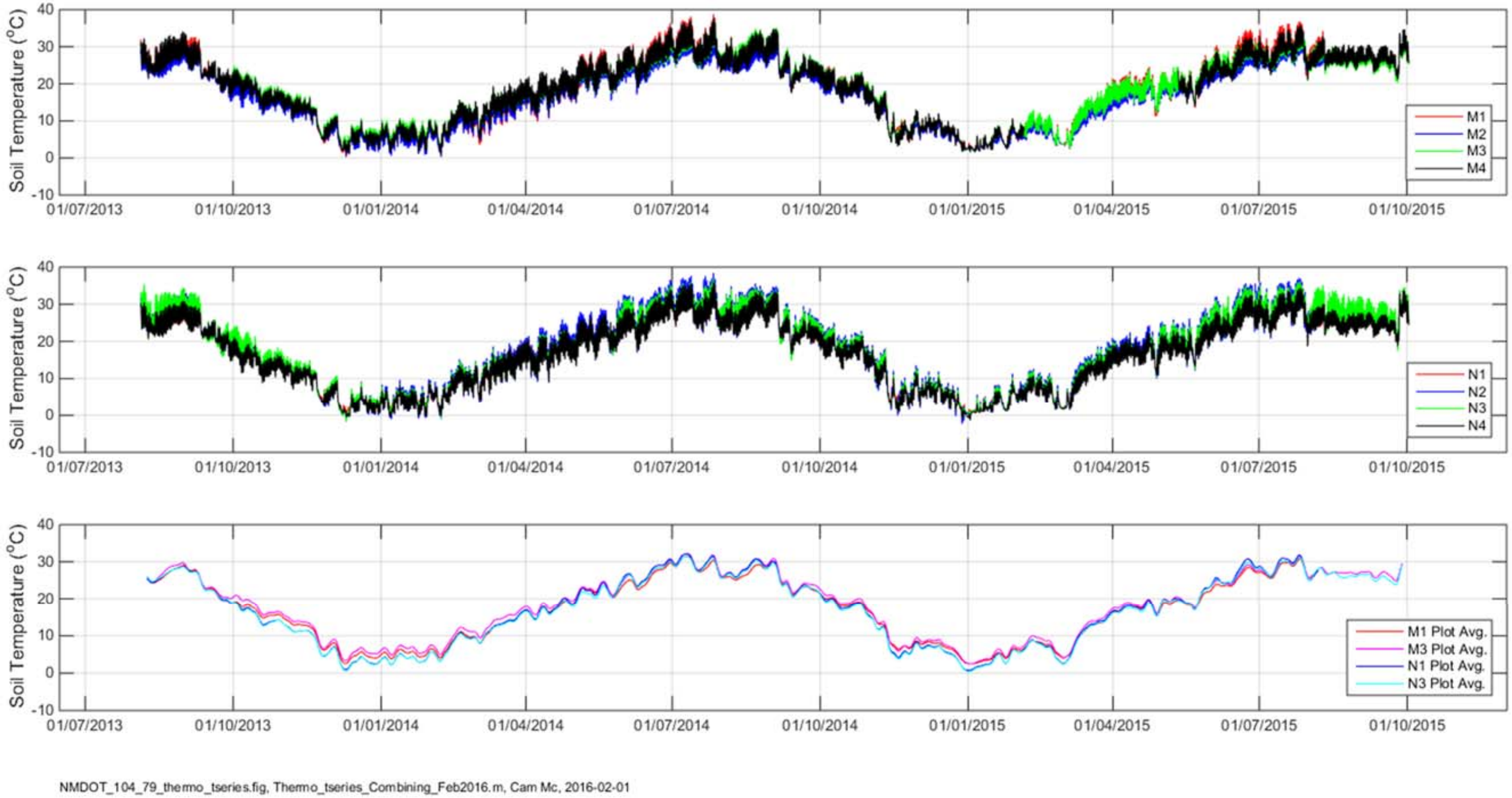


Figure 4-22. Test plot 104-79 soil volumetric water content

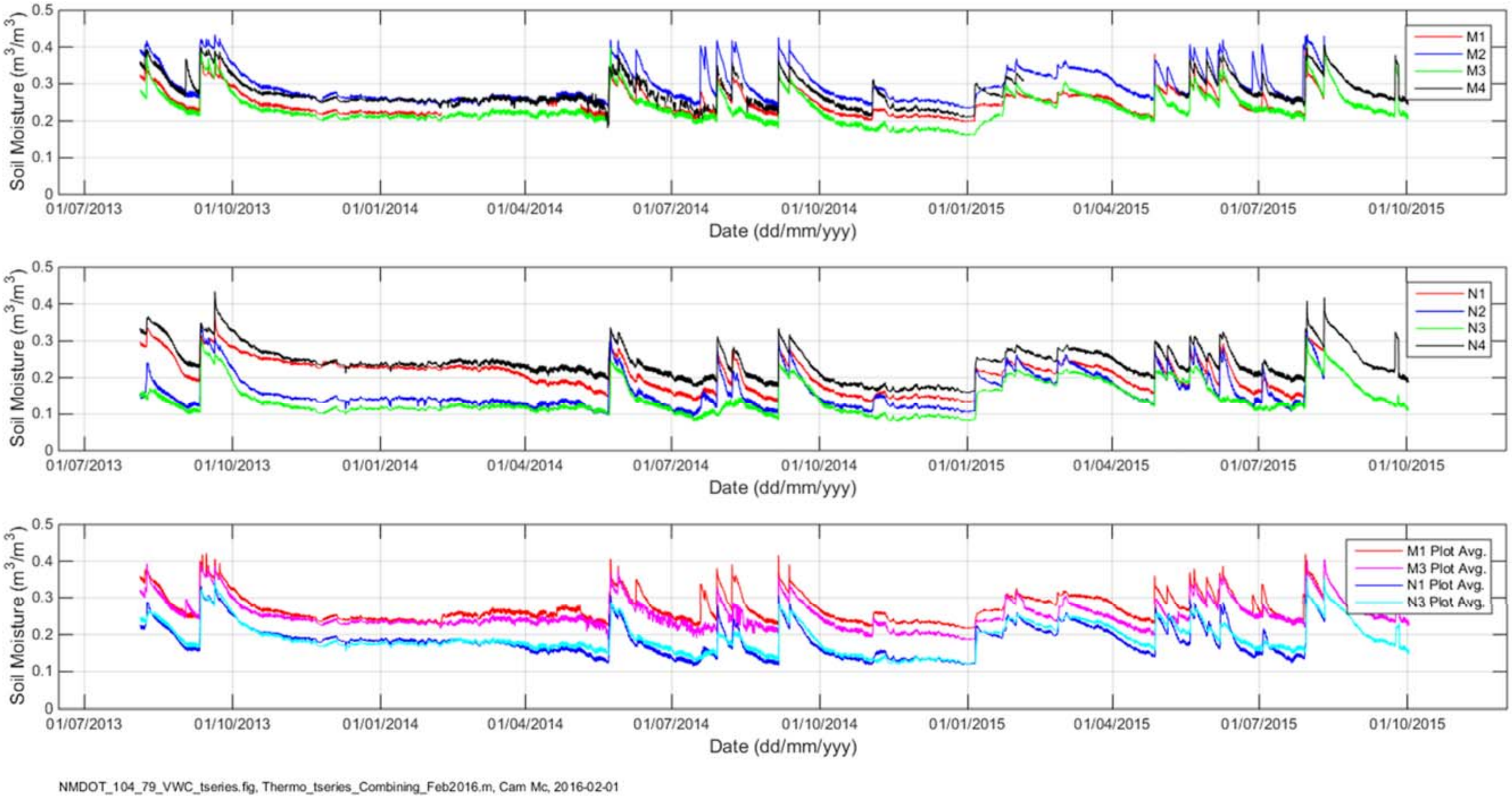


Figure 4-23. Test plot 555-12 soil temperatures

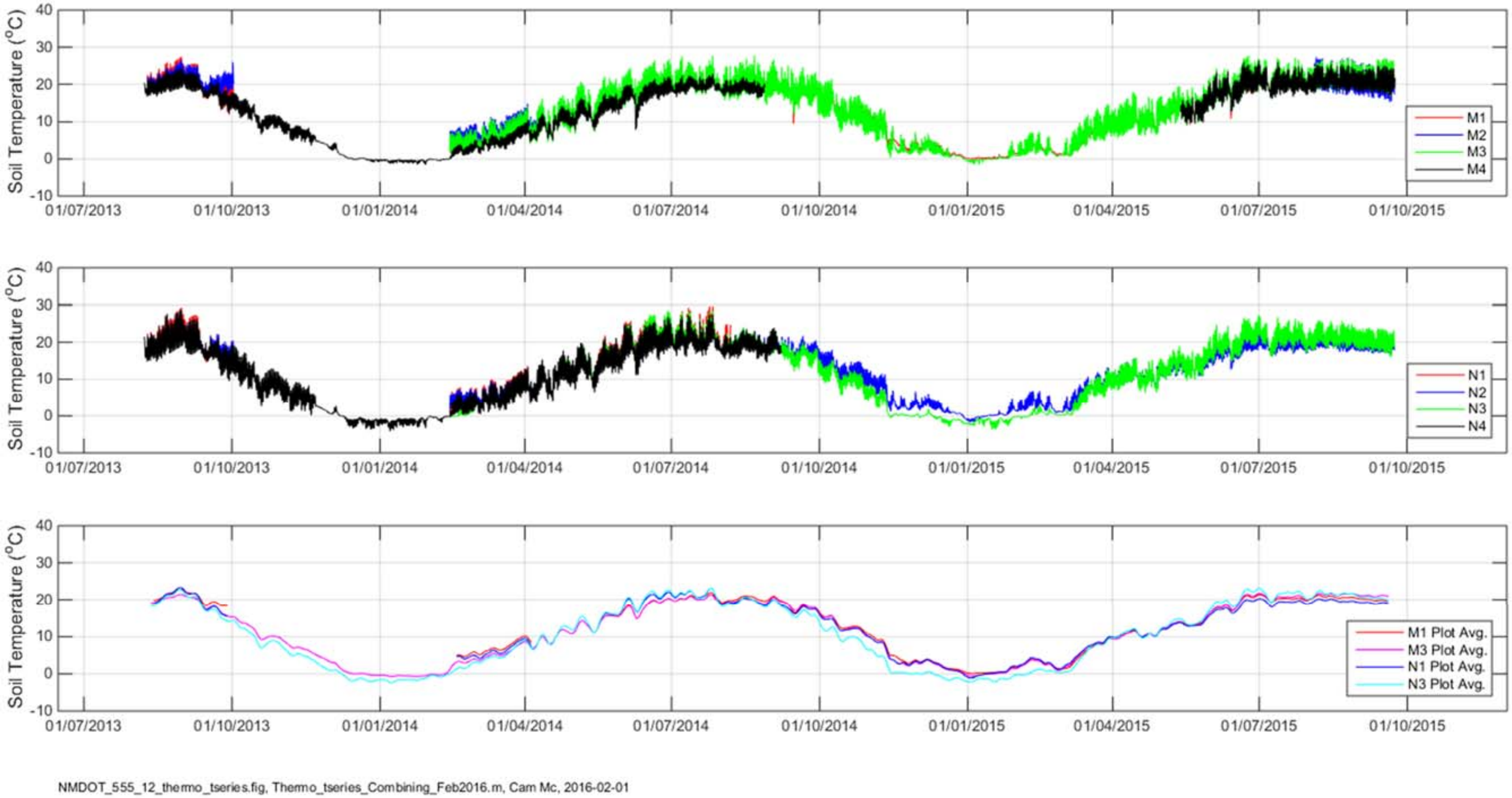
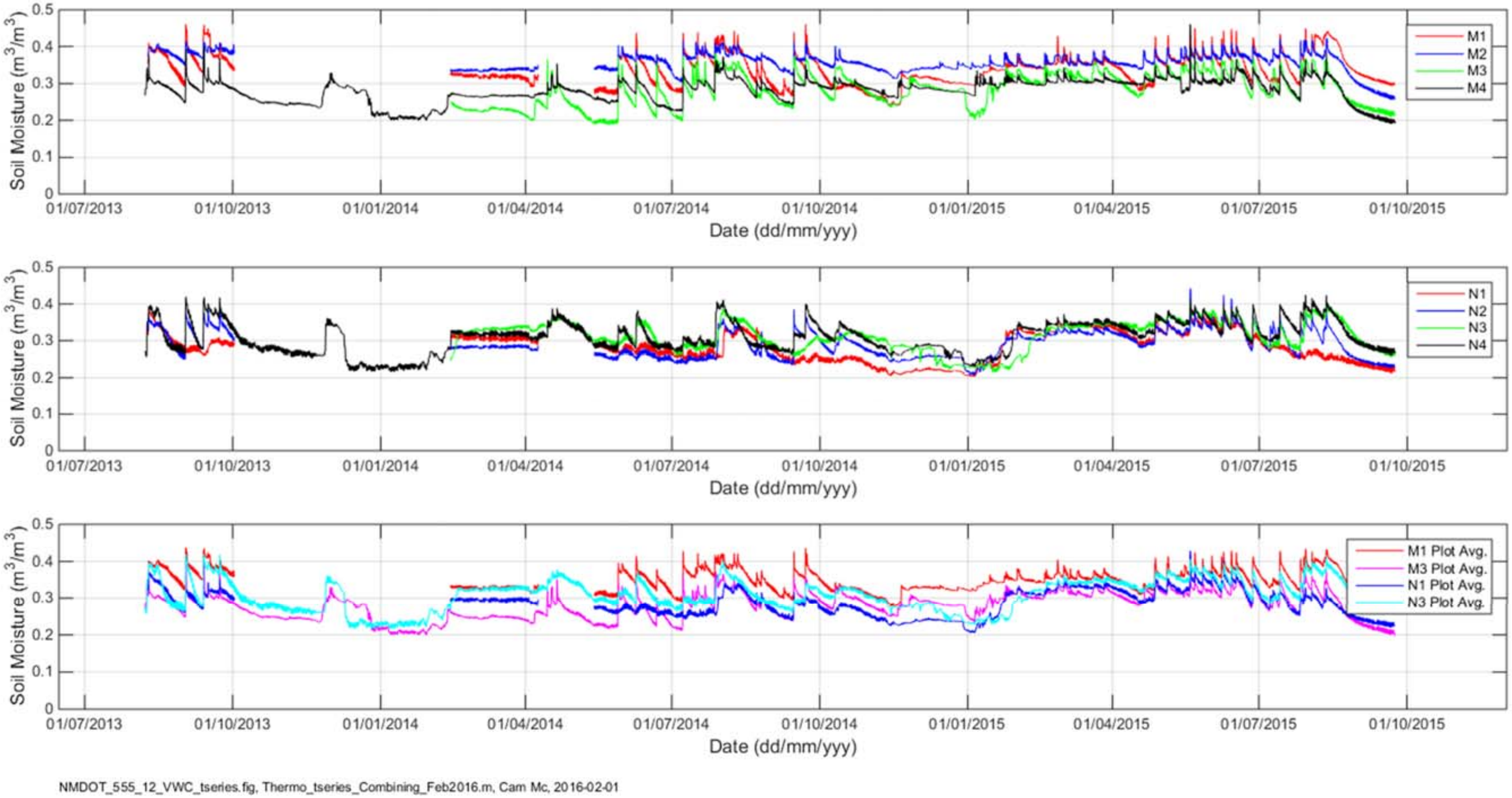


Figure 4-24. Test plot 555-12 soil volumetric water content



4.4.3 Qualitative Analysis of Surface CO_2 Fluxes at ROW Test Plots

Discrete measurements of surface CO_2 flux, and soil temperature and moisture were measured seasonally at the test plots from summer 2013 to fall 2015. The number of test plots monitored, the number of measurements recorded, and the duration of the measurements varied at both the primary and the secondary test plots. Primary test plots were monitored more frequently, included more subplots, and typically included overnight monitoring. Monitoring at the secondary sites were typically limited to daytime recordings at subplots M1, M3, N1, and N3. Table 4-10 summarizes the subplots monitored and the dates they were monitored.

Discrete measurements at the subplots (e.g., M1) were recorded in pairs, with measurements over bare soil collected just before or just after measurements over vegetation. The same measurements were then recorded at an adjacent subplot (e.g., N1). In this fashion, paired (bare and vegetation) measurements were recorded by stepping through each subplot. Time permitting, repeat measurements were recorded over 1 to 2 days, so that time series of the surface CO_2 fluxes could be constructed.

NEE can change quickly. For example, in summer it changes from positive to negative between 6 am and 9 am, and then from negative back to positive between 3 pm and 6 pm. Since measurements in separate subplots (e.g., M1, M3, N1, and N3) could not be recorded simultaneously, results were binned into 3-hour time intervals over each 24-hour day (i.e., 00:00 to 03:00, 03:00 to 06:00, etc.). Flux measurements occurring within the time bins were averaged and the time coordinate was assigned the median value among all measurements that were recorded within those 3 hours.

Both M and N Zones of the ROWs contain bare and vegetated surfaces. To accurately estimate the plot-wide NEE, the bare and vegetated soil fluxes measurements were weighted by the proportion of the subplot area that was covered by bare soil or vegetation. In some cases, there were valid flux measurements over vegetation during a 3-hour time bin, but no corresponding flux measurements over bare soil. In these instances, the average bare-soil flux measured during the day was used to compute the weighted flux estimate for the subplot. This was an acceptable compromise as the diurnal variations in bare-soil fluxes were minor.

In other cases, there were valid flux measurements over bare soil during a 3-hour interval, but no corresponding measurement over vegetation. For data recorded from 00:00 to 06:00, and from 18:00 to 24:00, only the bare-soil fluxes were used to calculate the NEE. This approach tended to minimize overnight NEE as it excluded CO_2 being released by plant and root respiration overnight. Between 06:00 and 18:00, if no surface CO_2 fluxes were measured over vegetation, no weighted subplot-wide flux estimate was calculated. This was because it wasn't possible to estimate the time-varying contribution of GPP to NEE during daylight hours.

This analysis of the data resulted in time-averaged (8 intervals per day) surface-cover-type (bare soil versus vegetation), weighted estimates of NEE for each subplot (M1, M3, N1, and N3) for all eight test plots. Additionally, for the summer 2015 data, we had NEE measurements recorded both prior to, and after, mowing.

Table 4-10. Summary of discrete measurements of surface CO_2 fluxes

Test Plot	Date Recorded	Subplots Sampled	Test Plot	Date Sampled	Subplots Sampled
Primary Test Plots			**Secondary Test Plots**		
104-79	8/4 - 8/5/2013	All	**021-15**	9/24/2013	M1, M3, N1, N3
	9/28 – 9/30/2013	M1, M3, N1, N3		2/12/2014	M1, M3, N1, N3
	2/5/2014	M1, M3, N1, N3		5/14/2014	M1, M3, N1, N3
	5/4/2014	All		7/29/2014	M1, M3, N1, N3
	8/19 – 8/20/2014	All		9/29/2014	M1, M3, N1, N3
	10/12 – 10/13/2014	M1, M3, N1, N3		5/11/2015	M1, M3, N1, N3
	5/9 – 5/10/2015	M1, M3, N1, N3		8/3/2015	M1, M3, N1, N3
	7/20/2015	M1, M3, N1, N3		9/22/2015	M1, M3, N1, N3
	10/13 - 10/14/2015	M1, M3, N1, N3	**120-31**	9/25/2013	M1, M3, N1, N3
469-39	8/3 – 8/4/2013	All		9/28/2013	M1, M3, N1, N3
	9/30 – 10/2/2013	M1, M3, N1, N3		2/12/2014	M1, M3, N1, N3
	2/4/2014	M1, M3, N1, N3		7/27/2014	M1, M3, N1, N3
	5/5-5/6/2014	All		9/29/2014	M1, M3, N1, N3
	8/18 - 8/19/2014	All		5/12/2015	M1, M3, N1, N3
	10/13 - 10/14/2014	M1, M3, N1, N3		8/4/2015	M1, M3, N1, N3
	5/8 - 5/9/2015	M1, M3, N1, N3		9/22/2015	M1, M3, N1, N3
	7/21 - 7/22/2015	M1, M3, N1, N3	**469-02**	9/29/2013	M1, M3, N1, N3
	10/12 - 10/13/2015	M1, M3, N1, N3		8/18/2014	M1, M3, N1, N3
555-12	8/6 - 8/7/2013	All		10/14/2014	M1, M3, N1, N3
	9/23 – 9/25/2013	M1, M3, N1, N3		5/8/2015	M1, M3, N1, N3
	2/12/2014	M1, M3, N1, N3		7/21/2015	M1, M3, N1, N3
	5/11-5/12/2014	All		10/12/2015	M1, M3, N1, N3
	7/28 - 7/29/2014	All	**472-07**	9/18/2013	M1, M3, N1, N3
	09/28 - 09/29/2014	M1, M3, N1, N3		2/5/2014	M1, M3, N1, N3
	5/11 - 5/12/2015	M1, M3, N1, N3		5/10/2014	M1, M3, N1, N3
	8/2 - 8/3/2015	M1, M3, N1, N3		8/11/2014	M1, M3, N1, N3
	9/21 - 9/22/2015	M1, M3, N1, N3		9/21/2014	M1, M3, N1, N3
				5/7/2015	M1, M3, N1, N3
				7/28/2015	M1, M3, N1, N3
				10/14/2015	M1, M3, N1, N3
			537-43	10/5/2013	M1, M3, N1, N3
				4/30/2014	M1, M3, N1, N3
				8/12/2014	M1, M3, N1, N3
				9/22/2014	M1, M3, N1, N3
				6/7/2015	M1, M3, N1, N3
				7/26/2015	M1, M3, N1, N3
				9/27/2015	M1, M3, N1, N3

Figures 4-25 through 4-27 graph the results of the seasonal surface CO_2 flux data for the three primary test plots against the 10-year mean of 30-minute NEE measurements recorded at the Kendall station were also included (the solid blue line). In each figure, the data for the winter, spring, summer, and fall seasons are in the top through bottom panels. Data for the M Zone subplots are shown in green, while N Zone data are in black. For cases where the M Zone was mowed, the M Zone data are shown in red.

Values two standard deviations (2σ) from the mean are indicated with dashed blue lines. The binned and weighted discrete surface CO_2 flux measurements were then overlaid for comparison. In general, the discrete results followed the diurnal and seasonal patterns expected based on the Kendall station data. Below is a description of the data on a seasonal basis. Data for the five other (secondary) test plots are in Appendix B and showed the same general patterns as those at the three primary test plots.

The discussion below primarily focuses on the M Zone treatments as differences in CO_2 flux observations between the Control (N1) and Imprinting (N3) were generally insignificant and inconsistent in response.

Winter

Kendall LTER station data of winter NEE were generally low (± 2 μmol/m^2/s) with no significant difference between daytime and nighttime fluxes. This is due to the low microbial respiration and little to no plant photosynthesis or respiration in the winter dormancy period. Discrete measurements at the test plots do show that fluxes are non-zero and usually slightly positive, within the 2σ from the Kendall station data. There did not appear to be large differences between winter NEE measured in the N versus the M Zones.

Spring

Discrete measurements in spring at test plot 104-79 were within the 2σ of the Kendall station data. At test plot 469-39, the data were within the 2σ during spring 2014, but in spring 2015, the daytime and nighttime NEE differences were greater than the Kendall station data. Coincidentally, the monitoring at test plot 555-12 occurred on the same two days in 2014 as 2015. While daytime fluxes were within 2σ of the Kendall station data, the measured nighttime NEE was higher than the long-term mean of the Kendall station data.

Summer

Unmowed, summer NEE measurements during the daytime were consistently negative, which was expected due to net sequestration of atmospheric CO_2 by photosynthetic plants. The magnitude of the daytime minima at the primary test plots was typically within 2σ of the Kendall station data for all test plots. The extreme negative NEE measured before mowing on July 21, 2015, at test plot 469-39, is an exception; no recorded summer, daytime NEE at the secondary test plots exceeded the 2σ Kendall station data (Appendix B). There do not appear to be significant or consistent differences between the NEE measured in the M Zones versus the N Zones of the test plots during summer.

Summer nighttime NEE measurements were both within and greater than the 2σ Kendall station data, depending on test plot and study year. For example, all three summer nighttime NEE measurements shown in Figure 4-25 are within 2σ of the Kendall station data. Conversely, one of three and two of three series of nighttime NEE measurements at test plots 469-39 and 555-12 (Figures 4-26 and 4-27, respectively) were greater than the 2σ of the Kendall station data. Results from the secondary test plots were similar, with summer nighttime NEE measured both within and greater than the 2σ of the Kendall station data.

After mowing, consistent increases in NEE were measured with respect to the expected values at both the primary and secondary test plots. During daytime, this resulted in either positive (M1 = Low Mow) or less negative (M3 = High Mow) NEE. This is consistent with a reduction in the leaf area of the plants and potentially enhanced plant respiration as they replaced photosynthetic tissues. This response is best illustrated in Figure 4-27, where subplot M1 (Low Mow) NEE switches from being extremely negative, to extremely positive immediately after mowing. The magnitude of the NEE change observed for subplot M3 (High Mow) also changed; however, the NEE remained slightly negative after mowing (i.e., the subplot was still acquiring more CO_2 than it released).

Nighttime NEE after mowing also showed differences between subplots M1 (Low Mow), M3 (High Mow), and N1 (control). Again, this is best shown in Figure 4-27, where at subplot M1 nighttime fluxes clearly exceeded the M3 and N1 NEE throughout the night and into the early morning. This general trend in CO_2 fluxes before versus after mowing occurred at all test plots. Graphs of this data for all test plots are in Appendix B.

Fall

The discrete fall measurements of NEE differed most from NEE data at the Kendall station. In each of Figures 4-25 through 4-27, and most cases for the secondary test plots (Appendix B) the daytime NEE was more negative than that typically recorded over the 10-year history at the Kendall station. There were, however, inter-year variations in the magnitude of the difference between the discrete daytime measurements at the test plots and the 2σ from the Kendall station data. A closer examination of the data revealed that higher levels of fall soil moisture appeared to be correlated with the most negative daytime NEE measured in fall.

Similarly, night-time NEE measurements in fall were also consistently higher with respect to the 2σ from the Kendall station data. These results indicated that the vegetation along New Mexico ROWs remained photosynthetically active later into the fall than the vegetation at Kendall station. This could be due to thermodynamics (i.e., differences in temperature or soil moisture), soil type(s), or vegetation type(s). This has not been investigated further, but is noted as the main difference between the discrete chamber-based observations and the average of the long-term (i.e., 10-year) eddy-covariance data at the Kendall station.

Figure 4-25. Test plot 104-79 seasonal surface CO_2 fluxes

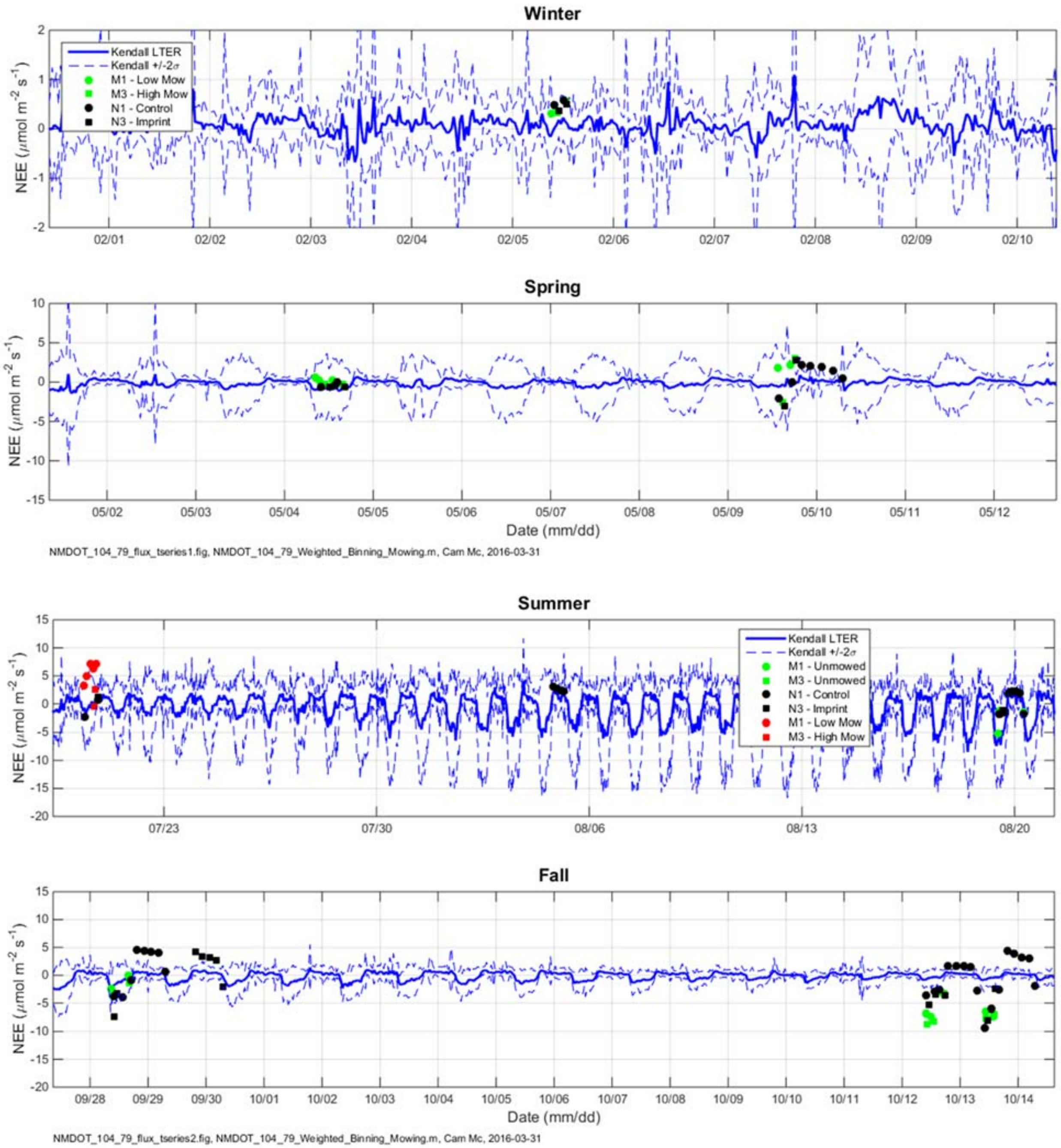


Figure 4-26. Test plot 469-39 seasonal surface CO_2 fluxes

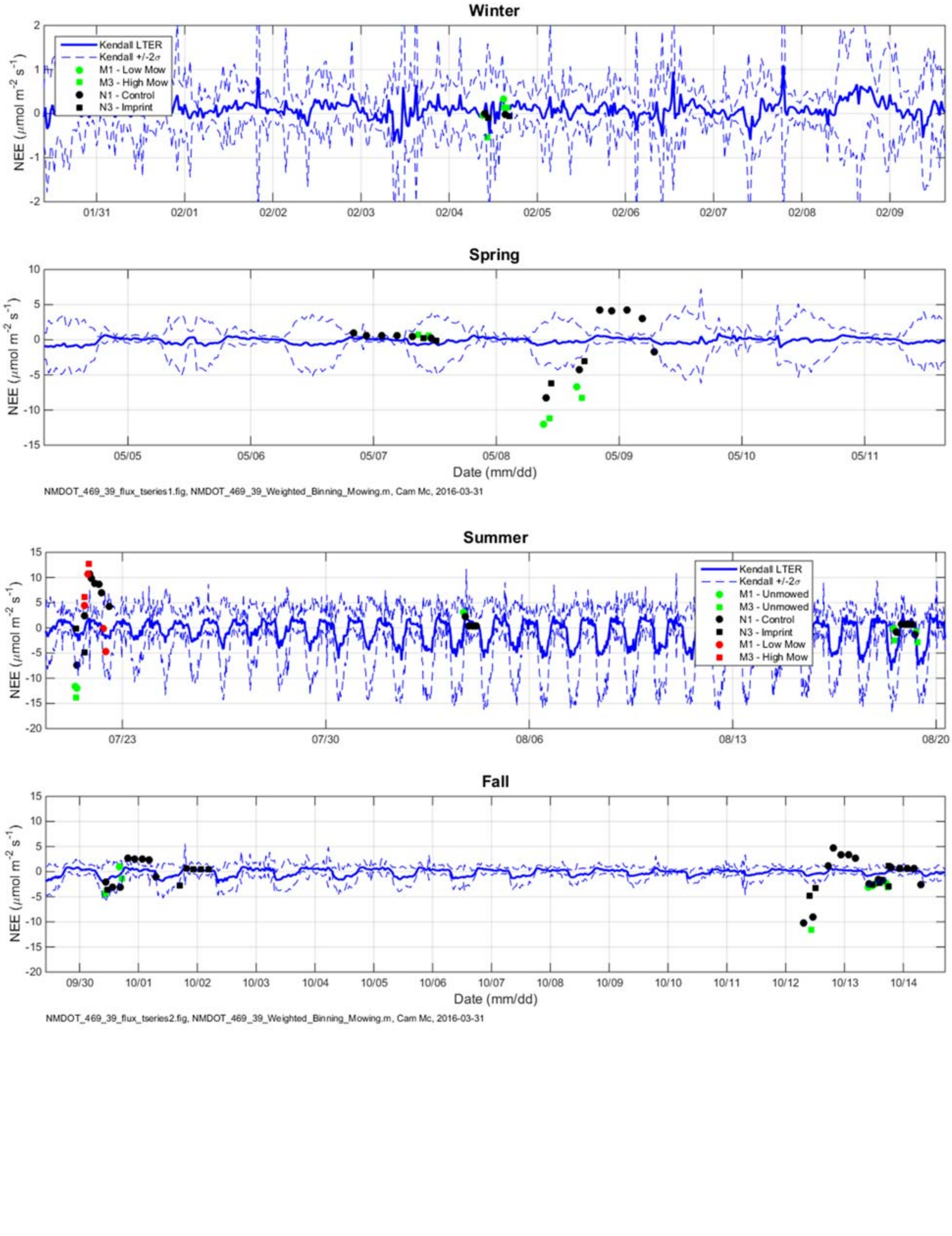
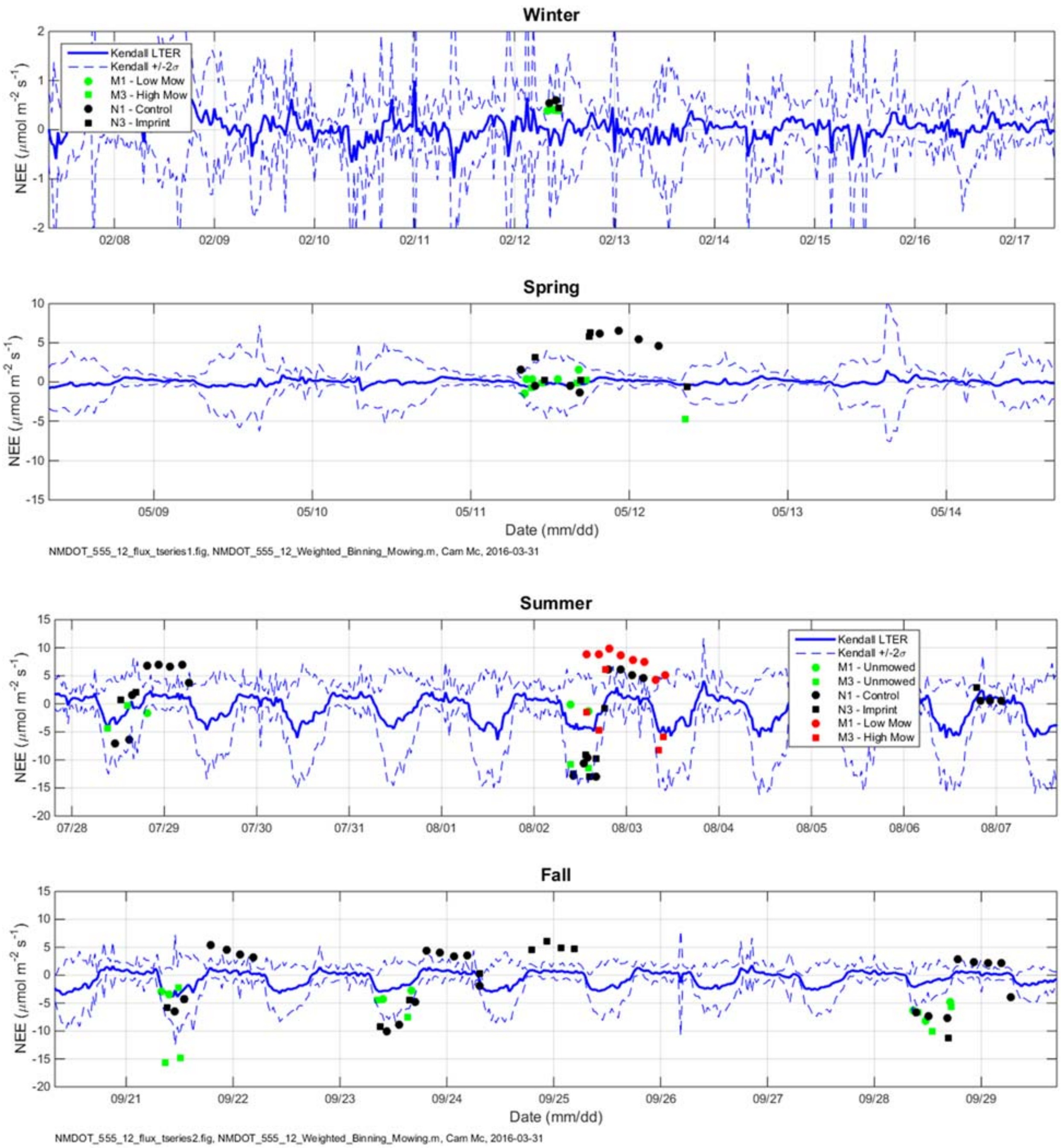


Figure 4-27. Test plot 555-12 seasonal surface CO_2 fluxes



4.4.4 Quantitative Comparison of Surface CO_2 Fluxes to Kendall Station Data

The previous section provided a qualitative comparison of the discrete surface CO_2 flux measurements at the ROW test plots to the LTER station data. As expected, diurnal and seasonal patterns in NEE were observed including daytime carbon uptake, nighttime carbon emissions, non-zero wintertime fluxes, and peak productivity following the summer monsoon. However, quantitative differences between the measurements and the Kendall station data occur due to differences daily and annual variability in solar insolation, air temperature, soil moisture, soil and vegetation community composition, etc. between the two places.

Here we provide a quantitative comparison between the observed and 3-hour binned ROW NEE and the 10-year average Kendall station NEE data during the same 3-hour bins. To partially account for natural variability in soil temperature, soil moisture, cloud cover, etc., the mean Kendall station NEE is the average of the daily 3-hour bin for the week centered on the date of the discrete NEE measurement at the ROW test plot. For example, the fluxes measured on a Wednesday between 09:00 to 12:00 are compared to the (10-year) average (and $\pm 2\sigma$) NEE measured between 09:00 and 12:00 on Sunday through Saturday of that week.

We do not expect a 1:1 correlation between the test plot NEE measurements and the Kendall station data due differences in site thermodynamics, and site-specific soil and vegetation composition. It is also inappropriate to perform Model I linear regression on the data[1], as there is both inherent variability and uncertainty in both the LTER data and the test plot measurements of NEE (neither variable is independent). Instead, a Model II linear regression was used and the Kendall station data was compared versus the ROW measurements.

Slopes less than unity are indicative of one or both of: more negative daytime NEE and/or larger nighttime NEE at the ROW test plots. Slopes greater than unity were not observed, but would be indicative of higher rates of daytime photosynthesis and nighttime respiration at the Kendall station. Figures 4-28 through 4-30 compare the Kendall station results versus the observations from the three primary test plots. Appendix C provides the comparison of observed NEE to Kendall station for the secondary test plots. The top two panels of each figure are the results for the M1 and M3 subplots. The bottom two panels of each figure are the N1 and N3 subplot results. The Kendall station data include error bars representing $\pm 2\sigma$ of the 10-year average for the 3-hour bins ± 3 days centered on the test plot monitoring. For the flux measurements at subplots M1 and M3, before mowing are represented by the green symbols. Measurements following low mowing (subplot M1) or high mow (subplot M3) are represented by red symbols. The Model II linear regressions are included as lines, but for the M1 and M3 subplots do not include the observations after low or high mowing (i.e., red symbols are excluded from the regressions).

<u>Test Plot 104-79</u>

At test plot 104-79, the Model II regressions resulted in slopes that varied between 0.36 and 0.51 and show daytime NEE at the test plots are more negative (positive) than the Kendall station averages (Figure 4-28). Similarly, nighttime NEE was more positive compared to the Kendall station averages. Methodological differences could have influenced these results and differences in fluxes due to differences in site thermodynamics (i.e., soil temperature and moisture) were not accounted for in this representation (Section 5.4). However, the results were generally consistent with test plot 104-79 being a higher productivity system than the Kendall station (i.e., higher daytime photosynthesis and higher nighttime respiration).

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[1] Model I linear regression assumes that there is no uncertainty in the independent variable (X), only the dependent variable (Y). Model II regression allows for uncertainty in both variables.

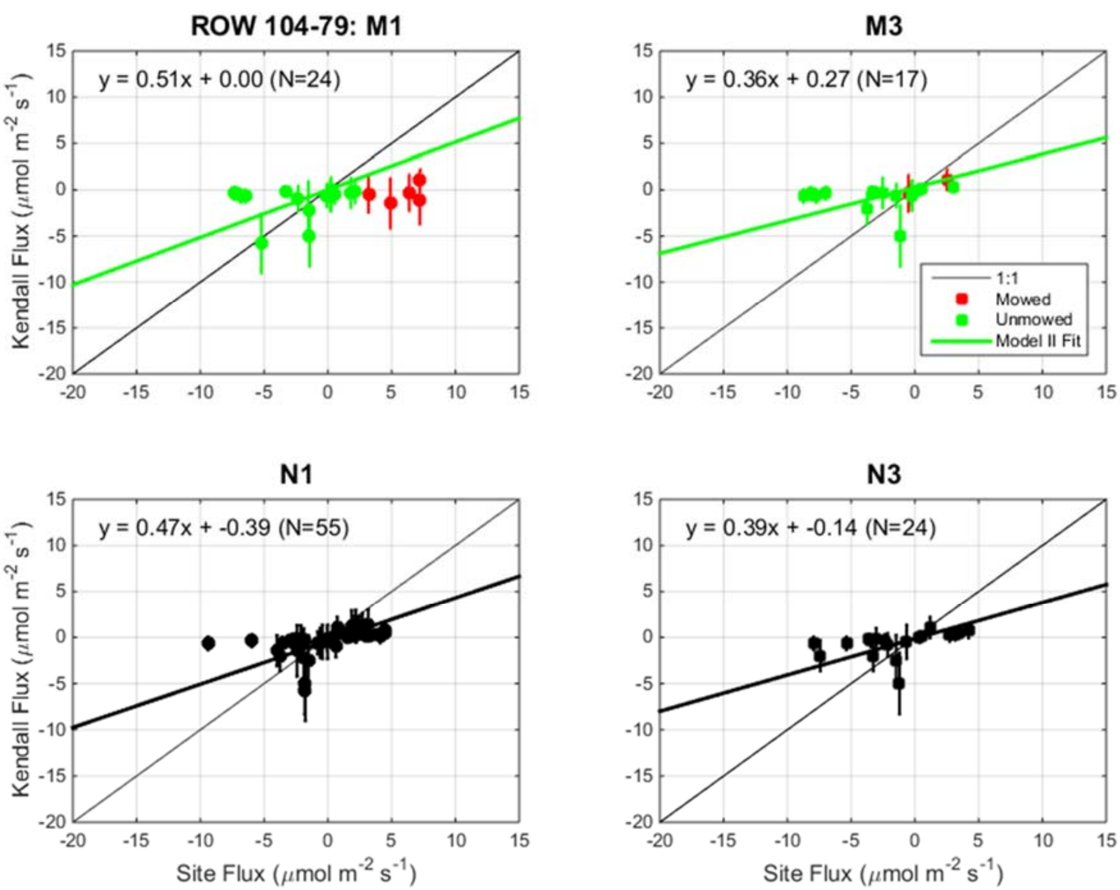
For all four subplots at test plot 104-79, there was a small cluster of observations that are much more negative than the corresponding values expected from the Model II regression (Figure 4-28). These correspond to the monitoring events on October 12 and 13, 2014, and October 13 and 14, 2015. For 2 consecutive years, it appears that the ecosystem at test plot 104-79 remained productive well into the fall, whereas vegetation at the Kendall station had typically become dormant by this time of year.

After low-mowing in subplot M1, the observed daytime (06:00 to 18:00) CO_2 fluxes are positive, from 3.2 to 7.2 μmol/m^2/s (mean = 5.4). The expected NEE (based on Kendall station data) ranged from -1.4 to -0.3 μmol/m^2/s (mean = -0.8). This difference could be due simply to higher rates of respiration at the ROW test plots compared to Kendall station during these 3-hour intervals. However, the measured post-mowing fluxes were closer not to the Kendall station average, but to the expected value based on the Model II linear regression. Inverting the Model II linear regression predicted that the measured daytime CO_2 fluxes at subplot M1 should have between -2.8 and -0.6 μmol/m^2/s.

The magnitude of the post low-mowing NEE change at subplot M1 from daytime net carbon sink (i.e., negative NEE) to net carbon source (i.e., positive NEE) is likely greater than can be accounted for by natural variability.

At subplot M3, there is only a single daytime (06:00 to 18:00) post-high-mowing measurement. It occurred at 17:18 and had a value of -0.5 μmol/m^2/s. The expected NEE based on the Kendall station data is -0.3 μmol/m^2/s, but the expected value based on the Model II regression is -1.6μmol/m^2/s. This result indicates that although high mowing appears to have reduced the relative amount of carbon uptake at M3, the subplot remains a small carbon sink, rather than converting to a carbon source (as observed at M1).

Figure 4-28. Kendall station NEE versus mowed and unmowed NEE at test plot 104-79



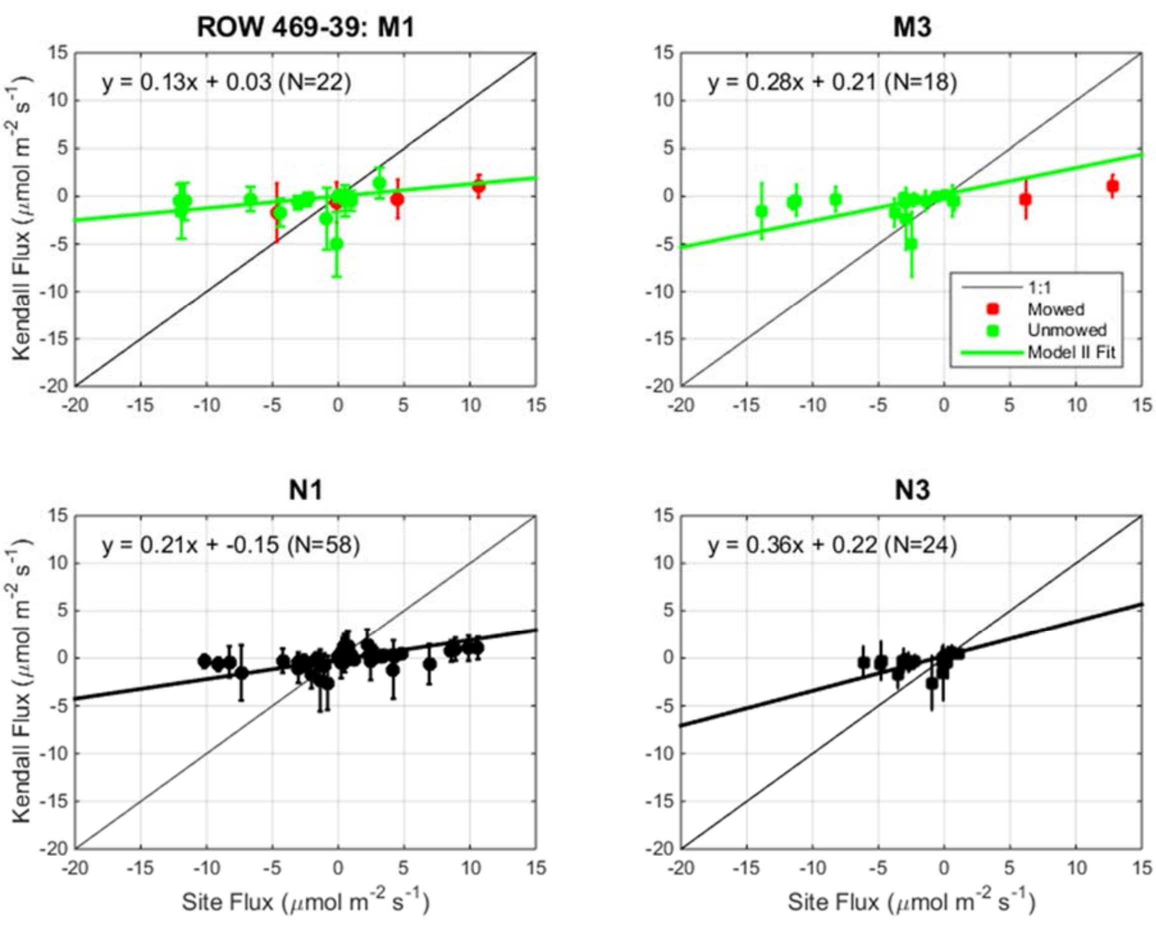
Test Plot 469-39

At test plot 469-39, the Model II regressions produced a well-constrained fit that mostly fell within the 2σ variability of the Kendall station (Figure 4-29). The exception was fall daytime NEE measurements that were more negative than -5.0 μmol/m^2/s, extremes simply not observed at the Kendall station in fall. As observed at test plot 104-79, the slopes of the Model II regression indicated that the ecosystem at test plot 469-39 had higher productivity than the Kendall station.

Post-low-mowing at subplot M1, the expected daytime NEE based on the Kendall station data were -1.7 to -0.3 μmol/m^2/s (mean = -0.9). However, the expected value based on Model II regression was -13.7 to -2.4 μmol/m^2/s (mean = -7.1). The measured daytime NEE were -4.7 and +4.5 μmol/m^2/s (mean = -0.1). In this case, the low mowing resulted in a less negative to positive daytime NEE, consistent with the system becoming a lesser carbon sink due to plant stress and reduction in active plant biomass as a result of the low mowing.

There were fewer post-mowing measurements at subplot M3 in 2015. Only a single daytime NEE was measured for evaluating the effects of high mowing. Based on Kendall station and the Model II regressions, fluxes should have been slightly negative late in the day (-0.3 and -1.7 μmol/m^2/s, respectively). The observed NEE was +6.2 μmol/m^2/s, indicating that high mowing can result in reductions in photosynthesis and the ecosystem switching from a daytime carbon sink to a daytime carbon source.

Figure 4-29. Kendall station NEE versus mowed and unmowed NEE at test plot 469-39



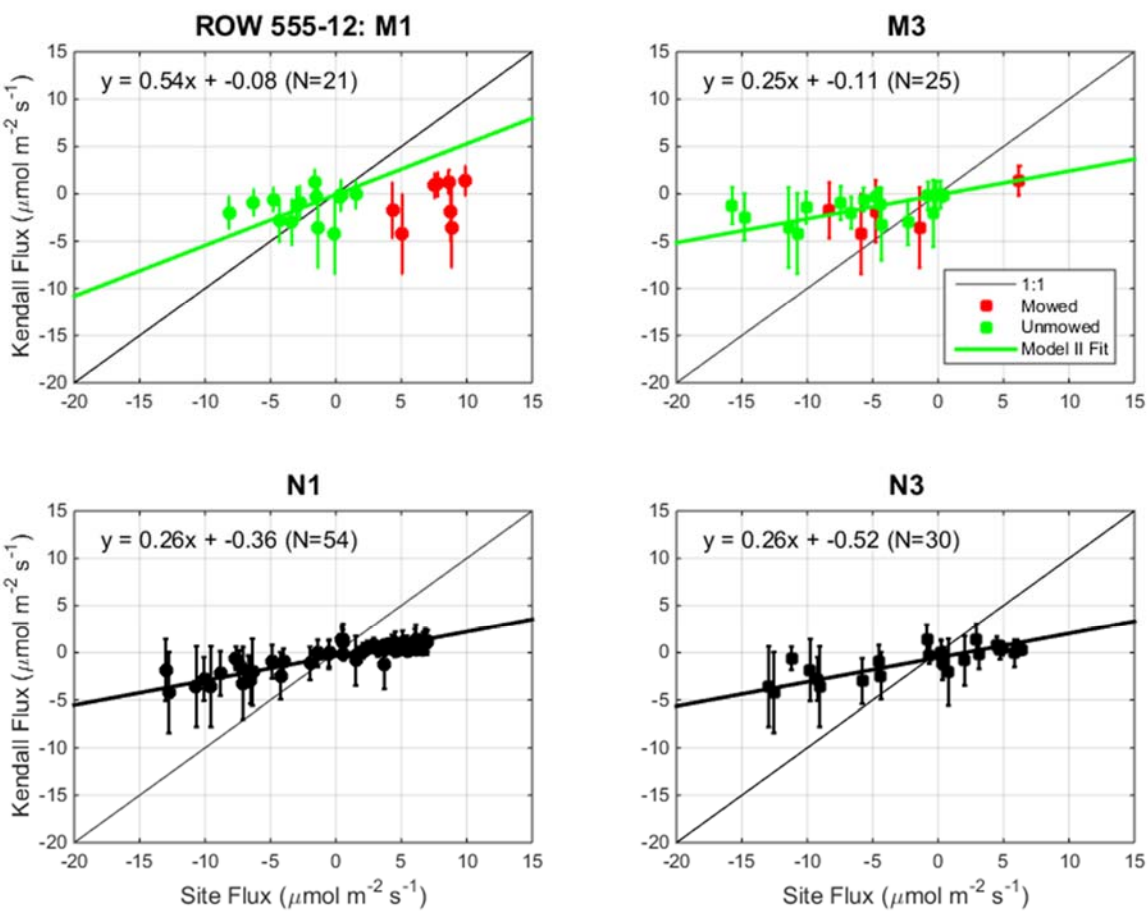
Test Plot 555-12

Results from test plot 555-12 provide perhaps the most compelling results of the study. The Model II regressions were relatively well-constrained with the Kendall station data, especially for the N Zones (Figure 4-30). Slopes less than unity indicated a typically more productive system, consistent with the cooler, wetter conditions observed at the Lower Montane test plots, as compared to both the Prairie test plots and the Kendall station.

After low-mowing at subplot M1, there was a profound reversal from a daytime carbon sink to daytime carbon source. Kendall station data predicted daytime NEE between -4.2 and -1.7 µmol/m²/s (mean = - 2.8). The Model II regressions predicted daytime NEE values between -7.7 and -3.2 µmol/m²/s (mean = -5.1). The measured NEE ranged from +4.3 to +8.8 µmol/m²/s (mean = 6.7, N = 4). This shift from daytime carbon sink to source cannot be explained by system variability and demonstrates the effects of low-mowing on the ROW's daytime primary productivity.

Overnight measurements at test plot 555-12, subplot M1, reflected the effect of low mowing on nighttime respiration. Based on the Kendall station data, nighttime NEE should have been +0.9 to +1.4 µmol/m²/s (mean = 1.1). The Model II regression predicted nighttime NEE of +1.8 to +2.7 µmol/m²/s (mean = 2.3). The measured NEE was +7.5 to +9.9 µmol/m²/s (mean = 8.4, N = 4). This magnitude of increase in nighttime NEE after low mowing probably cannot be explained by natural variability. Nighttime respiration is likely elevated due to the vegetation's response to low mowing, i.e., the plants were repairing their damaged tissues.

Figure 4-30. Kendall station NEE versus mowed and unmowed NEE at test plot 555-12



After high mowing at subplot M3, there was less impact on daytime NEE than for the Low-Mow subplot. Based on the Kendall station data, daytime NEE should have been -1.7 to -3.6 μmol/m^2/s (mean = -2.8). The Model II regression predicted values of -6.4 to -16.4 μmol/m^2/s (mean = -10.8). The measured daytime NEE ranged from -1.4 to -8.3 μmol/m^2/s (mean -5.1, N = 4). Although high mowing had an effect on daytime NEE, it did not cause the M Zone to switch from a daytime carbon sink to carbon source, only to a smaller carbon sink.

There was only one nighttime NEE measurement at subplot M3. The Kendall station data and Model II results suggested a nighttime NEE of +6.2 and +1.4 μmol/m^2/s, respectively. The measured NEE was 5.9 μmol/m^2/s, which is high compared to the Model II prediction. It is likely that nighttime NEE after high mowing will be elevated as plants repair damaged tissues; however, the magnitude of the increase in nighttime NEE may be less than that of the low-mowing case.

4.5 Summary of Responses to Treatment

4.5.1 Managed Zone Responses

Differences in soil carbon stock within M Zone treatments were generally insignificant and equivocal in response. Vegetation responses to the High Mow treatment compared to the Low Mow was a general pattern of increased aboveground biomass and canopy cover, though these differences were not significant except for the increased total standing biomass associated with the High Mow treatment at Prairie test plots in 2014.

As expected, unmowed summer daytime NEE measurements were consistently negative due to net sequestration of atmospheric CO_2 by photosynthetic plants. After mowing, a consistent increase in NEE was measured at both the primary and secondary test plots, where daytime NEE was either positive for Low Mow (M1) or less negative for High Mow (M3) treatments. This was consistent with a reduction in the leaf area and increased respiration as plants repair their tissues and regrow leaves. Nighttime NEE after mowing also showed differences between subplot M1 (Low Mow), M3 (High Mow), and for the Control subplot (N1), where M1 nighttime fluxes exceeded the NEE at M3 and N1 through the night and into the following early morning.

4.5.2 Natural Zone Responses

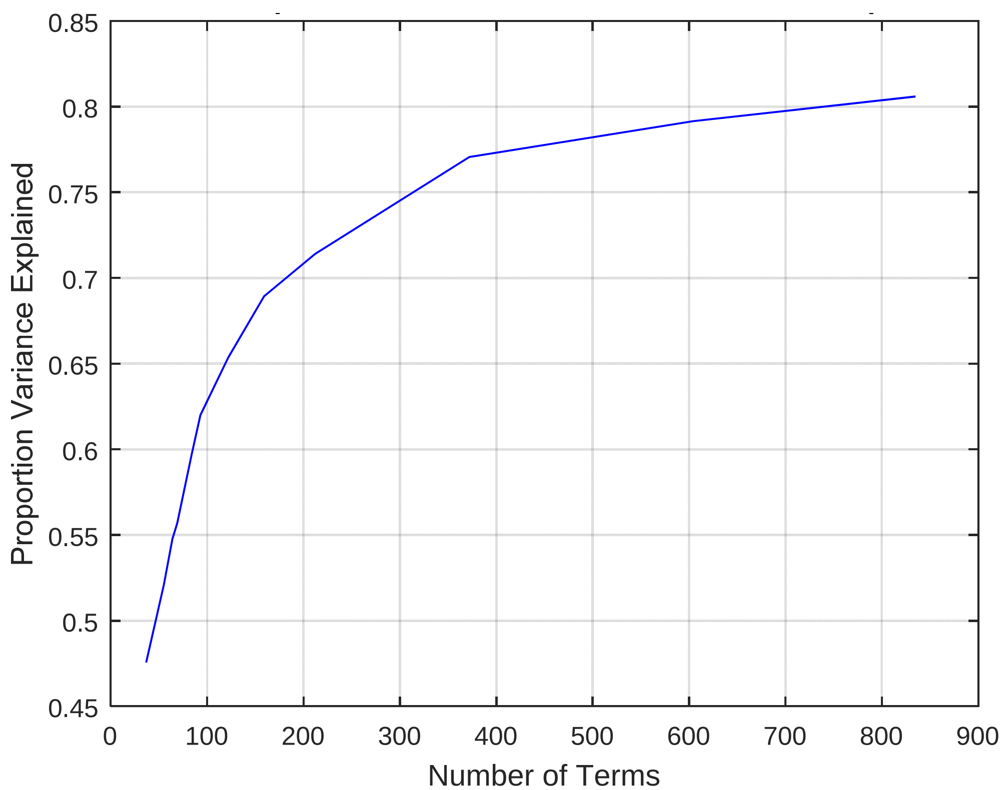
Similar to the M Zone, differences in soil carbon stock between the Control subplot N1 and the Imprinted subplot N3 were mostly insignificant and equivocal in response. In general, aboveground biomass and canopy cover responses to Imprinting, compared to the Control, were varied and insignificant. Only more litter cover associated with the imprinting treatment was significantly different to the Control at both Prairie and Lower Montane test plots in 2015. Furthermore, no apparent treatment effects on CO_2 flux in the Imprinted subplot were observed compared to the Control.

5 ECOSYSTEM MODELING RESULTS

5.1 Fourier Expansion

Model fit for the Fourier expansion method increased with the number of periodic components (i.e. Fourier frequencies) with squared correlation (R^2) of approximately 0.8 possible. However, satisfactory fit with coefficient of R^2 of 60 percent or more required nearly 100 frequencies (Figure 5-1). The large number of terms necessary to achieve a reasonable fit suggests the NEE dynamics are either driven by complex combinations of many linear processes, or that perhaps a smaller number of causative processes may interact nonlinearly. This latter possibility suggests that the EDM analysis may provide a lower dimensional description of NEE fluctuations to serve as the basis for a predictive model.

Figure 5-1. Coefficient of determination plotted against number of Fourier frequencies included in model



5.2 Empirical Dynamic Model

The EDM was fit to physical process data using cross validation to identify the smallest combination of process variables that optimized out-of-sample predictive quality. Selected models were validated by comparing model predictions, based on measured physical variables (data) from ROW test plots. NEE was also measured over short periods (discrete measurements) of time to independently validate the model's NEE predictions. This section summarizes the model selection and model validation steps.

5.2.1 Model Selection

Out of the 17 models tested, models with less than three variables resulted in squared correlations substantively below 0.6, whereas 6 models that included three or more process variables with their lagged versions for lags varying from 1 to 6 (3-hour bins) generally resulted in squared correlations of 0.6 or greater.

Results for four univariate models and the three best multivariable models are summarized in (Table 5-1 and Figure 5-2). The strongest univariate model was based on NDVI with squared correlation of 0.50, which was better than any other univariate prediction scheme, all of which had squared correlations less than 0.36. The NDVI-only model was improved substantively by adding soil temperature or PAR, but was unimproved when soil moisture was included along with NDVI.

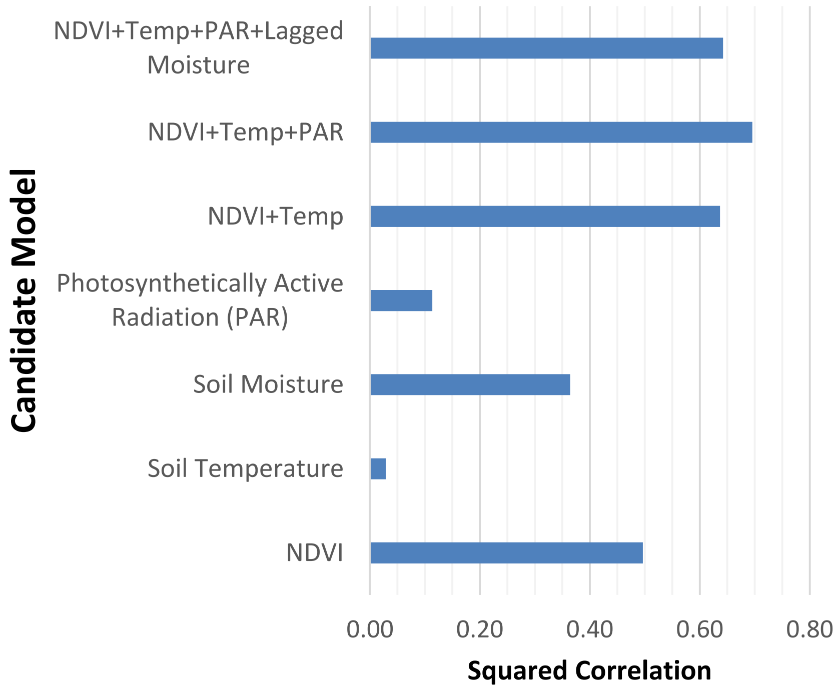
The strongest predictions were obtained from Model 12, which included NDVI, soil temperature, and PAR, and had squared correlation of 0.70. This three-variable model performed no better than the bivariate (NDVI and soil temperature) model and had slightly lower R^2 than the simpler Model 12 (including NDVI, soil temperature, and PAR).

Other more complex models, including up to nine process variables, some two-way interactions and lagged versions, had lower squared correlations than any of the top three models, and were only marginally better than the univariate model using only NDVI. This reduction in out-of-sample predictive quality was expected and illustrates reduced out-of-sample predictions caused by overfitting models to idiosyncratic features of the training sets that are not replicated in the validation set. For simplicity, those results are not shown here.

Table 5-1. Combinations of process variables tested for predicting NEE with EDM

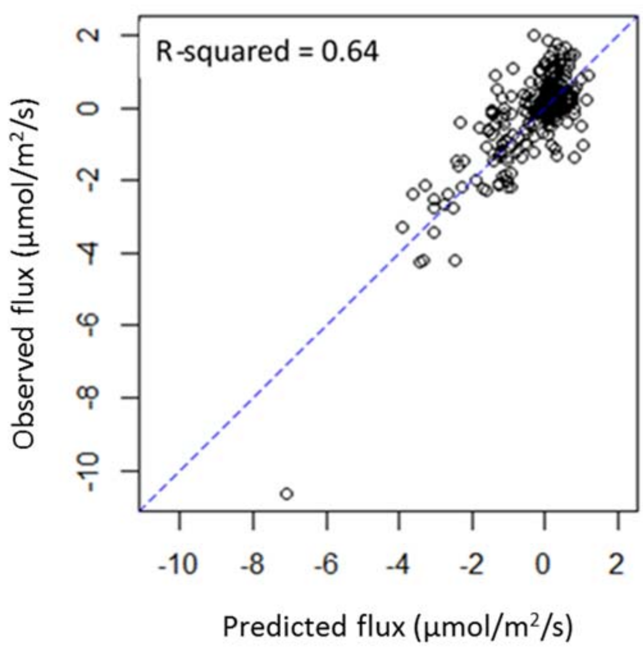
	Model Number						
Process Variables	**1**	**2**	**3**	**4**	**5**	**12**	**17**
NDVI	X				X	X	X
Soil Temperature		X			X	X	X
Soil Moisture			X				X
Photosynthetically Active Radiation (PAR)				X		X	X
Lagged Soil Moisture							X
Squared Correlation (Monthly Average)	0.50	0.03	0.36	0.11	**0.64**	**0.70**	0.64

Figure 5-2. Squared correlation coefficients between observed and predicted weekly average NEE for each of 123 month-year-station combinations excluded from the training subset.



Observed and predicted 8-day weekly averages for each year and station combination were plotted in Figure 5-3, including a one-to-one line showing that observed and predicted values agree well and are unbiased with relatively balanced distribution of values above and below the one-to-one line. These values were calculated by first training the model on all data, excluding 1 year at one station. The 3-hour NEE values were then predicted for the excluded station-year, averaged by week, and then compared with actual weekly averages. Each dropped year provided 46 8-day weekly averages for comparison to actual averages. These results represent the out-of-sample predictive quality expected when extrapolating temporally within the set of locations represented by conditions at the Kendall and Audubon LTER stations. The validation results provided in the next section describe the extrapolation both spatially and temporally beyond the training data.

Figure 5-3. Test plot NEE observed vs predicted weekly average NEE by Model 17



5.2.2 Model Comparison to Recorded Field Observations

To validate model performance, the EDM output for subplots M1, M3, N1, and N3 at each test plot were compared to the discrete NEE measurements recorded at those test plots. Model II linear regression was used to evaluate the results quantitatively, similar to the approach used when comparing the discrete NEE measurements to the long-term average data from the Kendall LTER station (Section 4.4.4). If the EDM model is predicting diurnal and seasonal variations in NEE at the test plots well, regression slopes close to 1:1 and increased coefficients of variation (i.e., R^2) is expected. Where this is the case, we can potentially conclude that the EDM , trained using regionally relevant observations (i.e., LTER station data), and using site-specific thermodynamics (i.e., soil temperature, soil moisture, and PAR); provides a good prediction of diurnally and seasonally varying NEE; and therefore can predict net annual change in carbon at the subplot level for each ROW test plot.

The follow subsections compare the EDM predictions to the observations from the three primary test plots. Results for all test plots are in Appendix D.

<u>Test Plot 104-79</u>

In general, the Kendall station data are not well correlated with the discrete NEE observations from either the N or M Zones at test plot 104-79. As discussed in Section 4.4.4, the site-specific observations typically show higher nighttime NEE, as well as more negative daytime NEE, especially in October.

Regressions of predicted NEE versus observed NEE resulted in slopes that vary between 0.31 and 0.66, as compared to 0.36 and 0.51 for linear regressions of Kendall NEE versus observed NEE (Table 5-2). The slopes derived for the EDM predictions versus the observations at subplots M1 and M3 resulted in no improvements compared to the average Kendall data. The EDM predictions for subplots N1 and N3 were in better agreement with the observations (i.e., regression slopes are closer to 1:1). Correlations between the EDM predictions and observations in the M Zone remained poor, while EDM predictions improved the correlations for the N Zone. The correlation coefficient improved from 0.26 to 0.68 for subplot N1; the correlation coefficient improved from 0.19 to 0.52 for subplot M3.

Figure 5-4 shows the time series of EDM-predicted NEE for subplots M1, M3, N1, and N3. The results indicated that the regression slopes and the poor correlation between model predictions and the observations at subplots M1 and M3 were driven by more negative daytime NEE and more positive nighttime NEE observations in fall 2014 and spring 2015. The same is true for subplots N1 and N3; however, their less negative daytime NEE data in fall 2014 could better explain the variance for the fit. Regression parameters are summarized in Table 5.2 and are illustrated in Figure 5-4 for each subplot.

The inability of the EDM model to predict observed high-amplitude fluxes is potentially linked to the use of the Kendall and Audubon station data as the EDM training set. Since the fall 2014 and spring 2015 NEE observations are were beyond 2σ of the mean Kendall NEE for that time of year (Figure 4-25), the EDM model would have difficulty predicting fluxes of this magnitude because, at Kendall and Audubon, their occurrence is highly improbable.

Table 5-2: Regression slopes and R^2 for Kendall station and EDM-predicted NEE versus measured NEE at test plot 104-79

Subplot	Slope Comparison		R^2 Comparison	
	Kendall vs. Test Plot Observations	EDM vs. Test Plot Observations	Kendall vs. Test Plot Observations	EDM vs. Test Plot Observations
M1	0.51	0.31	0.02	0.01
M3	0.36	0.39	0.00	0.24
N1	0.47	0.66	0.26	0.68
N3	0.39	0.54	0.19	0.52

Figure 5-4. EDM-predicted NEE time series for test plot 104-79, subplots M1, M3, N1, and N3 and comparison to seasonal NEE observations

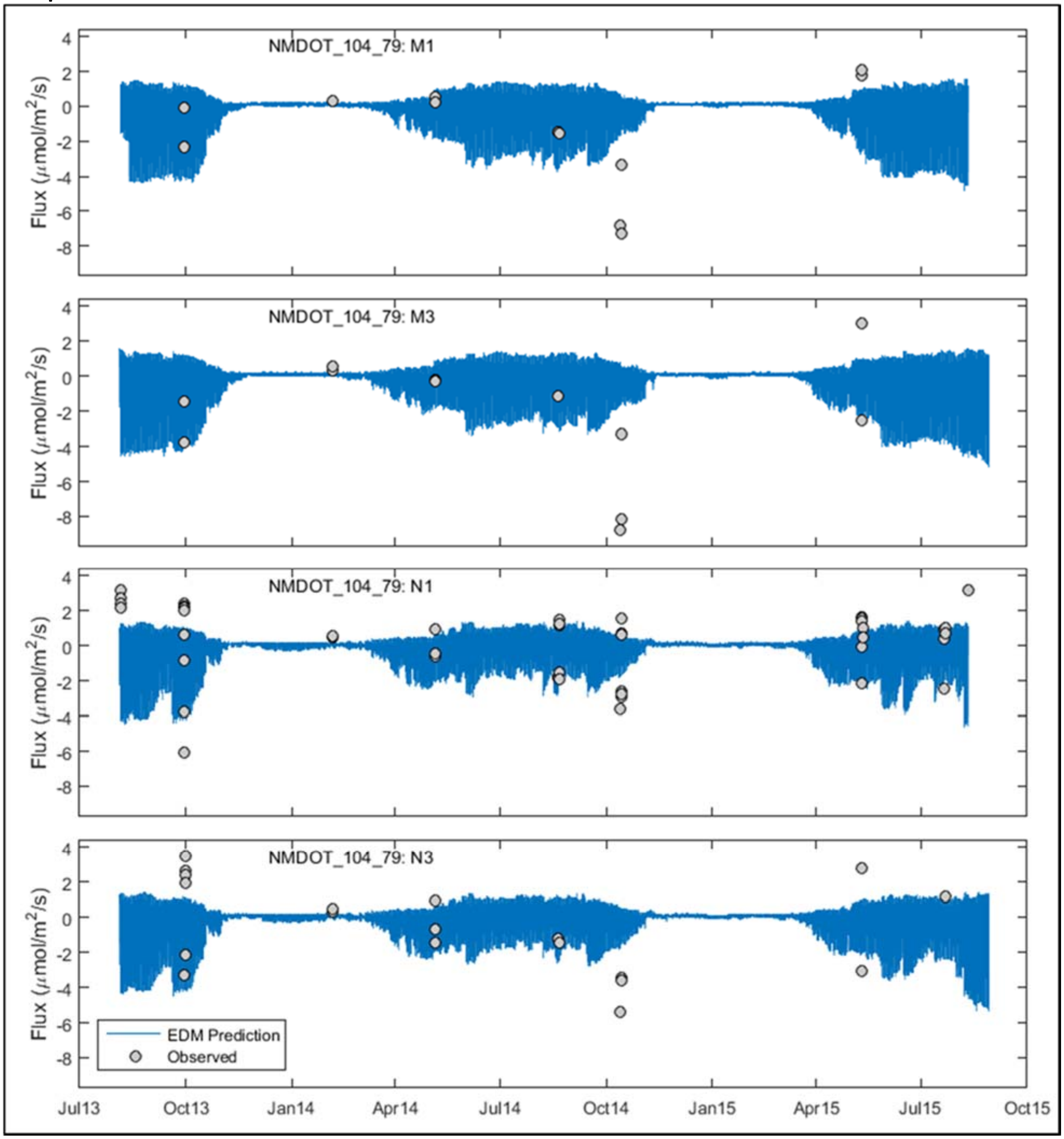
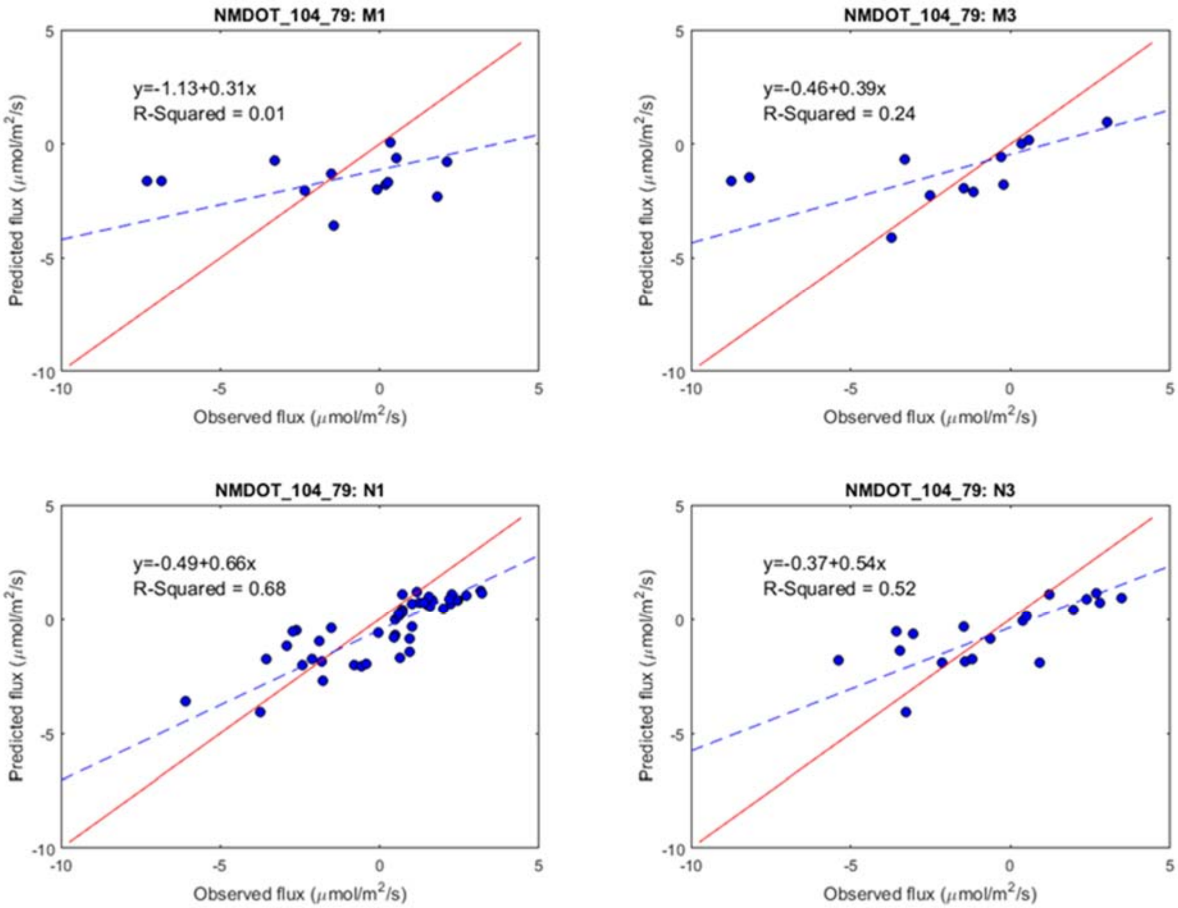


Figure 5-5. Linear regression NEE time series for test plot 104-79, subplots M1, M3, N1, and N3 and comparison to seasonal NEE data



Test Plot 469-39

The average Kendall NEE data are not well correlated with the test plot data at any of the subplots, M or N Zone. The EDM versus data Model II linear regressions of NEE resulted in slopes that varied between 0.36 and 0.96 as compared to 0.13 and 0.36 (Table 5-3). In each case, the model-predicted NEE were a better fit to the discrete observations than the regressions against the NEE averages from the Kendall data.

The EDM predictions produced NEE estimates that were well correlated with the data from subplots M1 and M3, resulting in significant improvement. The coefficient of variation also increased from near-negligible values for the Kendall average compared to values of 0.64 and 0.84 from the EDM. Model predictions in the N Zone also showed improvement: Slopes below 0.4 improve to 0.71 and 0.96, while coefficients of variation are fair at 0.42 and 0.38 for subplots N1 and N3. Figure 5-6 graphs the time series of EDM NEE predictions for subplots M1, M3, N1, and N3. Figure 5-7 illustrates the Model II linear regressions for each subplot.

As described for test plot 104-79, the differences in slopes and variance for test plot 469-39 are challenged by low sample numbers and the inability of the EDM to simulate large fluxes measured in the spring and fall. Once again, the inability of the EDM to predict the observed high-amplitude fluxes is linked to the use of the Kendall and Audubon station training data. Measured fluxes in the spring and fall at test plot 469-39 were sometimes beyond 4σ from the Kendall station mean NEE values in spring and fall (Figure 4-26). These extreme differences were not considered likely by the EDM (i.e., they did not happen at Kendall or Audubon station) resulting in under-prediction of the diurnal NEE amplitudes at test plot 469-39 during these times of year.

Table 5-3. Regression slopes and R^2 for Kendall station and EDM-predicted NEE versus measured NEE at test plot 469-39

Subplot	Slope Comparison		R^2 Comparison	
	Kendall vs. Test Plot Observations	EDM vs. Test Plot Observations	Kendall vs. Test Plot Observations	EDM vs. Test Plot Observations
M1	0.13	0.36	0.00	0.64
M3	0.28	0.44	0.00	0.84
N1	0.21	0.71	0.22	0.42
N3	0.36	0.96	0.09	0.38

Figure 5-6. EDM-predicted NEE time series for test plot 469-39, subplots M1, M3, N1, and N3, and comparison to seasonal NEE observations

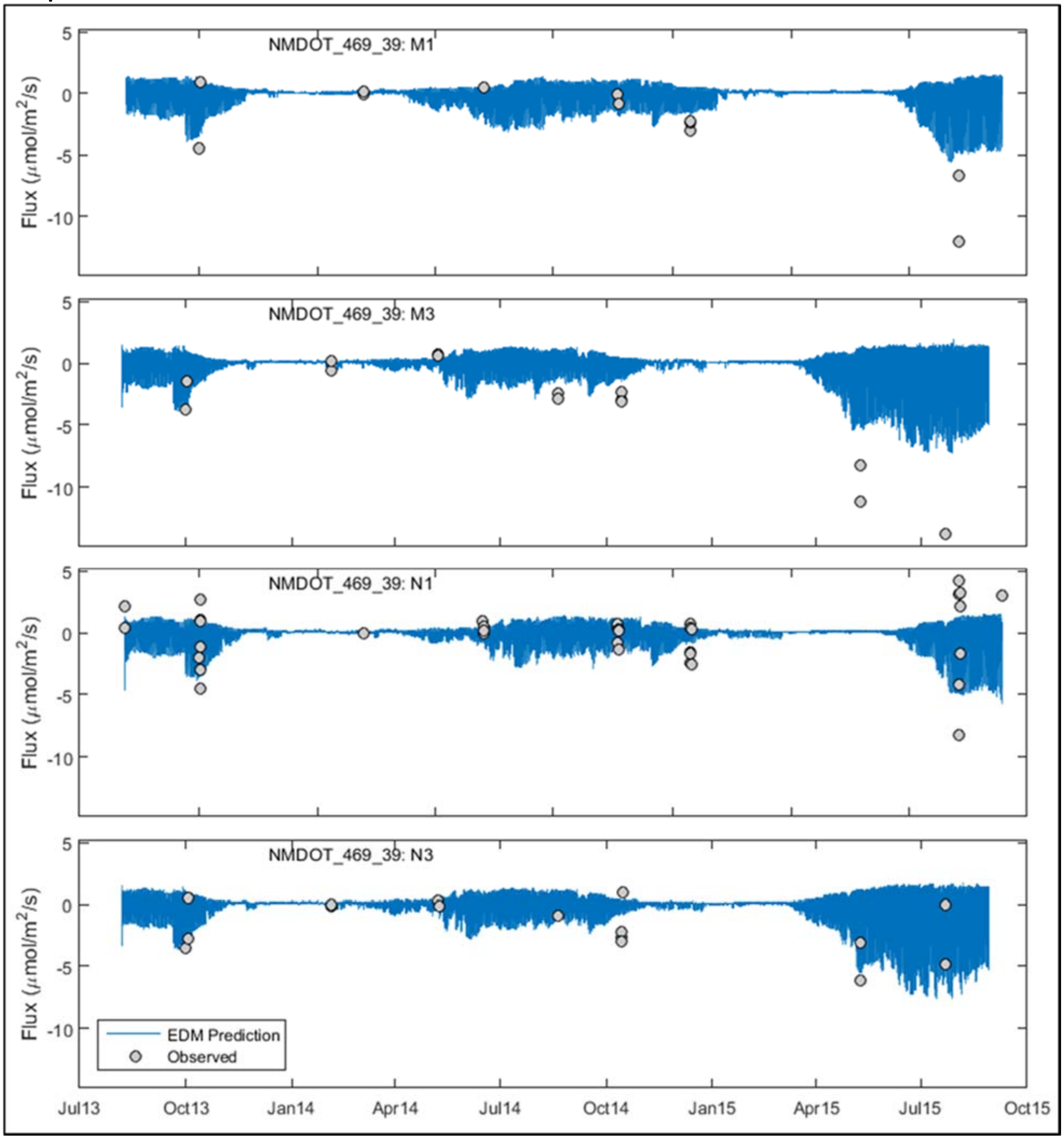
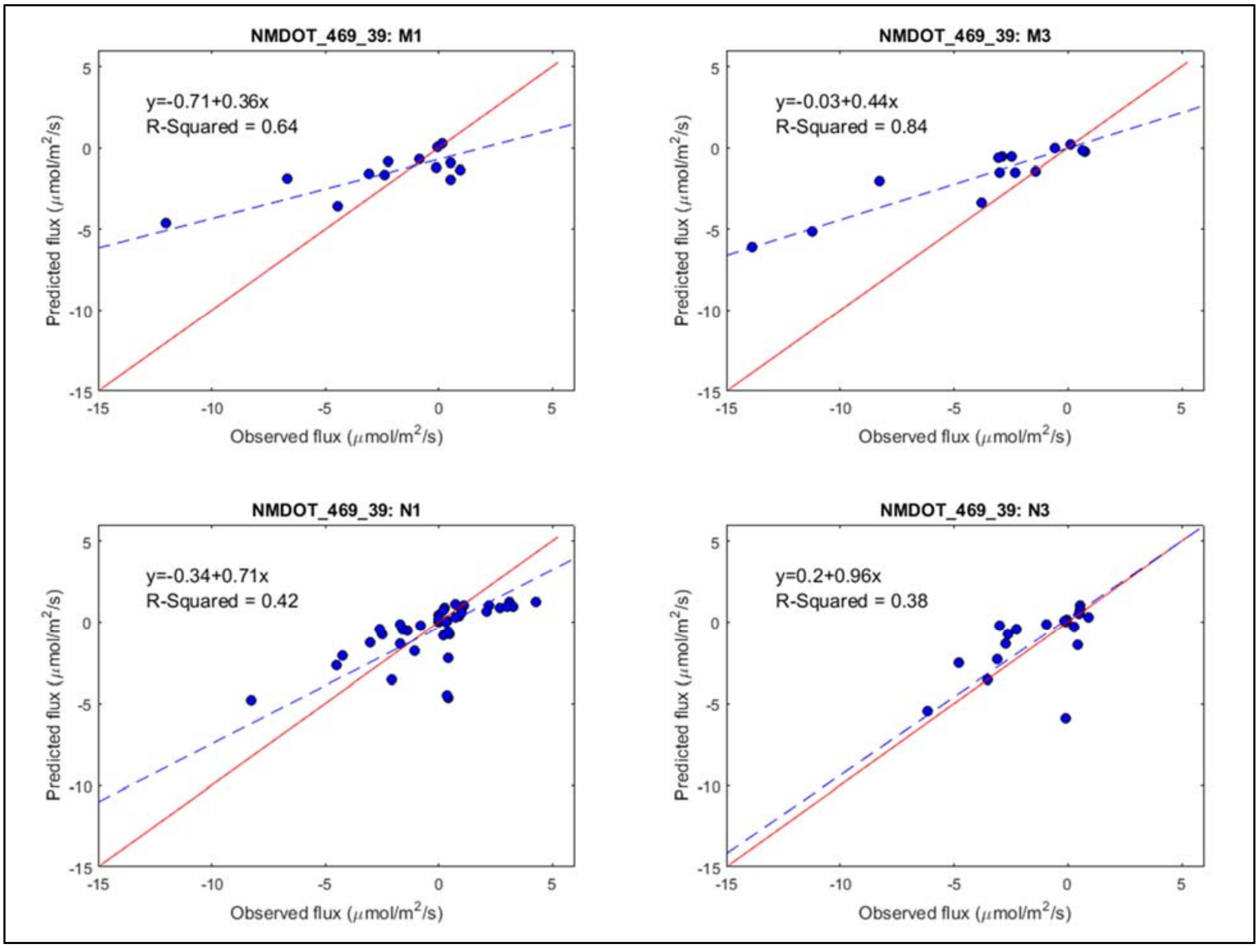


Figure 5-7. Linear regression NEE time series for test plot 469-39, subplots M1, M3, N1, and N3, and comparison to seasonal NEE data



Test Plot 555-12

The average Kendall NEE data are not well correlated with the test plot data from the M Zone subplots, but are well correlated with data from the N Zone subplots. Except for subplot M1, with a slope of 0.54, the slopes of the regression for the Kendall NEE data are approximately 0.25.

The EDM versus test plot observations Model II regressions of NEE result in slopes that vary between 0.48 and 0.84 as compared to 0.25 and 0.54 for the same regressions of Kendall station data versus the test plot observations (Table 5-4). In each case, the slope of the model predictions were improved for the slopes derived from the average Kendall data.

Whereas the average Kendall NEE data are not well correlated with the test plot observations (R^2 = 0.08 and 0.28) from the M Zone subplots (M1 and M3), they are well correlated (R^2 = 0.76 and 0.63) for the N Zone subplots (N1 and N3). The EDM predictions for M1 and M3 have improved slopes, but coefficients of variation remain poor, with less than approximately 30 percent of the variance explained. Coefficients of variation for the Kendall station data were already high, using the EDM improved the R^2 value for subplot N1 but degraded it for N3, although slopes were closer to 1:1.

Figure 5-8 graphs the time series of EDM-predicted NEE for the subplots of test plot 555-12, and Figure 5-9 illustrates the Model II linear regressions for each subplot.

Like the other two primary test plots, the model was not able to simulate the large fluxes observed at test plot 555-12 during the spring and fall. EDM also had difficulty predicting large fluxes observed in August 2015. Again, the inability of the EDM to predict these observed high-amplitude fluxes is from using the Kendall and Audubon station data for the training set where these extreme fluxes are not typically observed.

Table 5-4 Regression slopes and R^2 for Kendall station and EDM-predicted NEE versus measured NEE at test plot 555-12

Subplot	Slope Comparison		R^2 Comparison	
	Kendall vs. Test Plot Observations	EDM vs. Test Plot Observations	Kendall vs. Test Plot Observations	EDM vs. Test Plot Observations
M1	0.54	0.84	0.08	0.06
M3	0.25	0.59	0.28	0.31
N1	0.26	0.50	0.76	0.85
N3	0.26	0.48	0.63	0.32

Figure 5-8. EDM-predicted NEE time series for test plot 555-12, subplots M1, M3, N1, and N3, and comparison to seasonal NEE observations.

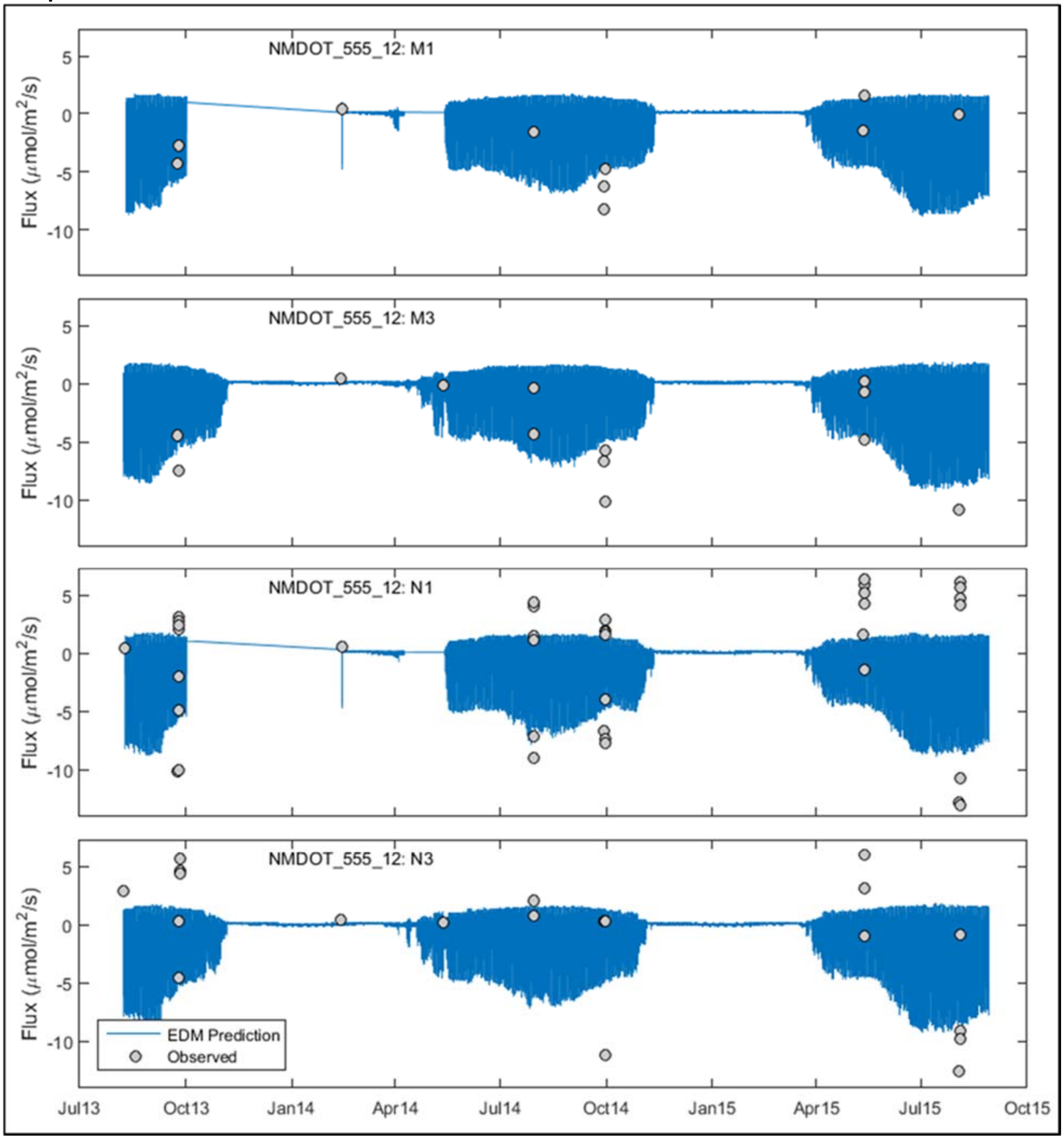
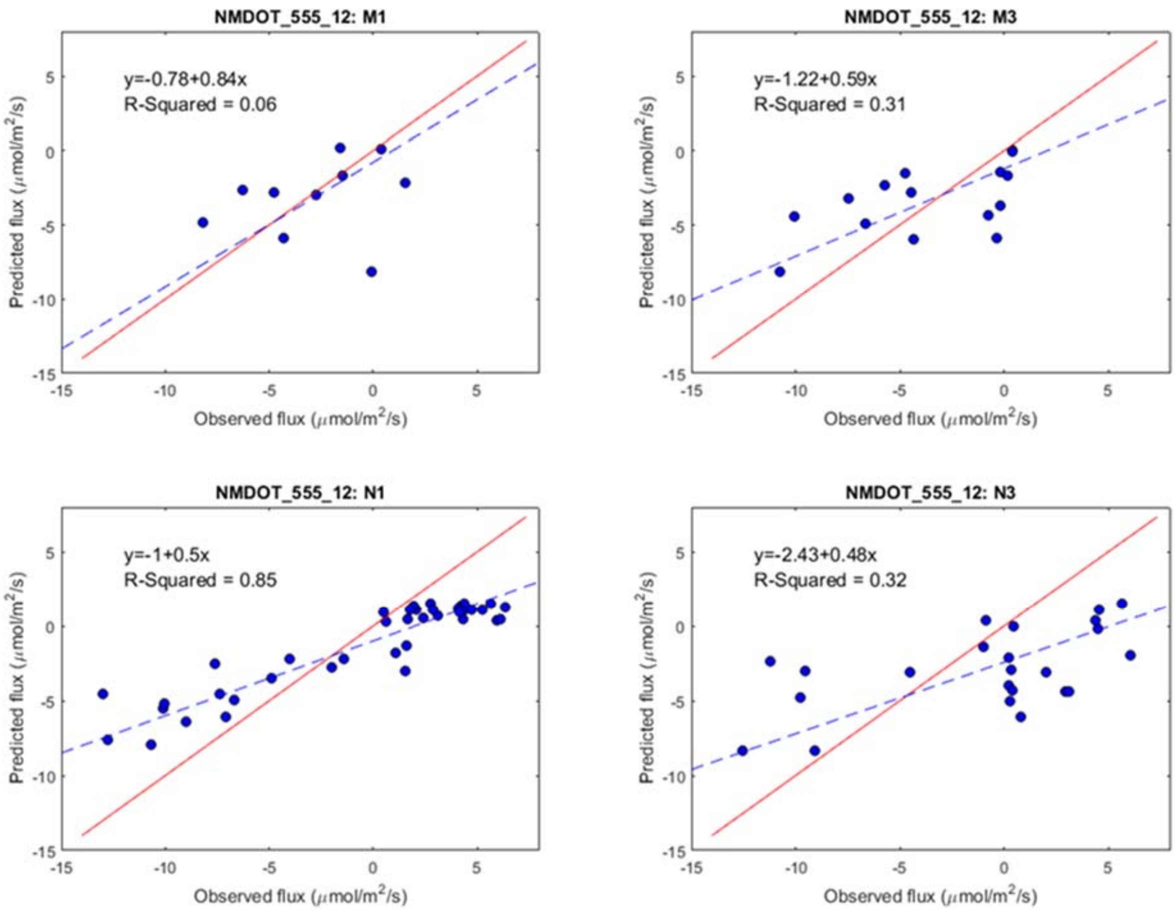


Figure 5-9. Linear regression NEE time series for test plot 555-12, subplots M1, M3, N1, and N3, and comparison to seasonal NEE observations



5.3 Predicting Annual Changes to Carbon

The objective was to evaluate the ability of current and modified land-use practices (treatments) to alter the amount of carbon being stored along highway ROWs in New Mexico. The baseline estimates of the productivity of these ecosystems were based on data from the Kendall, Audubon, and Sevilleta LTER stations. Table 5-5 summarizes the annual integrals of CO_2 fluxes with respect to time. This resulted in an estimate of the annual change in the mass of carbon stored or released per square meter of ROW (g-C/m^2). Positive values indicate net loss of carbon from the system, while negative values indicate net uptake of carbon from the atmosphere. It cannot be determined whether stored carbon is present in leaves, roots, or stems, or to what extent the stored carbon becomes plant litter etc. after senescence; only that over the year, carbon is being stored or released by the ecosystem as whole.

The annual integrals of CO_2 flux from all three LTER stations indicate that these ecosystems can be either net sources or sinks of carbon to the atmosphere. Mean annual soil temperatures vary among the stations, but do not appear to vary by year. However, a clear relationship between mean annual VWC and annual integrals of CO_2 flux are not obvious. This is likely due to VWC changing little in fall, winter, and spring compared to during the summer monsoon season.

Table 5-5. Summary of annual carbon source/sink strength for the three LTER stations

Station	Year	Annual Integral ($g\text{-}C/m^2$)	Mean (St. Dev.)	Mean Soil Temperature (°C)	Mean Volumetric Water Content (m^3/m^3)
Kendall	2007	-75.4	-46.1 (52.9)	19.7	0.05
	2008	-50.4		19.4	0.07
	2009	-29.2		19.3	0.08
	2010	-135		18.6	0.10
	2011	14.2		18.8	0.08
	2012	-62.7		19.6	0.09
	2013	15.8		19.0	0.10
Audubon	2004	268	109.7 (137.4)	19.2	0.09
	2005	87.1		20.4	0.09
	2006	-62.9		19.6	0.07
	2007	147		19.1	0.12
Sevilleta	2010	-70.3	-13.4 (78.1)	17.8	0.10
	2011	96.4		17.0	0.08
	2012	-11.7		17.2	0.09
	2013	-68.2		N/A	N/A

Notes: $g\text{-}C/m^2$ = grams of carbon per square meter; St. Dev. = standard deviation; °C = degrees Celsius; m^3/m^3 = meters cubed of water per meter squared of earth; N/A = not applicable (no data).

The grasslands of New Mexico are designated as Zone F and Zone G grassland regions in the Chicago Climate Exchange (CCX) Offset Protocol (Brown et al. 2009). Exchange offsets for Zone F are calculated at 0.2 metric tonnes of carbon dioxide equivalents per acre per year (t CO_2e/a/yr); offsets for Zone G are calculated at 0.4 t CO_2e/a/yr. The equivalent value in g-C per meter squared is -13.5 to -27 $g\text{-}C/m^2$. When the Kendall, Audubon, and Sevilleta station annual integrals were tested (using a Student's t-test) against mean Zone F and G values, they were indistinguishable in all cases (α=0.05).

We then used the EDM model results to compute the integrals for the subplots M1, M3, N1, and N3 for the eight ROW test plots for 2014. The results are summarized in Table 5-6 for the Prairie test plots and in Table 5-7 for the Lower Montane test plots. For different test plots and different subplots there were occasional missing soil temperature and moisture data. This resulted in some missing data from the integrals (i.e., there were no model-predicted values for those data). As these values were typically a small fraction of the total available daily data, these missing values were ignored.

The EDM model predicted that all Prairie test plots in 2014 were net sinks of atmospheric carbon. The highest net carbon sink appeared to be test plot 120-15, while the least productive test plot was either 469-02 or 469-39. Included in Table 5-6 are the results of Student's t-tests, which evaluated whether the 2014 EDM simulations were considered indistinguishable (H=0) or distinct (H=1) from the pooled annual results from the Kendall, Audubon, and Sevilleta data. Probability statistics (P) indicated how robust the determination was; small values of P suggesting the EDM results are distinct and significantly different from the LTER data.

At test plots 104-79, 469-02, and 469-39, the 2014 carbon sequestered in the N Zone was comparable to the amounts of carbon sequestered at the LTER stations. At test plot 469-02, the M Zone carbon sink was similar to the LTER stations, but for 104-79 and subplot M1 at 469-39, the M Zones were predicted to be greater sinks of carbon than the LTER stations. At Prairie test plots 120-31 and 472-07, the 2014 carbon sink was significantly greater than the averages at the LTER stations for both the M and N Zones.

EDM predicted that all the Lower Montane test plots would be greater carbon sinks in 2014 than the LTER stations (Table 5-7). Missing data for M1 and N1 at test plot 021-15 accounted for less carbon sequestered at these subplots in 2014. Data recovery for the other test plots was good and indicated that the Lower Montane test plots have the potential to store three or four times as much carbon as the Prairie test plots, and potentially ten times more carbon than predicted for Zone F and Zone G offsets under the CCX Rangeland protocol (Brown et al. 2009).

Table 5-6. Summary of annual carbon source/sink strength for Prairie test plots

Test Plot	Subplot	Days	No Mowing	H (vs LTERs)	P (vs LTERs)	Days Mowing Scenario	Low Mow	High Mow
104-79	N1	365	-45	0	0.092	363	-44	-46
104-79	N3	365	-43	0	0.105	363	-48	-47
104-79	M1	365	**-79**	**1**	**0.009**	363	-76	-92
104-79	M3	365	**-79**	**1**	**0.009**	363	-75	-90
120-31	N1	365	**-123**	**1**	**0.000**	363	-106	-132
120-31	N3	365	**-113**	**1**	**0.001**	363	-101	-125
120-31	M1	365	**-130**	**1**	**0.000**	363	-114	-138
120-31	M3	365	**-122**	**1**	**0.000**	363	-108	-134
469-02	N1	359	-11	0	0.586	357	-17	-18
469-02	N3	361	-52	0	0.058	359	-48	-55
469-02	M1	365	-49	0	0.071	363	-43	-47
469-02	M3	360	-23	0	0.335	359	-22	-24
469-39	N1	365	-21	0	0.371	363	-24	-31
469-39	N3	365	-17	0	0.450	363	-21	-26
469-39	M1	365	**-57**	**1**	**0.041**	363	-59	-62
469-39	M3	365	-15	0	0.493	363	-17	-22
472-07	N1	365	**-94**	**1**	**0.003**	363	-72	-96
472-07	N3	365	**-96**	**1**	**0.003**	363	-70	-101
472-07	M1	365	**-93**	**1**	**0.003**	363	-74	-103
472-07	M3	365	**-111**	**1**	**0.001**	363	-82	-115

Note: H= Student's t-test hypothesis: H=0 indistinguishable from the LTER pooled data, H=1 distinct from the LTER pooled data
Bolded values are significantly different that pooled annual integrated NEE from LTER stations based on P-statistic

Table 5-7. Summary of annual carbon source/sink strength for Lower Montane test plots

Test Plot	Subplot	Days	No Mowing	H (vs LTERs)	P(vs LTERs)	Days Mowing Scenario	Low Mow	High Mow
021-15	N1k	213	**-70**	**1**	**0.016**	211	-78	-81
021-15	N3	365	**-249**	**1**	**0.000**	363	-239	-255
021-15	M1	213	**-75**	**1**	**0.011**	211	-82	-85
021-15	M3	365	**-271**	**1**	**0.000**	363	-250	-276
537-43	N1	324	**-342**	**1**	**0.000**	324	-351	-351
537-43	N3	365	**-296**	**1**	**0.000**	363	-318	-304
537-43	M1	323	**-382**	**1**	**0.000**	323	-394	-383
537-43	M3	365	**-312**	**1**	**0.000**	363	-335	-319
555-12	N1	287	**-245**	**1**	**0.000**	287	-227	-241
555-12	N3	365	**-256**	**1**	**0.000**	363	-246	-261
555-12	M1	287	**-259**	**1**	**0.000**	287	-230	-254
555-12	M3	365	**-250**	**1**	**0.000**	363	-234	-249

Note: H= Student's t-test hypothesis: H=0 indistinguishable from pooled LTER data, H=1 distinct from pooled LTER data
Bolded values are significantly different that pooled annual integrated NEE from LTER stations based on P-statistic

5.4 Predicting the Effects of Mowing

Post-mowing measurements of NEE were recorded at the primary test plots. These measurements were of short duration and limit the ability to predict the effects of mowing on NEE over short-time scales and/or on the net annual uptake of carbon. The EDM can be used to predict the effects of mowing on short- and long-term NEE. However, this requires the model to accurately simulate the response of vegetation to mowing, including reductions in daytime NEE due to loss of photosynthetic plant biomass, and nighttime NEE due to increased respiration as plants repair and rebuild their damaged and lost photosynthetic biomass.

Figure 5-10 illustrates annual NDVI profiles for Natural (Control), as well as the predicted effects of low, high and deferred mowing scenarios on NDVI (Section 3.3). Small differences in spring NDVI for the N Zone for the low- and high-mow scenarios are real as there is more vegetation cover in the M Zone than the N Zone.

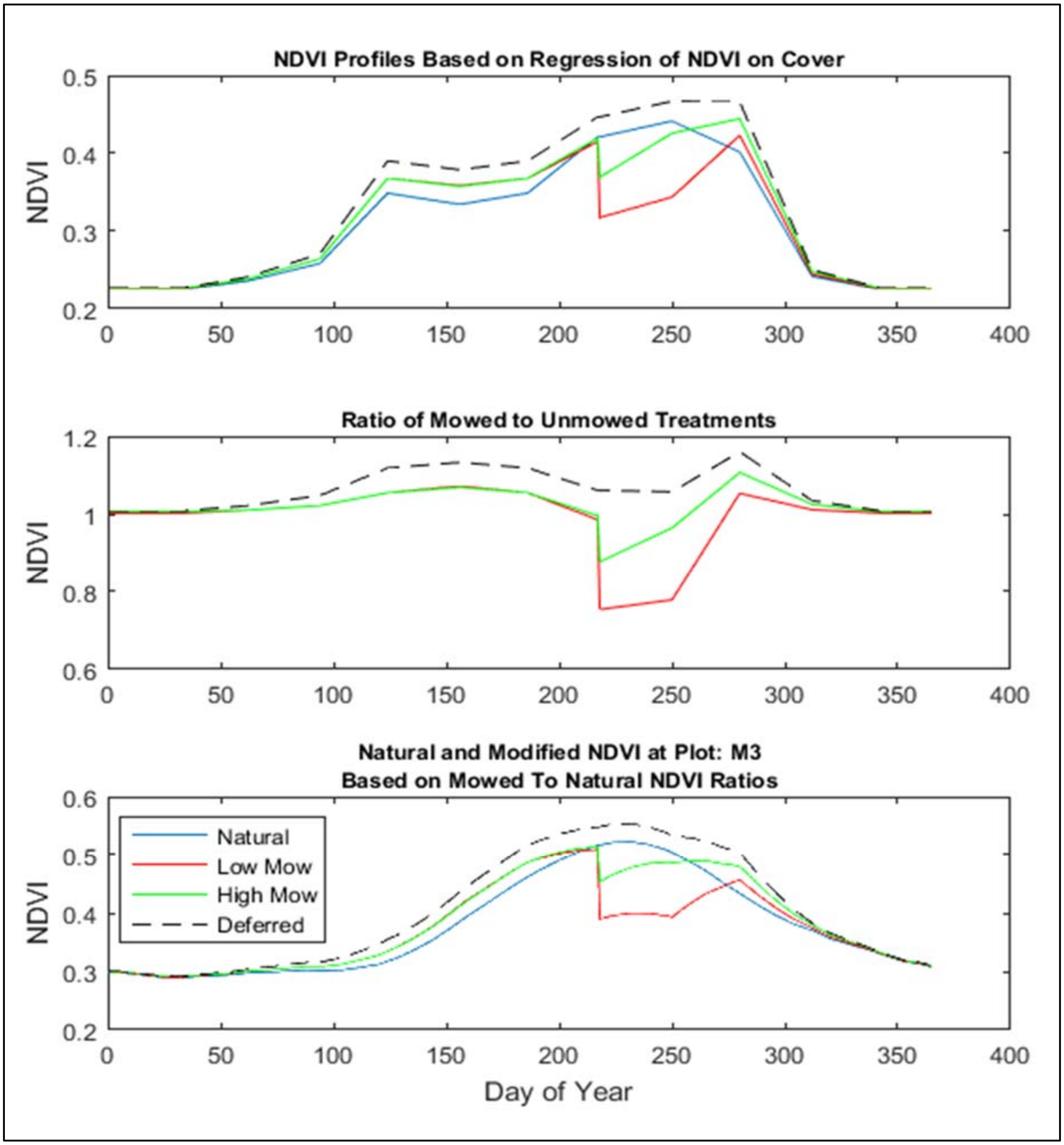
Figures 5-11 through 5-13 illustrate the effects of these treatment adjustments to NDVI on the EDM predictions for daily NEE for each of the three primary ROW test plots. Tables 5-6 and 5-7, above, include columns of the predicted annually integrated NEE for the low- and high-mowing scenarios, if these treatments were applied to each of the subplots, even though only subplots M1 (Low Mow) and M3 (High Mow) are currently managed using mowing.

At Prairie test plots 104-79 and 469-39, the EDM predicted that mowing would have negligible effects, or potentially a small increase in the total amount of carbon stored annual by each of the subplots. For example, under no mowing at test plot 104-79, the EDM predicted carbon uptake of -78.8 g-C/m^2; under low- and high-mowing, the EDM predicted -75.6 and -91.5 g-C/m^2 (Table 5-6). Similarly, at test plot 469-39, the unmowed M1 subplot was predicted to uptake -56.6 g-C/m^2, whereas under low- and high-mowing, the system was predicted to uptake -59.3 and -62.5 g-C/m^2, respectively (Table 5-6).

Mowing often results in greater net annual uptake of CO2 by the vegetation along the ROW as seen in the time series summarizing the predicted effects of mowing at test plots 104-79 and 469-39 (Figures 5-

11 and 5-12). In each case, mowing is simulated in the model by adjusting the NDVI values (Figure 5-10). While reduction in NDVI results in an immediate decrease in the magnitude of the daytime NEE (i.e., uptake of atmospheric CO_2), it also reduced the magnitude of nighttime NEE (i.e., release of CO_2 to the atmosphere).

Figure 5-10. Parameterization used to simulate the effects of mowing on NDVI



The discrete post-mowing measurements of NEE at test plots 104-79 and 469-39 (Figures 5-11 and 5-12, respectively) indicate that daytime NEE could become less negative and/or switch to being positive post low mowing. Thus, the model appeared to simulate daytime reductions in NEE well. However, nighttime flux measurements also indicated that plant respiration rates post- mowing were equivalent to, or higher than, respiration rates observed when test plots were not mowed. This is logical, since the plants were working to repair damaged tissues. How long these rates remain high couldn't be determined from the test plot observations, but other sources indicated a period of several weeks

(Detling et al. 1979). The EDM predictions at test plots 104-79 and 469-39 did not reflect the flux observations at the plot level after mowing. In other words, suppression of the NDVI post-mowing artificially indicated to the model that it was now in a different “season” with respect to the relationships established between observed NDVI and predicted NEE. Since the EDM response is tightly coupled to NDVI and changes in NDVI, it under-predicted daily nighttime NEE and artificially reduced (i.e., more negative) carbon uptake in 2014 under low- and high-mowing scenarios.

To the extent that suppressed daytime photosynthesis rates and nighttime respiration rates were greater after mowing, annual integrals of NEE should have been higher (i.e., less negative), indicating that the ROWs were less a sink than if there were no mowing. As indicated in Table 5-6, this was not well simulated by the current EDM.

The post-mowing data from Lower Montane test plot 555-12 offers an interesting comparison to the EDM predictions for the Prairie test plots. At test plot 555-12, the unmowed EDM predictions indicated that all subplots were net carbon sinks, and that subplot M1 sequestered approximately 259 g-C/m^2. Post low mowing, the EDM predicted sequestration of -230 g-C/m^2, an 11 percent decrease. Post high mowing, the EDM predicted only a 2.3 percent decrease (-254 g-C/m^2) in annual carbon storage. Given the number of uncertainties associated with the EDM, these differences are not likely significant.

However, analysis of the time series data indicated that, at test plot 555-12, nighttime respiration rates were not suppressed after adjusting NDVI values, only daytime NEE (Figure 5-13). Post-mowing, the model didn’t predict an increase in respiration rates, nor was it really expected. Why EDM predictions at test plot 555-12 did not result in suppressed nighttime NEE (as measured at 104-79 and 469-398) is probably a result of the wetter climate at the test plot and the inability of the model to account for the more dynamic range of CO_2 flux observed at the site.

Figure 5-11. EDM-predicted NEE in 2014, with and without mowing for Low-Mow scenario, at test plot 104-79

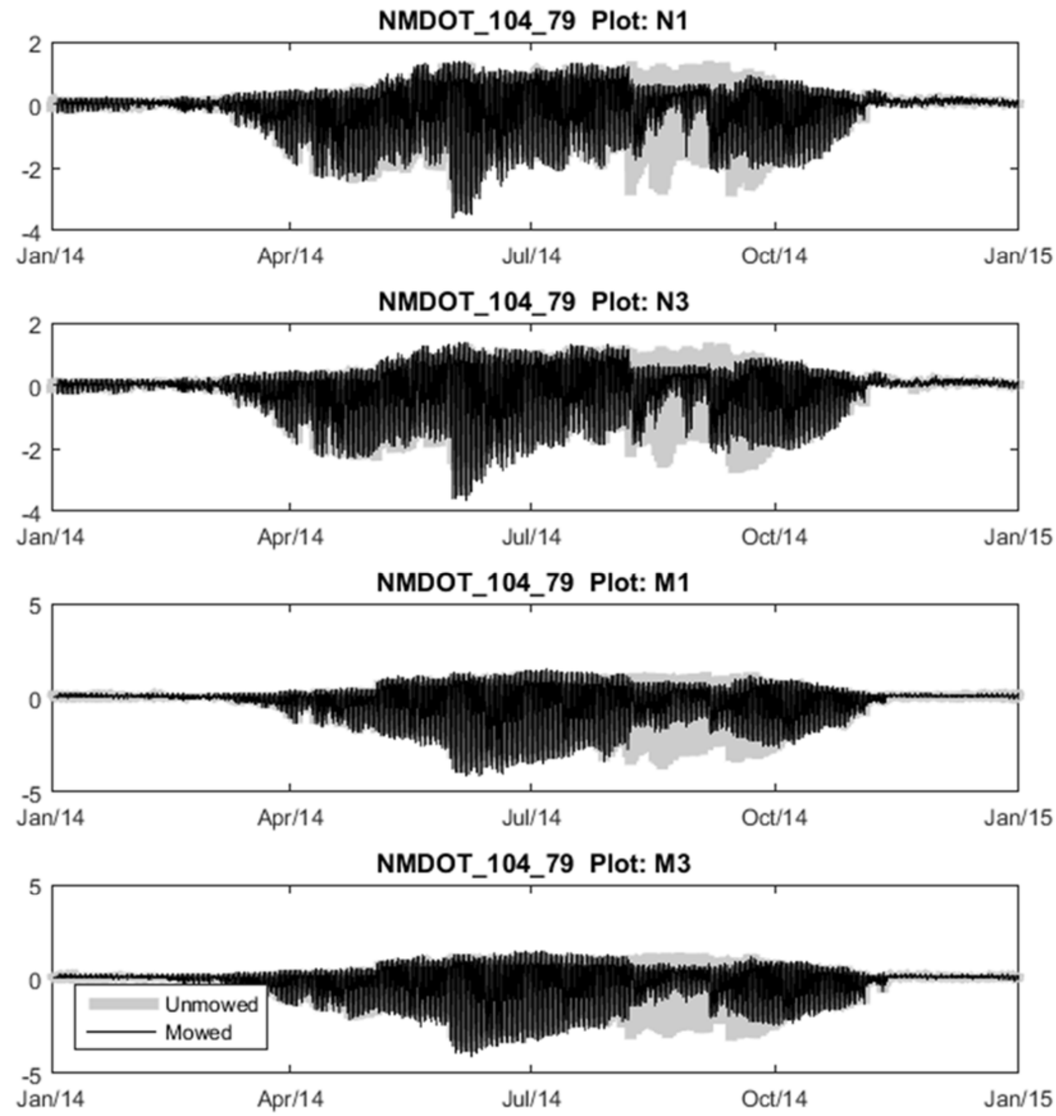


Figure 5-12. EDM-predicted NEE in 2014, with and without mowing for Low Mow scenario, at test plot 469-39

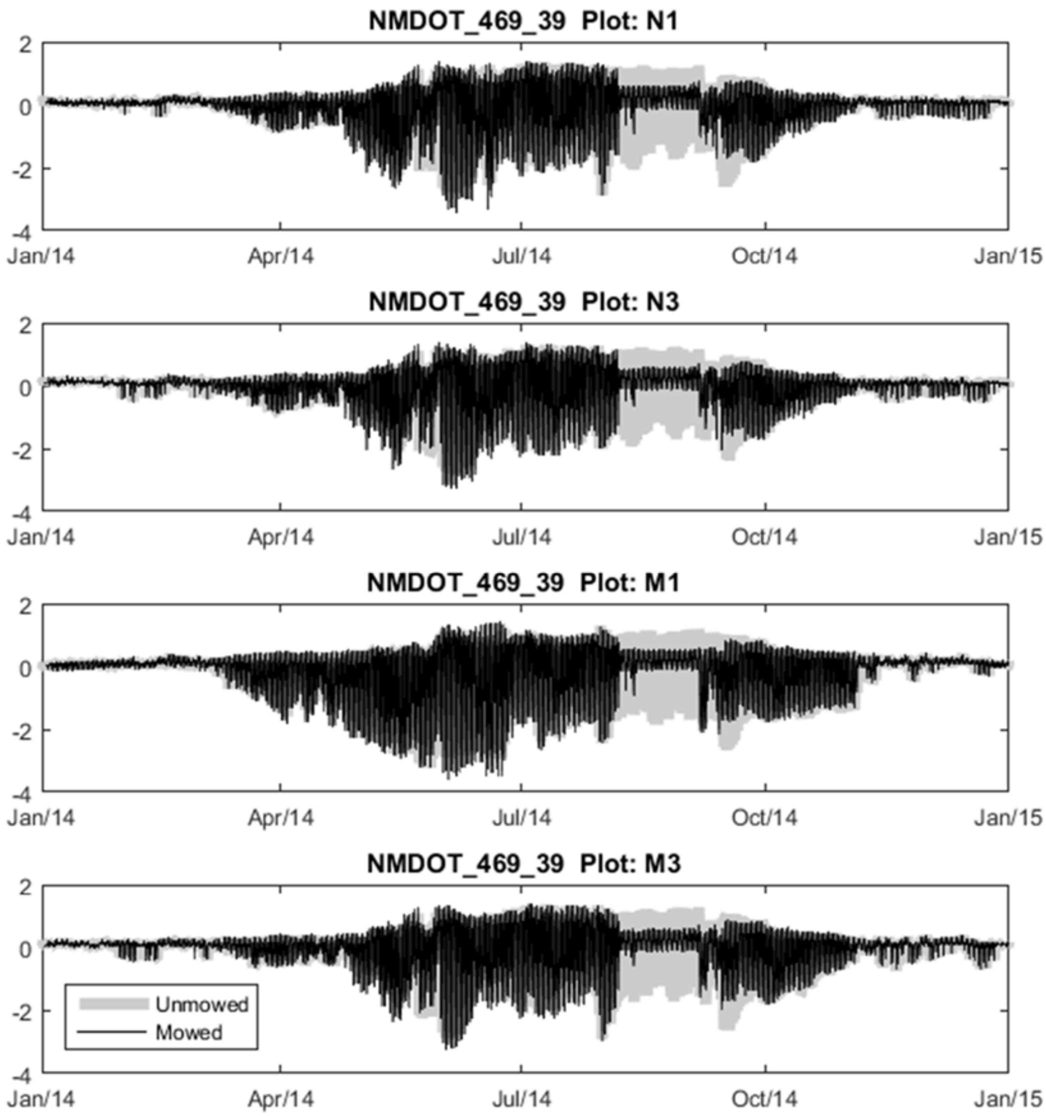
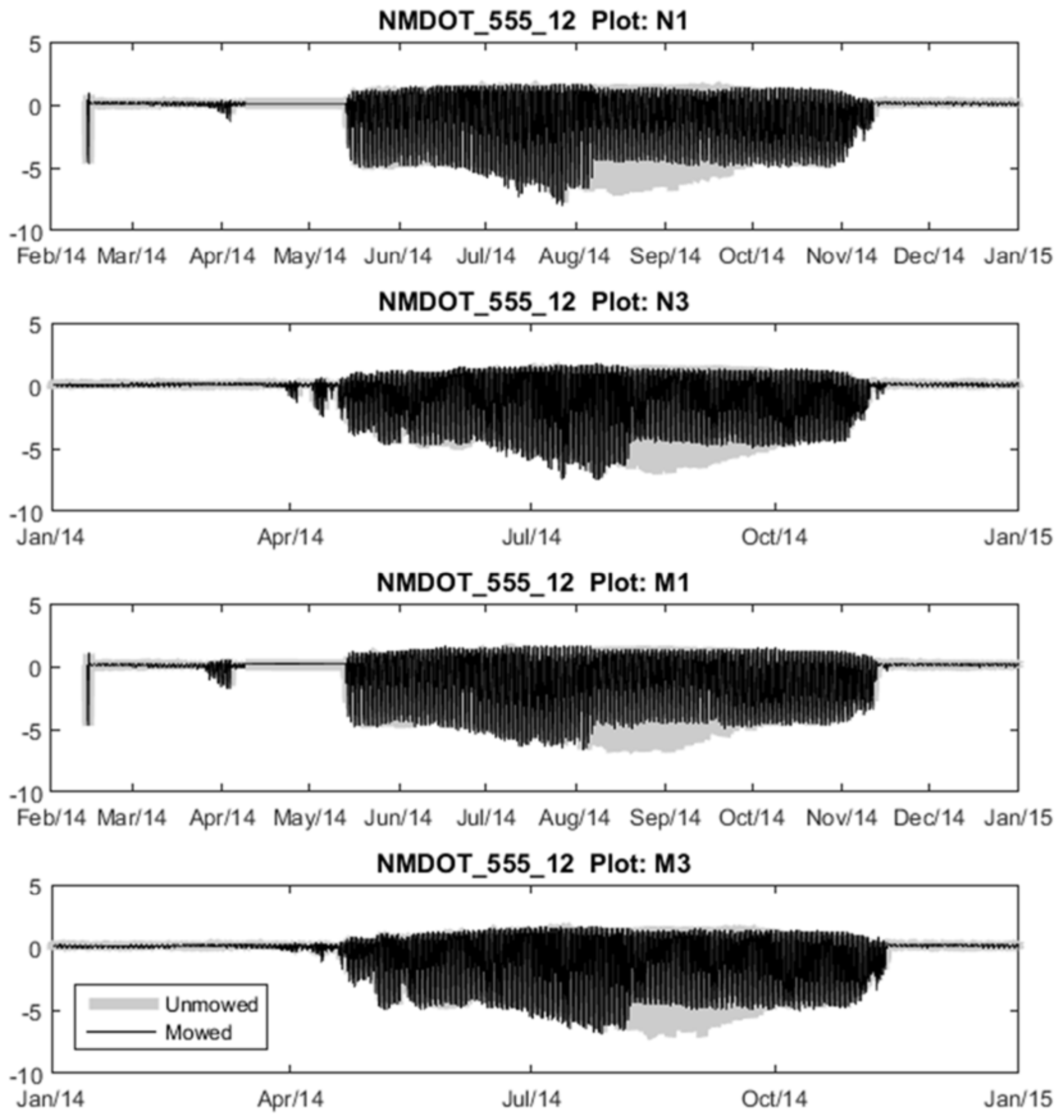


Figure 5-13. EDM-predicted NEE in 2014, with and without mowing for Low Mow scenario, at test plot 555-12



5.5 Modeling Discussion

The EDM predictions are encouraging, but do not provide conclusive evidence that the effects of mowing on annual carbon budgets can be accurately and reliably predicted with the current model. Trends are certainly evident and, in general, the EDM predictions are better correlated with the discrete subplot-level measurements recorded at each test plot. One way to potentially increase the accuracy of the predictions would be to model separately gross primary productivity (GPP) and ecosystem respiration (R_e), and then combine them to produce an NEE estimate. This may be particularly useful when trying to estimate the effects of mowing, since R_e and GPP would be predicted to have very different responses to mowing.

Even if robust predictions of annual carbon uptake could be generated and ROW management practices (treatments) could be modified to optimized carbon uptake, the overall magnitude of the predicted changes for ROWs in New Mexico may be small and vary from site to site (Table 5-8). For example, the difference in carbon uptake between the High Mow and Low Mow subplots was approximately less than 1 percent (~19 g-C/m^2) at test plot 555-12 to 17 percent (~20 g-C/m^2) at test plot 120-31. Similarly, the average predicted difference in carbon uptake between the High Mow and Low Mow subplots was 5 percent (~4 g-C/m^2) and 4 percent (~10 g-C/m^2) at Prairie and Lower Montane test plots respectively (Figure 5-14).

The predicted average annual carbon sequestration (~-70 g-C/m^2/yr for Prairie and ~- 285 g-C/m^2/yr for Lower Montane) are consistent with the annual NEE rates Gilmanov and others (2010) determined in their global survey of extensively managed grasslands (255 ± 521 g-C/m^2/yr). On a carbon dioxide equivalent basis, predicted results for 2014 (high-mow prairie = 1.1 t CO_2e/a/yr; high-mow montane = 4.3 t CO_2e/a/yr; natural, prairie = 0.9 t CO_2e/a/yr; natural, montane = 4.0 t CO_2e/a/yr) are higher than Zone F (0.2 t/acre) and G (0.4 t/acre) for the CCX grassland protocol (Brown et al. 2009).

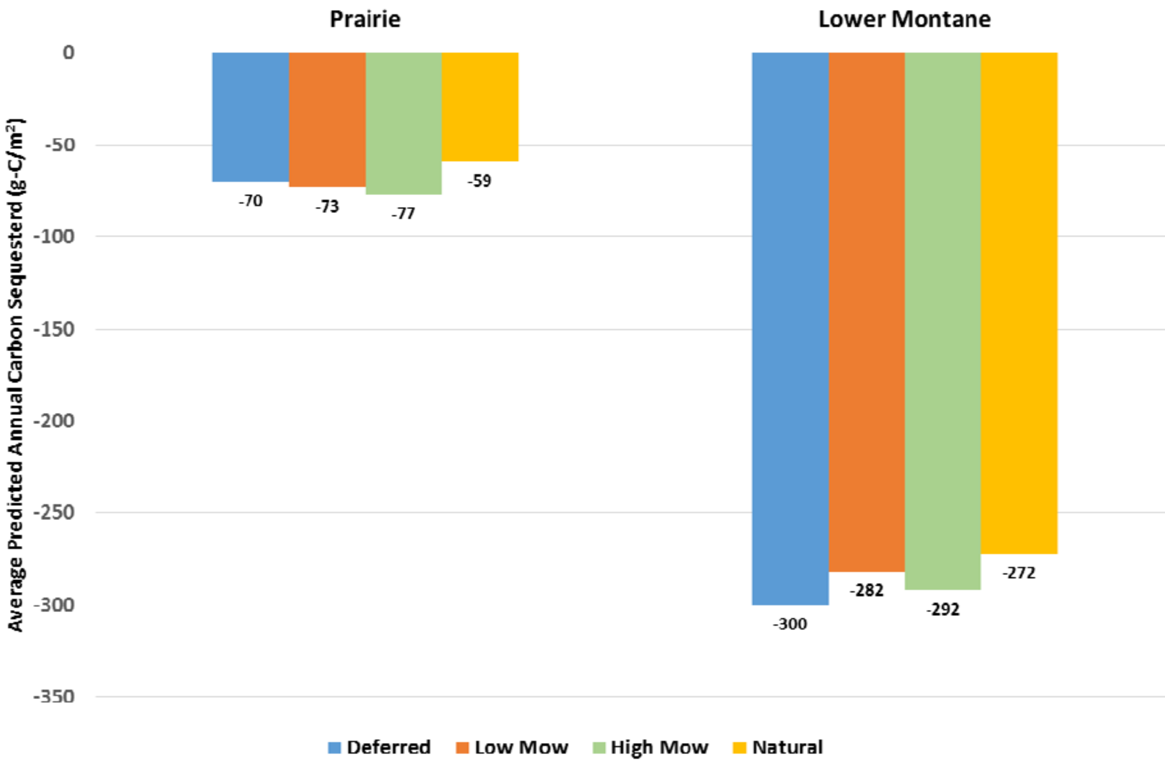
Annual NEE measured the LTER stations (Kendall, Audubon, and Sevilleta) showed significant variation about a mean of 4 g-C/m^2, ranging from -135 to 268 g-C/m^2 on an annual basis (Table 5-5). This natural variability in carbon uptake in response to periods of drought or wetness include years when the semi-arid grassland ecosystem is a GHG source emitting CO_2 to the atmosphere and other years when the ecosystem is a sink and sequestering CO_2. The climate-driven interannual variation is substantial and could mask any predicted NEE responses in the ROW to different mowing regimes.

Table 5-8. Summary of EDM predicted 2014 annual NEE (g-C/m^2/yr) for mowing and natural control scenarios at ROW test plots

Test Plot	Managed			Natural (Control)
	Deferred Mow	Low Mow	High Mow	
Prairie				
104-79	**-79**	-76	**-90**	-45
120-31	**-122**	-114	**-134**	-123
469-02	-23	-43	-24	-11
469-39	-15	-59	-22	-21
472-07	**-111**	-74	**-115**	-94
Lower Montane				
21-15	**-271**	-250	**-276**	-249
537-43	-**374**	-365	-351	-319
555-12	**-255**	-232	**-251**	-250

Note: Bolded NEE values for deferred and High Mow treatments indicate greater annual sequestration compared to Low Mow

Figure 5-14. Average NEE predicted from EDM in Prairie and Lower Montane for mowing scenarios and Natural (Control)



In a future scenario where NDVI or vegetation cover is measured more frequently at the test plot level, the effects of mowing on NEE could be measured and these data integrated into the EDM. For now, the estimate of the response of NDVI to mowing is needed, to test the model's ability to predict changes to NEE as a result of mowing. This could be accomplished by adjusting the NDVI values input into the model, reducing NDVI consistently with other studies that have parameterized the response of NDVI to changes in vegetation cover and in particular capture the full dynamic range of the CO_2 fluxes observed at the test plots.

6 NMDOT HIGHWAY ROW VEGETATION OFFSET PROTOCOL FRAMEWORK AND DEVELOPMENT

Sections 1 through 5 of this report described the method of SOC estimation and the results of the proof-of-concept for the NMDOT ROW vegetation study. This section describes the requirements for a carbon offset protocol that would be suitable for quantifying, monitoring, and verifying a highway ROW's increased carbon uptake that would generate offset credits for sale into the North American voluntary offset market. The proposed protocol should be consistent with the expectations and requirements of a major North American voluntary offset program to quantify, monitor, and verify the atmospheric benefit. To generate program-recognized offsets based on changing the roadside vegetation management practices in highway ROWs (the project), the project would have to comply with the quantification, monitoring, and verification rules of an offset program authority (OPA; the program).

6.1 Background

6.1.1 Carbon Offset Overview

An "offset" is a recognized, project-based reduction of GHG emissions (reduction) or enhancement of CO_2 removals (removal) from the atmosphere. Many projects and their activities can lead to a-reduction or removal, but they do not automatically become offsets. "Recognized," in this instance, means that a reduction or removal- project was in full compliance with the offset project development rules of an OPA.[2]

The recognition of an OPA is sought by offset project developers as the compliance, verification, and registration processes of the OPA provide assurance to prospective buyers that the offset represents an actual, conservatively-quantified, atmospheric benefit. This assurance is the foundation for the over-the-counter and exchange-based financial markets focused on buying and selling offset credits. The OPA provides the standards for delivery of offsets that create actual atmospheric benefit. The OPA also provides the platforms for tracking and registering offsets to: 1) prevent double counting, 2) clearly demonstrate ownership of offsets, and 3) verify retirement of offsets. Compliance with the quantification, monitoring, and verification requirements of the OPA is a fundamental step towards establishing the financial value of carbon offsets, as the financial value is largely based on the recognized and generic atmospheric benefit of the offset. The benefit is generic in that all recognized offsets provide the same atmospheric benefit of a 1 tonne of either CO_2 equivalent (CO_2e) emission reduction or CO_2e enhanced removal.

6.1.2 Offset Protocol

An offset protocol is a detailed set of requirements that prescribes how to quantify, monitor, and verify reductions or removals for a particular type of offset project.[3] A protocol will likely include requirements for (at least): 1) a selection of sources, sinks, and reservoirs (SSRs); 2) selection of a baseline scenario; 3) quantification of reductions or removals; and 4) data management, monitoring,

[2] An offset is distinct from an emissions allowance (or a permit). Under a cap-and-trade program, governments issue allowances and regulated emitters must "retire," or give back to the government, one allowance for every tonne of GHG emitted. The number of allowances issued thus creates a cap on emissions. On the other hand, offsets are voluntarily created from a project's emission sources or sinks that were not regulated through a cap-and trade-program. The basic idea behind the offset mechanism does not change when it is integrated with, or linked to, an emission trading scheme; for example, the offsets were created by reducing emissions that were not regulated, and applied by regulated emitters to offset some or all of their regulated emissions. Offsets and allowances are similar, in that they are measured on a generic 1 tonne of CO_2e.

[3] In some offset programs, the term "methodology" rather than protocol is used, but the two terms have the same basic meaning.

verification, and reporting. A project developer will select an existing protocol, adapt an existing protocol, or develop a new one in the planning process.

Each major offset program has a comprehensive way of assessing whether or not a protocol is suitable for a proposed project. Offset programs fall into two broad categories, compliance system programs and voluntary system programs.

6.1.3 Compliance and Voluntary Offset Systems

The compliance systems allow regulated GHG-emitters to apply offsets from qualifying projects to meet their GHG-emission-compliance obligations. Offsets are an alternative to internal emission reductions and purchased allowances to meet these compliance requirements. In most cases, these GHG sources are regulated under cap-and-trade emission trading systems. The U.S. has two such systems, the California Greenhouse Gas Cap-and-Trade Program and the Regional Greenhouse Gas Initiative (RGGI). In Canada, three GHG emission-regulation systems provide for use of offsets for compliance: British Columbia (BC's) GHG Reductions Target Act system (which is focused on regulating provincial government's GHG emissions), Alberta's Specified Gas Emitters System, and Quebec's Cap-and-Trade System for Emission Allowances. The Ontario government is developing a greenhouse cap-and-trade system with a proposed implementation date of January 2017.

California, BC, Ontario, and Quebec are part of the Western Climate Initiative (WCI), which released its design recommendations for a regional emission trading system in September 2008. The design of the California cap-and-trade system allows entities covered by its cap to satisfy up to 8 percent of their regulatory obligations by surrendering carbon offset credits generated by offset projects that use an Air Resources Board (ARB) "compliance offset protocol." The Quebec system has a similar provision for offsets, as will the Ontario system.

Voluntary systems include a wide range of approaches to facilitate the use of offsets by private companies, public organizations, and individuals that want to achieve voluntarily-assumed GHG emissions objectives. Voluntary system offsets that are fully recognized and issued by a voluntary program are known by the generic term, Verified or Voluntary Emissions Reductions (VERs), but some offset programs, such as the Climate Action Reserve (CAR), use their own terms, like Climate Reserve Tonne (CRT) in the case of CAR.

There is a proliferation of standards, protocols, and program rules across the voluntary market, which reflects the differing objectives of the backers of the various projects, but consensus in North America on key attributes for offsets is progressing as compliance markets take hold, especially the WCI-related cap-and-trade programs, and as certain voluntary offset programs gain the largest offset market sale shares.

An international system of standards has evolved to improve the legitimacy, transparency, and fungibility within and across all offset programs, systems, and markets. The International Organization for Standardization (ISO) released its 14064 standard in 2006, and the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) issued its GHG Protocol for Project Accounting in December 2005. It provides common definitions, accounting frameworks, and quantification options that can be adopted or adapted by individual offset projects, programs, or standards. To address transparency and rigor in offset standards, a group of non-profit organizations (NPOs) launched the Voluntary Carbon Standard (VCS) in late 2007. It is a voluntary offset standard and has rapidly gained market share since its introduction.

The following attributes are generally viewed as minimum parameters for ensuring volunteer offset credibility amongst buyers of offsets (BSR 2007):

- Additional: Reductions are "surplus" offsets that would not have occurred under "business as usual" (baseline scenario) and would not cause leakage or additional emissions elsewhere.

- Real: Offsets are from tangible physical projects with evidence that they have or will imminently reduce or remove.
- Measurable: Reductions are objectively quantifiable by peer-review within acceptable, standard, margins of error.
- Permanent: Reduction streams are unlikely to be reversed, and have safeguards to ensure that reversals will be immediately replaced or compensated.
- Verifiable: Performance is monitored by an independent third-party verifier with appropriate local and sector expertise.
- Enforceable: Offsets are backed by legal instruments that define offsets' creation, provide for transparency, and ensure exclusive ownership.
- Synchronous: Offsets are matched to emission flow periods with rigorous and conservative accounting that designates assessment boundaries and baseline calculations.

6.1.4 Three Major North American Voluntary Offset Programs

The three major North American voluntary offset system programs are:

- Climate Action Reserve (CAR), a U.S. voluntary offset program operated by a California-based NPO that has developed several offset project protocols that are widely used across the U.S. CAR has also started developing protocols for Mexico-based offset projects and has had discussions with parties in Canada about developing protocols that could be used there.
- Verified Carbon Standard (VCS) was developed by a Washington, DC, NPO. This program has gained broad support from voluntary offset project developers and its protocols are being used for terrestrial carbon projects around the world.
- American Carbon Registry (ACR) was founded in 1996 by Winrock, a Washington, DC, NPO, and was the first private voluntary offset program in the world.

CAR, VCS, and ACR are the only voluntary offset programs that have been approved as registries by the ARB, which operates the California cap-and-trade system. The California GHG-emissions-regulated system was a primary purchase motivator and price influencer in the North American voluntary offset marketplace. A survey of 2009 purchases showed that 74 percent of offset purchases developed to meet CAR requirements came from entities making pre-compliance buys, i.e., they bought offsets that they thought would be accepted into U.S. compliance systems at a price they thought would be lower than when the compliance system is implemented. The other 26 percent of CAR program offsets was purchased for strictly voluntary purposes, such as a corporate social responsibility (CSR) commitment. An estimated 42 percent of VCS offset purchases were for pre-compliance and 25 percent of ACR purchases (Point Carbon 2010).

The position of these three voluntary offset programs has been reinforced by their direct relationship to the California cap-and-trade system. ARB's designation of them as Offset Project Registries helps ARB administer their compliance program. CAR, VCS, and ACR are the only Offset Project Registries outside of ARB. The Offset Project Registries entities help facilitate listing offset projects developed using the Compliance Offset Protocols, and the reporting, verification, and issuance of the Registry Offset Credits. These Registry Offset Credits can ultimately be converted into ARB's Offset Credits, and used by regulated California entities to meet their compliance obligations. Certain existing offset projects can also be used within the early action element of the regulated California system. ARB has approved use of offset credits from certain offset projects developed through either CAR, VCS, or ACR for conversion into ARB offset credits for use in ARB's Early Action Offset Program.

The formal association that these three voluntary offset programs have with the California GHG-emissions-regulated system is reflected in the prices of their offset credits, and these factors have combined to reinforce their primacy amongst developers of voluntary offset projects in North America.

Offset prices vary based on the broad offset market category (compliance versus voluntary), project type (e.g., fuel switching versus forestry projects), location (political risk issues), market demand (better economic conditions lead to higher GHG emissions, lead to need for more offsets) and the stringency of the offset program requirements (CAR offsets priced higher than CCX offsets).

Offset prices in the compliance market are driven primarily by the supply of, and demand for, offsets and allowances. As a consequence, compliance market offsets attract much higher prices than do voluntary market offsets.

6.1.5 Overview of Terrestrial Carbon Offset Projects

The offset project (or GHG assessment) boundary is delineated by SSRs that would be affected by an offset project and ultimately controlled by an offset project operator. Only direct GHG reductions and removals that occur within the offset project boundary are eligible for crediting with an offset. In general, North American protocols adhere to the principles and structure in the ISO 14064-2 protocol standard for identifying and classifying SSRs that compose the offset project boundary.

Vegetation (e.g., prairie grasslands) SOC and forests are considered to be important reservoirs and act as GHG sinks when they are not subject to major reversals of carbon storage. For example, conversion of croplands to grasslands can result in both net emissions (from sources) or net removals or sequestration of CO_2 in biomass (below-ground and aboveground), and soil carbon pools (or reservoirs) (ACR 2013). When carbon content reaches a steady-state in a given pool, and this steady-state is maintained on the long term, it is considered a reservoir and its carbon is considered to be sequestered "permanently," although subject to reversal from human sources (e.g., tilling the soil) or natural disturbance (e.g., a wildfire).

Removal (sequestration) offset projects are a focus of offset project developers because emissions associated with them are unlikely to be capped within a GHG-emission-regulatory system. For example, under ARB's cap-and-trade program, forest offset projects are the majority (75 percent) of compliance offset credits and the largest number of early action offset credits. At this time, early action credits are the largest share (46 percent) of the ARB offset credits issued, but this share will diminish as the deadline for the operation of early action projects (under early action quantification methods) was December 31, 2014. The amount of offset credits by project type that ARB has issued as of February 25, 2016, is shown in Table 6-1.

Table 6-1. ARB Offset Credits

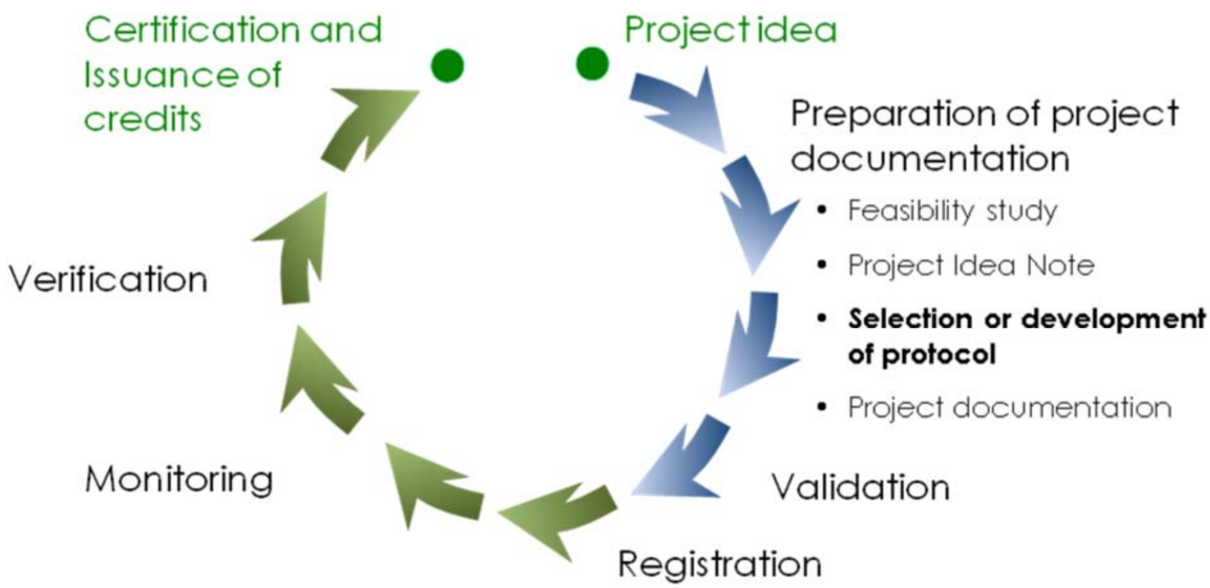
Offset Project Type	Compliance Offsets	Early Action Offsets
Ozone Destruction	4,634,965	6,261,710
Livestock	528,351	1,487,497
U.S. Forest	14,701,828	8,144,995
Mine Methane Capture	280,667	2,321,547
Total	19,865,144	18,215,749

Source: California Air Resources Board

6.2 Carbon Offset Project Development Process

In general, there are five key stages in the offset project development process, and key elements of each stage are guided by the contents of an offset protocol. An overview of the project development process is shown in Figure 6-1.

Figure 6-1. Overview of offset project development process



6.2.1 Stage No. 1 – Documentation

A feasibility study is recommended as best practice guidance. It should include the technical, operational, and financial feasibility considerations. The feasibility study would be an internal document that a project developer can choose to share with others at his or her discretion.

An important technical step during this stage is to identify suitable quantification, monitoring, and verification protocols. If no protocol is available for the type of offset project being considered, the project developer needs to draft a new protocol or adapt a protocol from one of the many that have been approved for other offset projects. The protocol will have to meet the requirements of the selected OPA.

The project plan is a detailed road map for how the offset project will be conducted and the estimated reduction or removal that will be realized. The major North American voluntary offset programs, and most compliance systems, require a project plan to be submitted as part of their compliance documentation process. Typically, an offset project plan's main elements are:

- Technical description of the project;
- Identification and justification of protocol(s);
- Potential baseline scenarios and the selected baseline scenario and justification of reasonableness of its underlying assumptions;
- Assertion and associated evidence that the selected baseline scenario will result in a conservative estimate of the project's reduction or removal;
- Assertion and associated evidence that the offset incentive overcomes or partially overcomes certain obstacles to conducting the project;

- Selection of SSRs and an assertion that they result in an accurate and conservative estimate of the project's reduction or removal;
- Quantified project reduction or removal and associated calculations;
- Monitoring and quality assurance/quality control plan; and
- A risk-mitigation and contingency plan (for removal projects).

6.2.2 Stage No. 2 – Validation

Validation is a form of non-financial assurance. The offset project developer should hire a firm with specialized knowledge of and expertise in GHG-emission quantification and quality assurance as a third-party validator. The validator will assess the project plan in relation to the requirements of the offset protocol and the OPA's other standards. In particular, the validator will judge whether or not the plan contains material errors, omissions, or misrepresentations. The third-party validator will also determine if the selected protocol is suitable for the offset project under consideration, and consistent with the requirements of the OPA. A project developer needs a statement of assurance from the validator to move onto subsequent stages.

6.2.3 Stage No. 3 – Monitoring and Project Report

In most situations, a project will operate and be monitored for 1 or more years before a project report is researched and written. It is the project developer's responsibility to prepare the project report, which will contain detailed information and data about the project and its performance, including the project's emission reduction or removal enhancement.

Data for this report will likely have been documented during the monitoring of relevant sources of emissions and removals over the initial year of operation. The project developer is responsible for monitoring and quantifying the project's reduction or removal in accordance with the project plan and the selected protocol.

6.2.4 Stage No. 4 – Verification

The project developer submit the project verification report to a third-party verification firm that the developer hires. Verification is a recurrent step that is conducted at prescribed intervals. The intervals between project verification reports will be specified in either the selected protocol or in the OPA's standards. For reduction projects, the usual practice is an annual verification report. For terrestrial carbon sequestration offset projects, there is typically longer intervals between verification reports.

The ISO 14065 standard precludes the use of the same firm for the validator's statement of assurance and verification exercises. The verifier might only issue a statement of assurance when it is satisfied that the assertions in the project verification report are materially correct and a fair and reasonable representation of the reduction or removal, as set out in the project plan, and there have been no material changes in the implemented project compared to the validated project plan.

6.2.5 Stage No. 5 – Certification and Issuance of Offset Credits

Offset recognition is an official status accompanied by an official document or certificate of such by the OPA. Typically recognition results from meeting two conditions: verification of the project report, and of the project not receiving a previous recognition as an offset in another program. The project developer will have shared information with the OPA through the project development cycle, but the recognized offset will not occur until the project report is verified in accordance with the OPA's requirements.

6.3 Highway ROW Vegetation Project Offset Protocol Framework

The following offset protocol framework identifies important protocol elements specific to the North American offset program that will need to be addressed: the current status of the potential NMDOT highway ROW carbon sequestration research project in relation to protocol requirements, and the next steps for the offset project, or options and solutions for addressing project gaps.

This section has been developed according to the best available practices and draws from the knowledge and experience of people who have been involved in developing grasslands and soil carbon offset protocols and projects. Along with using the standards and best practices in the current small suite of terrestrial carbon protocols, there are standards, rules, and best practices from other offset systems and project types that could add information to NMDOT's highway ROW vegetation management practices.

Offset protocols are detailed and often complex documents containing mathematical equations for project reductions and removals by pools and sources. They are not intended as a general summary of a quantification approach. The target audience for a protocol is potential project developers who should be familiar with the format of offset protocols of the OPA.

Below is a list of important elements that are either critical parts of, or directly related to, terrestrial carbon offset protocols.

- Applicability: Activities, project areas, and jurisdictions that are eligible for inclusion in the offset project.
- Baselines: How to develop appropriate baseline scenarios to demonstrate incrementality.
- Quantification: How to accurately and most economically measure baseline data and project SSRs.
- Permanence: Options for providing insurance and assurance.
- Monitoring and Verification: Who will conduct third-party verification and how, and what are the costs for potential project developers/proponents.[4]
- Ownership and crediting: How to clearly define claims of ownership of removal enhancement and ownership of the associated offset.

A key element in an offset protocol for a terrestrial carbon offset project is a requirement to estimate potential "leakage" and quantify a reduction in offset credits to accommodate the estimated leakage. Leakage is when an affected SSR is influenced by the project activity through changes in either market demand or supply of products or services associated with the project.

Affected SSRs refer to an unintended change in GHG emissions or removals elsewhere resulting from the offset project such that the overall net GHG emissions associated with the project are diminished or fully negated. An example from a sequestration offset project is when a company lowers or eliminates its timber harvest as a result of a forest management offset project and timber is harvested within the same region to obviously make up for the supply reduction of the sequestration project. The increased harvest in another part of the region is an "affected source."[5]

[4]In some offset programs, verification and crediting are not elements of protocols, they are handled through a program standard, but they are included here as success of their application and protocols are linked.

[5] Leakage can also be present with emissions reduction focused offset project. For example, a company that replaces a fossil-fuel burning boiler with a biomass-fueled boiler and moves the old boiler to another of its operations would negate the GHG-emission reduction value of the biomass fueled boiler. The GHG emissions associated with the moved fossil-fuel burning boiler are an "affected source." Similarly, a project that plans to use biomass for fuel would not produce a net reduction in emissions if the biomass was previously being used by another firm that has since switched to fossil fuels.

Leakage is not expected for a highway ROW vegetation offset project as the baseline scenario of sustaining vegetation on the sides of highways is not altered through the proposed offset project.

6.3.1 Applicability

This section of a protocol focuses solely on clearly identifying the project types for which GHG quantification methods have been developed and presented elsewhere in the protocol, and thus the project types to which the protocol applies. These eligibility requirements are designed to be as broad and non-restrictive as possible, while still ensuring that projects with relevant aspects not covered by the provided quantification methods are clearly identified as being not eligible to use this version of the protocol. Such ineligible project types could become eligible later, through revision of protocol methods. For example, applicability conditions for additional roadside vegetation management practices could be added to the protocol later. Some potential roadside vegetation management practices that could be considered for later inclusion in this protocol are described in Section 6.5.8. If they were added, then other parts of the protocol would likely have to be modified as well to capture the sinks and sources within the new offset project assessment boundaries.

Typically, a protocol applicability section will include a project definition and a few eligibility conditions that set boundaries around the project type, including the project area and the eligible geographic areas or government jurisdictions.

<u>Project Situation</u>

The NMDOT ROW carbon sequestration project underlies the basis for establishing the project definition. The focus of the project's Phase 2 study became the change in roadside vegetation mowing practices. This change in management activity would be mowing to maintain roadside vegetation at a height of 10 to 12 inches rather than 6 inches. The basis of the offset project is that the activity of increasing the mower blade height results in less defoliation. As documented in Section 1.2.1, defoliation can reduce SOC through the following processes:

- Ceases/slows root growth
- Decreases photosynthesis
- Reduces root mass in soil

Therefore, it follows that a reduction in defoliation would increase SOC.

Understanding of the applicability condition for the management activity contemplated by the offset project is relatively complete as the focus is on a single management activity, the increased height of the mower blade for roadside vegetation.

Although the mowing management practice of this offset project could be done in states other than New Mexico, the unavailability of a biogeochemical or an empirical dynamic model (EDM) that is calibrated and validated in relation to the atmospheric effect of less defoliation on roadside vegetation across other microclimates and geographic areas is a barrier to broader application of the proposed protocol at this juncture.

<u>Protocol Direction</u>

For this protocol, the offset project would be defined as the prevention of emissions of GHGs to the atmosphere through conserving the aboveground and below-ground carbon stocks of roadside vegetation and avoiding non-vegetation maintenance activities on the eligible project area.

In terms of the project's geophysical area, the highway ROW that includes the roadside area is readily defined in terms of legal parcels of land, but the area being mowed is not readily defined in legal terms. However, offset project boundaries do not need to be coincident with parcel boundaries (i.e. the project area may contain a portion of a parcel) and a geographical information system file (GIS shapefile) could define the project area. The project area does not have to be contiguous, there can be areas of roadside exempted from the project for various reasons. Therefore, a project area could be based on the included roadside area of a highway maintenance district, of which there are six in New Mexico, and defined as the roadside area dominated by native or introduced grass species.

The protocol's applicability section would likely include a statement that synthetic fertilizer would not be applied in the project area (to avoid N_2O emissions), and that other management practices than mowing vegetation could also occur on the project area, but that the incidental management practices would not threaten the integrity of the soil carbon stocks and is otherwise compatible with the maintenance of roadside vegetation.

The applicability section would also state the jurisdictional applicability of recognized offset projects (and their offset project boundary) under this protocol. Although the current study focuses on New Mexico, the protocol could use the U.S. as the applicable jurisdictional area.

6.3.2 Offset Project GHG Assessment Boundary

The offset project GHG assessment boundary delineates the GHG SSRs that will be assessed to determine the net change in emissions. The GHG assessment boundary is not the same as an offset project's physical boundary, rather it encompasses all SSRs, regardless of where or who controls or owns them, that could be significantly affected by a project activity.

The validator of a project plan will assess the reasonableness of the project developer's selection of SSRs to affirm that the estimated project reduction or removal:

- is an accurate and conservative estimate of the reduction and/or removal;
- are clearly owned by the project developer;
- will be achieved during the validation period;
- will be achieved from controlled SSRs within the project offset boundary, but includes any increases in emissions or reductions in removals (as compared to the baseline scenario) from non-controlled SSRs

High-quality protocols include specific direction on identification and selection of SSRs. Identifying and selecting relevant SSRs is a two-step process: 1) identify baseline scenario and project SSRs, and 2) select relevant baseline scenarios and project SSRs for monitoring or estimation from the group of identified SSRs.

The ISO 14064 standard recommends using a systems approach to determine SSRs attributable to a project. This entails examining SSRs during the project's life cycle, i.e. from "cradle-to-grave." However, as a life cycle assessment of the project may result in a very large number of SSRs, the protocol writer applies criteria, such as control, ownership, and significance (i.e. materiality), to select the "relevant" SSRs for the project's reduction and removal quantification. In addition, monitoring or estimation costs can be quite high for some SSRs, so the trade-off between the cost of monitoring or estimating minor SSR emissions must be weighed against the implications for quantification credibility of excluding them. The ISO 14064-2 standard neither specifies inclusion of certain SSRs, nor sets out criteria for selecting the ones that should/must be quantified. It is up to the protocol writer to use procedures and criteria for identifying SSRs and selecting the ones relevant for quantification.

The following information is usually identified for each SSR:

- A description of the SSR;
- Whether the SSR is associated with the baseline scenario, project activity, or both;
- The gases associated with each source (e.g. CO_2 , CH_4, N_2O);
- The method used to quantify each source;

- A determination whether a particular SSR is included in the GHG assessment boundary;
- Justification/explanation for the inclusion or exclusion of an SSR from the GHG assessment boundary.

Generally offset programs require that all significant changes in SSRs associated with project activities be included in the GHG calculations. Some programs (such as CAR) defined what is considered to be 'significant.' However, in general, relevant SSRs can only be excluded from the project's GHG assessment boundary if:

- The project is likely to reduce GHG emissions; therefore, the exclusion from the assessment boundary would be conservative (i.e., would result in a lower number of GHG reductions); or
- The total increase in GHG emissions from all excluded SSRs is likely to be less than five percent of total GHG reductions achieved by a project (CAR 2011).

Project Situation
A preliminary GHG assessment boundary and list of identified SSRs for the NMDOT ROW project is shown in Figure 6-2. The figure is based on the assumption that the change in mowing blade height is the sole management practice that is conducted that results in the generation of offsets.

Figure 6-2. Offset GHG assessment boundary for NMDOT ROW Vegetation project

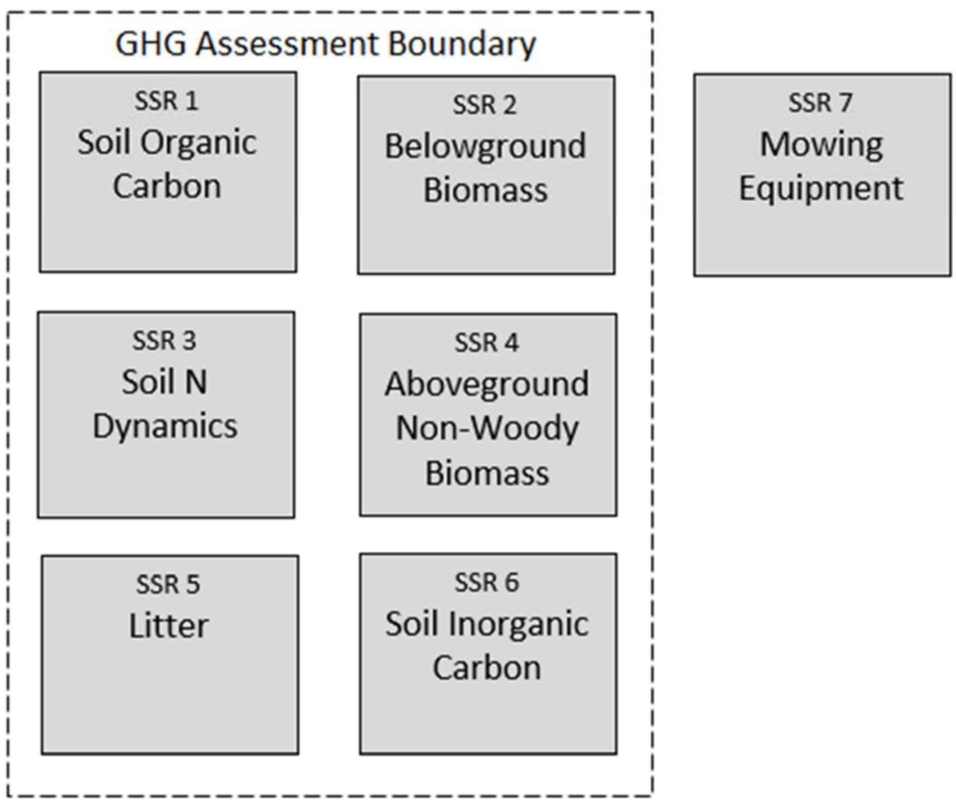


Table 6-2 describes the selected SSRs in more detail, and provides the rationale for their inclusion/exclusion from the GHG assessment boundary.

Table 6-2. SSR Description for the NMDOT Highway ROW Vegetation Protocol

SSR	Gas	Included/Excluded from Assessment Boundary	Rationale for Inclusion/Exclusion
SSR 1 = Soil Organic Carbon	CO_2	Included	Change in SOC (carbon sequestration) is anticipated between the baseline scenario and project activity
SSR 2 = Below-ground Biomass	CO_2	Included	Change in CO_2 emissions are anticipated between the baseline scenario and project activity
SSR 3 = Soil Nitrogen Dynamics	N_2O	Included	The amount of nitrous oxide emitted under the project activity may change relative to the baseline scenario
SSR 4 = Aboveground Non-Woody Biomass	CO_2	Included	Change in CO_2 emissions are anticipated between the baseline scenario and project activity
SSR 5 = Litter	CO_2	Included	Change in CO_2 emissions are anticipated between the baseline scenario and project activity
SSR 6 = Mowing Equipment and Transportation	CO_2, CH_4, N_2O	Excluded	Excluded as these emissions are expected to be the same under the baseline scenario and project activity
SSR 7 = Soil Inorganic Carbon	CO_2	Included	Change in soil inorganic carbon (carbon sequestration) could occur between the baseline scenario and project activity

SSRs related to shrubs, woody vegetation, and trees, which were considered in CAR's Grassland Project Protocol (2015), have not been included this project since the baseline scenario (Low Mow) and project activity (High Mow) both occur in the managed ROW, where shrubs, woody vegetation, and trees will not be present due to the safety hazards. Similarly, soil nitrogen dynamics due to fertilization that have been considered in similar protocols (CAR, 2015; Government of Alberta 2012) have not been included since no fertilization is anticipated and will be specifically excluded in the protocol's applicability section.

For this project, the preliminary identification of GHG SSRs determined that the same SSRs are present under both the baseline scenario and the project activity, i.e., there are no additional GHG sources as a result of project activities.

Protocol Direction

To continue to develop the GHG assessment boundaries and SSR identification for the NMDOT ROW vegetation project protocol, further work is anticipated :

- Further consideration of how the project (e.g. increased mowing height) affects soil nitrogen dynamics, and hence further confirmation of whether this potential source of N_2O (SSR) is included or excluded from the GHG assessment boundary. This could be a review of published literature initially, and depending of the results of the review, could need to be determined through direct measurement.
- Further consideration of the potential change in soil inorganic carbon as a result of the project activity, and subsequent confirmation and justification that this SSR is included or excluded from the GHG assessment boundary. Similar to soil nitrogen dynamics, this could be a review of

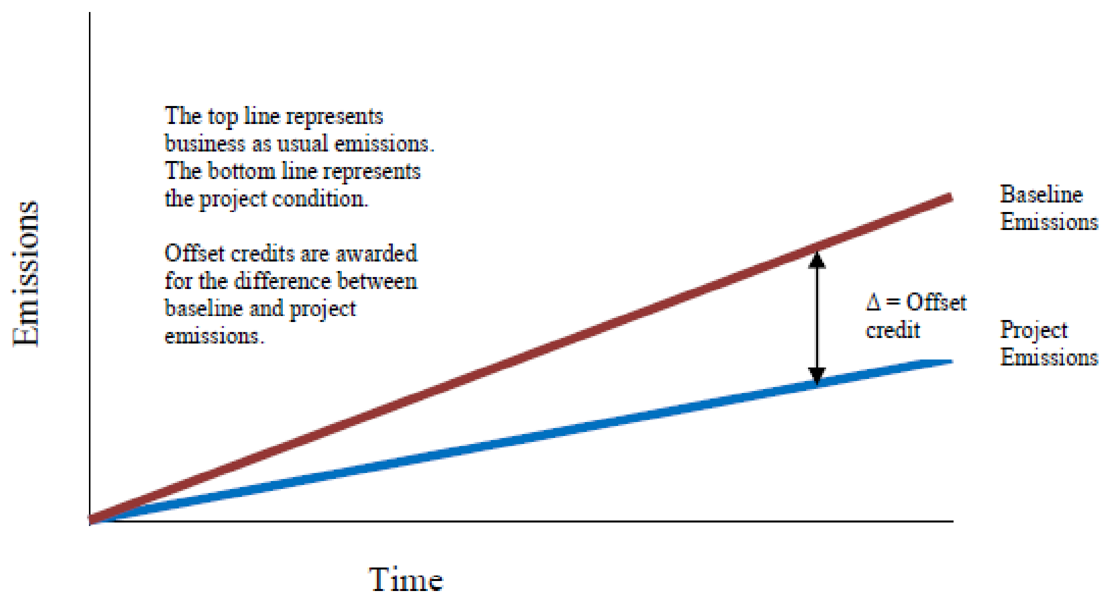
published literature initially, and depending of the result of the review, could need to be determined through direct measurement.

- Confirmation that SSRs relating to shrubs, woody vegetation, and trees are not applicable to the project. This would likely require confirmation that this type of vegetation is not present within the offset project area (i.e. within the managed ROWs). Alternately, the protocol could specifically exclude these sources from consideration, which could potentially limit the project area of ROW that is applicable under the protocol.
- Consideration of whether soil CH_4 would be a potential SSR; that could change under the baseline scenario and project activity, and therefore needs to be assessed within the GHG assessment boundary.

6.3.3 Quantification

All SSRs within the GHG assessment boundary are included in the quantification of GHG-emission reductions. GHG reductions are quantified by comparing project emissions against baseline emissions for the SSRs within the GHG assessment boundary (Figure 6-3). Project emissions are subtracted from baseline emissions to quantify the project's net GHG-emission reductions, as demonstrated in Figure 6-3 below.

Figure 6-3. GHG emission reductions as a function of baseline and project emissions



Source: Government of Alberta, 2013

Project developers must decide between direct measurement and modeling SSR removals. Although the ISO 14064-2 standard clearly favours use of direct measurement over modeling, use of either biogeochemical process models or empirical models has become the standard approach to quantify the atmospheric benefit of changes in SOC of terrestrial carbon offset projects.

Protocols have varying degrees of specification about direct measurement, modeling, and other estimation techniques, some set minimum standards and others can be specific about allowed techniques. For example, CAR's Grasslands Project Protocol (2015) specifies a reliance on default factors modeled using DAYCENT (a biogeochemical process model),[6] whereas the VCS-approved Sustainable Grasslands Management Protocol (2014) offers use of either direct measurement or modeling to quantify baseline and project SOC, but evidence of peer-reviewed studies on the model's validity are required[7].

The quantification portion of a protocol for a high-quality offset program includes detailed mathematical equations for the computation of either reduction or removal for each of the SSR baseline scenario and project sources.

<u>Projection Situation</u>
For this protocol, quantification of both baseline and project emissions is based on an empirical ecosystem modeling approach that considers site-specific measurements, long-term ecological monitoring data, and NDIV – a measure of 'greenness' derived from satellite collected data.

The empirical ecosystem modeling approach (EDM) developed to date is considered to quantify SSRs 1, 2, 4 and 5. Further work is required to confirm the quantification approach for SSRs 4 (soil nitrogen) and 6 (SOC).

<u>Protocol Direction</u>
To continue to develop the quantification of GHG reductions for the NMDOT highway ROW vegetation protocol, further work could be required in the following areas:

- The study's EDM will require peer-review validation for its quantification of SOC of a ROW offset project in New Mexico.
- Detailed mathematical equations for the calculation of either the reduction or the removal for each of the SSR's baseline scenario and project activity need to be prepared.
- If SSRs of soil nitrogen dynamics, soil CH_4, and soil inorganic carbon are within the GHG assessment boundary, then a quantification approach for these would need to be identified.
- Further consideration of how the current SOC EDM-based quantification method can be calibrated and validated to different climatic regions, different vegetation types, and areas, including areas where a long-term data of NEE is not available.

6.3.4 Baseline Setting and Additionality
The related concepts of selecting the baseline scenario and demonstrating a project activity's additionality are central elements in offset project development. The baseline scenario and additionality are two sides of the same concept. The baseline scenario is a hypothetical measure that helps determine the volume of the project's reduction or removal. The baseline case is often described as the 'business as usual' case.

The baseline scenario is a qualitative representation of what would have happened if the project did not happen. The baseline scenario must be "reasonably likely" to occur if the project was not conducted. To be "reasonably likely," the scenario must be more than a mere possibility, but need not be a

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[6] The DAYCENT model (Parton et al. 1993) simulates daily cycling of carbon, nitrogen, and other nutrients in various ecosystems (CAR 2015). In the case of the CAR grasslands protocol, a number of different scenarios were run using the DAYCENT model to develop default factors by microclimate based on soil types and climatic regions.

[7] In this methodology, proponents may either make direct measurements of SOC or use modeling. If there are peer-reviewed studies [e.g., scientific journals, university theses, or work carried out by the project proponent] that demonstrates that the use of the selected model is valid for the project region, the model can be applied for estimating of carbon stock changes. Otherwise, direct measurement of carbon stocks will be carried out.

certainty, or the most likely, or more likely than not to occur. Therefore, with some offset projects, there could be more than one "reasonably likely" baseline scenario.

The reduction or removal must be beyond, or in addition to, the baseline scenario; project emissions must be less than baseline emissions.

The concept of additionality is that an offset project must result in reductions/removals of GHG emissions that are additional, or incremental, to what would have happened had the project not occurred (i.e., the baseline scenario).

CAR uses performance-standard baselines in its protocols, as a means to reduce the cost of estimating an offset's projects' atmospheric effects and to establish consistency in baseline determination across offset projects of the same type. This approach leads to additionality of an offset project in the event that the eligible management practices of a terrestrial carbon project result in CO_2 removals that exceed the performance-standard baseline determination, including any applicable mandatory land-use laws and regulations.

Project Situation
For the NMDOT ROW vegetation project, the baseline scenario would be mowing the ROW vegetation to 6 inches high. Correspondingly, the project activity would be mowing ROW vegetation to 10 to 12 inches high.

Protocol Direction
To develop the baseline scenario and demonstrate additionality for the NMDOT ROW vegetation protocol, more work is anticipated to be required:

- The time of year of mowing under the baseline scenario compared to the project activity could potentially complicate the calculation of net emission reductions, since the time of year of mowing has the potential to alter GHG emissions, and this would potentially need to be accounted for when quantifying the baseline emissions in a conservative manner (i.e. to underestimate net GHG emission reductions as a result of the project activities).
- Documentation/established audit trail would likely be required (to satisfy project validation and/or verification) that mowing was previously done to 6 inches high, and also the area of ROW where mowing currently occurs (since this would define the geographic area of the offset project).
- Based on the anticipated offset program for this specific project, further investigation of what the additionality 'tests' comprise, and whether the project could meet them. A performance-standard approach could possibly be adopted based on the SOC stocks of roadsides associated with mowing vegetation to 6 inches high by microclimate. It is possible that the additionality tests may even define which offset programs an option for this project, making the additionality test one of the key components to the future development of the project as an offset project.

6.3.5 Permanence
How to manage the permanence of carbon storage in biomass and soils within an offset system arises because soils and vegetation are at risk of releasing emissions from their stored carbon due to anthropogenic and natural disturbances. Many types of offset projects result in immediate and permanent GHG reductions and accompanying atmospheric benefits. For example, a project that replaces fossil-fuel consumption with a zero-rated biomass fuel. A lengthy period of monitoring carbon stocks is needed, however, for a terrestrial carbon-based offset to be considered permanent and fully interchangeable with offsets from projects that generate reductions (i.e. fuel switch) that are clearly permanent.

Although there is continued scientific investigation on the lifetime of CO_2 in the atmosphere, the Intergovernmental Panel on Climate Change (IPCC) uses a 100-year lifetime for CO_2 and the Global Warming Potentials of other GHGs are based on this 100-year timeframe. This is the minimum timeframe that high-quality offset systems, such as CAR and VCS, set as the minimum for a GHG reduction of a sequestration-focused offset project to endure.

Mandating risk management plans that incorporate reversal-mitigation tactics and actions is one way to limit reversal risk. It is helpful, however, to develop ways to account and compensate for reversals that occur prior to the minimum "permanence" time period that an OPA sets. Further, in cases where liability falls on the OPA, they may want to protect the integrity of the program establishing a safeguard against risks. Protocols include provisions requiring project developers to do this in several ways. For example, protocols can require that projects contract for appropriate insurance coverage, simply discount total offsets by a certain percentage, or place a certain amount of offsets in a reserve pool or "buffer" account. These buffer pools use a portfolio risk-mitigation approach, whereby all terrestrial carbon offset projects must contribute a percentage of their offset credits based on a reversal risk assessment, and the pool will replace stored carbon that is lost through emissions from an unintended reversal. Proponents remain responsible for intended reversals, such as replacing grasslands with crops, and compensate for the reversal with offset credits equal to the reversal's amount of GHG emissions.

The concepts of reversal risk management and mitigation planning, reversal accounting and compensation, and the offset project monitoring period are directly linked to a common goal of safeguarding the atmospheric benefit created by an offset project and its retired offsets.

Project Situation

The challenge in sustaining permanence of stored soil carbon for the proposed ROW project is that the project activity (management practice) must occur annually to sustain the incremental SOC gain. Forestry and avoided grasslands conversion projects are tied to either not performing a one-time event, or require management activities for only a few years. This challenge for the proposed ROW project is modest, in that seasonal mowing of roadside vegetation is a regular activity for NMDOT. The goal is to sustain the new management practice, on an annual basis over the long term, for at least 100 years. In this context, the challenge is akin to that faced in a conservation till soil project, where the annual seasonal tilling of soil is modified to reduce loss of soil carbon. In this case, there is the potential for the tilled agricultural lands to be sold and the new owner, or even the current owner, to revert to the former conventional tilling practices. The CCX and Alberta systems that allowed these projects used contractual commitments to provide assurance that the new practice will be sustained over the long term.

The likelihood of the ROW ownership changing hands is nominal, nevertheless, still present, and more likely in the case of road ROWs owned by municipal governments. In that event, the protocol allowed for a wide range of road ROW ownership situations.

Protocol Direction

The NMDOT ROW vegetation project protocol may have to incorporate a 100-year permanence requirement. The CAR program incorporates a 100-year permanence requirement and uses conservation easements to facilitate the risk management of avoidable reversals such as timber harvesting, in the case of forest conservation offset projects. On the other hand, the BC Forest Carbon Offset Protocol mandates preparation of mitigation and contingency plans to address avoidable and unavoidable risks (e.g., fire and pests), but leaves the choice of specific mechanisms, such as buffer pools, to project developers. The BC offset system requires validation by a third party of the offset project plan, so this approach can work, but it does treat project developers unevenly.

High-quality voluntary (and compliance) offset programs have specific term requirements to meet the permanence objective, so the project developer will have to see this requirement incorporated into a highway ROW offset protocol. For example, VCS uses a 100-year requirement from the time of the project start. CAR's approach uses a 100-year requirement from the point of the last issued credit (which would mean a period of 125 years in the event that the last credit was issued 25 years after project start).

Both VCS and CAR stipulate contributions of offset credits to a buffer pool based on stringent analyses of risk reversals by project type and its geographic location. Although neither CAR nor VCS have approved protocols for offset projects like the proposed NMDOT ROW project, the expectation is that a risk-based buffer pool mechanism would need to be incorporated into a highway ROW project (in the case of CAR and ACR), or will have to comply with the program-reversal risk standard (in the case of VCS).

6.3.6 Monitoring and Verification

A high-quality offset protocol will require the project developer to prepare a monitoring plan, which defines tasks so as to ensure that the reduction or removal claimed by the project are real, additional, and measurable. There is guidance from ISO and IPCC on offset monitoring procedures, and VCS has monitoring guidance in its program standard. The protocol will include the core contents of the monitoring plan. For example, CAR's Grasslands Project Protocol (2015) states that a "Monitoring Plan shall include a description of ownership of both the property and the emission reductions; the methods and frequency of data acquisition; a record keeping plan…QA/QC provisions to ensure that data acquisition and recordkeeping are carried out consistently and with precision." The protocol should also describe the geographic location of the project area and document the eligible management practices, stated in the applicability section, that must be included in the monitoring plan.

The protocol will state the minimum interval or frequency (such as at least every 2 years) at which monitoring and reporting of each data unit/parameter will occur.

Verification happens after an offset project has been initiated. Good offset practice has it as the first day of project operation (the offset protocol usually defines what is considered the first day of operation). The intervals at which project verification occurs are in either the OPA's protocol or in a verification standard of the offset program.

The purpose of the verification process is to provide a third-party assessment of the calculations of actual GHG reductions and removals. At this stage, the hypothetical baseline scenario and project activity removals are compared to the project's actual emissions and removals to determine the extent to which reduction or removal has occurred. Verification occurs periodically over the validation period, whereas validation occurs only once, and before the offset project is implemented (Section 6.2.2).

A verifier reviews the proponent's project report and, on the basis of its findings, provides an assurance that the assertions made in the project report are "fair and reasonable," as a whole and individually. A focus of the verification is to consider whether the project report is subject to material errors, omissions, or misrepresentations. The following list provides an overview of the main elements that are evaluated during the verification process:

- Ownership rights;
- Eligibility for offsets under the selected protocol;
- Project implementation and reduction calculation conformity with the selected protocol(s);
- Conformity of monitoring system to recognized standards (including equipment type and calibration procedures);
- Review of calculations, i.e. a check on consistency with statements in the project plan;

- Review of records and recordkeeping procedures (collection, storage frequencies, and tools), i.e., a check on accuracy and completeness of data.

Typically, verification is completed when a statement of assurance is issued by the verification firm. The contractual relationship is between the project developer and the verifier.

Project Situation
Recording of field measurements occurred within the experimental design of the Phase 2 proof-of-concept study. Section 2 provides information on the study's monitoring methods.

Protocol Direction
The monitoring methods of the Phase 2 study do not fully coincide with the typical structure, including frequency, for monitoring in terrestrial carbon offset protocols. A specific monitoring plan and verification requirements that are consistent with the selected offset program for terrestrial carbon offset projects will have to be prepared and incorporated into the highway ROW vegetation offset protocol. However, the general requirements for monitoring and verification of terrestrial carbon offset projects are well established. These general requirements would have to be integrated into the proposed protocol.

6.3.7 Ownership and Crediting

Offsets are an environmental commodity for which there has to be clear title ownership under major offset programs. The prerequisite for clear ownership of title to an offset is unambiguous ownership of its underlying reduction or removal. Multiple claims to a reduction and removal are possible through interests that parties have in different project aspects, such as funding all or part of a project, and ownership claims over an asset (such as land), which is used in the project.

Typically a protocol would require that an assertion from the project developer that there is a superior claim of ownership of the project reduction or removal to that of any other person, along the evidence of ownership.

A reduction or removal is unique, and therefore can only be counted once as an offset. A reduction or a removal from an offset project that has already received recognition through another voluntary market or compliance offset program would not be eligible for recognition as an "offset" under another offset program. This criterion prevents a project developer from selling the same offset to two different OPAs. Also, once a project developer has sold an offset, the reduction or removal underlying that offset cannot be applied to its own inventory. If a project developer was to count a reductions or removal in his or her inventory, then these reductions or removals would be counted more than once.

Offset projects can be conducted through various ownership structures, and the original owner of the reduction or removal can contractually transfer ownership to a project developer.

Project Situation
The ownership situation for the GHG removal by the higher mowing practice is clear in the New Mexico case, as the state is the owner of the highway ROW, and the state government conducts vegetation maintenance through the Maintenance Operation Section of the State Maintenance Bureau of the NMDOT.

Where a ROW was on leased land, the lease would have to incorporate language about ownership of GHG reductions or removals effected on the leased lands to remove ambiguity about their ownership on these lands. As concern about ownership of GHG reductions or removals is a relatively new one, old leases and even new ones do not incorporate language on the matter.

Protocol Direction

In the NMDOT ROW project, the fee owner of the ROW on which the project will be implemented is the State of New Mexico. Although proving such should be relatively straightforward, the offset protocol should stipulate that the project area owner is a legally constituted entity that has fee ownership and legal control of the land within the project area. The protocol should also provide for the case where the owner of the project area land conveys the rights to the emissions reduction or removals enhancement to another party, such as a project developer, and that the legal instrument used to convey those rights, such as a GHG rights contract. The protocol should also define the role of a project developer as the entity which holds legal title to the emissions reduction or removals enhancement related to the project, and is responsible for conducting the project and registering it with the OPA. The project developer can be the owner of the land within the project area, the State of New Mexico, in the case of the NMDOT ROW offset project.

6.4 Broadening Eligible Practices in a Highway ROW Protocol

Over the past 3 years, several state departments of transportation have sponsored research regarding roadside vegetation management practices in the context of their potential to sequester carbon in ROW soils and vegetation. While this body of research is relatively small, it geographically spans much of the U.S. and provides information about a variety of ROW vegetation management practices with the potential to capture and store carbon. We suggest that much of this information could support a ROW carbon sequestration protocol on a regional or national scale. Brief summaries of these other ROW carbon sequestration research efforts are provided below.

6.4.1 Ecologically Sustainable Roadside Vegetation Management

In Florida, Harrison (2014) defined ecologically sustainable roadside vegetation management as a 50-percent reduction in mowing (either in area or frequency), the total elimination of herbicides and fertilizers, and the establishment of wildflower planting areas in the ROW. The work determined the economic value of various ecological services provided by these sustainable vegetation management practices. The value assigned to carbon sequestration was $39 billion across Florida. The economic value of carbon sequestration more than doubled with the establishment of 1,000 acres of wildflower areas. The author recommended that if ROW carbon sequestration was monetized in a carbon market, the value of the ecological service should be based on the market price rather than the ecosystem service estimation.

6.4.2 Roadside Vegetation and Soil Management on Federal Lands

Ament and others (2014) examined potential carbon capture and storage techniques that could be implemented in “road effect zones” by eight federal land management agencies (FLMAs; e.g. U.S. Forest Service, National Park Service, military installations, etc.). Potential vegetation management practices to increase carbon capture and storage along road effect zones included:

- Increasing shrub density in ROWs as arrestors for errant vehicles
- Allowing the growth of woody vegetation behind guardrails
- Construction of living snow fences
- Reducing the effects of road salt and dust
- Minimizing disturbance during road design/repair
- Decommissioning/reclaiming abandoned roads

The authors estimated that the FMLAs could potentially capture and store over 8 million MTs of carbon annually, equivalent to the GHG emissions of over 6 million passenger cars. Interestingly, the authors used empirical NEE data from eddy-covariance towers in North America to calculate average NEE for major vegetation physiognomic classes (e.g. evergreen forests, grasslands, etc.). These average NEE rates were then tied to the existing vegetation within the road effect zones at four study sites in the western U.S. to estimate ROW carbon sequestration potential. The authors also provided details on how they calculated carbon emission associated with roadside mowing, fuel consumption for roadside vegetation maintenance, and the manufacturing of pesticides.

6.4.3 Protection and Enhancement of Pollinator Habitat

The preservation and restoration of native habitat for Monarch butterflies, honey bees, and other pollinators is currently a topic of great interest to roadside managers. Declining pollinator populations has been attributed to significant losses in native habitat, pesticide use, introduced diseases, parasites, and the spread of invasive species. Integrated Roadside Vegetation Management (IRVM) is being promoted to encourage planting and enhancing roadsides with native plant species in combination with environmentally sustainable vegetation management practices (Hopwood 2010). Rather than mowing and spraying, IRVM strives to create a diverse roadside plant community with grasses and flowering plants that provide food and pollen for insects, and hostplants for nesting, egg-laying, and larval development. High-quality pollinator habitat along roadsides also provides linkages or corridors for pollinators to move across highly modified landscapes such as agricultural areas in the Midwest.

In December 2015, President Obama signed into law the Fixing America's Surface Transportation (FAST) Act. The FAST Act includes new emphasis on efforts to support pollinators by protecting and enhancing grassland habitat in ROWs. Specifically, the FAST Act directs FHWA, when carrying out any program under Title 23, to encourage:

1. Integrated vegetation management practices on roadsides and other transportation ROWs, including reduced mowing; and
2. The development of habitat and forage for Monarch butterflies, other native pollinators, and honey bees by planting native forbs (e.g., flowering plants) and grasses, including native milkweed species, that can serve as migratory waystations for butterflies and facilitate migrations of other pollinators.

The FAST Act also affirms that activities to establish and improve pollinator habitat, forage, and migratory waystations may be eligible for federal funding if related to transportation projects under Title 23.

To date, the benefits of preserving and restoring pollinator habitat has not included any reference to the increased potential to sequester soil carbon. Given that both goals emphasize minimizing mowing and the establishing herbaceous plants in the ROWs, there are significant opportunities for synergistic strategies to achieve complementary goals.

6.4.4 Living Snow Fences

Wyatt and others (2012) provided a comprehensive review of the economic costs and benefits associated with living snow fences in Minnesota. Primarily a feasibility and implementation guide for transportation managers, a portion of the report and the companion payment-calculating tool (software) addresses and incorporates the potential economic benefits associated with soil and vegetation carbon sequestration. The calculations also account for avoided carbon emissions connected to the reduced need to remove snowdrifts with living snow fences once they are installed.

Sundstrom (2015) provided guidance in the design, function, construction, and care of living snow fences in Colorado. This report also details potential program set-up options on a state level. While no specific information is given regarding carbon sequestration, carbon capture by ROW vegetation is highlighted as a general benefit to establishing living snow fences.

6.4.5 Vegetation Filter Strips and Swales

Brouchard and others (2013), working in North Carolina, evaluated the potential of vegetated filter strips and swales stormwater controls to sequester soil carbon. The authors found higher soil carbon densities in wetland swales compared to dry swales. The rate of soil carbon sequestration in these vegetated roadside areas was estimated at 0.1 kg $C/m^2/yr$, which is comparable to sequestration rates reported for residential turf and grassland soils in more mesic climates.

6.5 Protocol Summary

Carbon offsets are sophisticated financial instruments that require substantial documentation, review, monitoring and verification before offset credits are issued. The process by which an offset is developed must be completely transparent, technically credible, compliant with regulatory guidelines and include stakeholder participation to give buyers complete confidence in the offset issued.

The offset protocol framework presented above identifies important elements specific to the North American offset program that will need to be addressed to develop the NMDOT highway ROW carbon sequestration project in relation to protocol requirements and provided direction as to the next steps to address current gaps and the minimum standard related to project additionality, boundary conditions, quantification, baseline, permanence, ownership and verification that would be required by an offset registry.

7 SUMMARY AND CONCLUSIONS

Highway vegetation management practices were evaluated to determine whether they could potentially increase biomass and cover of ROW vegetation during the growing season and lead to an increase in SOC. Research results indicate that High Mow subplots tended to have more canopy cover and aboveground biomass at the end of the growing season compared to Low Mow subplots. Prior to mowing, M zones had strong negative NEEs indicative of carbon sequestration. After mowing, High Mow subplots continued to sequester carbon while Low Mow subplots switched and became a CO_2 source. We also demonstrated the EDM is a promising method to predict NEE at the ROW test plots under different vegetation management scenarios, though further refinement of the EDM is needed to capture the full dynamic range of the CO_2 fluxes observed at the test plots.

A framework for a proposed highway ROW vegetation project within a North American voluntary offset program is provided to help guide research and policy with the development a protocol. The protocol must be able to accurately quantify, monitor and verify CO_2 removals from the atmosphere so they would qualify to be sold in a cap-and-trade carbon market. Key elements of a terrestrial carbon offset protocols are discussed at length including applicability, baselines, quantification, permanence, monitoring and verification, and ownership and crediting.

From our results, we estimated the gross potential profit associated with an offset project which would change the roadside mowing to a high mowing regime. The analysis ignores upfront costs required to develop the protocol and the operational fees that would be levied by the OPA to administer the project. For the profit analysis, we have assume a 6-meter wide mowing zone. Annual sequestration rates are based on average treatment differences illustrated in Figure 5-14. Average maximum differences are those observed at test plots where the High Mow treatment NEE was greater than the Low Mow (Table 5-8). The estimated return with the high mowing regime was calculated on a per kilometer basis based on current market price for carbon ($12.56) in the California cap-and-trade market (Climate Policy Initiative 2016) as well as the price established by EPA (2015) relative to the social cost of carbon ($40) and the price recommended by the United Nations Global Compact (UNGC) for corporate due diligence efforts when evaluating internal and external impacts (UNGC 2015).

Table 7-1 provides a preliminary profit estimates of a highway ROW roadside vegetation carbon offset project for New Mexico. From a financial perspective, the current carbon price of $12.56 results in low returns of $1.10 to $2.76/km/yr for Prairie and Lower Montane ROW respectively based on average sequestration rates. Significantly better returns are expected with increasing prices. At $100/t-$CO_2$e, average annual returns increase to $8.79/km/yr (Prairie) and $21.98/km/yr (Lower Montane) and would generate approximately $90,000 per year. Maximum NEE differences between high and low mowing in both Prairie and Lower Montane biomes result on significantly higher returns (Table 7-1). If the price of carbon was set at $100/t-$CO_2$e per UNGC recommendations, returns would be over $50 per kilometer and could generate an estimated $365,000 per year.

Based on this analysis, changing to a high mowing regime in New Mexico would result in the annual sequestration of 876 t-CO_2e on an annual basis (Table 7-1). This is equivalent to removing approximately 210 passenger cars from the road. Nearly a four-fold increase in CO_2 sequestration (3646 t-CO_2e) is estimated if NEE differences between high and low mowing were maximized in both Prairie and Lower Montane biomes. While this analysis highlights the potential to remove CO_2 from the atmosphere for NMDOT, offset project developers currently consider a minimum of 30,000 t-CO_2e/yr as a viable project in order to cover costs.

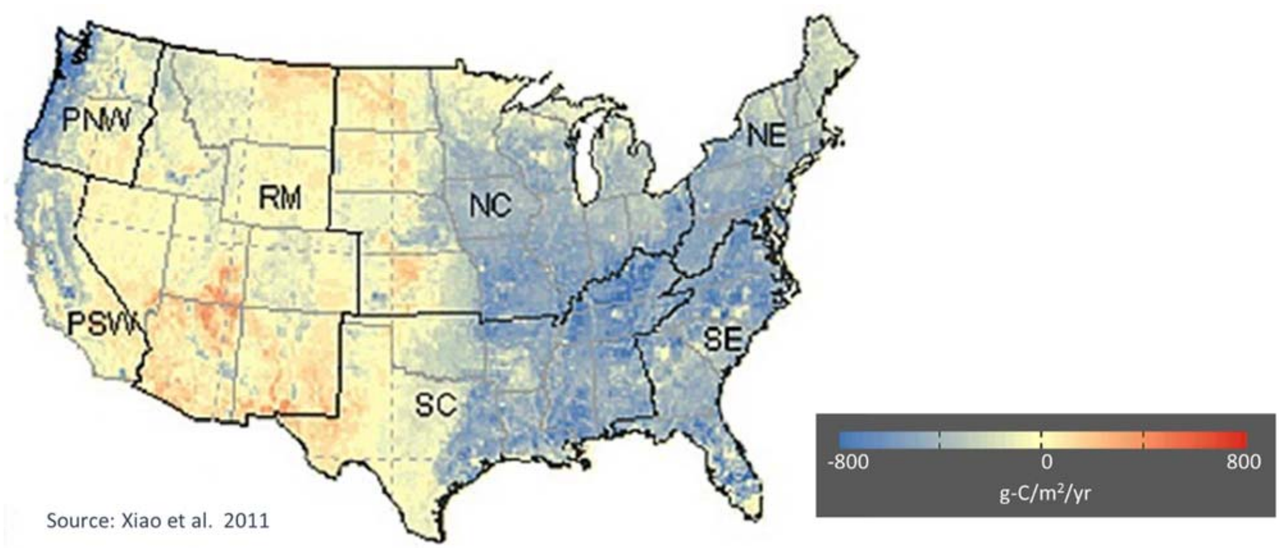
Table 7-1. Preliminary profit estimates for a ROW offset project in New Mexico under average and maximum carbon sequestration rates

Biome	High Mow NEE Improvement[1]		Total Length of State Hwy[2]	Annual Net Carbon[3]	Estimated return for a given Carbon Price[4]		
					$12.56	$40	$100
	g-C/m²	t-CO_2e/km	km	t CO_2e/yr	$/km/yr		
Average Sequestration Rate							
Prairie	4	15	4697	413	$1.10	$3.52	$8.79
Lower Montane	10	37	2106	463	$2.76	$8.79	$21.98
Maximum Sequestration Rate							
Prairie	25	95	4697	2582	$6.90	$21.98	$54.96
Lower Montane	23	84	2106	1065	$6.35	$20.23	$50.56

Notes:
1 = Difference in CO_2 sequestered between high and low mowing treatments
2 = Road length in kilometers from EMI 2013
3 = Assumes equivalent area along state highways of 1,263 ha and 2,818 ha in Lower Montane and Prairie biomes respectively
4 = $12.56 – California cap-and-trade market; $40 – EPA social cost of carbon; $100 – UN Global Compact recommendation

While small increases in ROW carbon sequestration are predicted under a High Mow scenario for New Mexico, there is potential in other regions of the U.S. that modification of mowing operations could have significant effects on carbon sequestration. To illustrate this potential, Xiao and others (2011) estimated NEE from land-cover types across the conterminous U.S. (Figure 7-1). The blue areas in Figure 7-1 illustrate where CO_2 is sequestered in plants or soils on an annual basis (darker blue areas represent higher potential to capture carbon). Conversely, red areas are net sources of carbon. Based on this analysis, annual NEE for the majority of New Mexico is greater than zero, meaning very little carbon is stored in our ecosystems and often they are sources of CO_2. Yet our research suggests high or deferred mowing sequesters more carbon in highway ROWs compared to low mowing despite the semi-arid climate.

Figure 7-1. Annual net ecosystem CO_2 exchange for the conterminous U.S.



Altering mowing practices in regions of the U.S. that have a greater potential to sequester CO_2 will likely result in significant increases in SOC in ROW soils. It requires DOTs to rethink mowing operations to understand when plants can tolerate a defoliation and continue to be a CO_2 sink while still being attentive to the need to maintain a clear zone along a highway. Specifically, ROW mowing practices that either enhance or have the least impact on root growth are likely to result in higher rates of soil carbon sequestration. In addition to the increased removal of CO_2 from the atmosphere, mowing frequency would likely be reduced and thereby qualify for additional reductions of greenhouse gas emissions due to decreased equipment use. Thus, establishing a highway ROW vegetation offset project in wetter and more productive regions of the U.S. could produce significant financial returns for state DOTs.

Finally, focusing on timing mowing operations when it is best for the roadside plant community rather than mowing when it is convenient for highway maintenance crews is essentially the basis of the FHWA Eco-logical approach. The Eco-logical approach promoted by FHWA works to identify and implement efficient/cost-effective measures to avoid/minimize ecological impacts of transportation infrastructure. This research suggests an added benefit to managing ROWs from an ecological perspective: ROWs could also remove CO_2 from the atmosphere and help slow global climate change.

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APPENDIX A

ROW Test Plot Soil Temperature and Moisture Summaries

Figure A-1: NMDOT ROW Test Plot 021-15 Soil Temperature

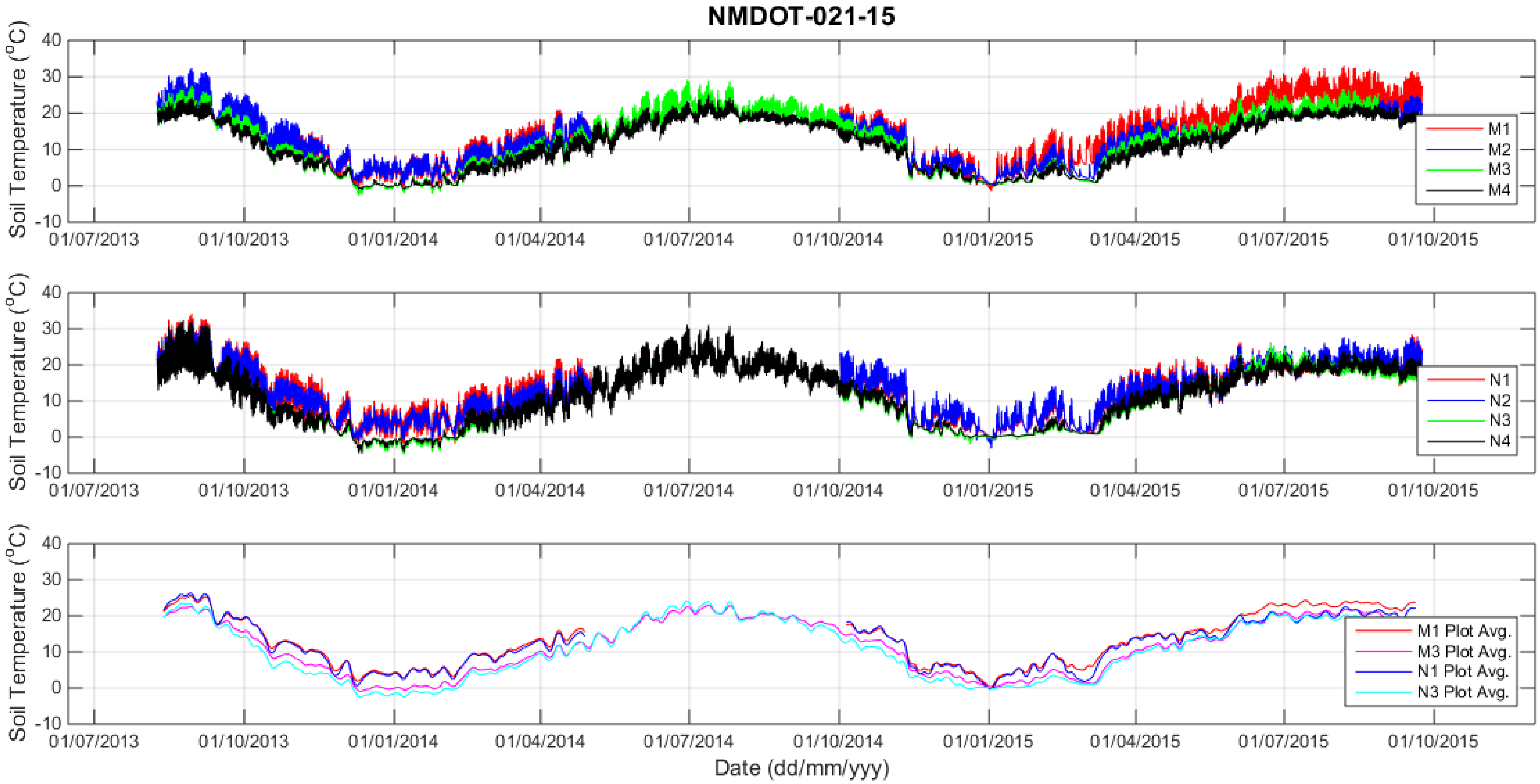


Figure A-2: NMDOT ROW Test Plot 021-31 Soil Moisture

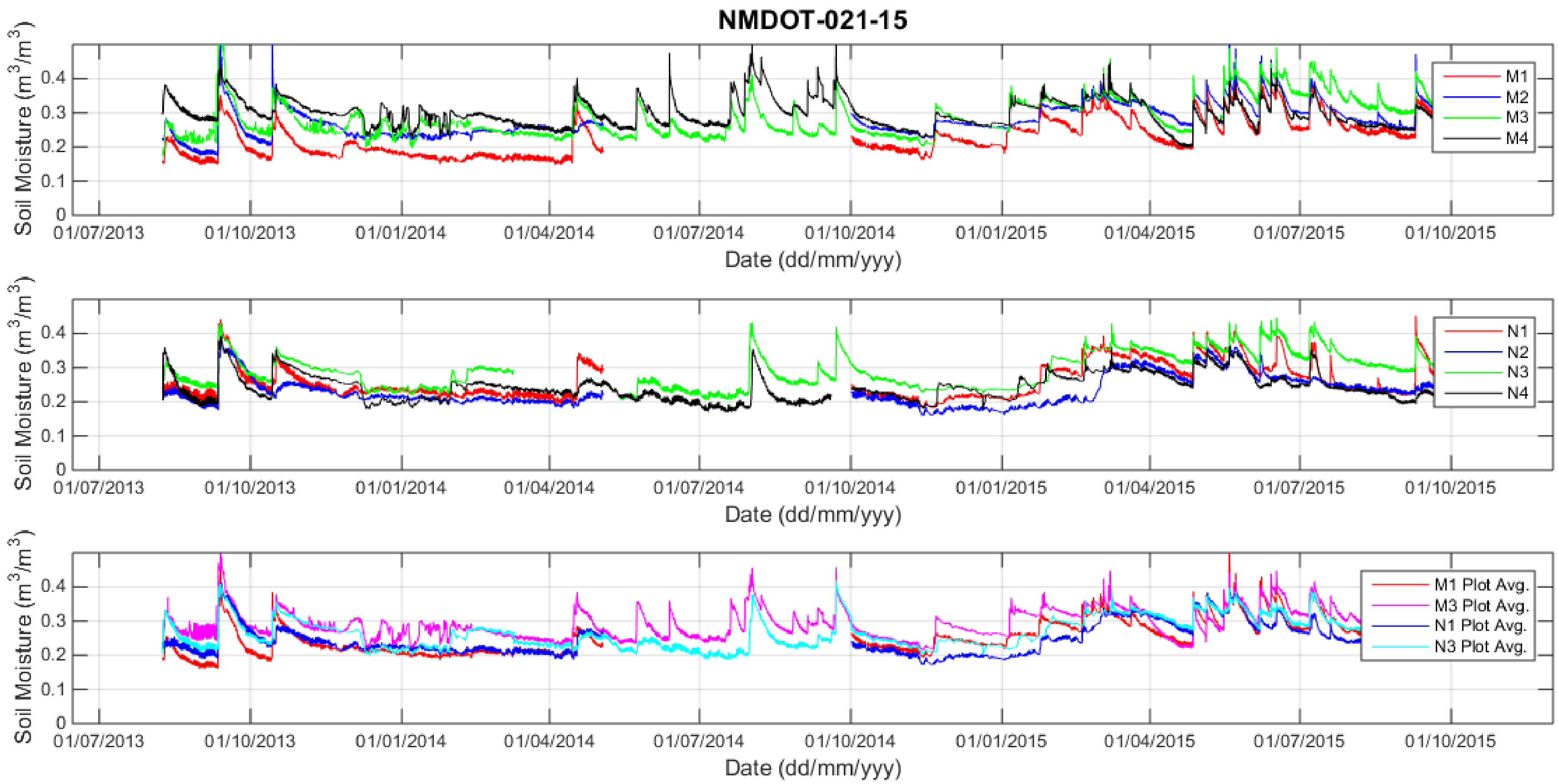


Figure A-3: NMDOT ROW Test Plot 104-79 Soil Temperature

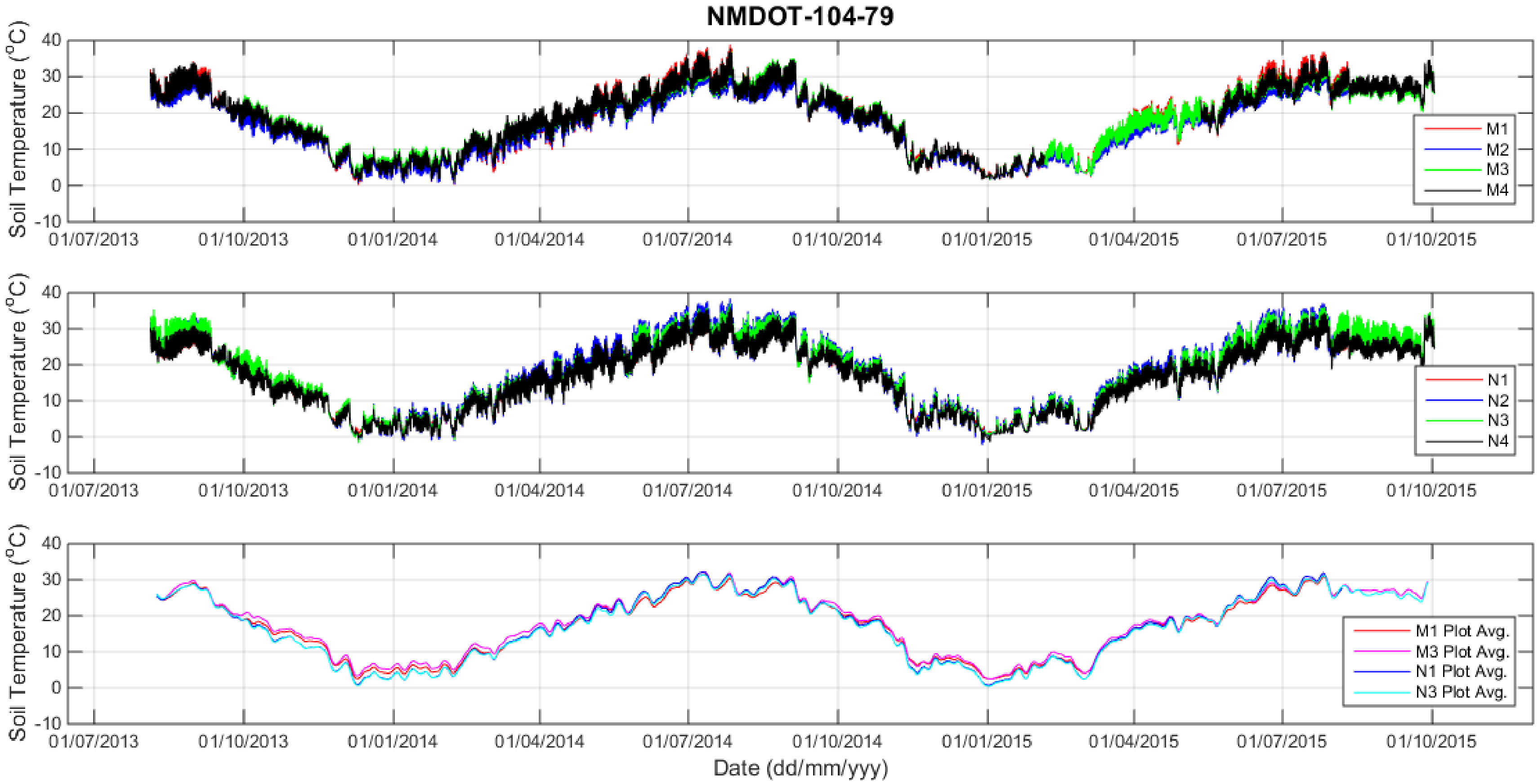


Figure A-4: NMDOT ROW Test Plot 104-79 Soil Moisture

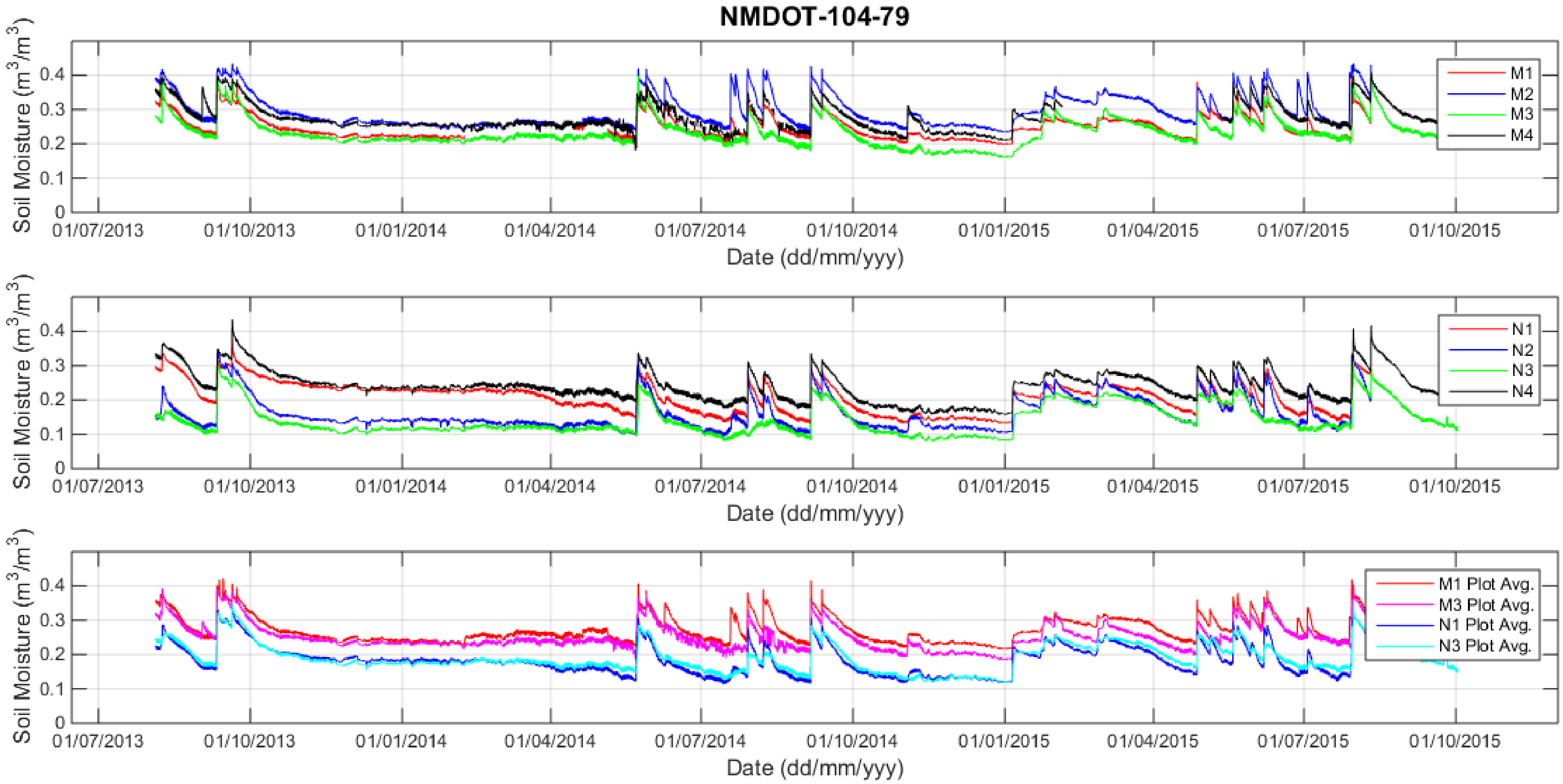


Figure A-5: NMDOT ROW Test Plot 120-31 Soil Temperature

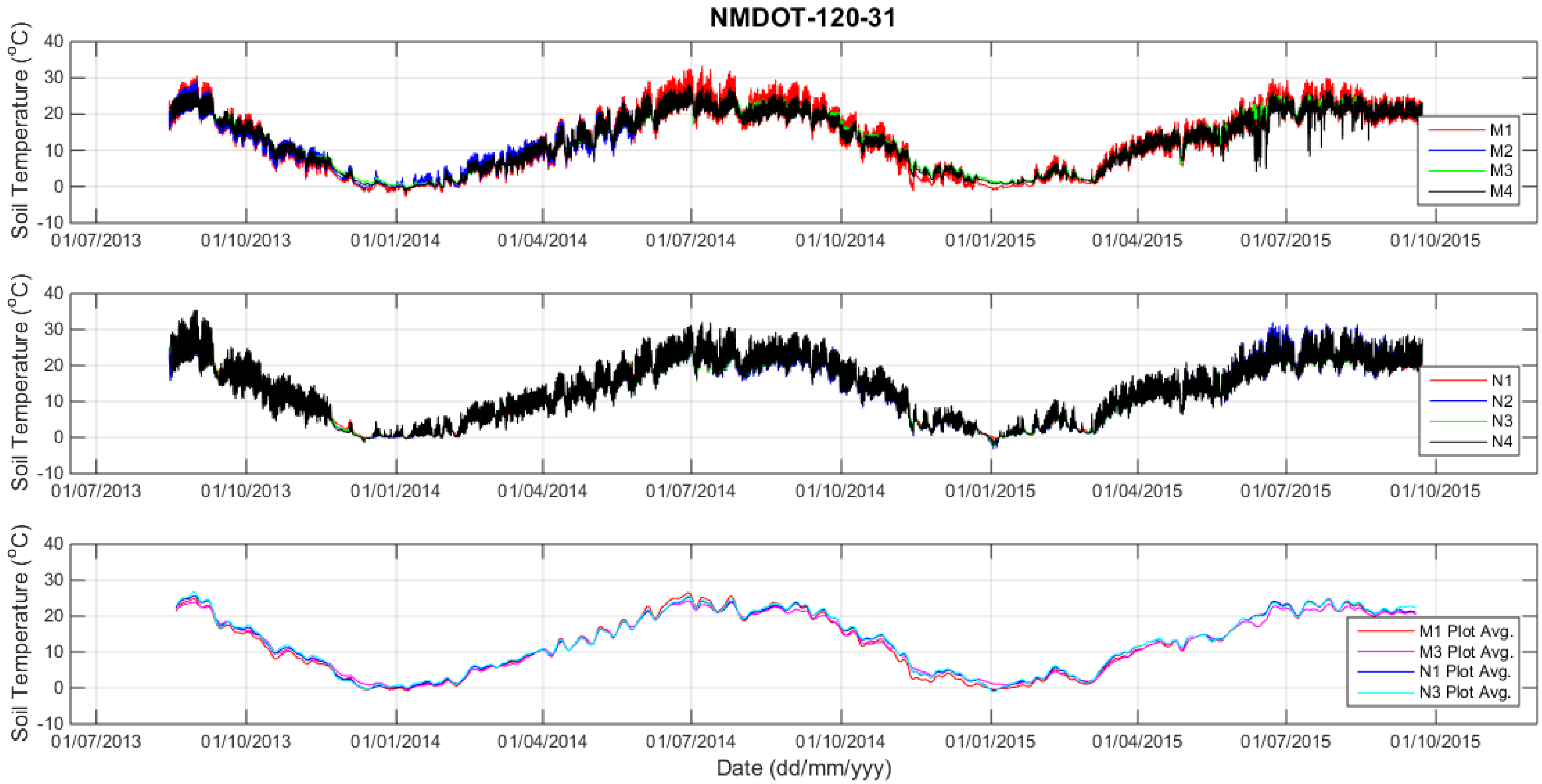


Figure A-6: NMDOT ROW Test Plot 120-31 Soil Moisture

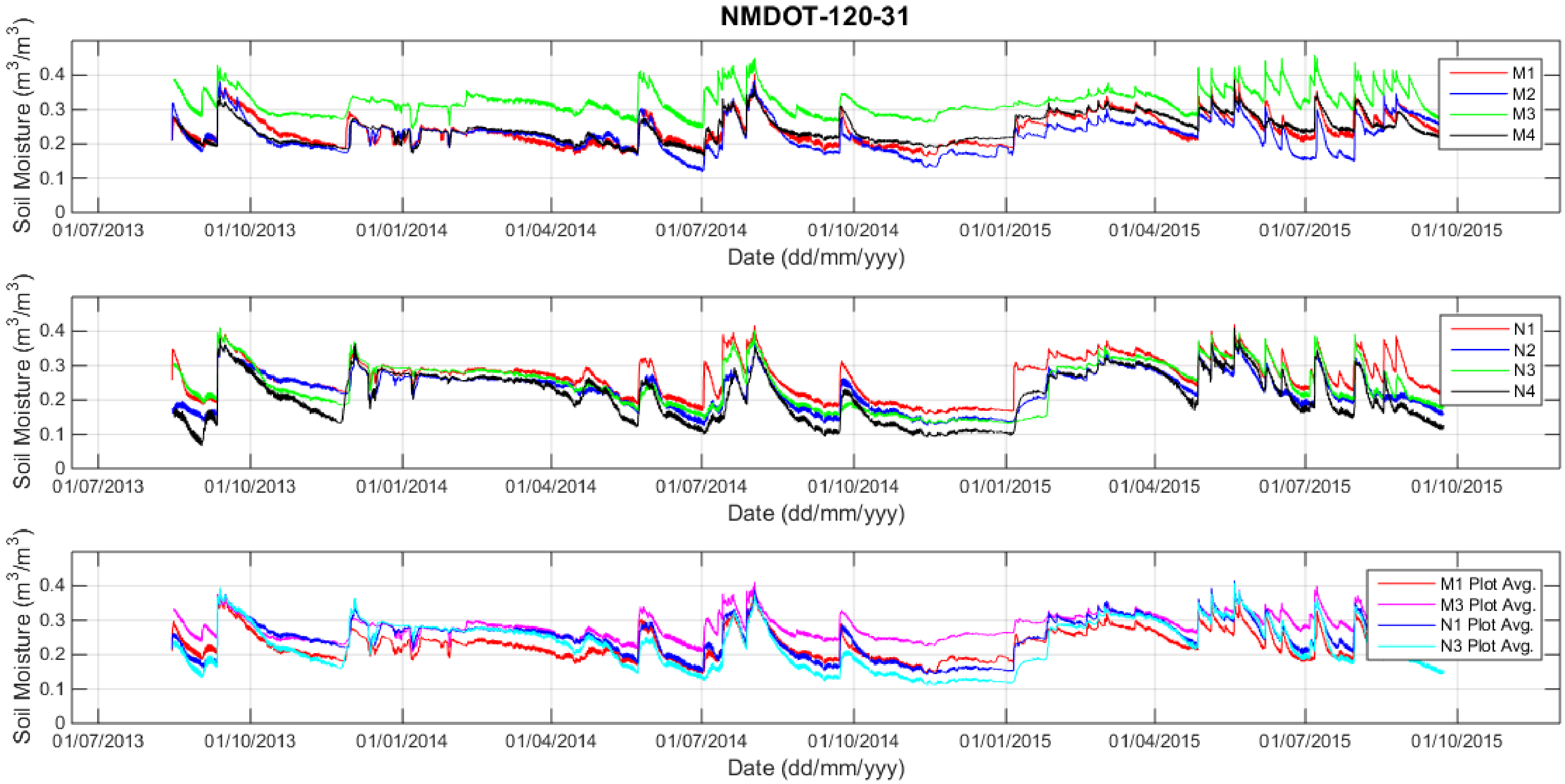


Figure A-7: NMDOT ROW Test Plot 469-02 Soil Temperature

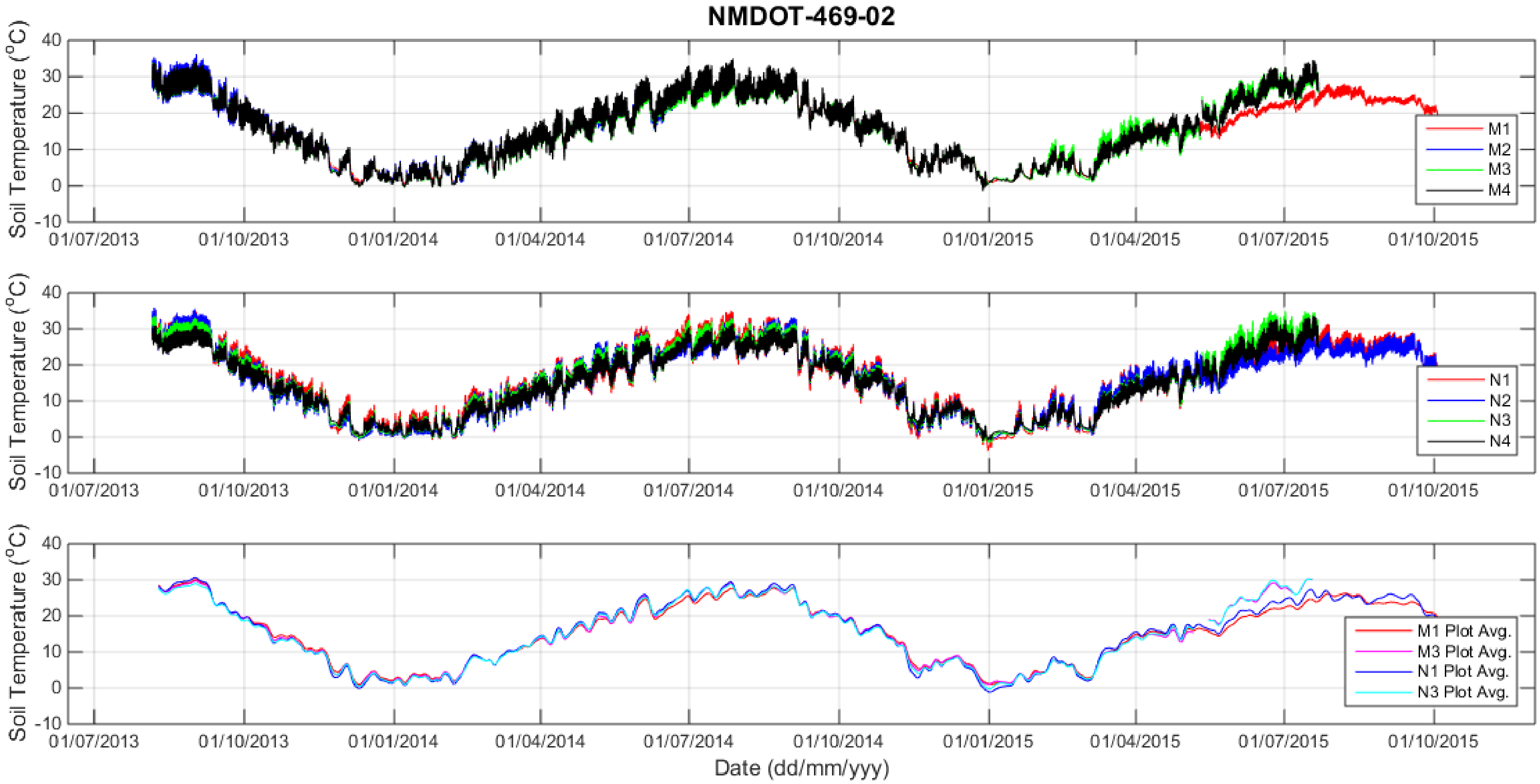


Figure A-8: NMDOT ROW Test Plot 469-02 Soil Moisture

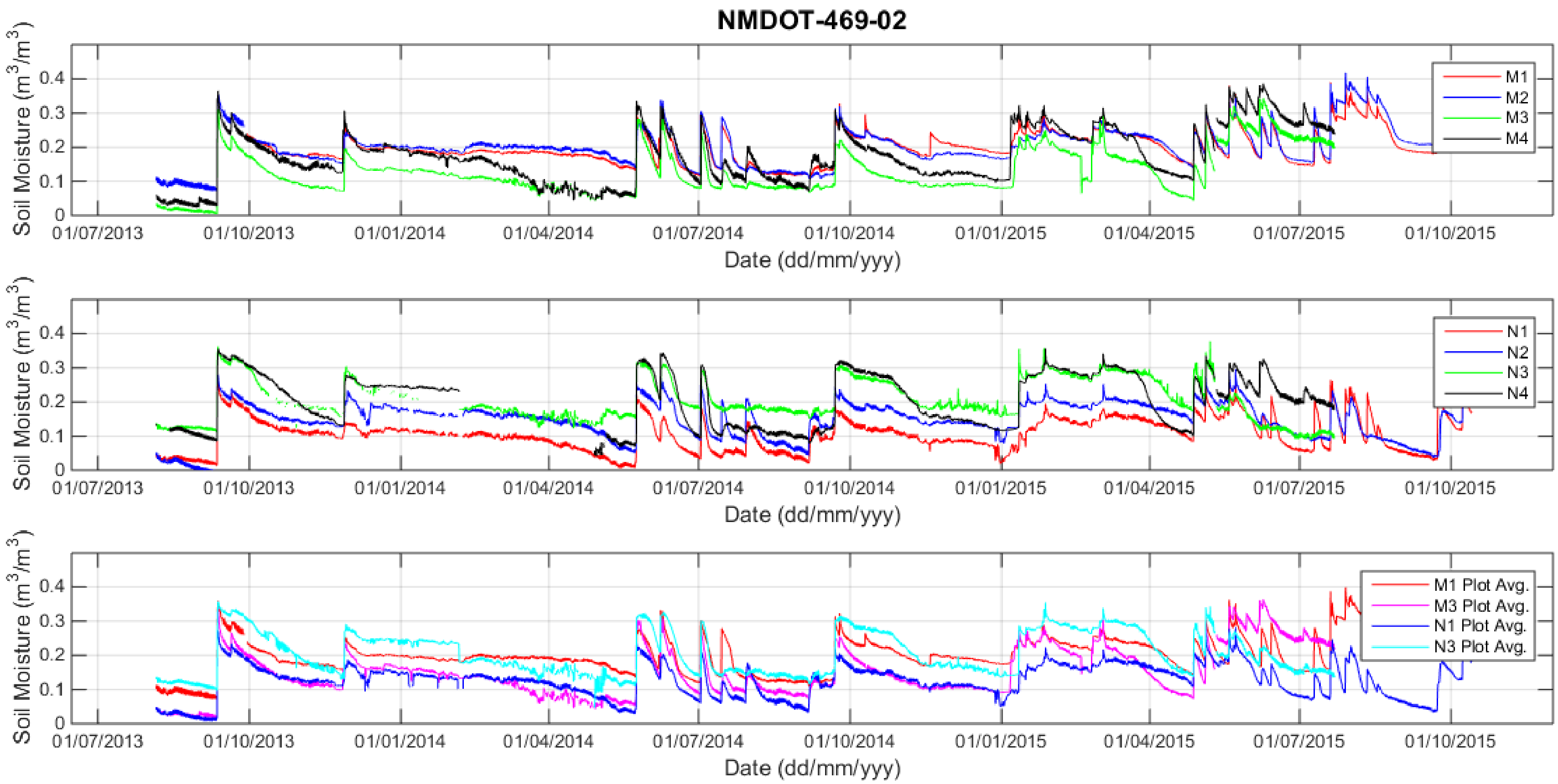


Figure A-9: NMDOT ROW Test Plot 469-39 Soil Temperature

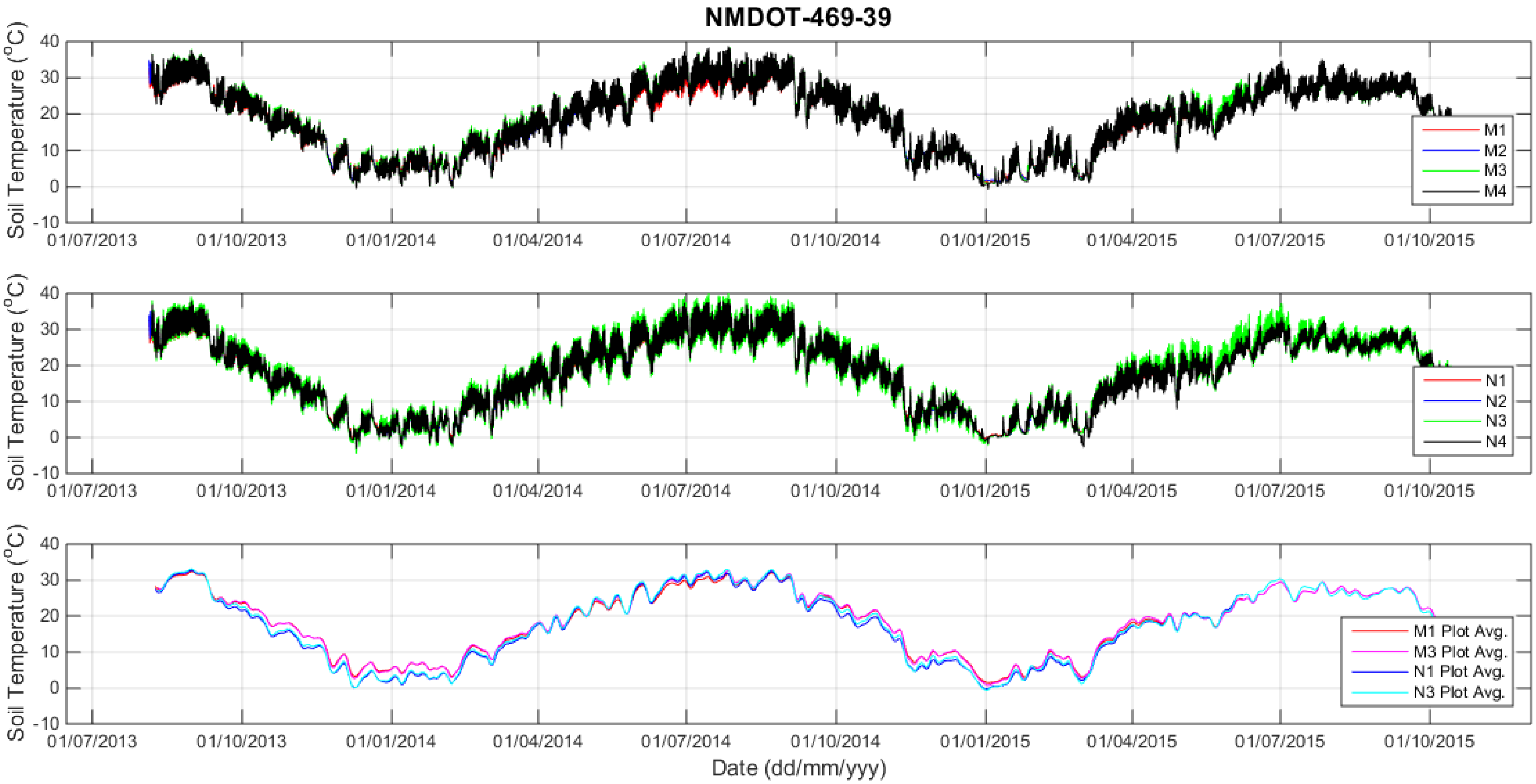


Figure A-10: NMDOT ROW Test Plot 469-39 Soil Moisture

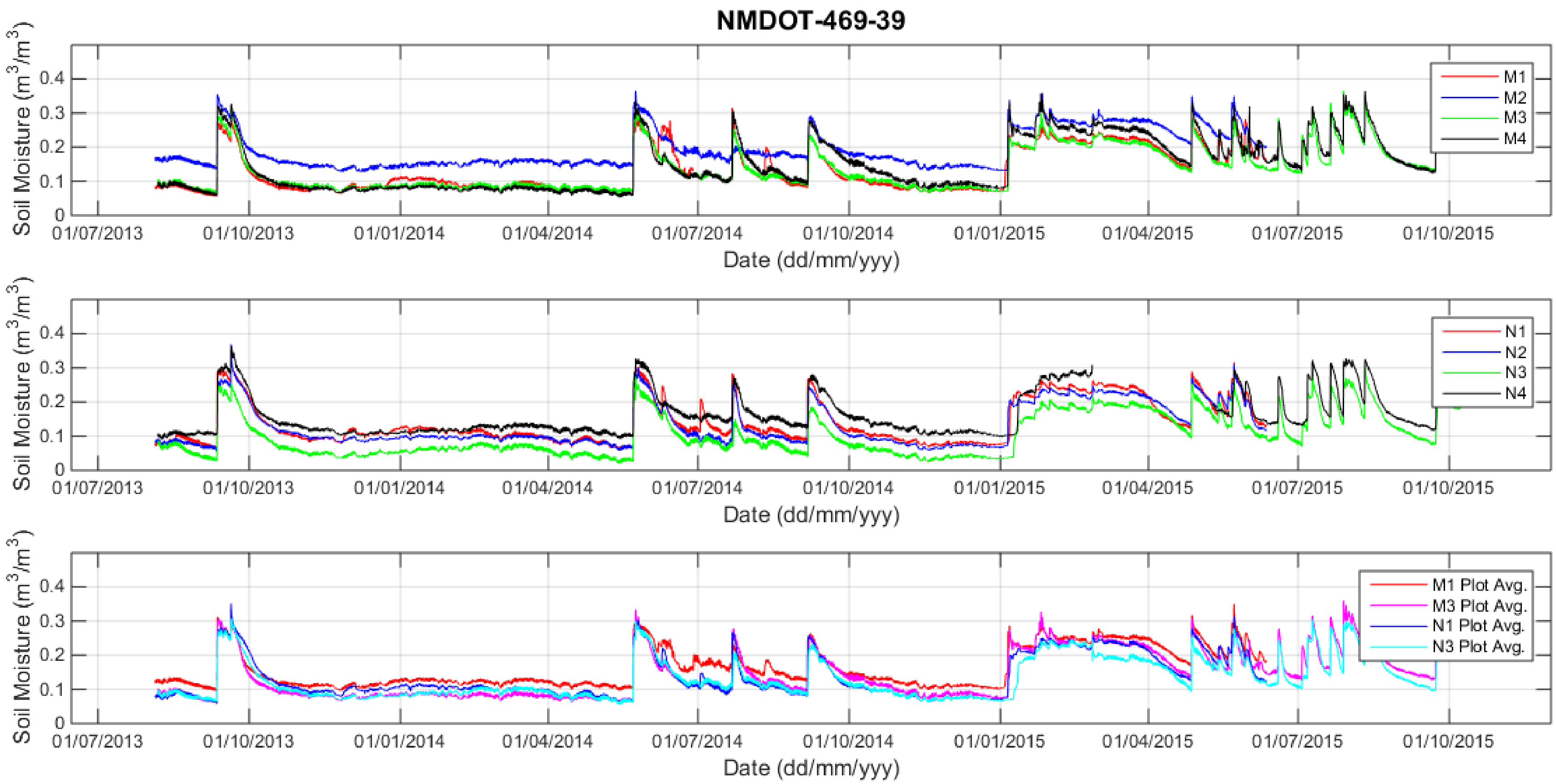


Figure A-11: NMDOT ROW Test Plot 472-07 Soil Temperature

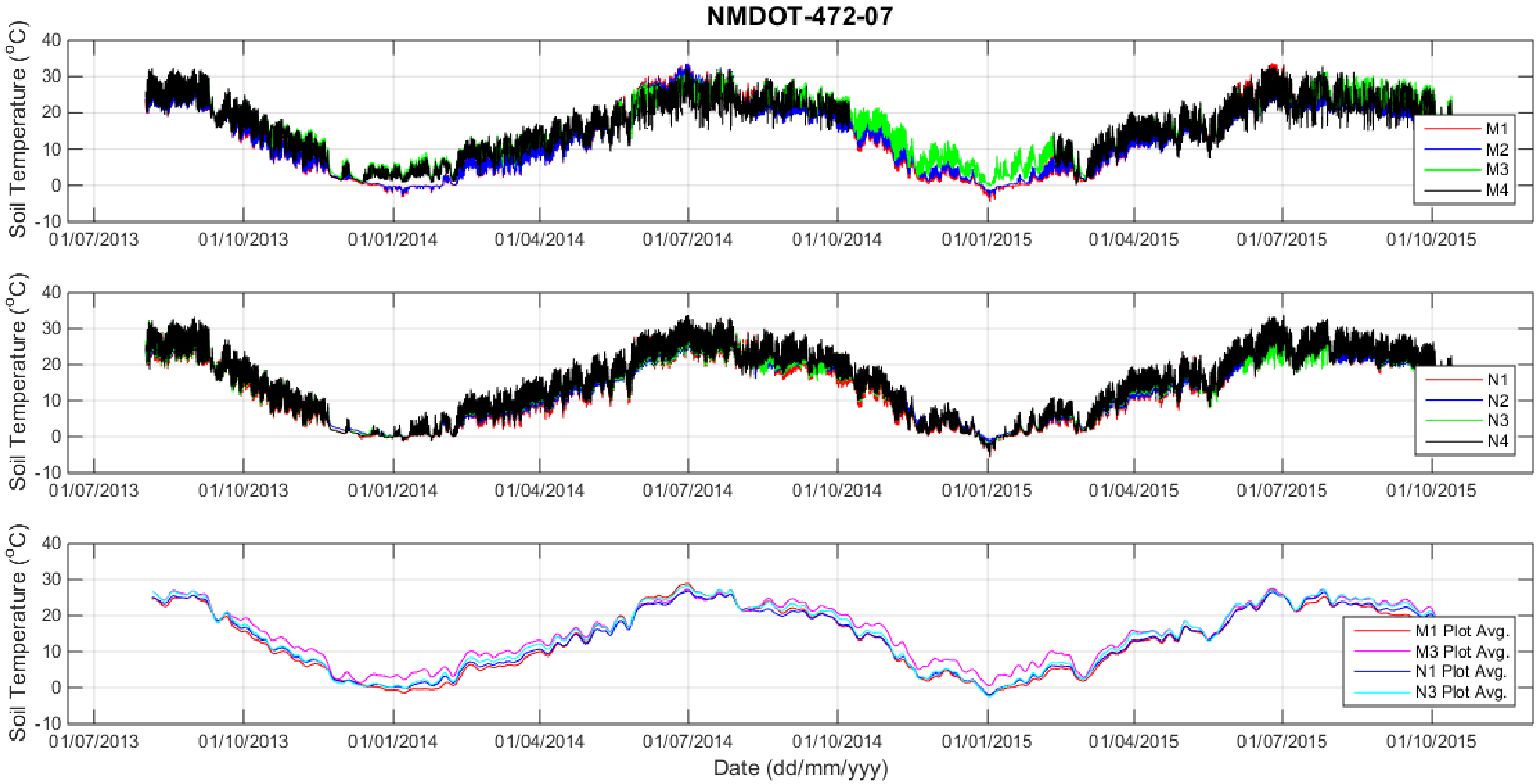


Figure A-12: NMDOT ROW Test Plot 472-07 Soil Moisture

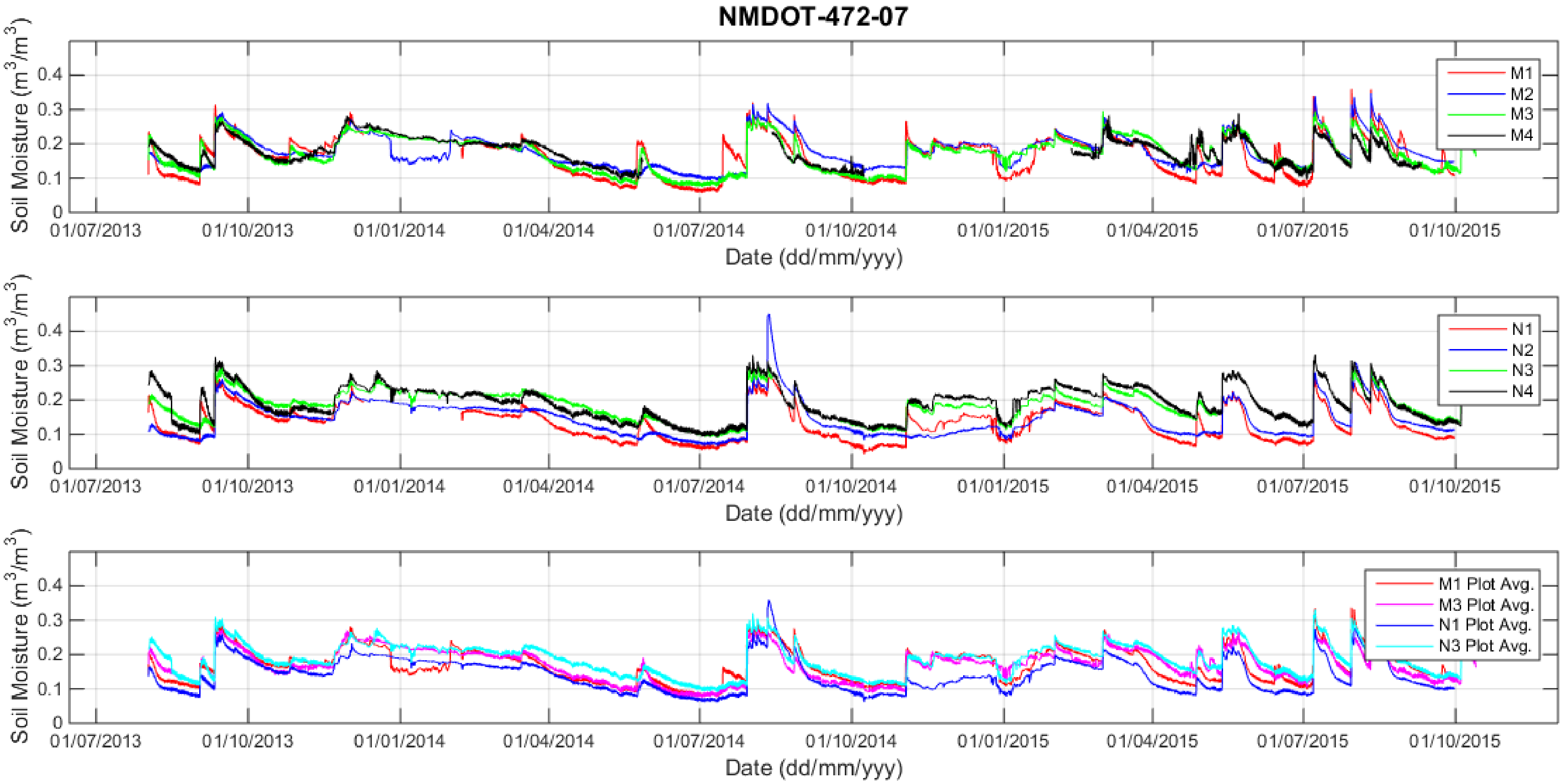


Figure A-13: NMDOT ROW Test Plot 537-43 Soil Temperature

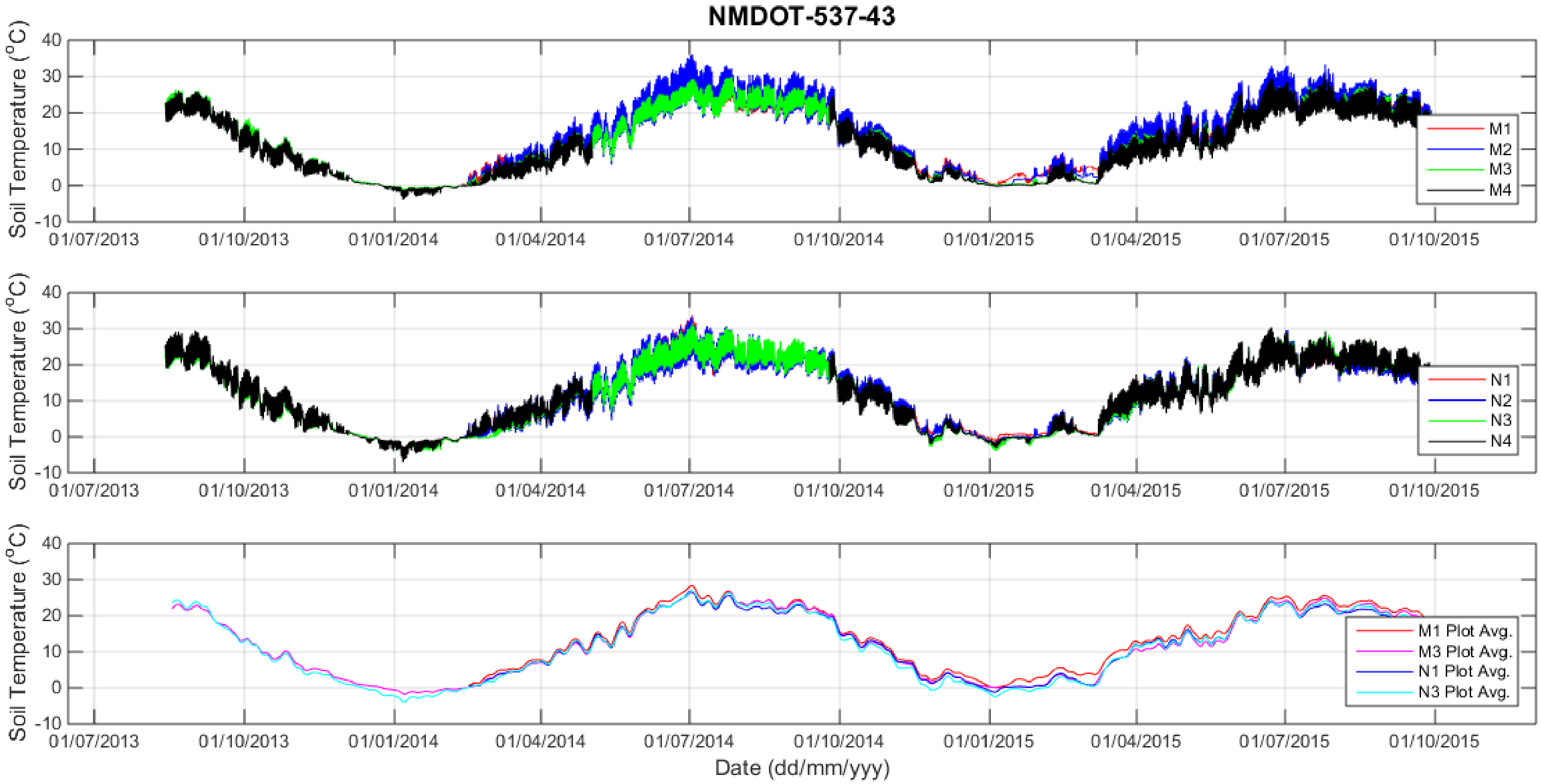


Figure A-14: NMDOT ROW Test Plot 537-43 Soil Moisture

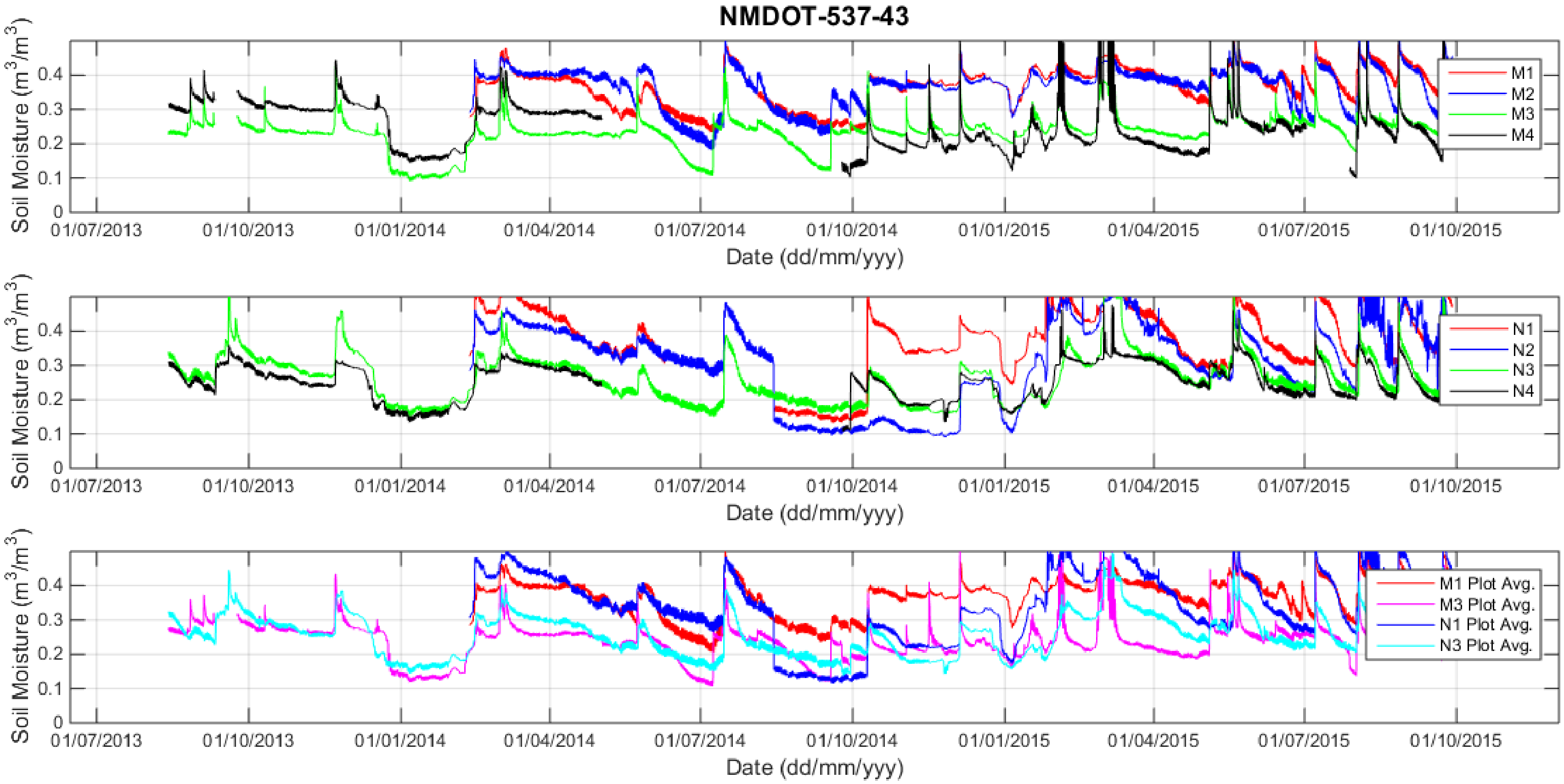


Figure A-15: NMDOT ROW Test Plot 555-12 Soil Temperature

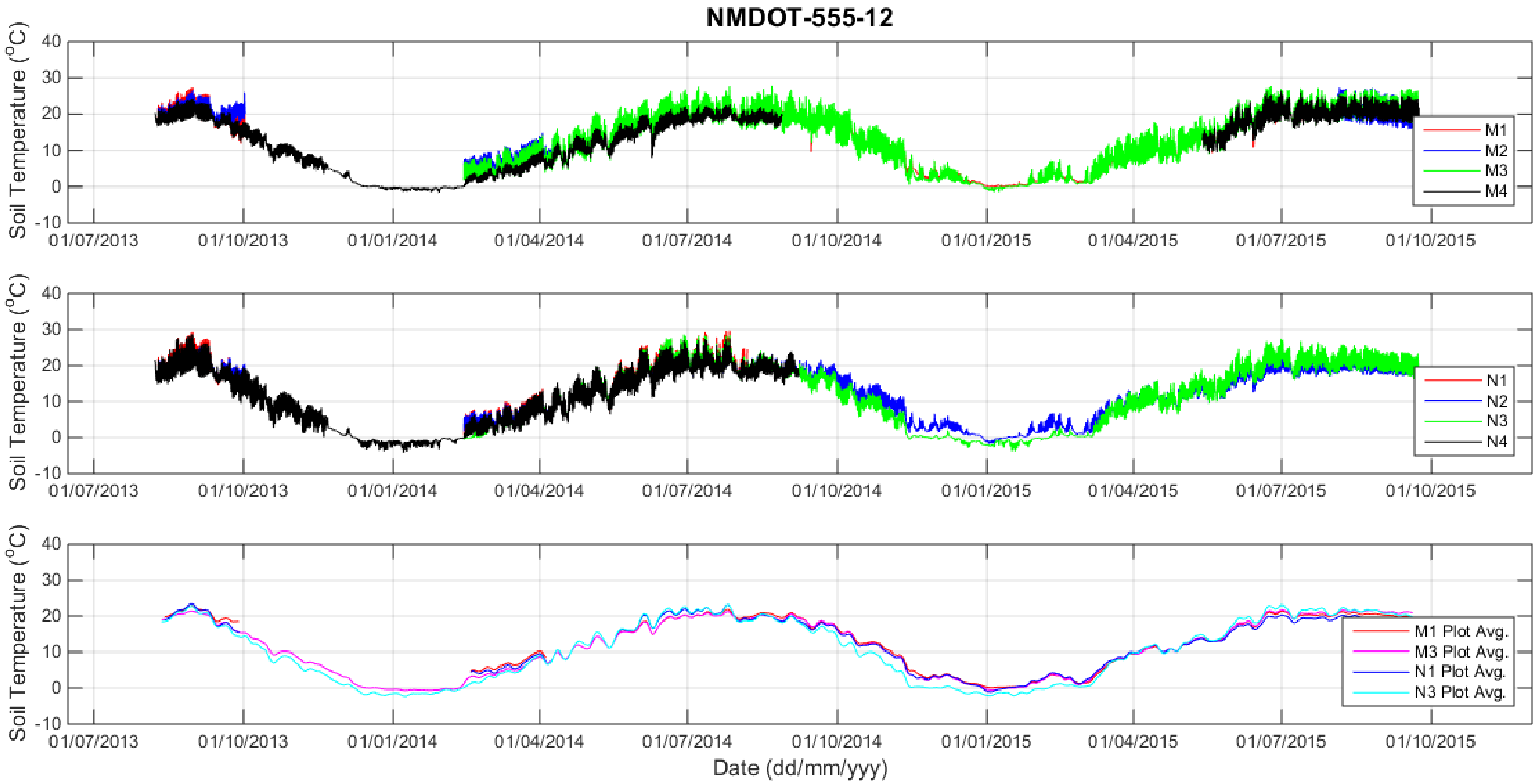
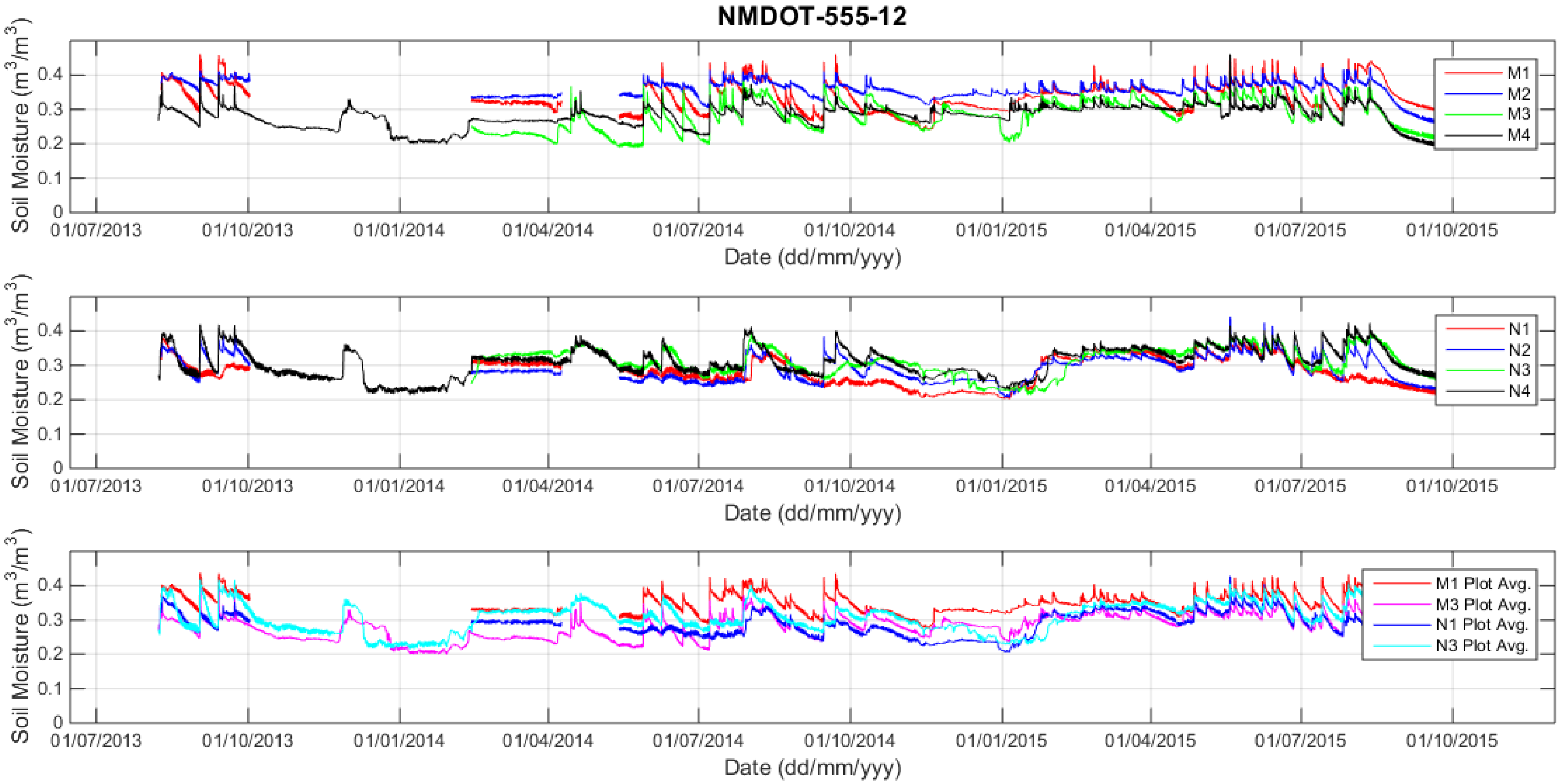


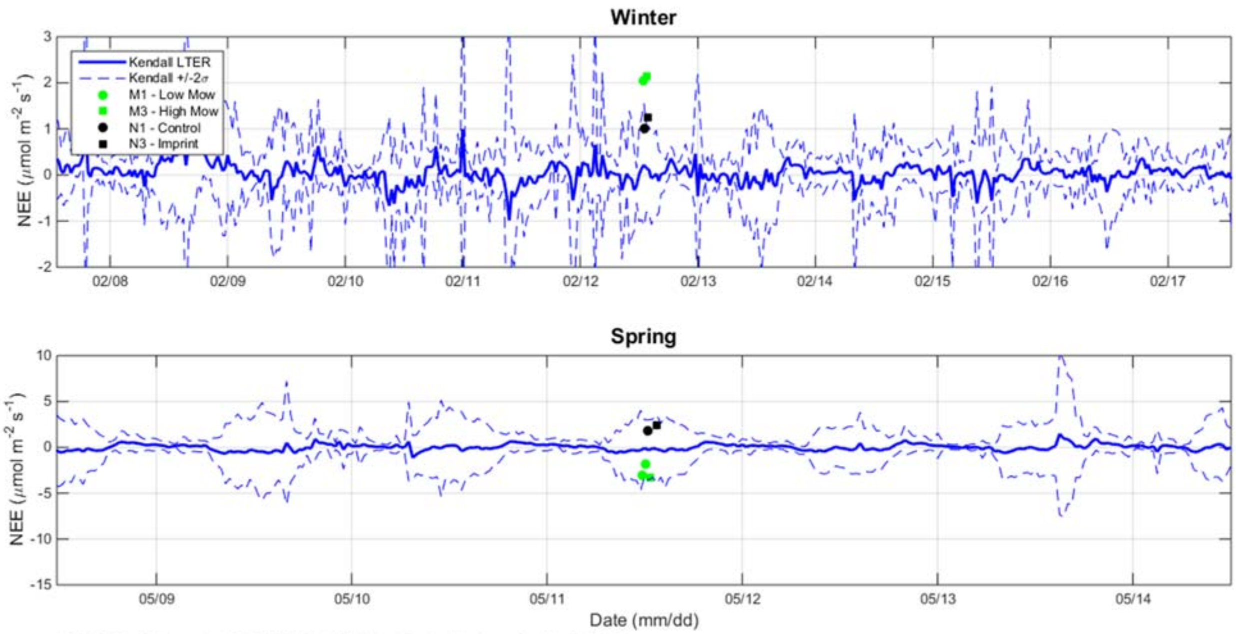
Figure A-16: NMDOT ROW Test Plot 555-12 Soil Moisture



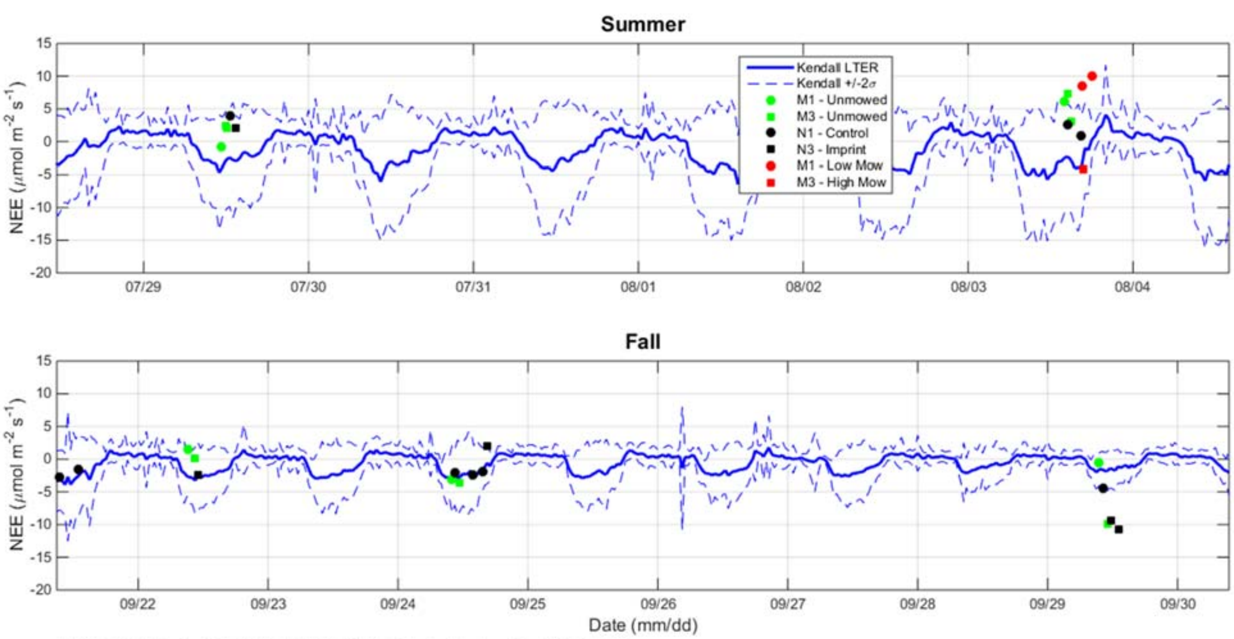
APPENDIX B

Seasonal ROW Test Plot Surface CO_2 Flux Summary Summaries

Figure B-1: Seasonal Fluxes Measured at 021-15 versus Kendall Station

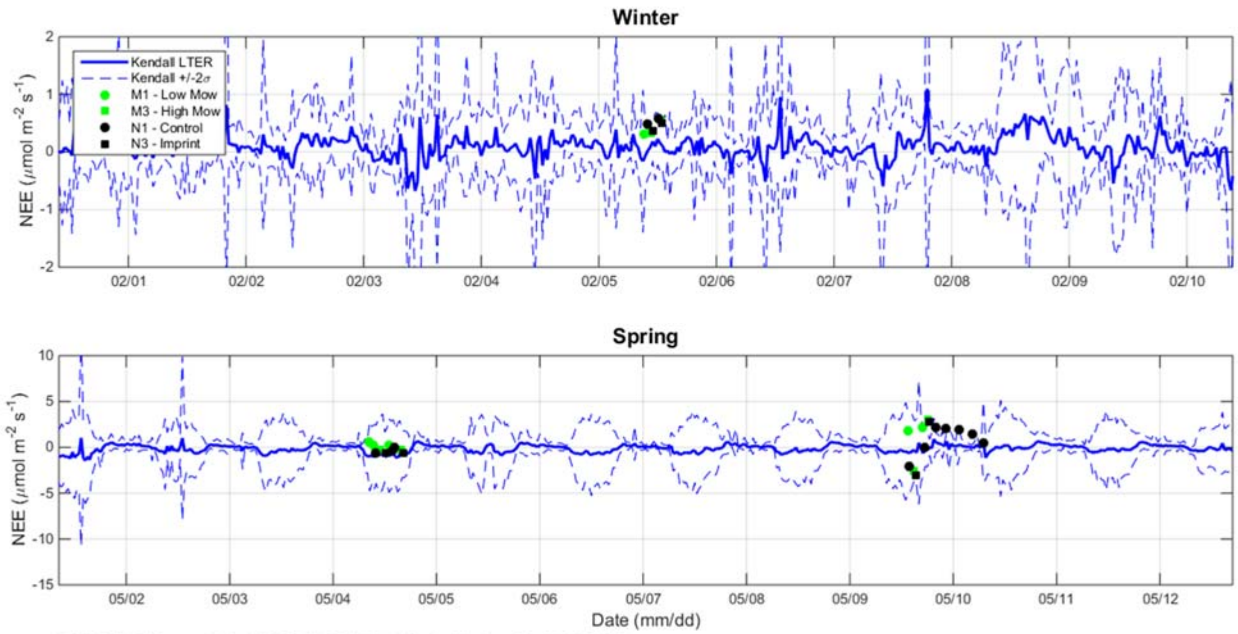


NMDOT_021_15_flux_tseries1.fig, NMDOT_021_15_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

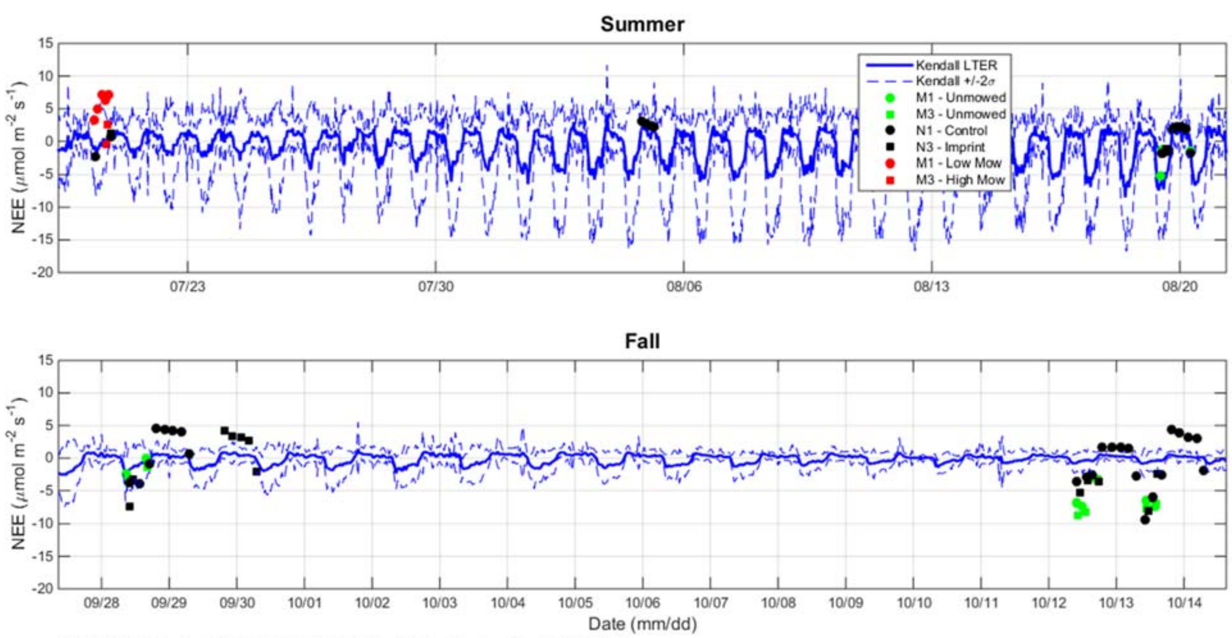


NMDOT_021_15_flux_tseries2.fig, NMDOT_021_15_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

Figure B-2: Seasonal Fluxes Measured at 104-79 versus Kendall Station

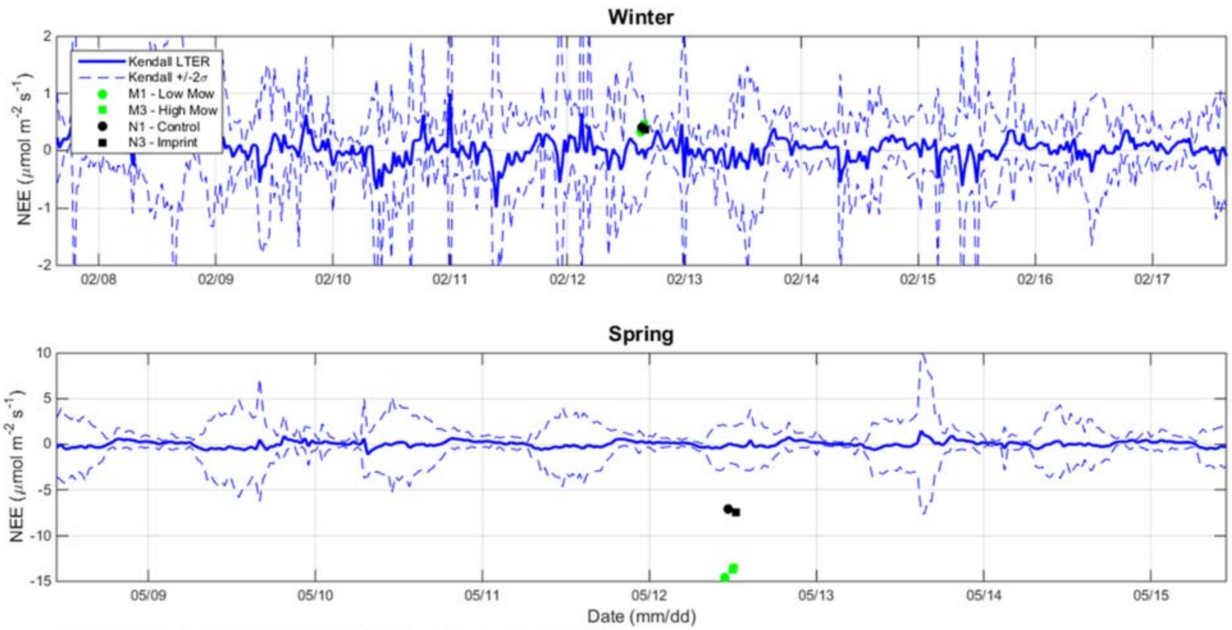


NMDOT_104_79_flux_tseries1.fig, NMDOT_104_79_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

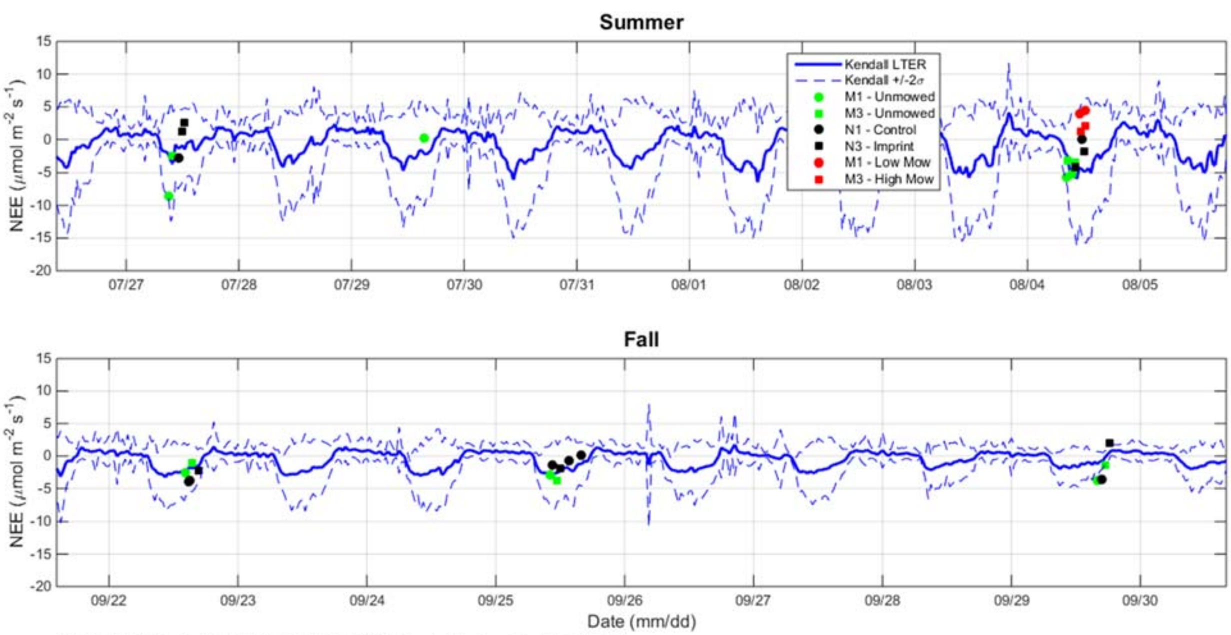


NMDOT_104_79_flux_tseries2.fig, NMDOT_104_79_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

Figure B-3: Seasonal Fluxes Measured at 120-31 versus Kendall Station

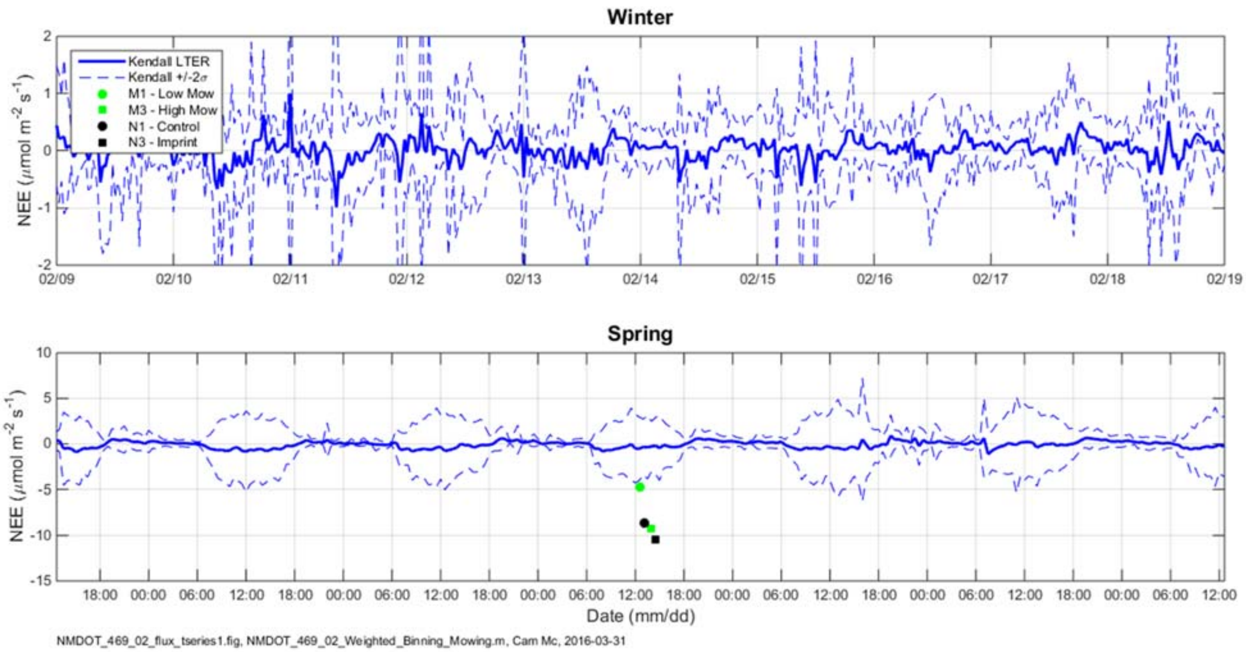


NMDOT_120_31_flux_tseries1.fig, NMDOT_120_31_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31



NMDOT_120_31_flux_tseries2.fig, NMDOT_120_31_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

Figure B-4: Seasonal Fluxes Measured at 469-02 versus Kendall Station



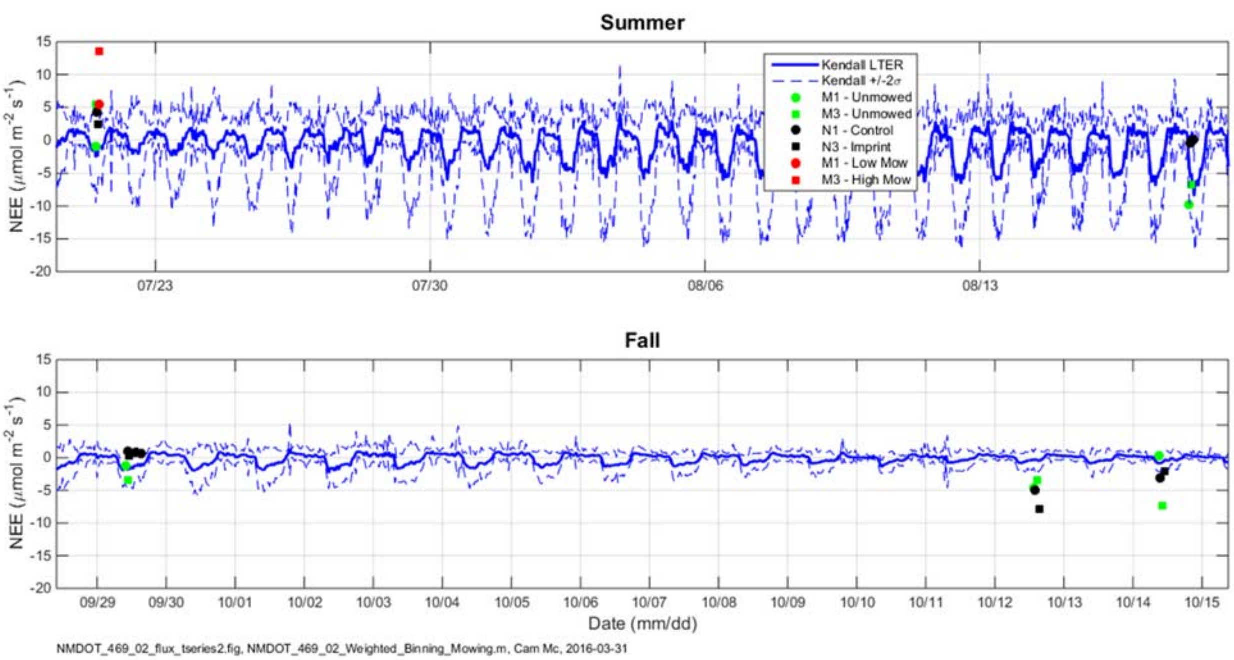
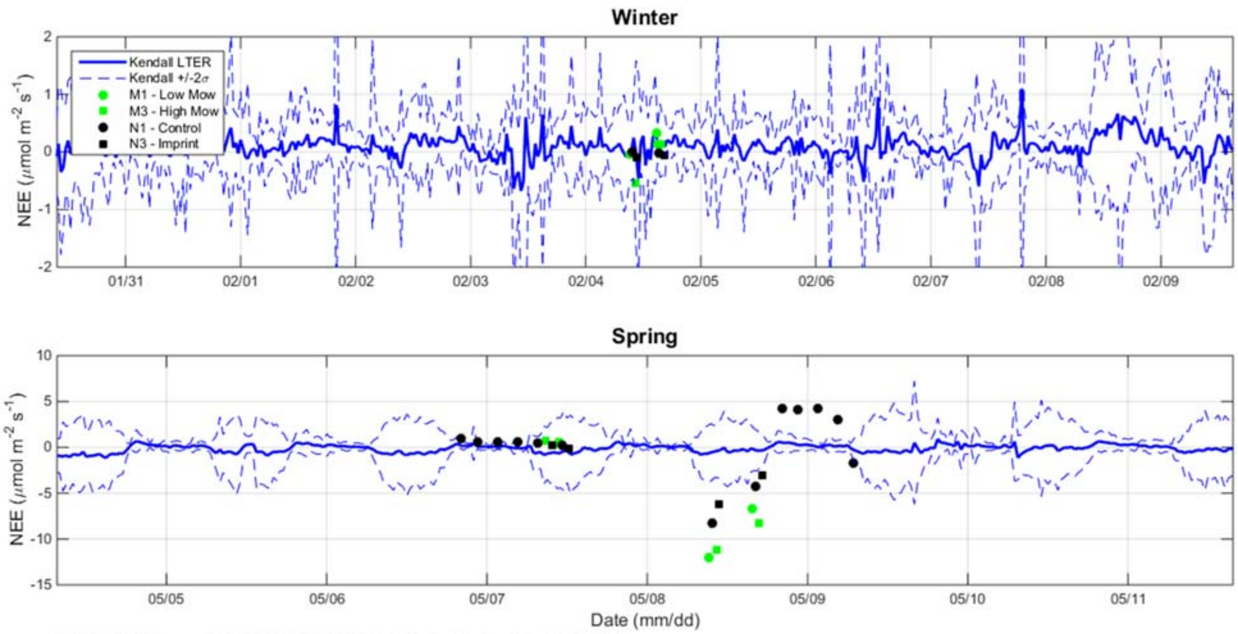
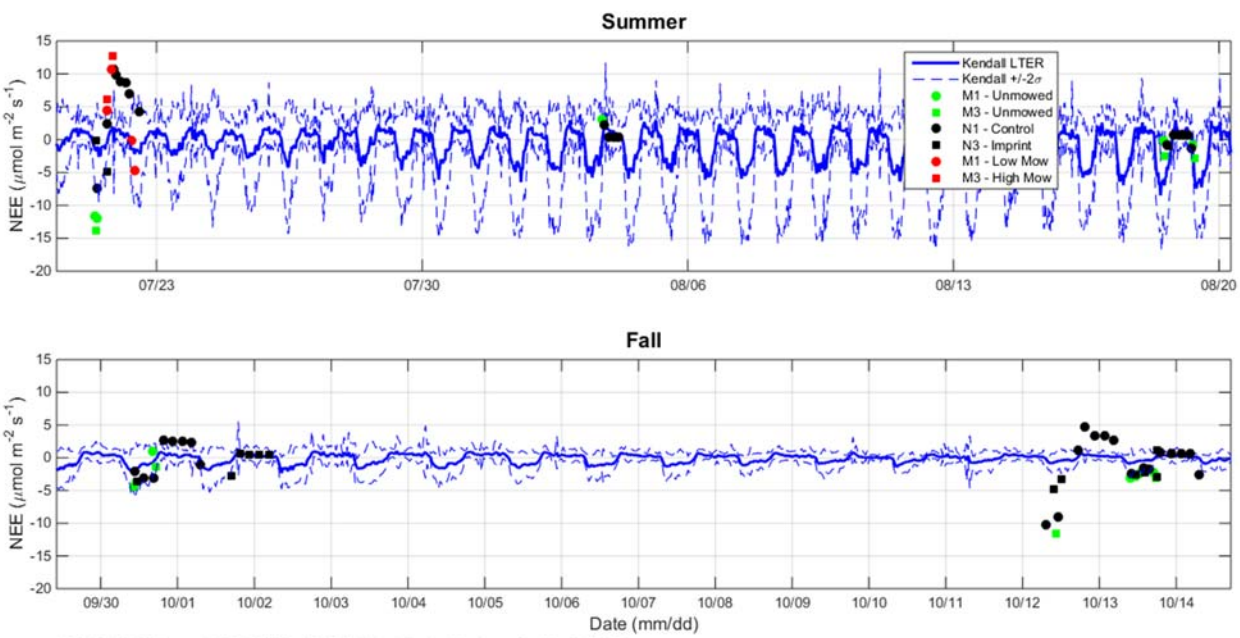


Figure B-5: Seasonal Fluxes Measured at 469-39 versus Kendall Station

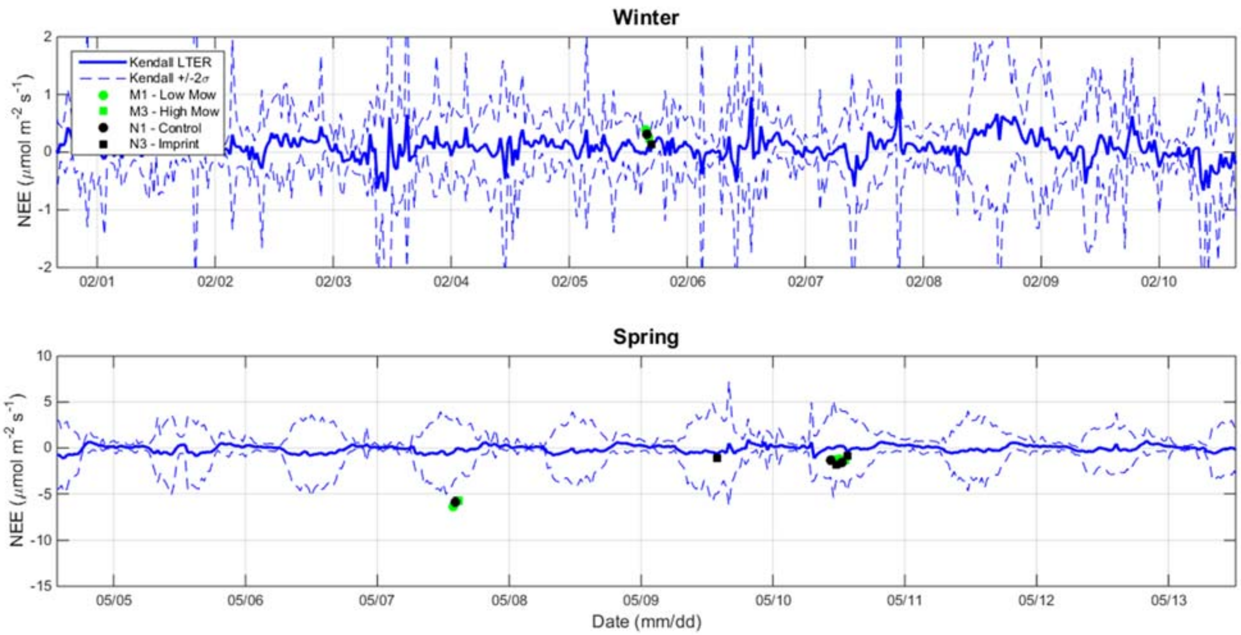


NMDOT_469_39_flux_tseries1.fig, NMDOT_469_39_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

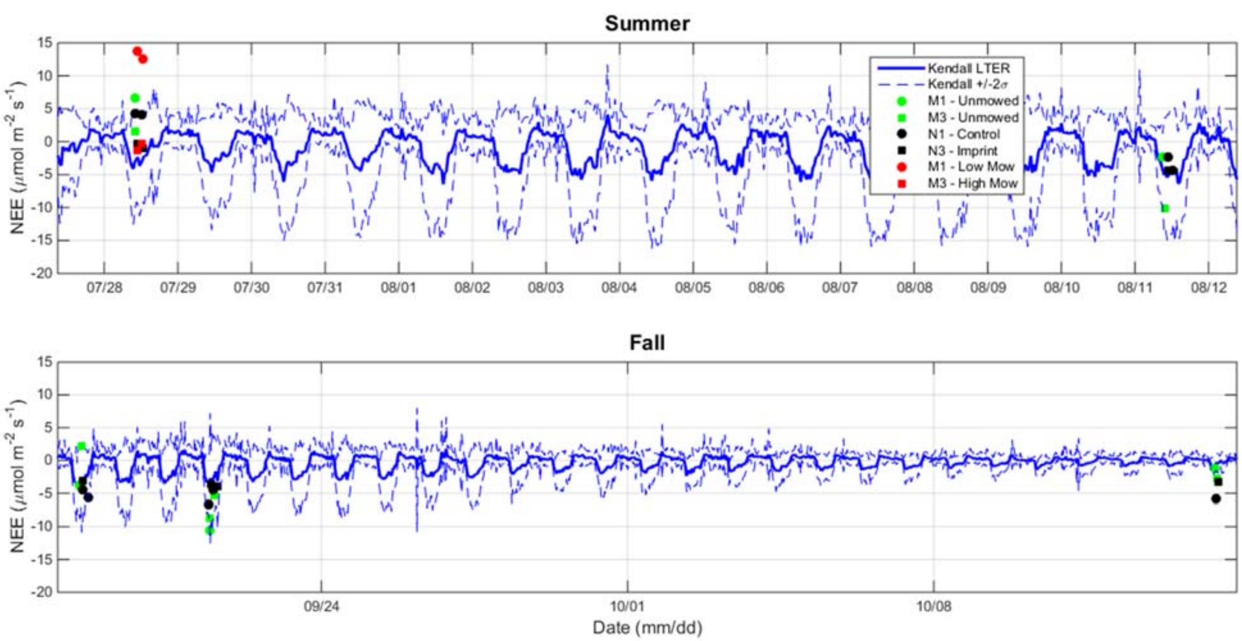


NMDOT_469_39_flux_tseries2.fig, NMDOT_469_39_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

Figure B-6: Seasonal Fluxes Measured at 472-07 versus Kendall Station

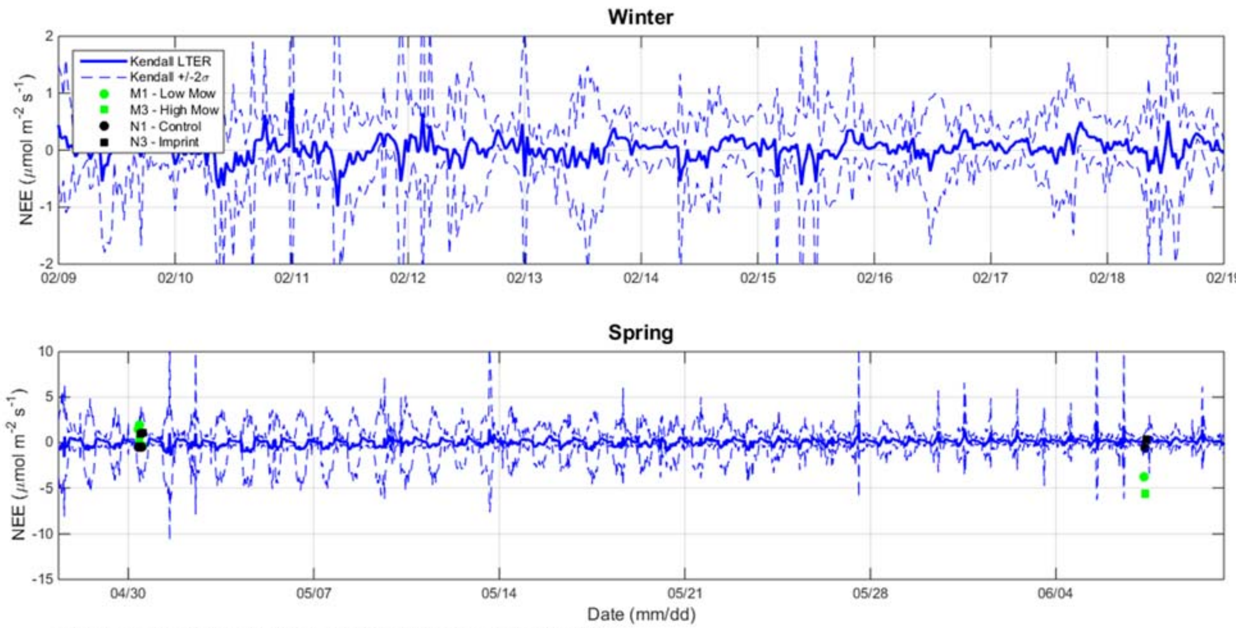


NMDOT_472_07_flux_tseries1.fig, NMDOT_472_07_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

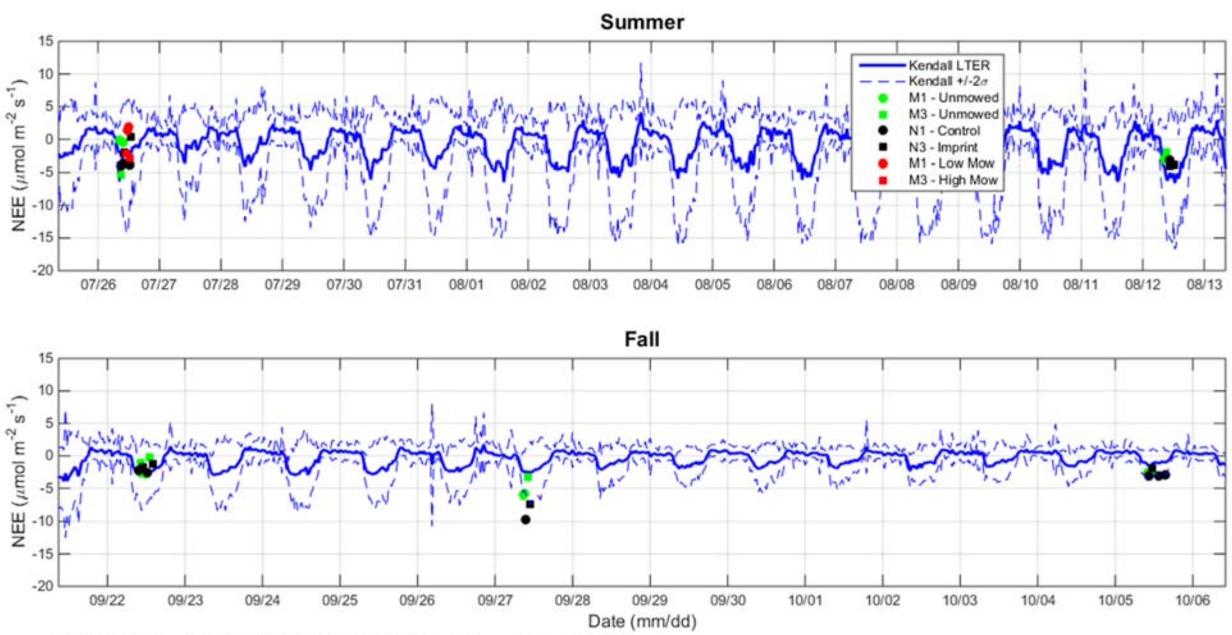


NMDOT_472_07_flux_tseries2.fig, NMDOT_472_07_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

Figure B-7: Seasonal Fluxes Measured at 537-43 versus Kendall Station

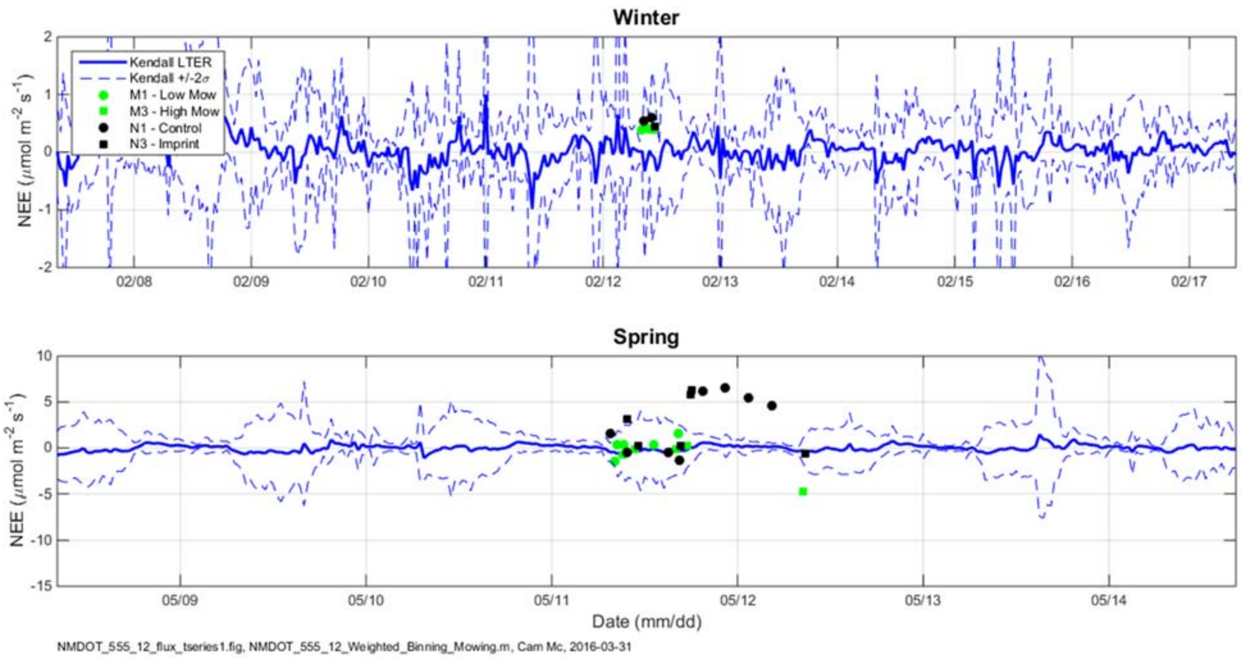


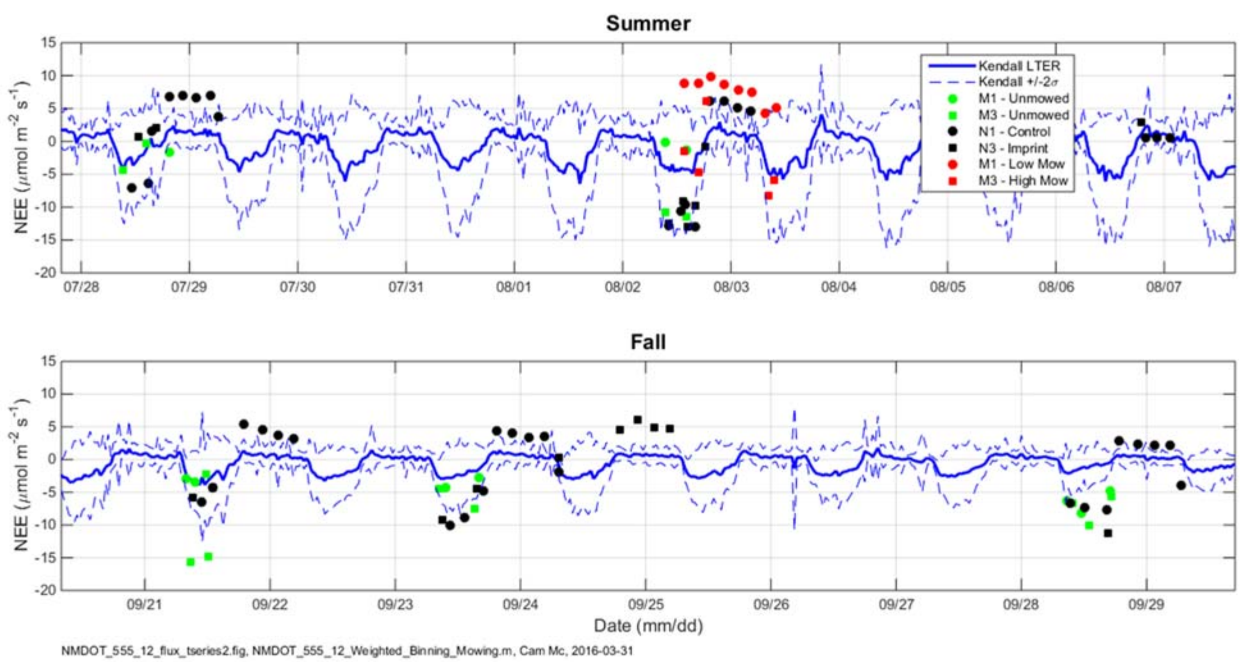
NMDOT_537_43_flux_tseries1.fig, NMDOT_537_43_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31



NMDOT_537_43_flux_tseries2.fig, NMDOT_537_43_Weighted_Binning_Mowing.m, Cam Mc, 2016-03-31

Figure B-8: Seasonal Fluxes Measured at 555-12 versus Kendall Station





APPENDIX C

Comparison of Observed NEE to Kendall LTER Station Data

Figure C-1: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 021-31

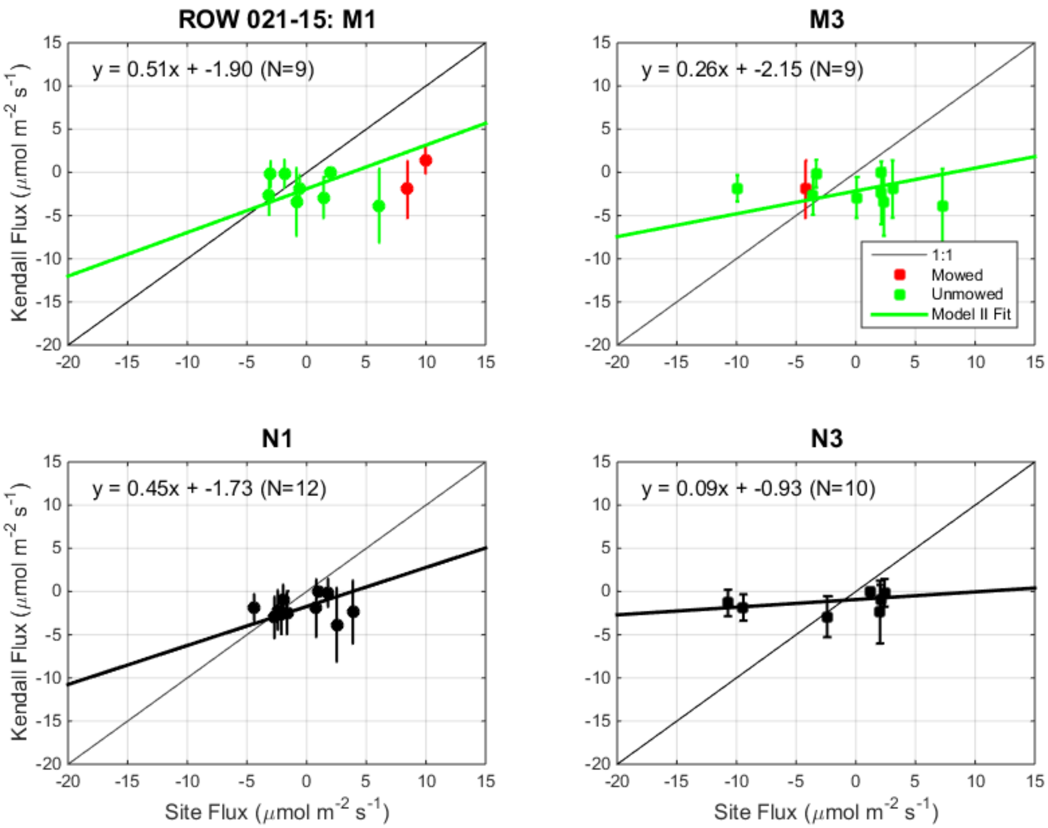


Figure C-2: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 104-79

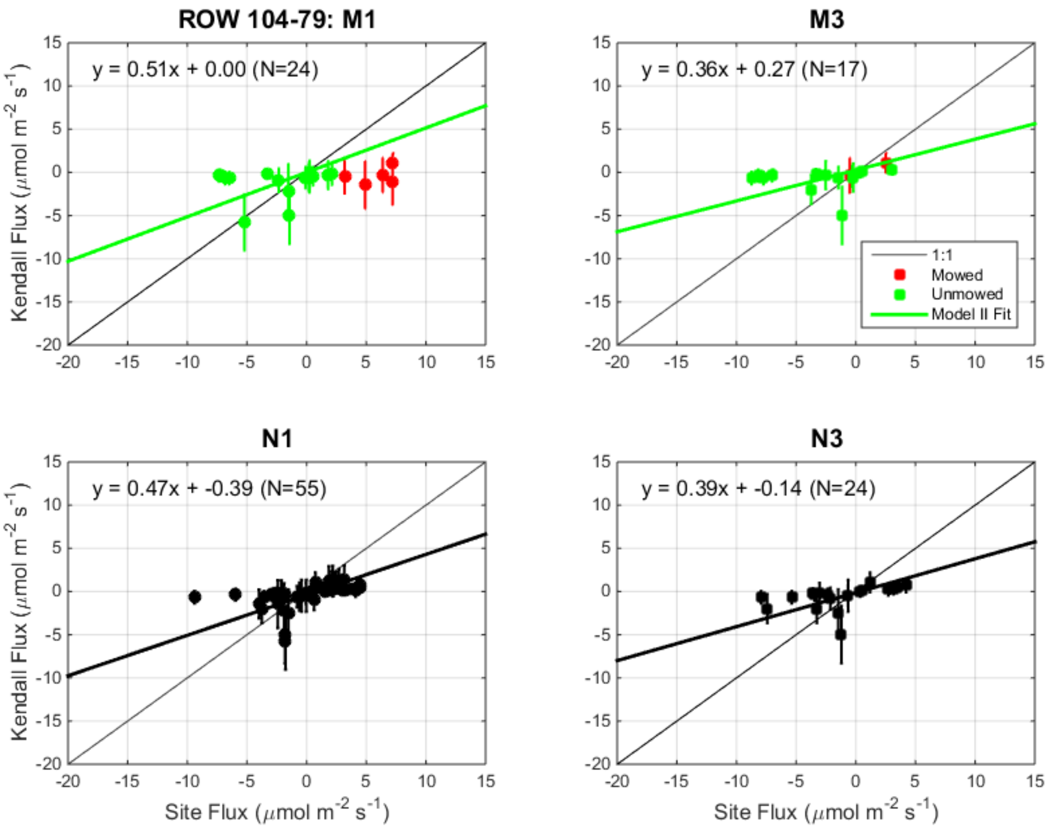


Figure C-3: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 120-31

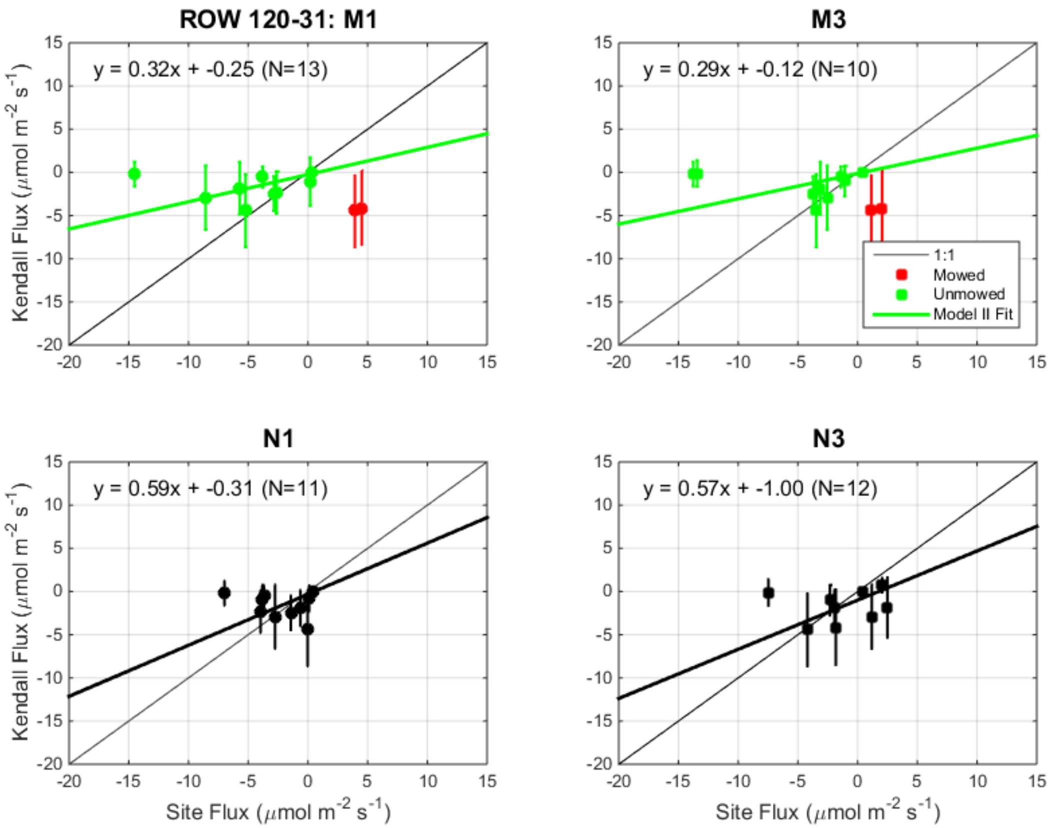


Figure C-4: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 469-02

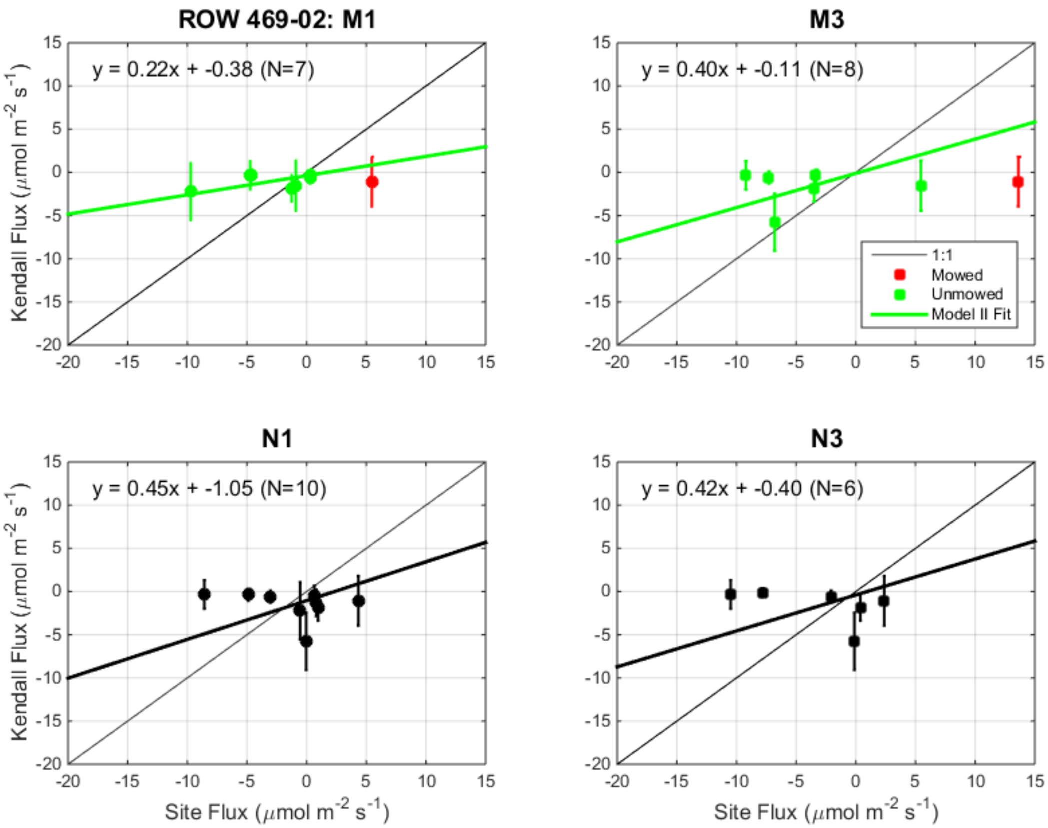


Figure C-5: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 469-39

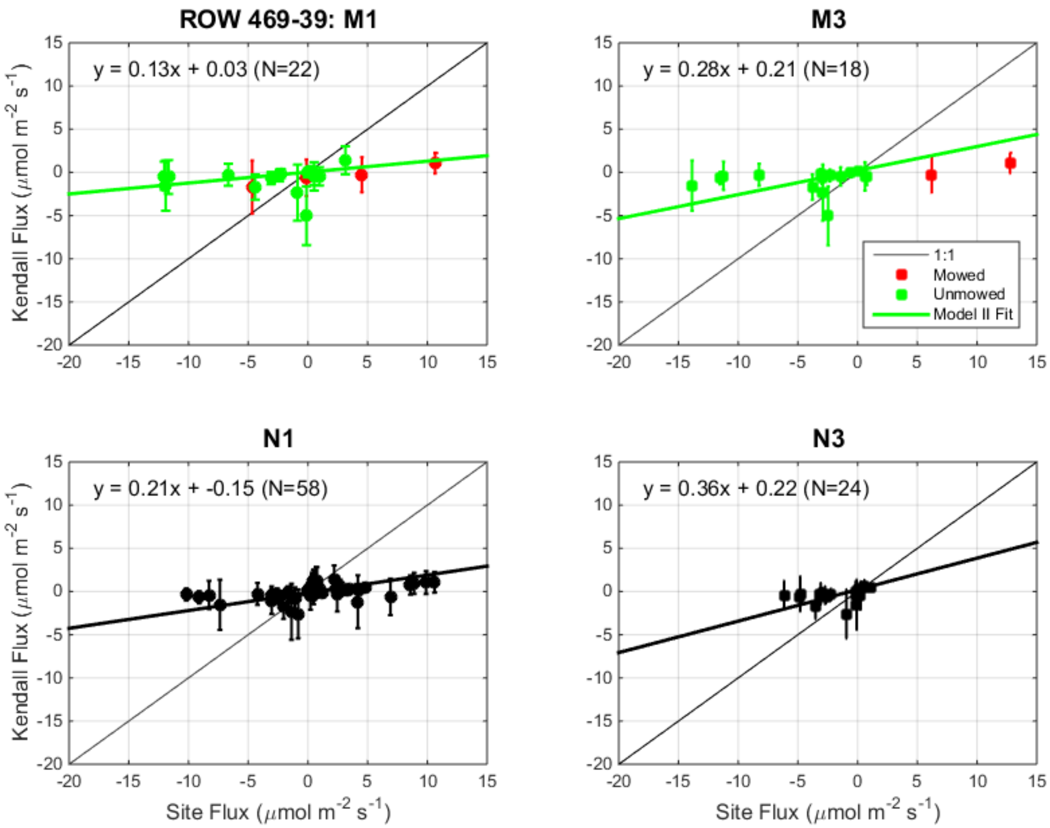


Figure C-6: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 472-07

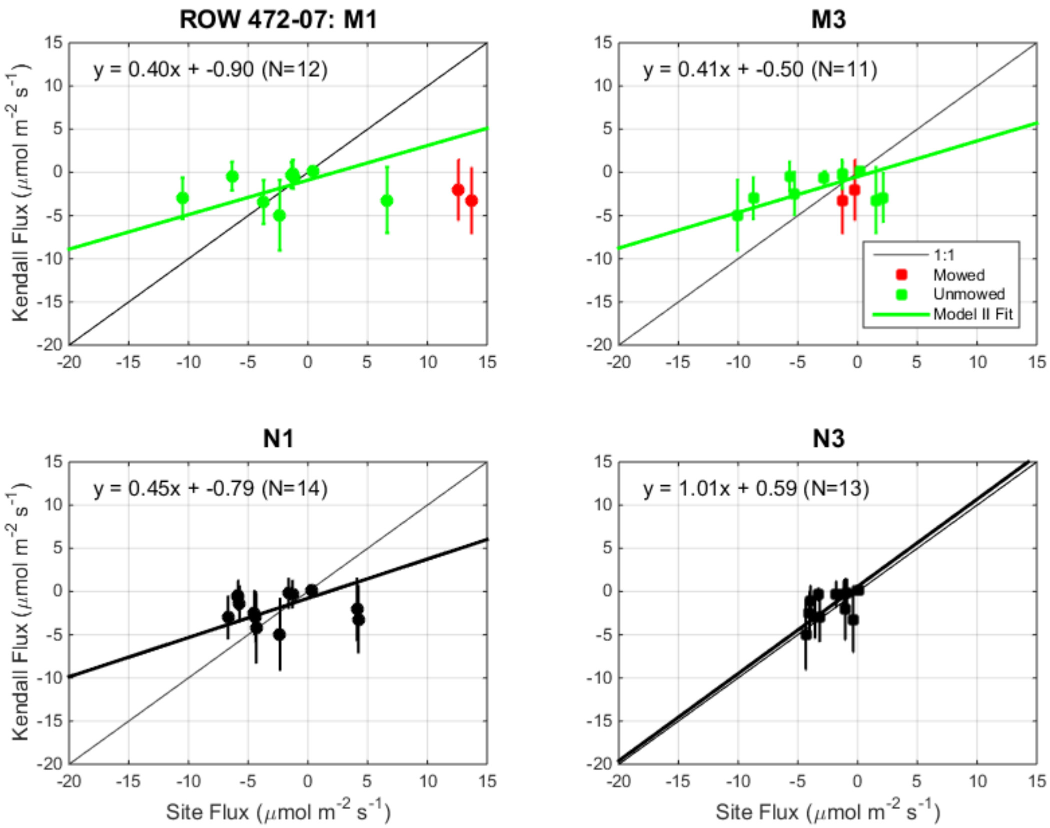


Figure C-7: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 537-43

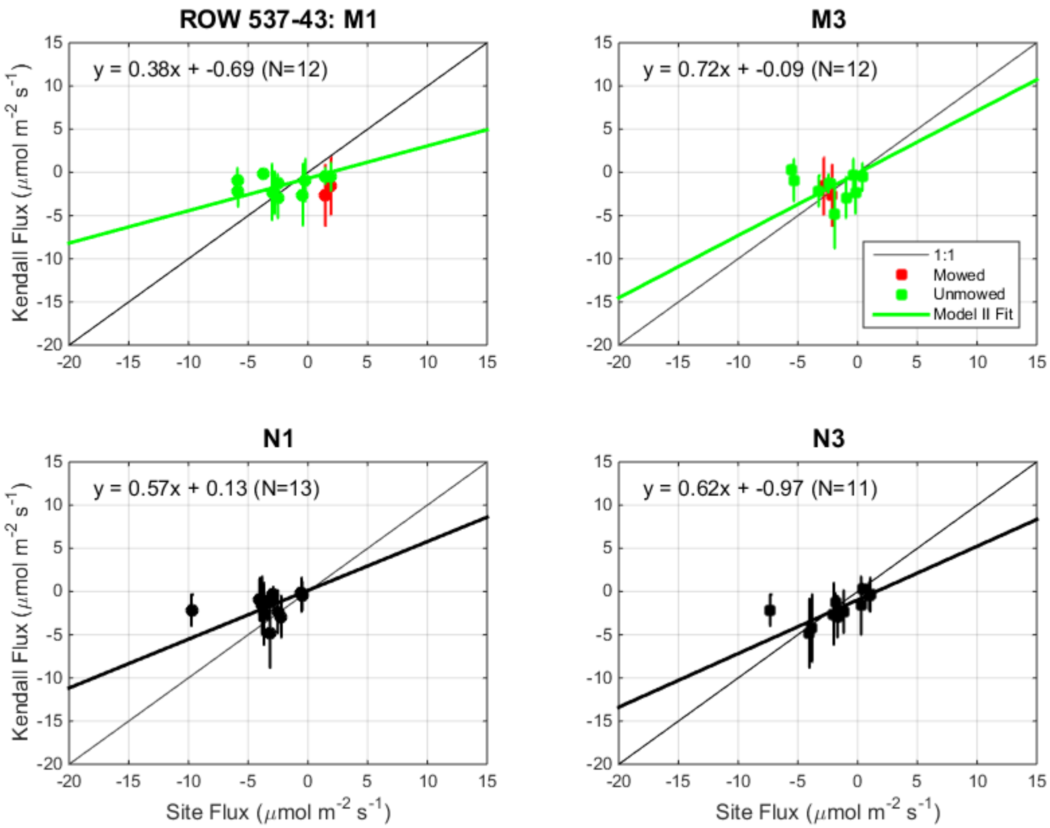
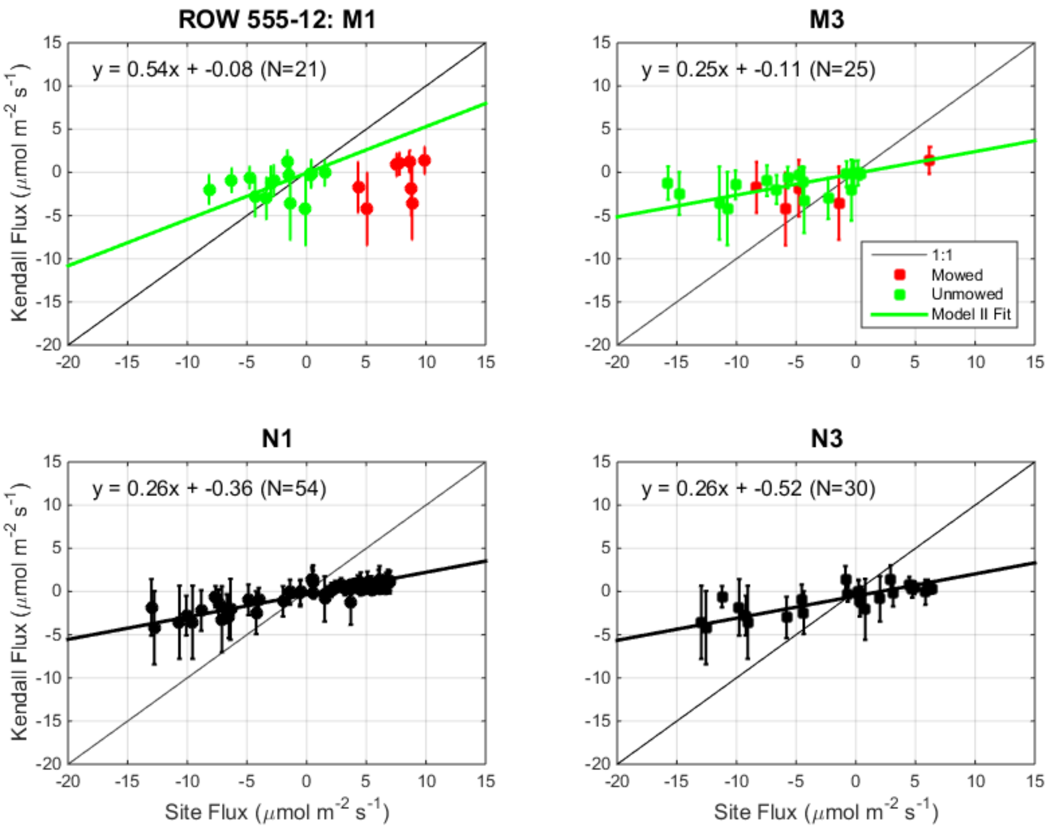


Figure C-8: Kendall Station NEE versus Mowed and Unmowed Observed NEE, Test Plot 555-12



APPENDIX D

Model Validation

Figure D-1. Detailed predicted versus observed NEE at 021-15 for M1 treatment.

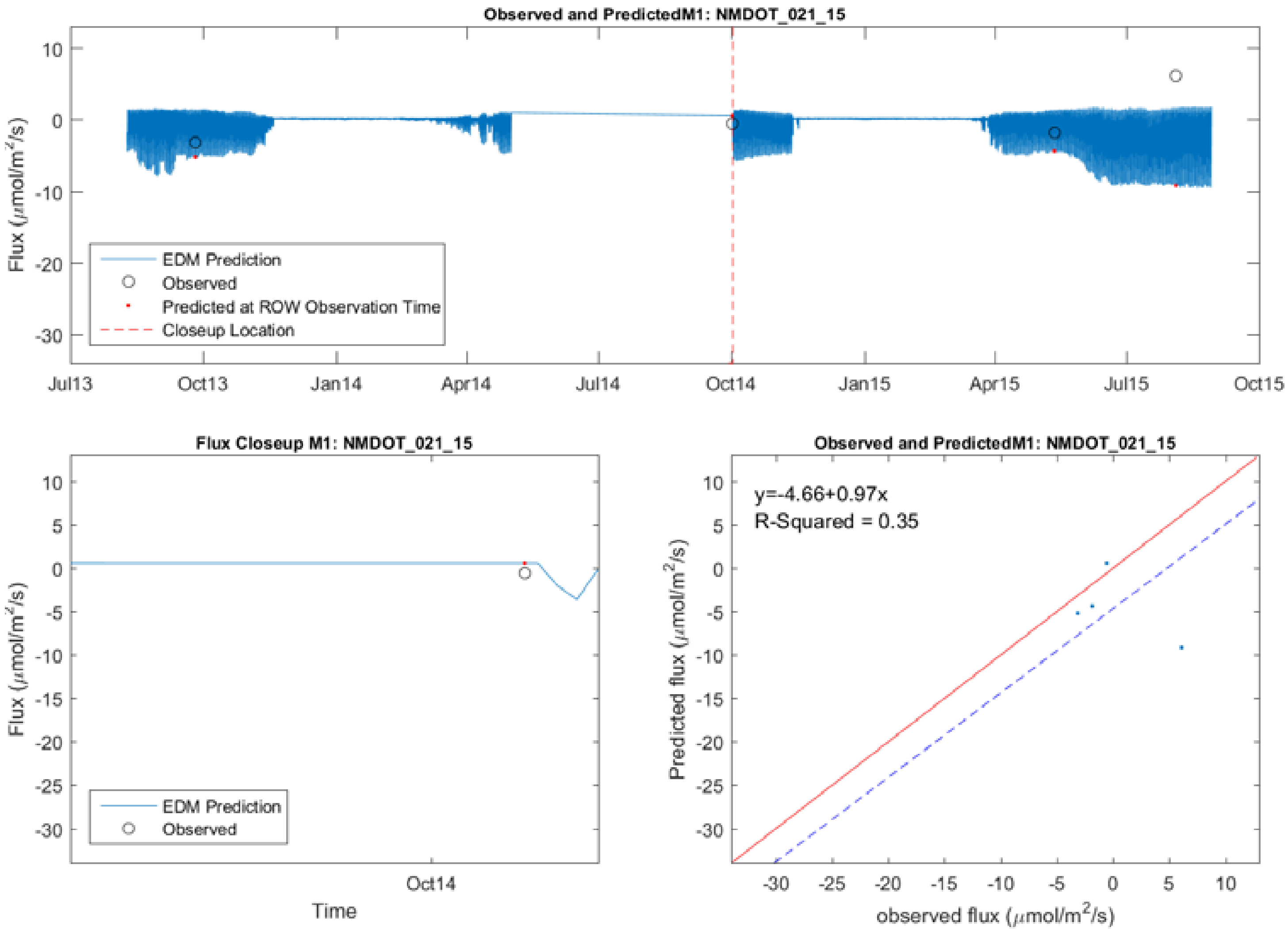


Figure D-2. Detailed predicted versus observed NEE at 021-15 for M3 treatment.

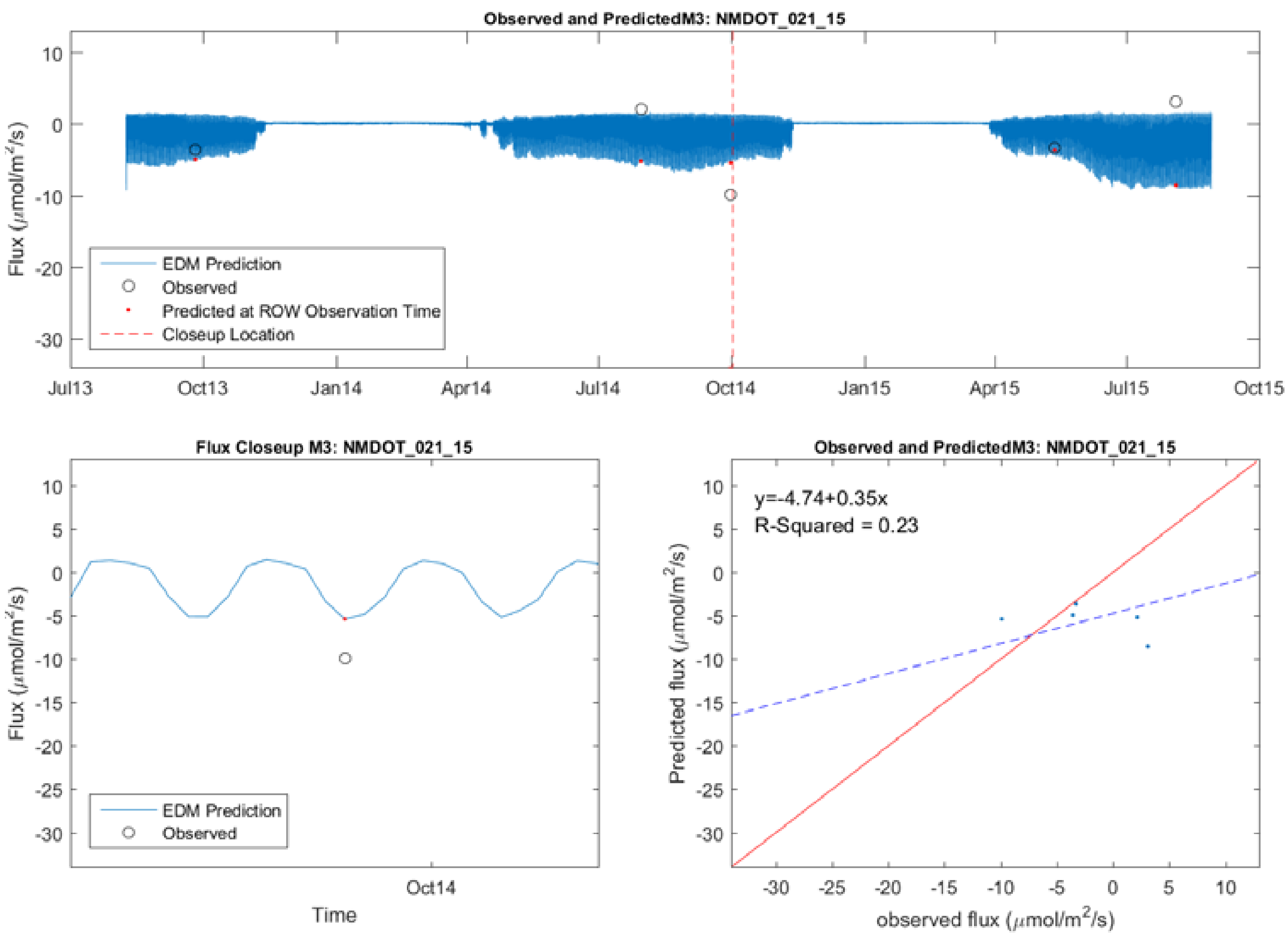


Figure D-3. Detailed predicted versus observed NEE at 021-15 for N1 treatment.

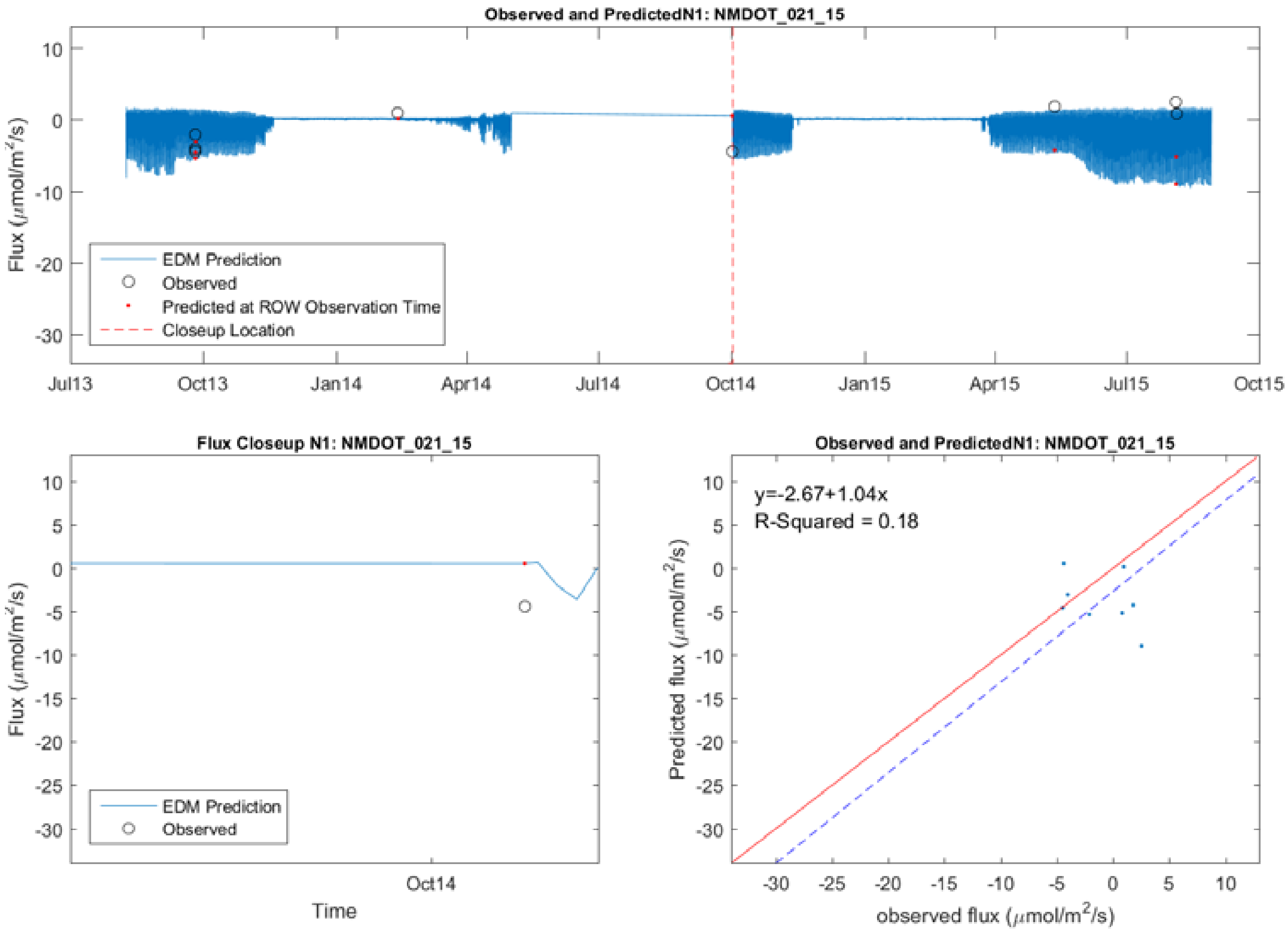


Figure D-4. Detailed predicted versus observed NEE at 021-15 for N3 treatment.

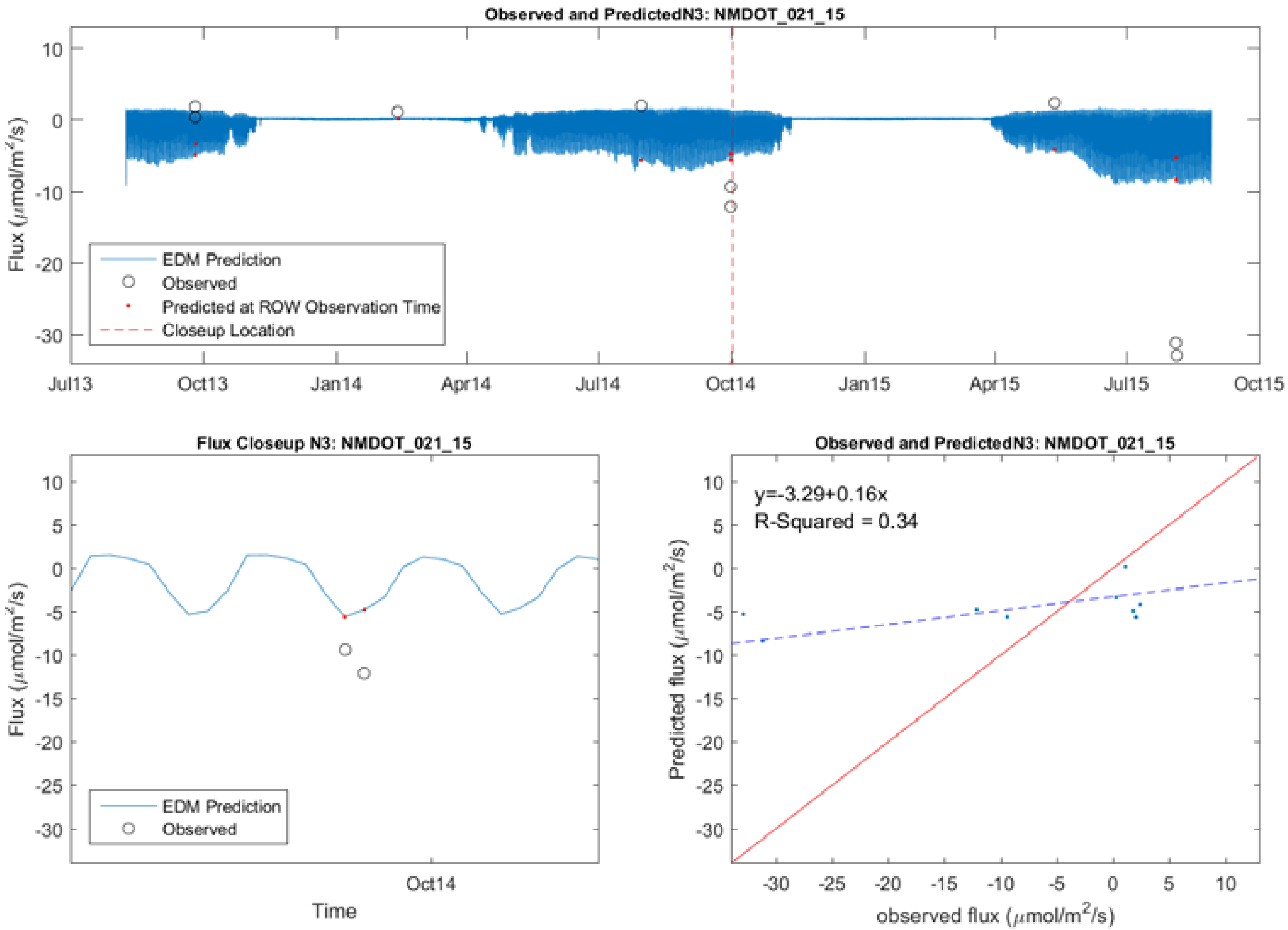


Figure D-5. Detailed predicted versus observed NEE at 104-79 for M1 treatment.

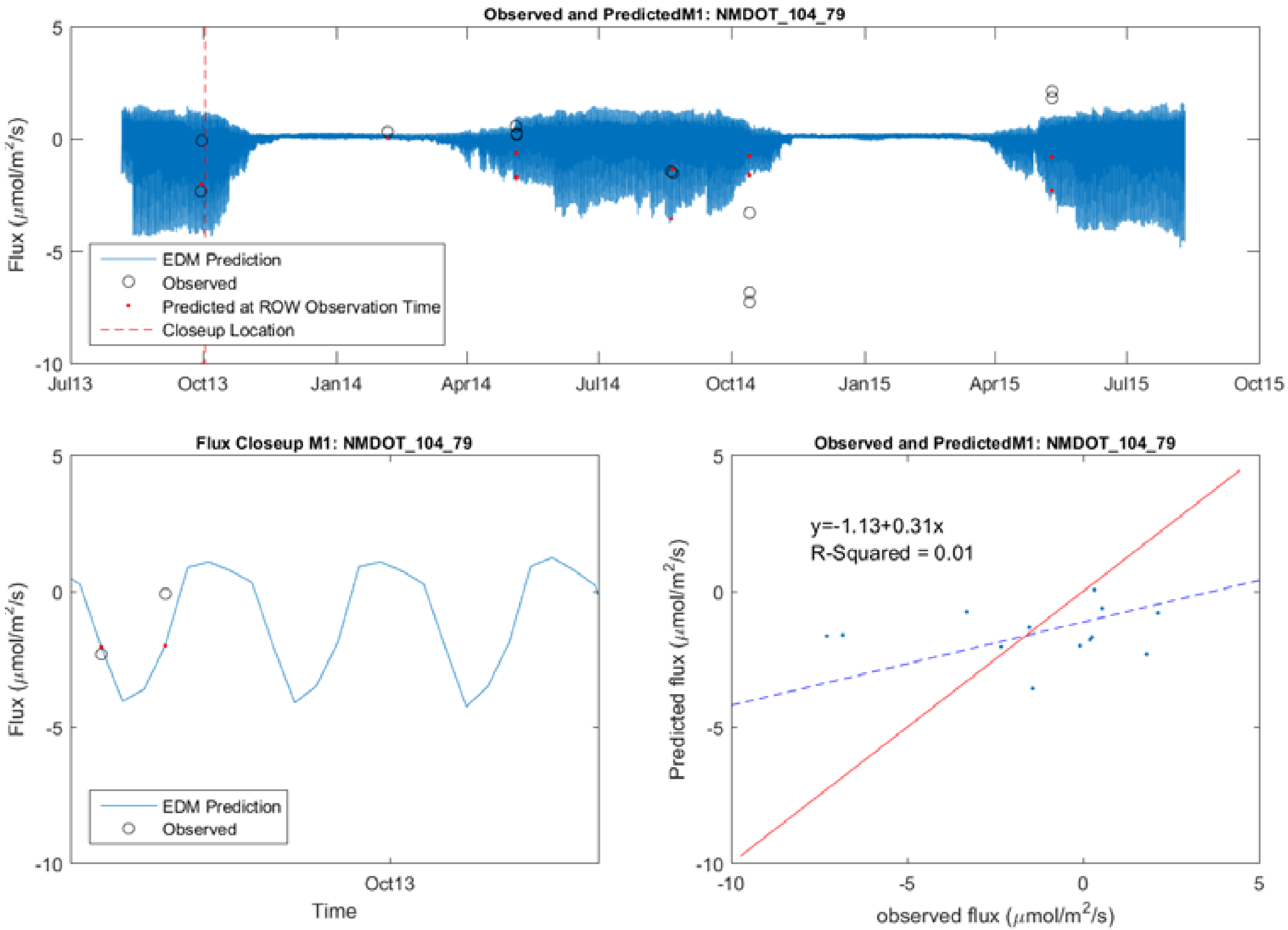


Figure D-6. Detailed predicted versus observed NEE at 104-79 for M3 treatment.

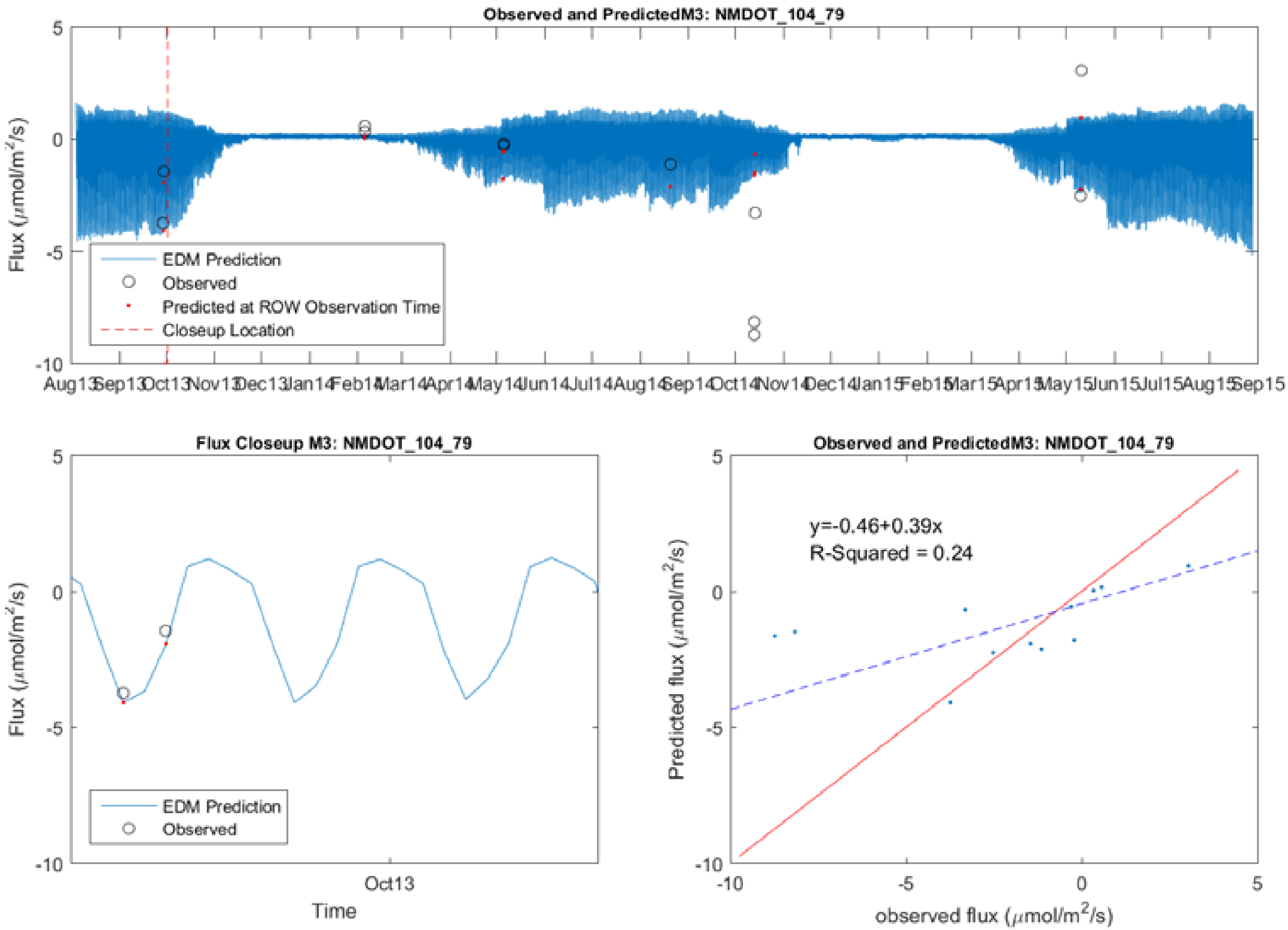


Figure D-7. Detailed predicted versus observed NEE at 104-79 for N1 treatment.

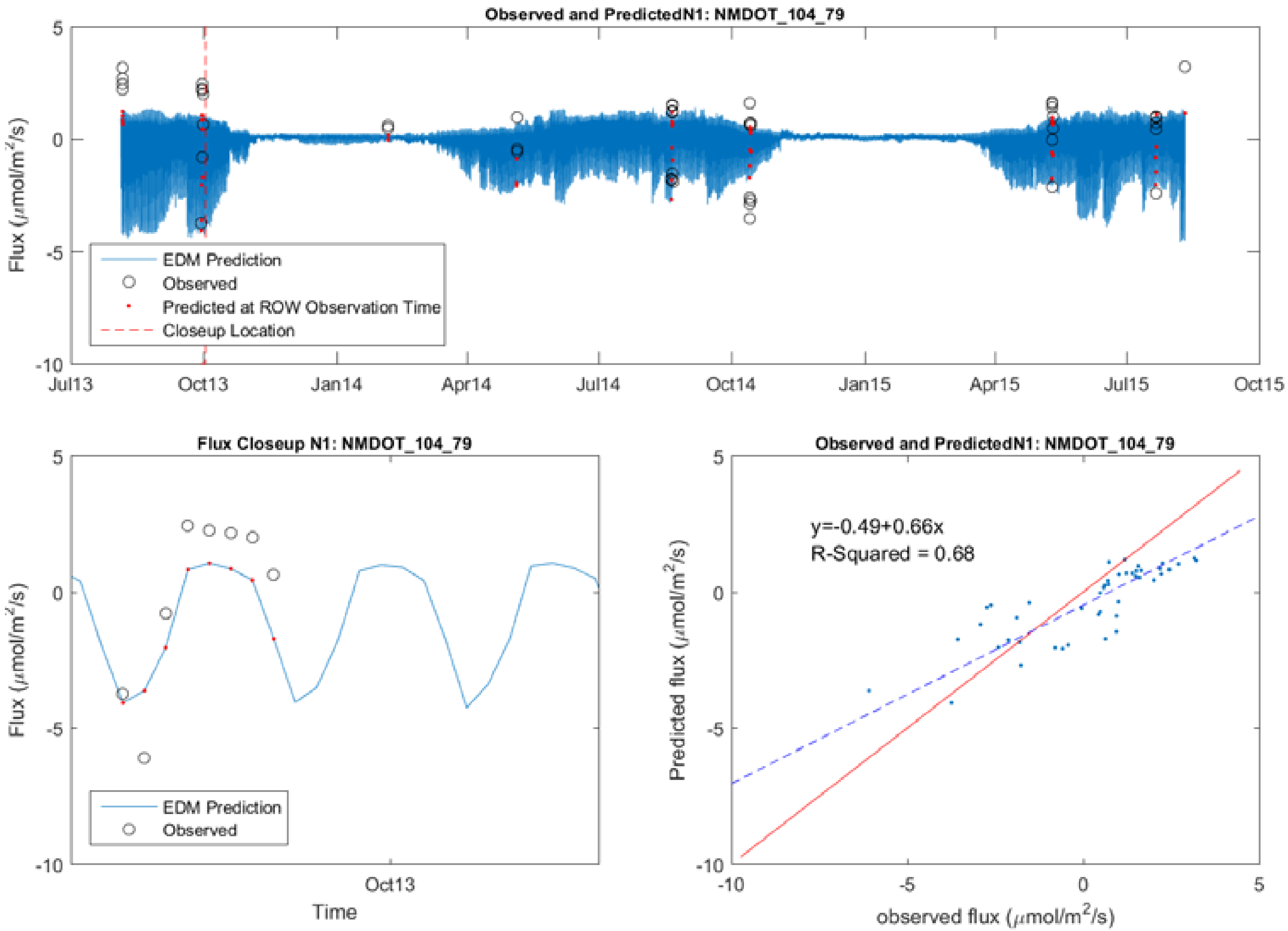


Figure D-8. Detailed predicted versus observed NEE at 104-79 for N3 treatment.

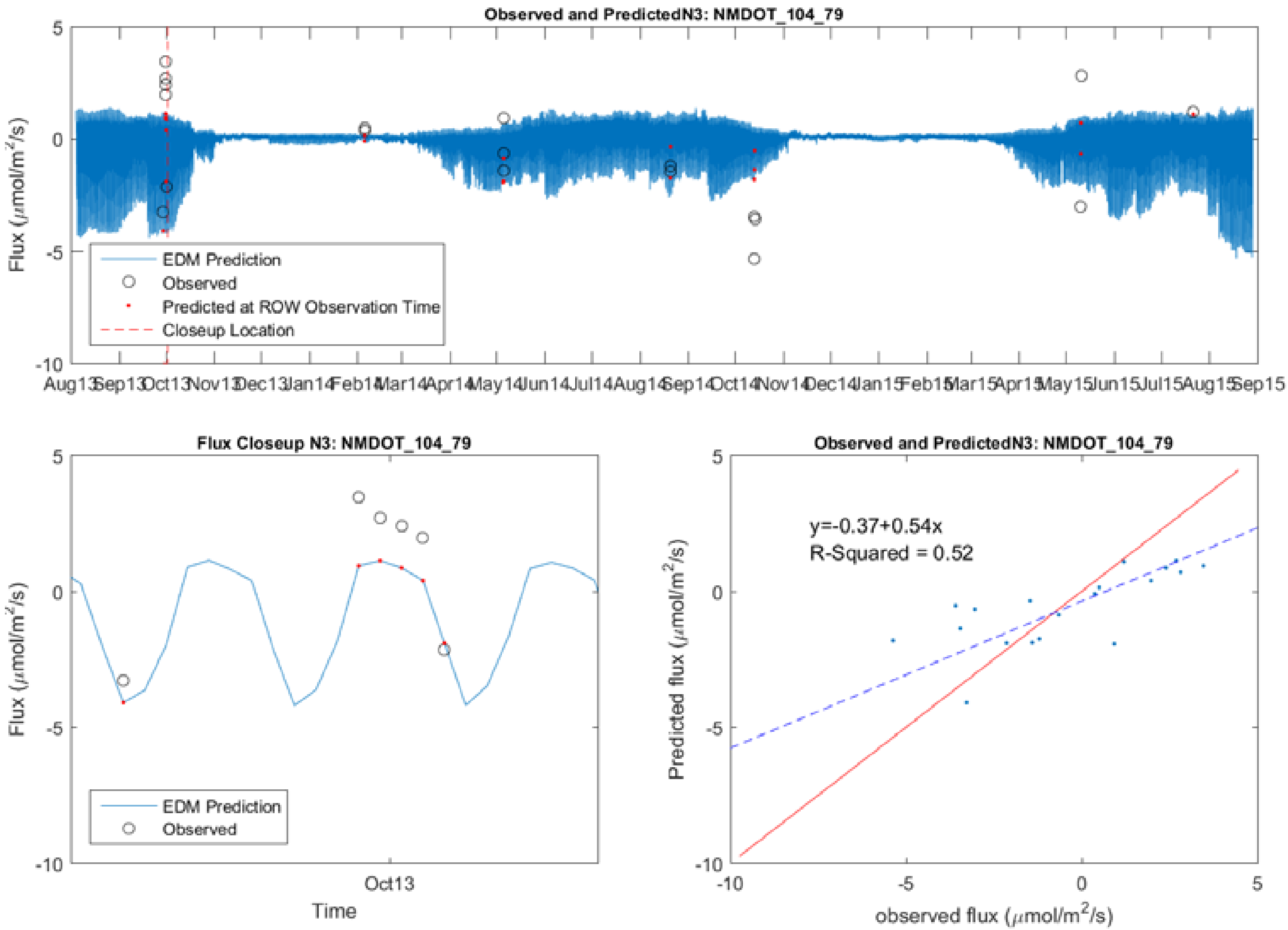


Figure D-9. Detailed predicted versus observed NEE at 120-31 for M1 treatment.

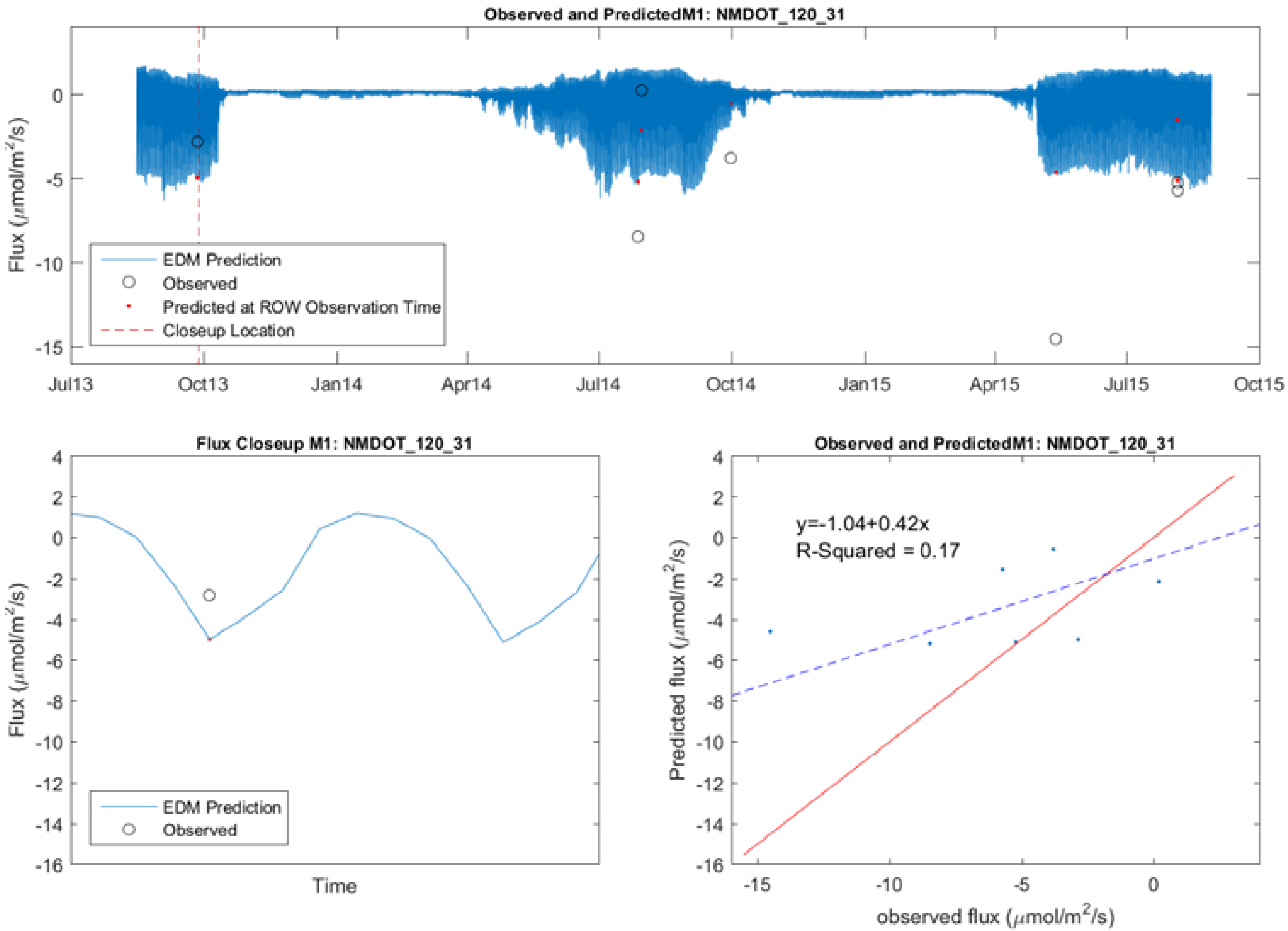


Figure D-10. Detailed predicted versus observed NEE at 120-31 for M3 treatment.

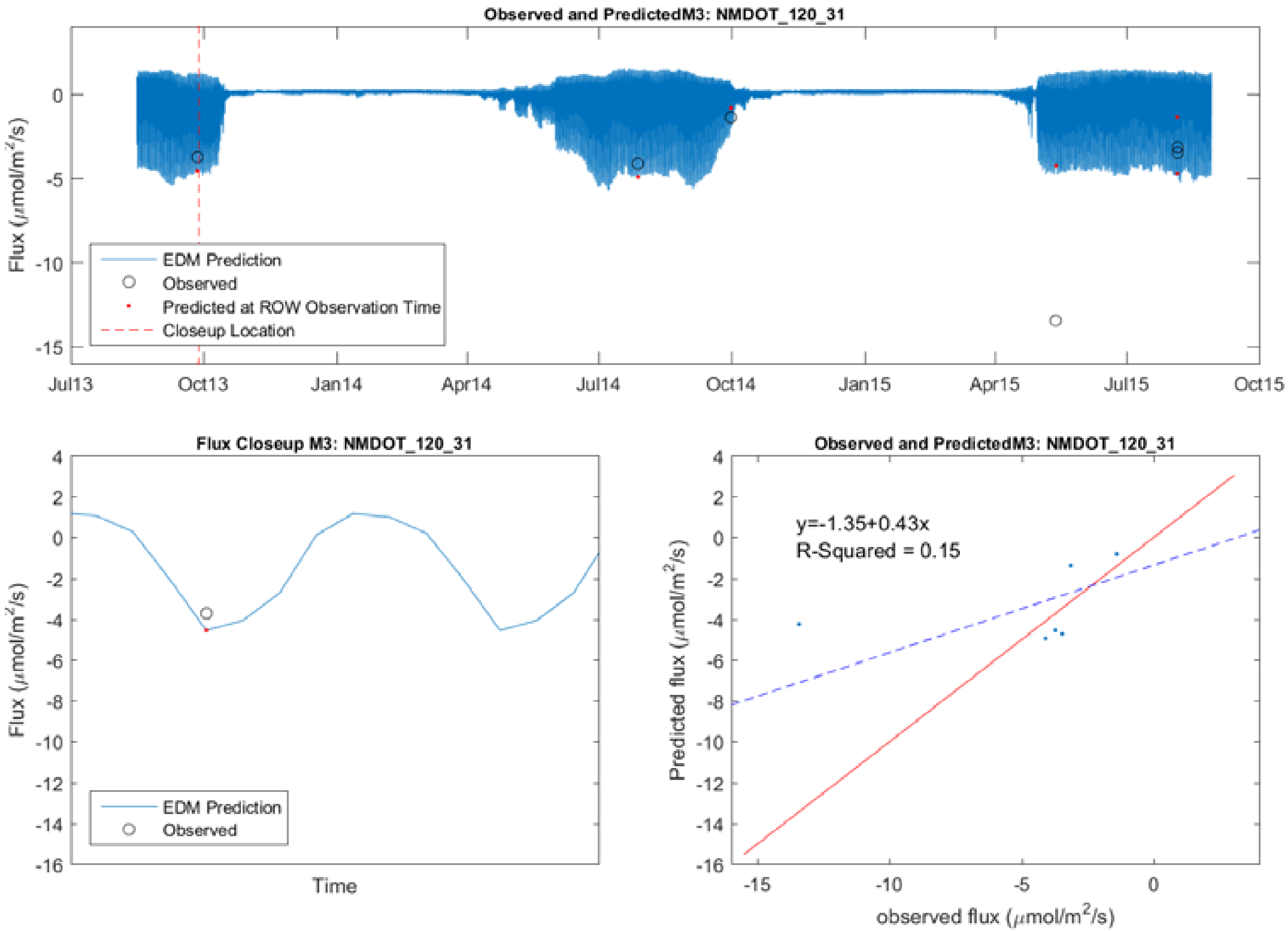


Figure D-11. Detailed predicted versus observed NEE at 102-31 for N1 treatment.

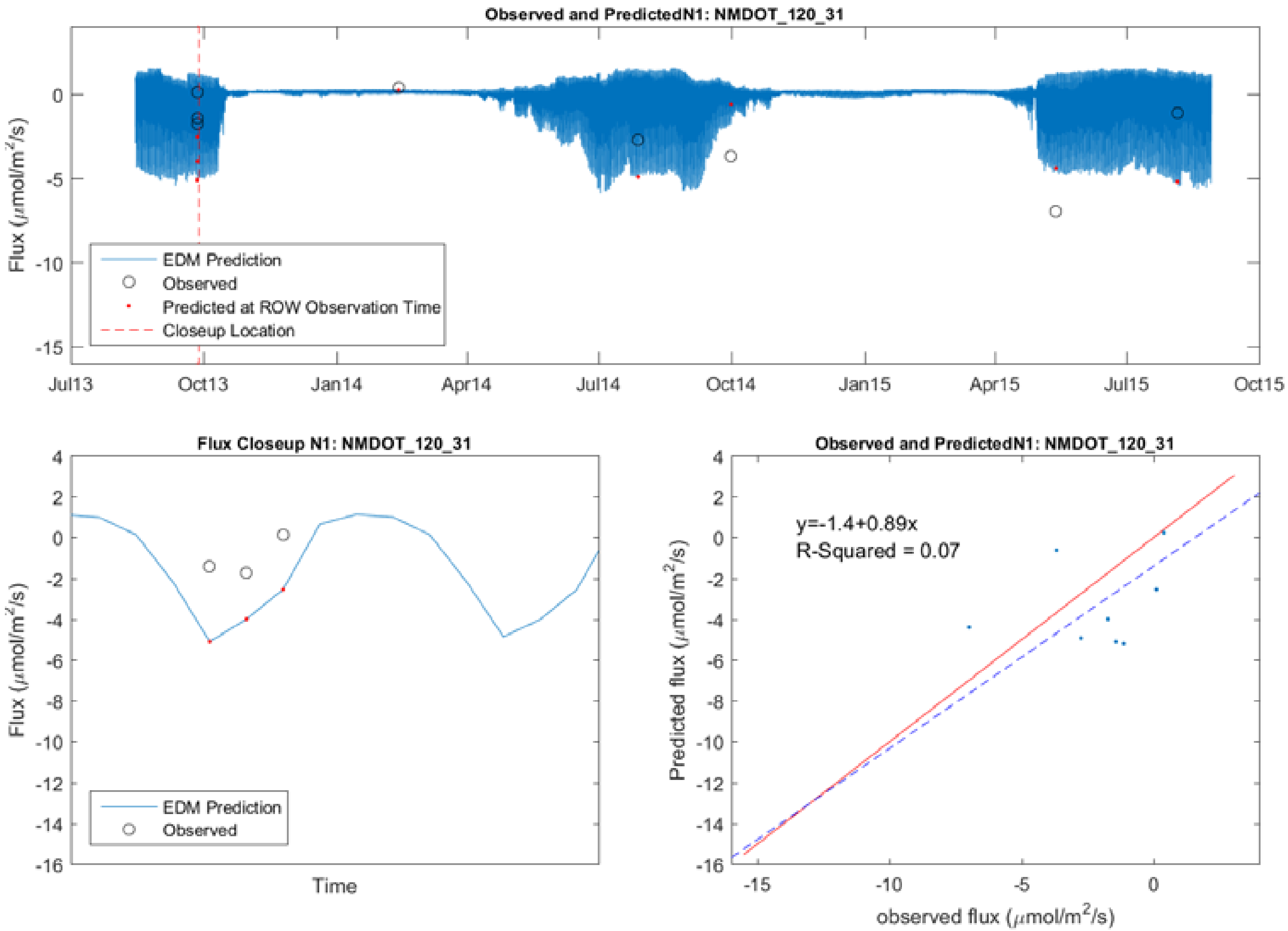


Figure D-12. Detailed predicted versus observed NEE at 120-31 for N3 treatment.

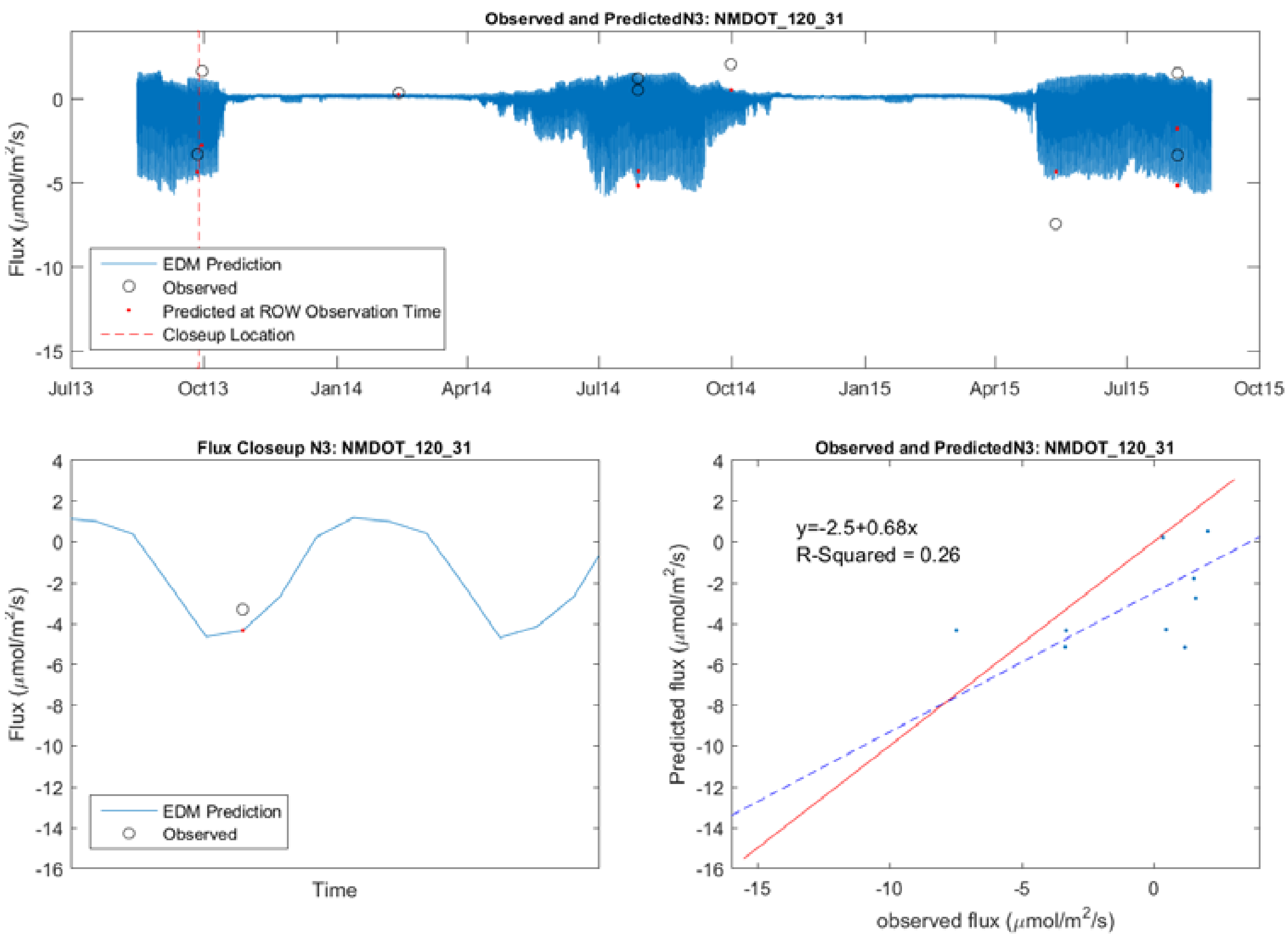


Figure D-13. Detailed predicted versus observed NEE at 469-02 for M1 treatment.

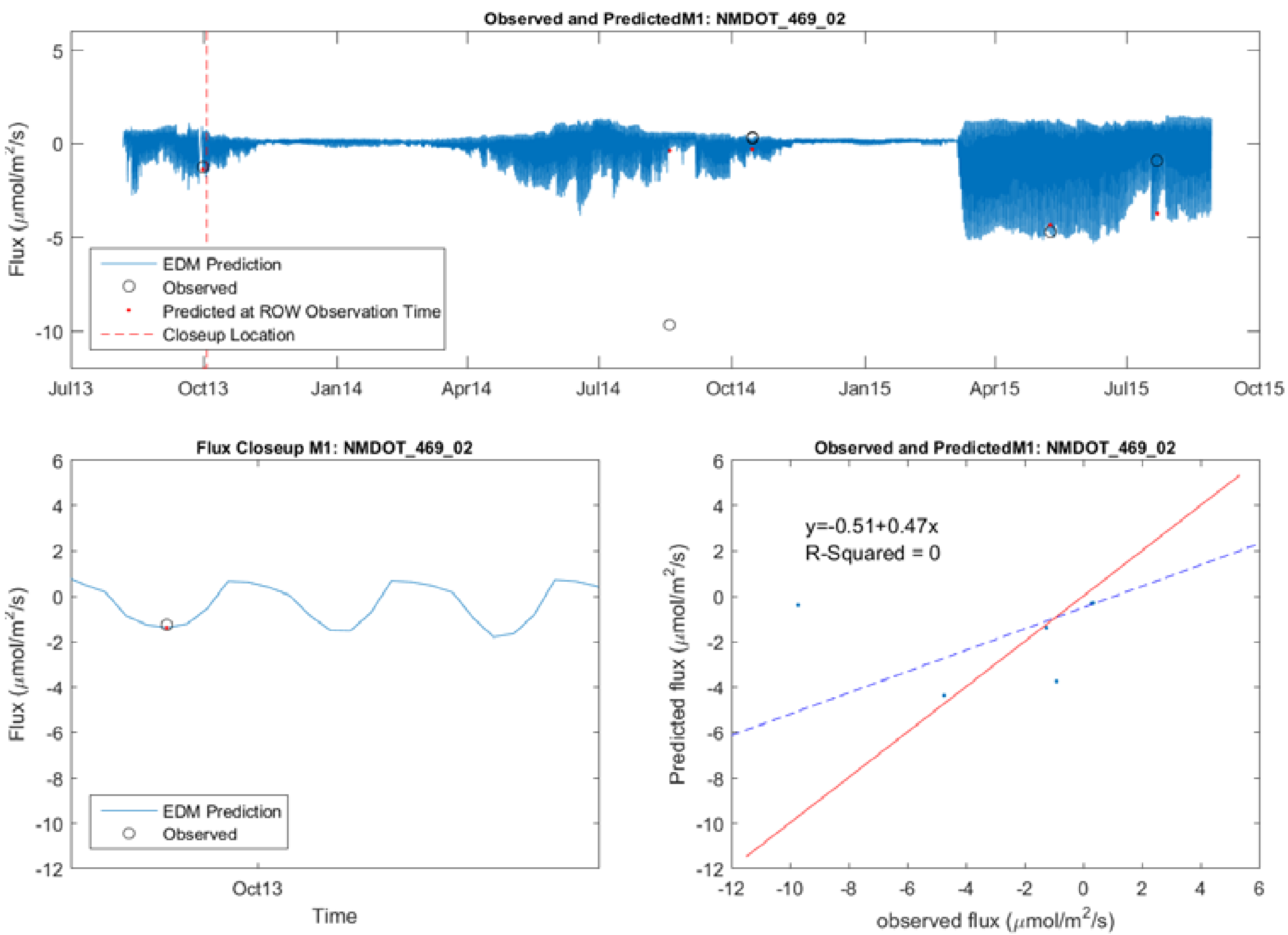


Figure D-14. Detailed predicted versus observed NEE at 469-02 for M3 treatment.

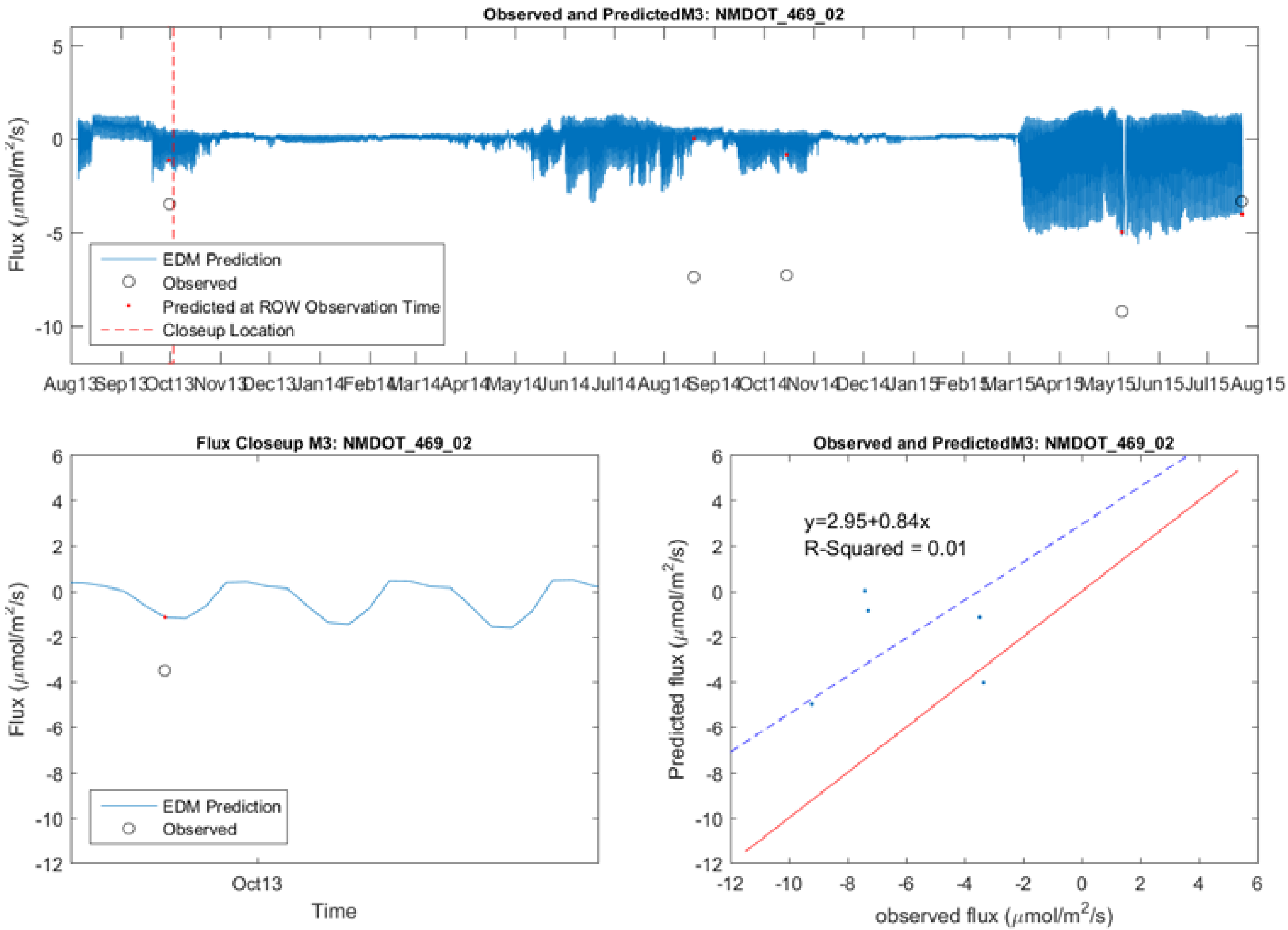


Figure D-15. Detailed predicted versus observed NEE at 469-02 for N1 treatment.

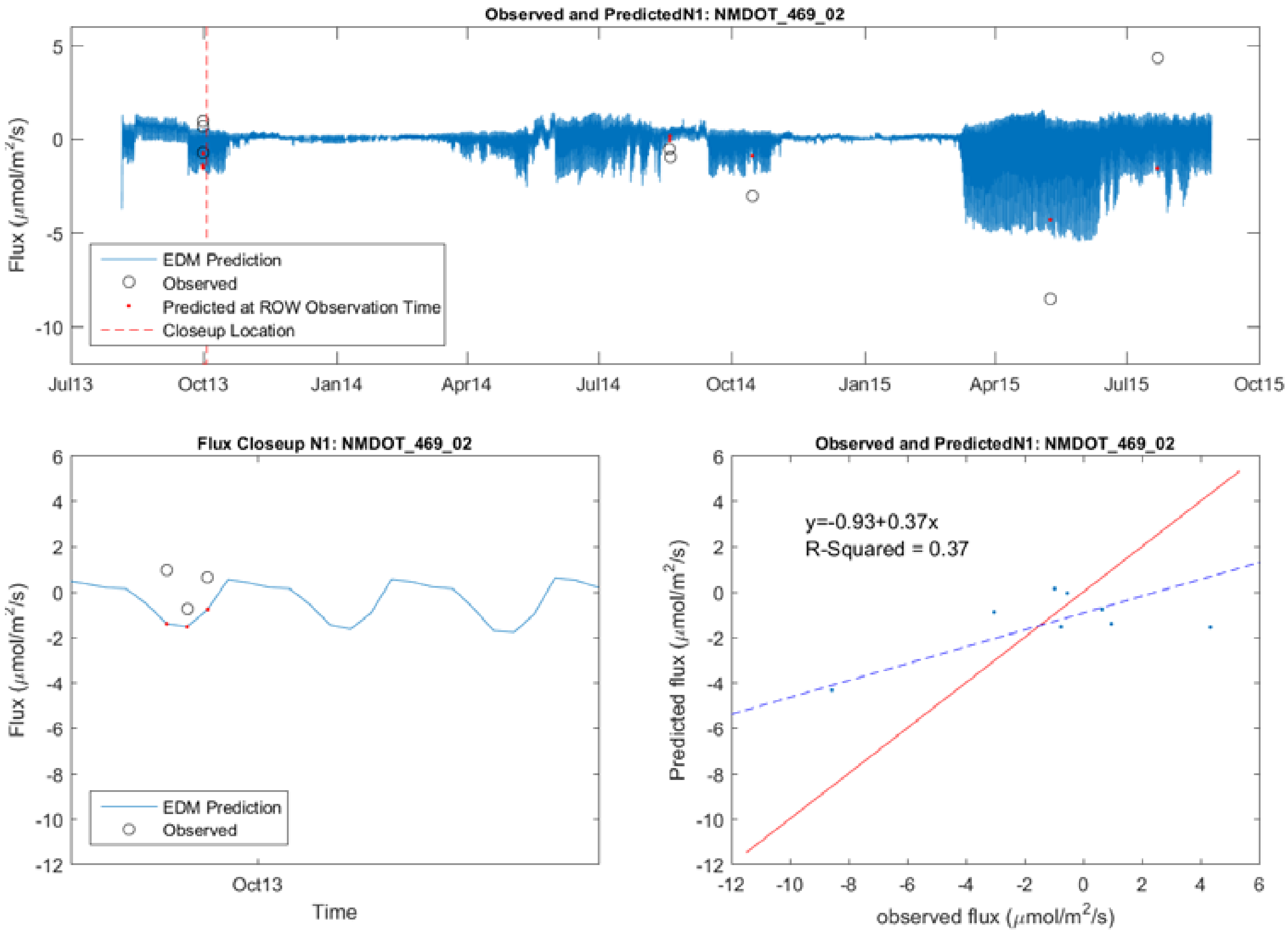


Figure D-16. Detailed predicted versus observed NEE at 469-02 for N3 treatment.

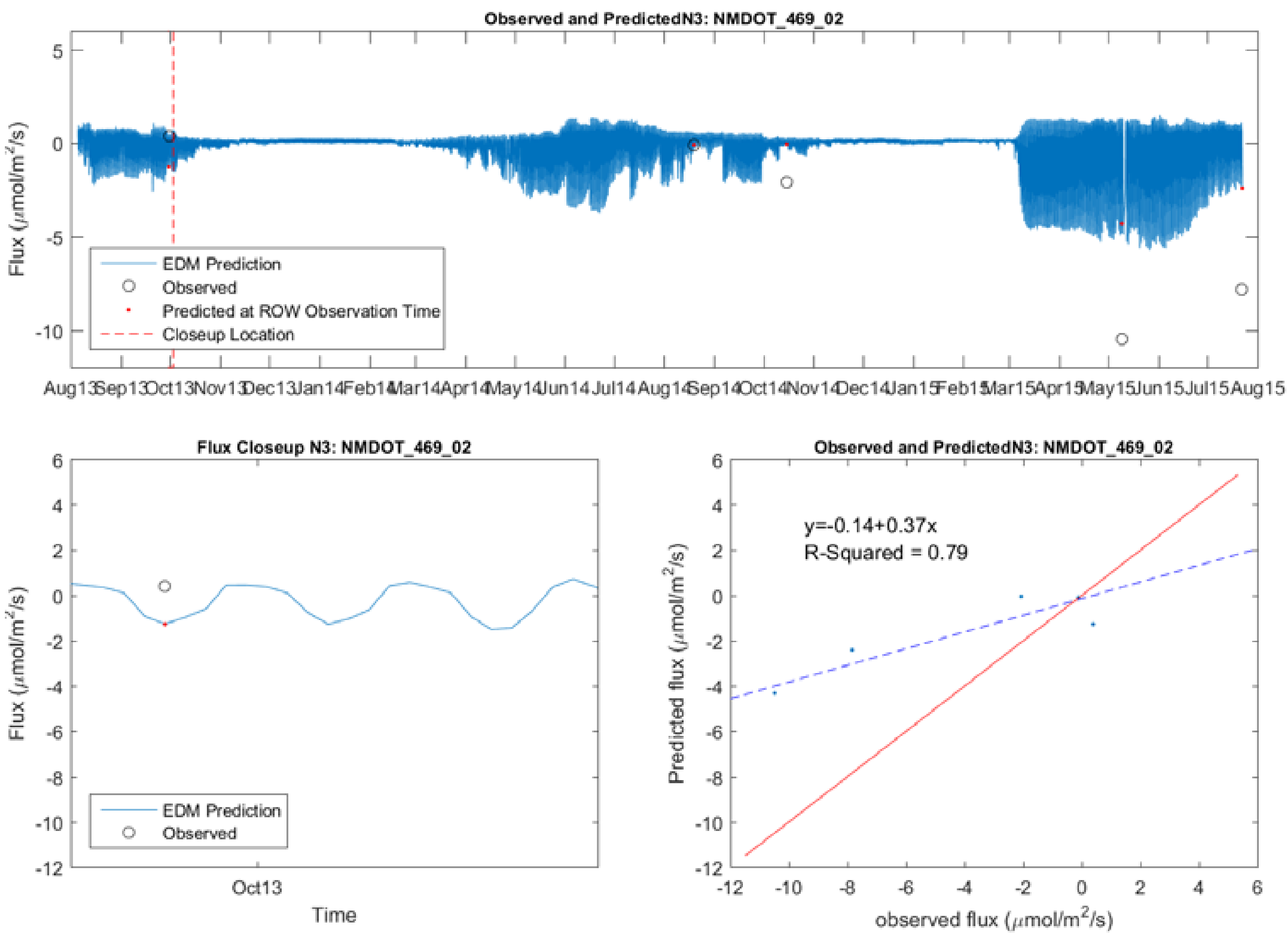


Figure D-17. Detailed predicted versus observed NEE at 469-39 for M1 treatment.

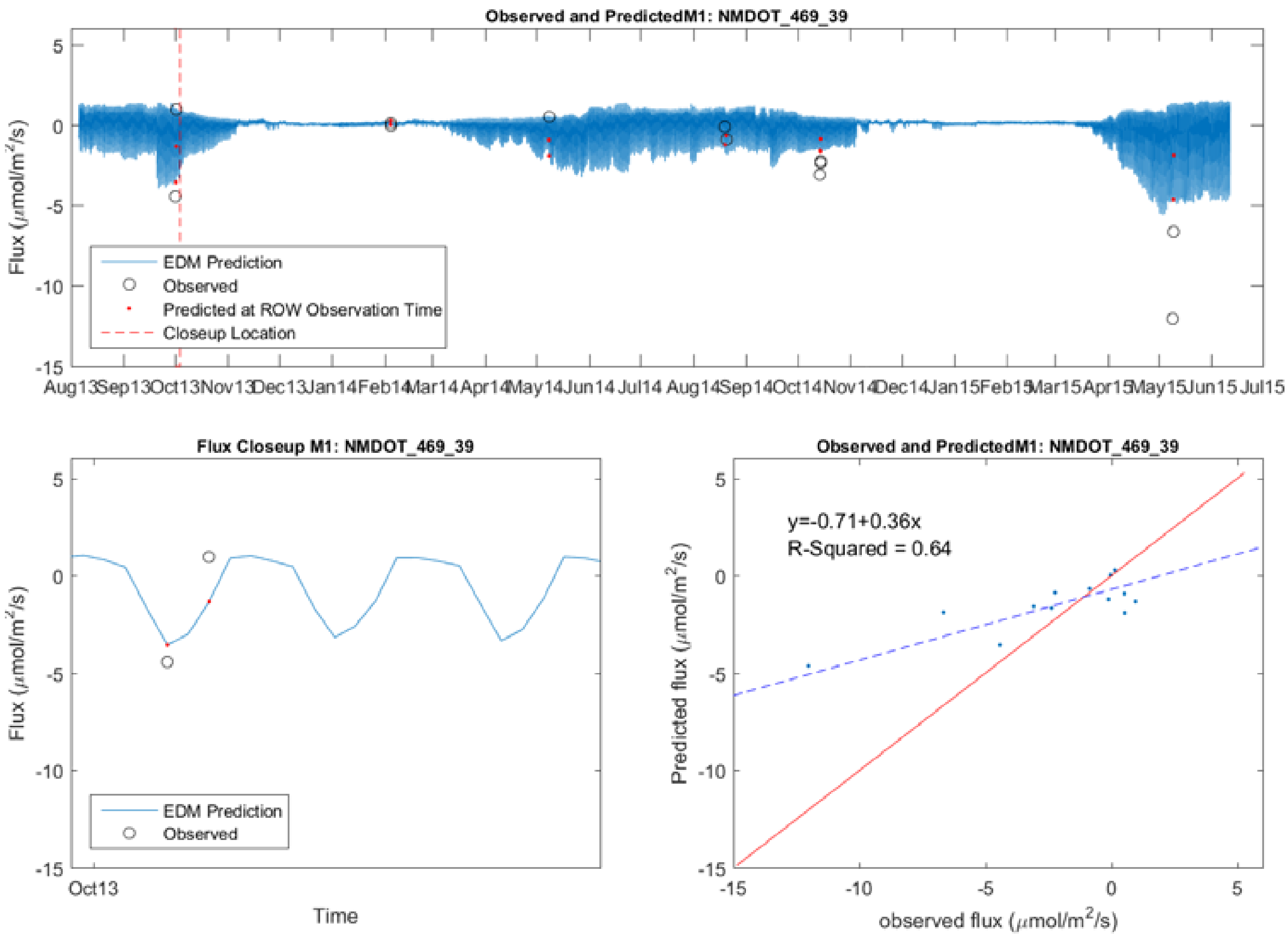


Figure D-18. Detailed predicted versus observed NEE at 469-39 for M3 treatment.

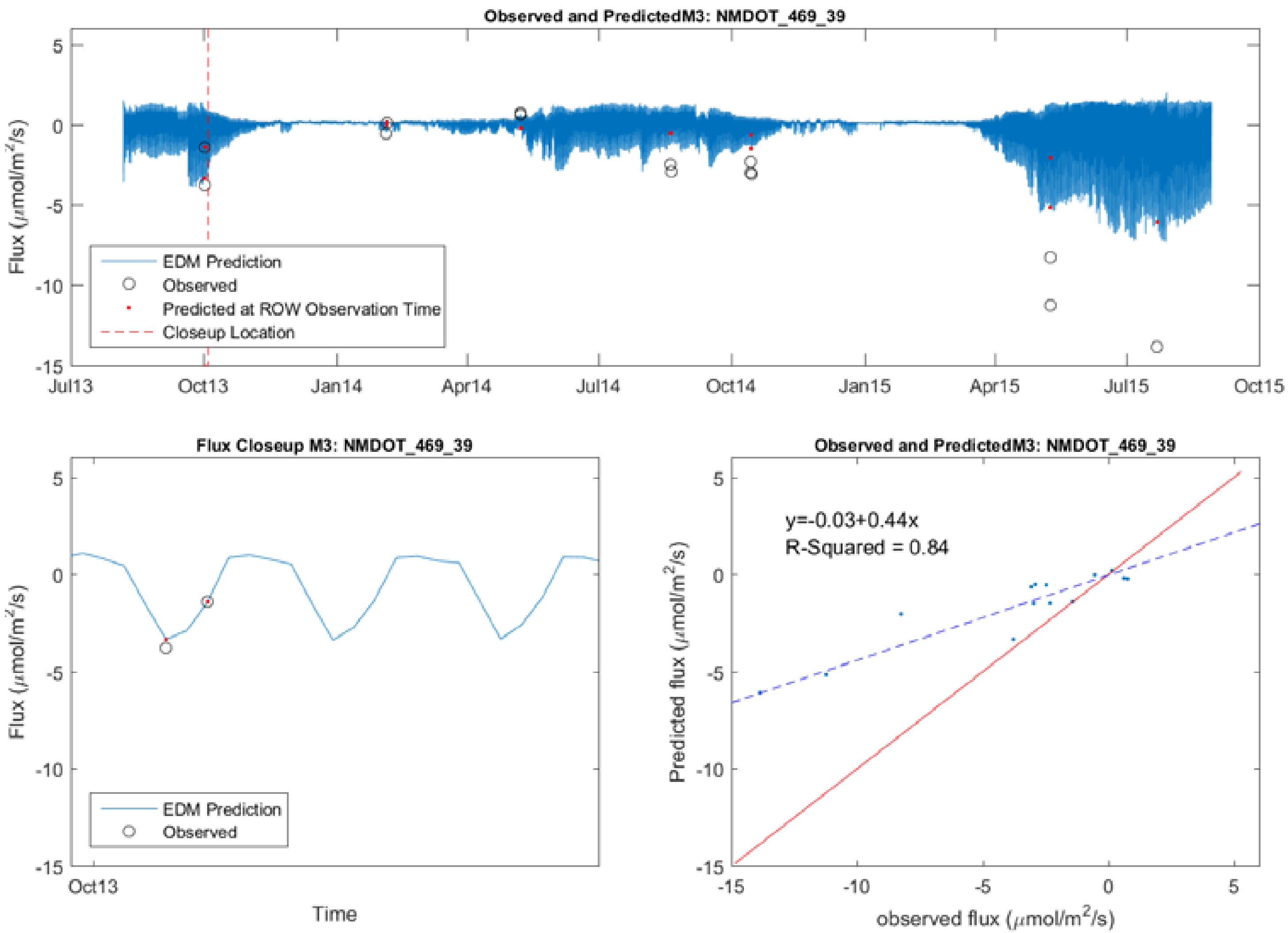


Figure D-19. Detailed predicted versus observed NEE at 469-39 for N1 treatment.

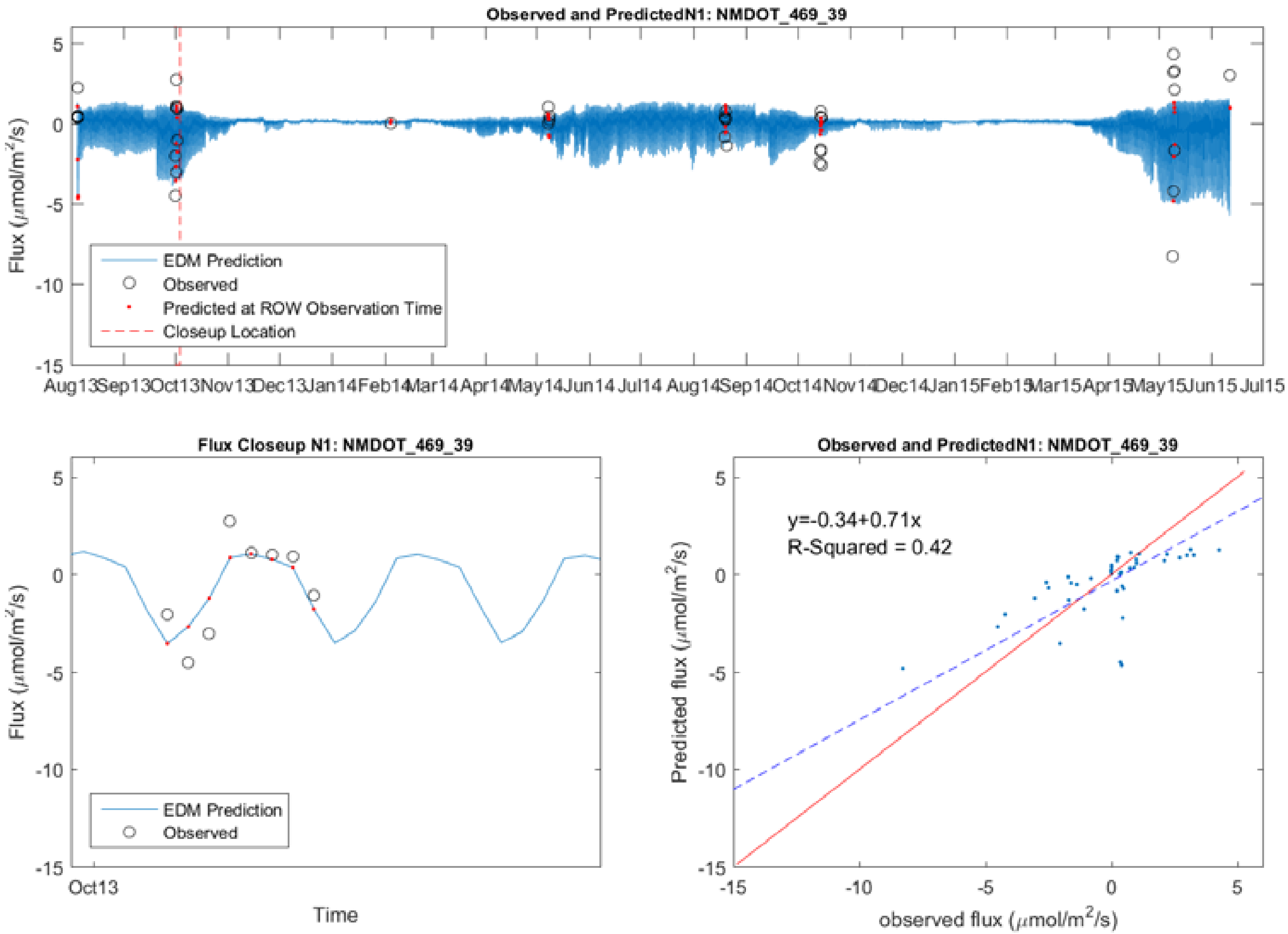


Figure D-20. Detailed predicted versus observed NEE at 469-3 for N3 treatment.

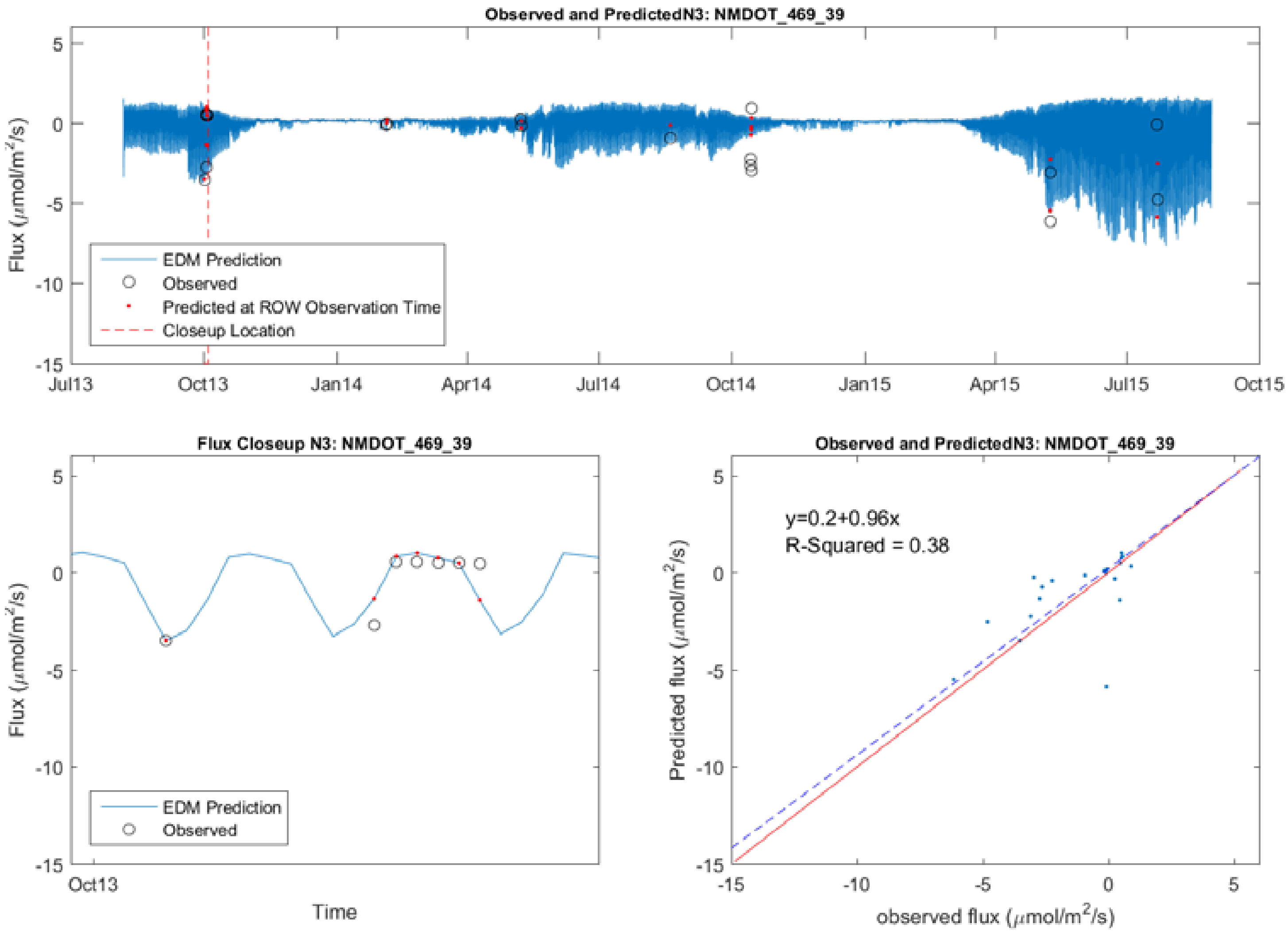


Figure D-21. Detailed predicted versus observed NEE at 472-07 for M1 treatment.

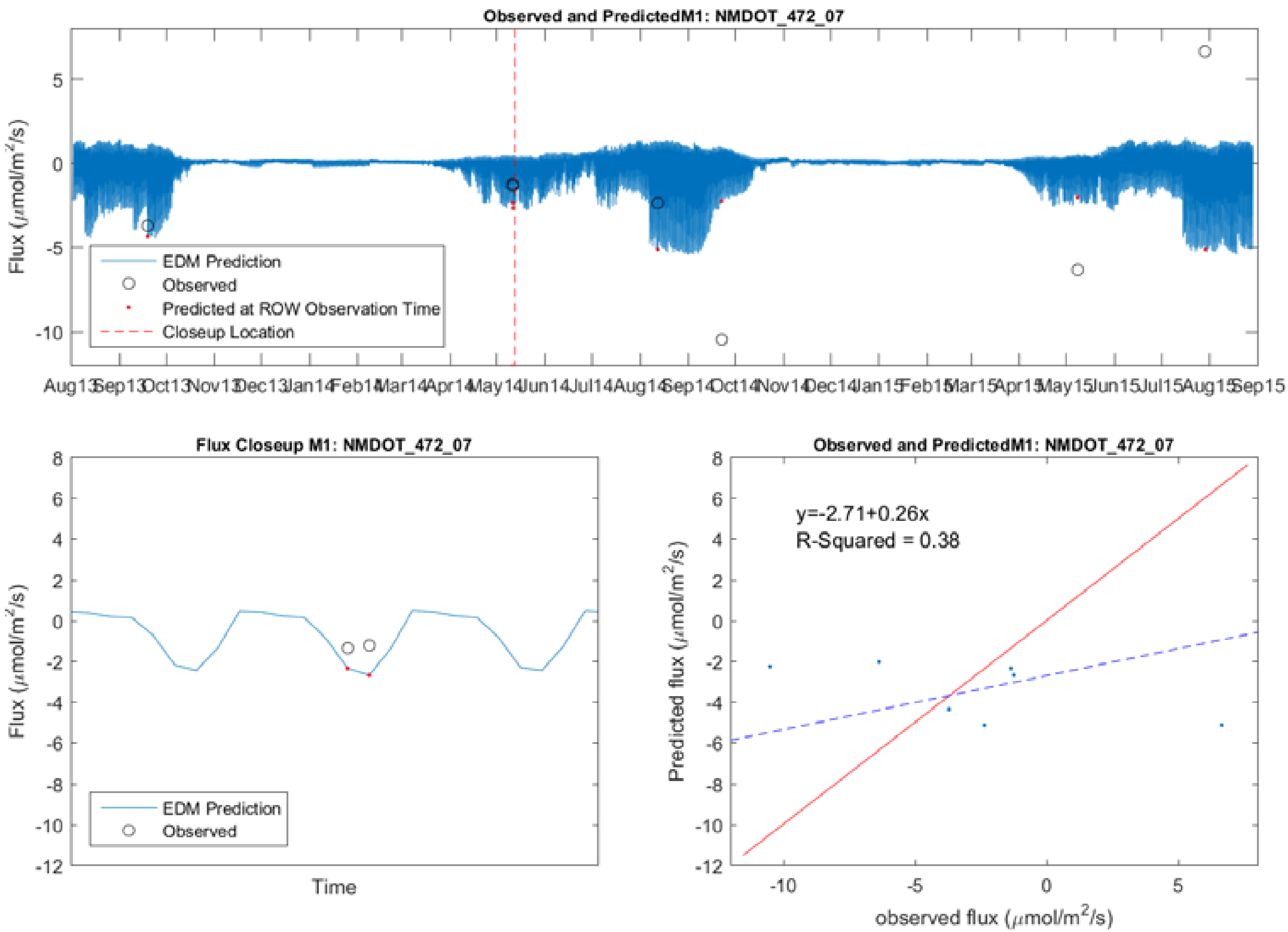


Figure D-22. Detailed predicted versus observed NEE at 472-07 for M3 treatment.

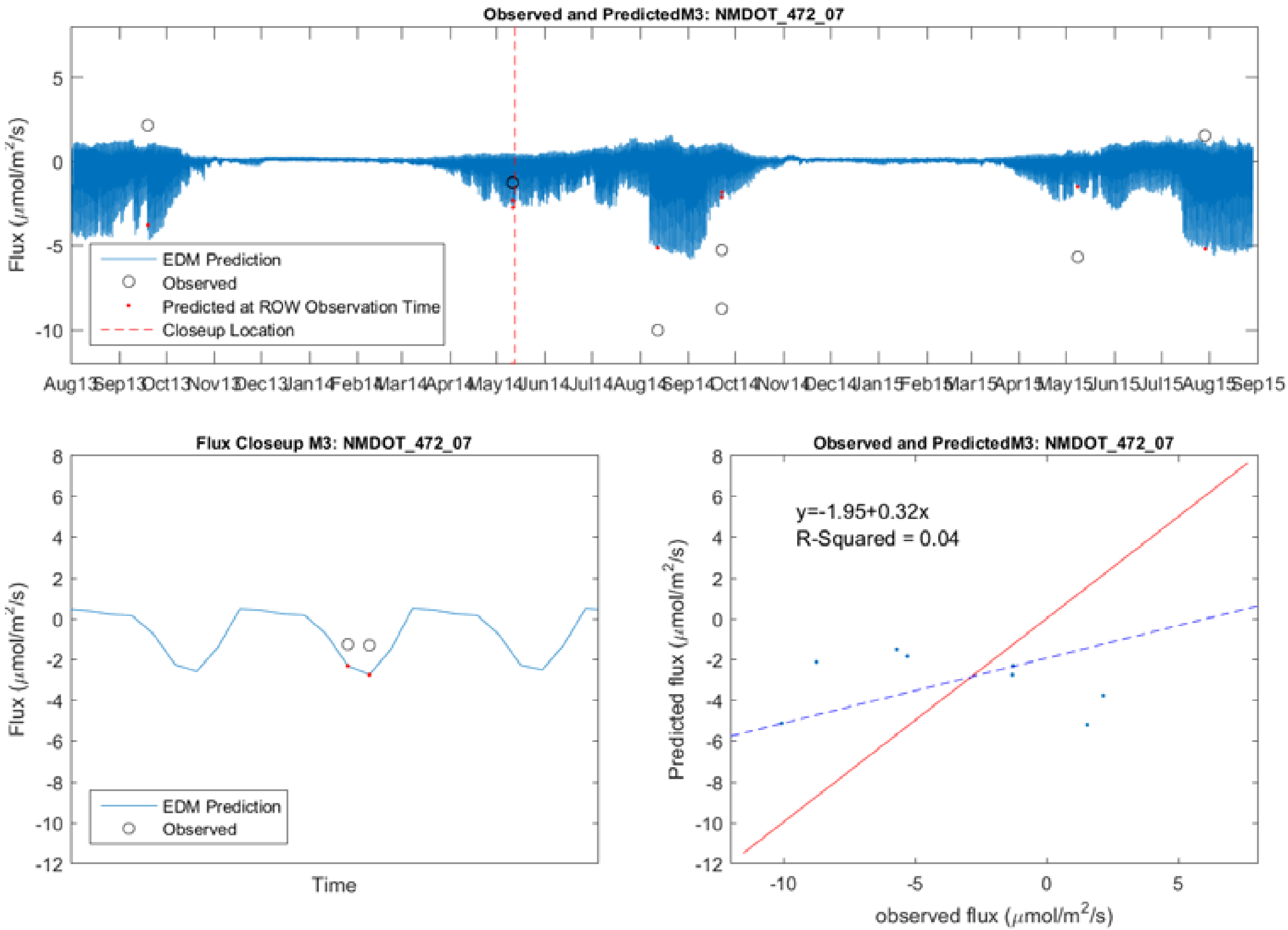


Figure D-23. Detailed predicted versus observed NEE at 472-07 for N1 treatment.

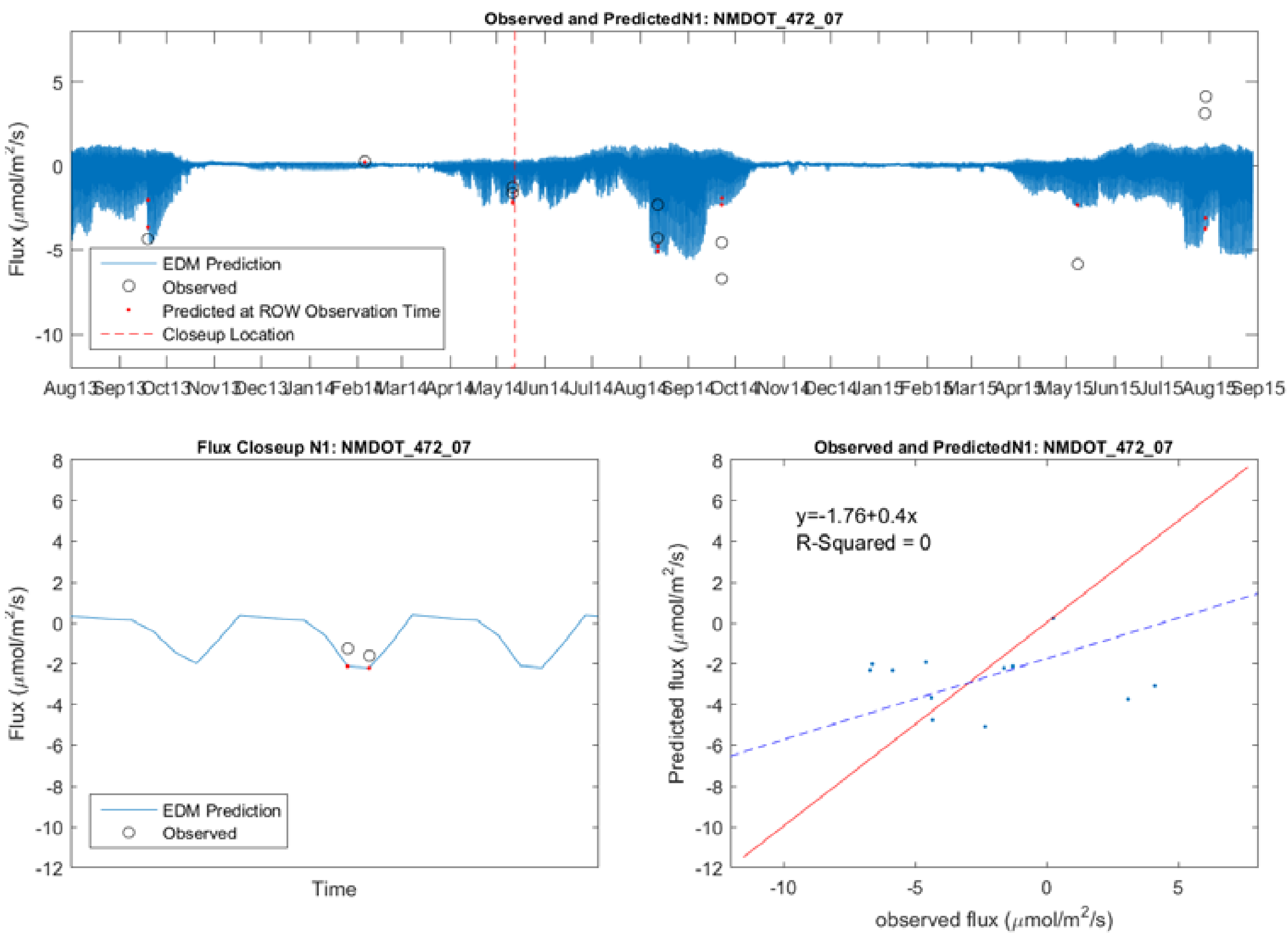


Figure D-24. Detailed predicted versus observed NEE at 472-07 for N3 treatment.

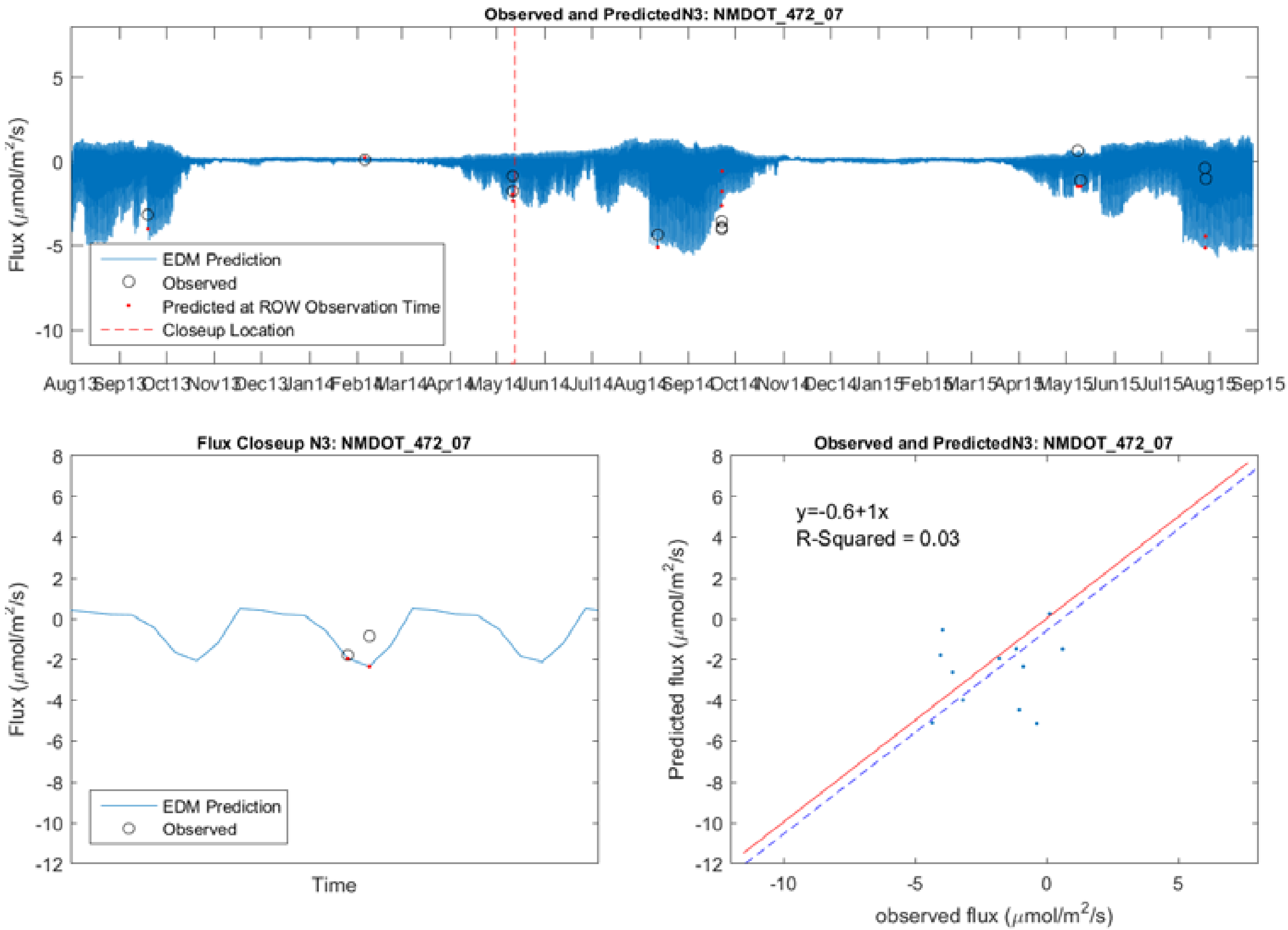


Figure D-25. Detailed predicted versus observed NEE at 537-43 for M1 treatment.

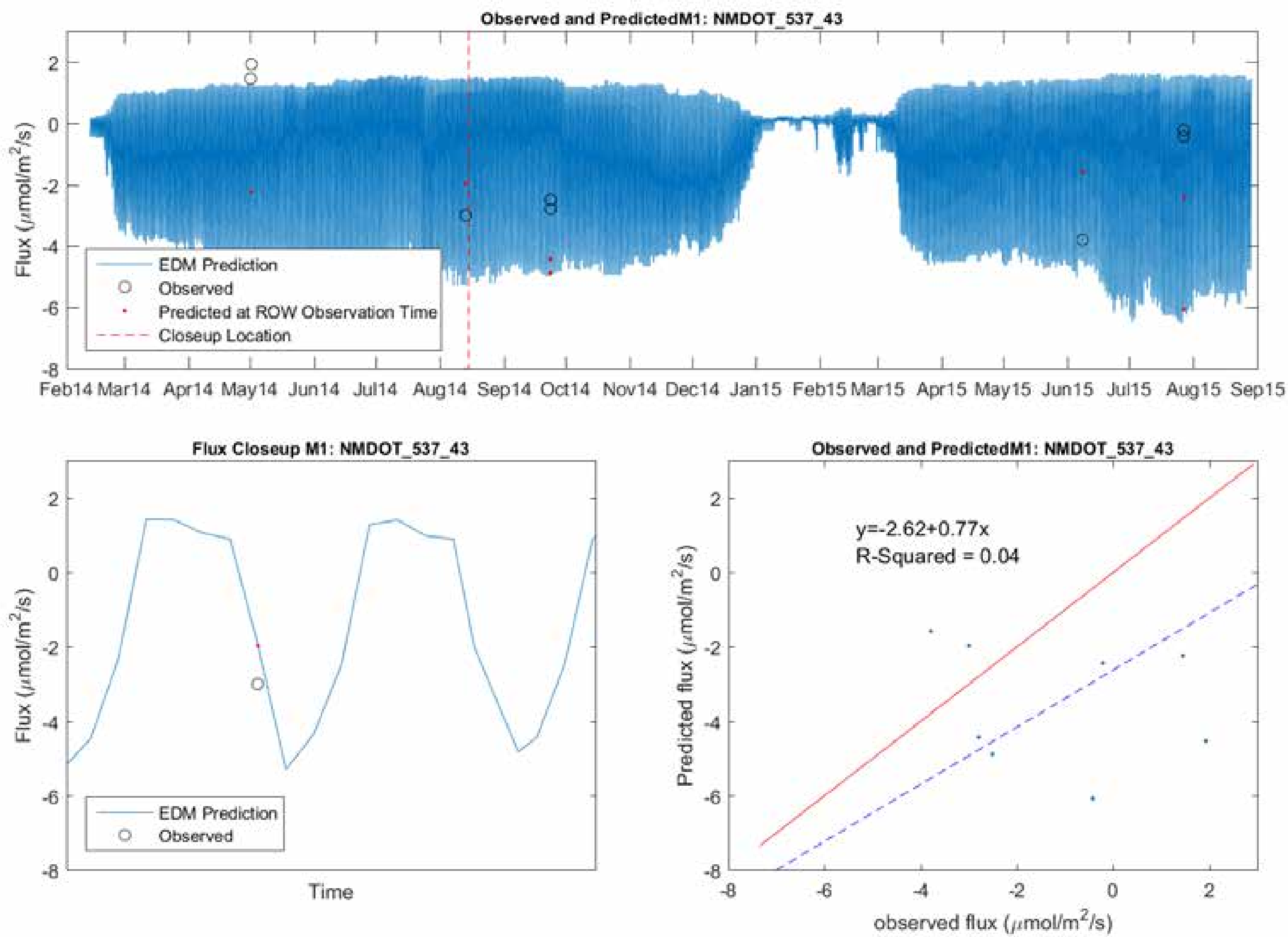


Figure D-26. Detailed predicted versus observed NEE at 537-43 for M3 treatment.

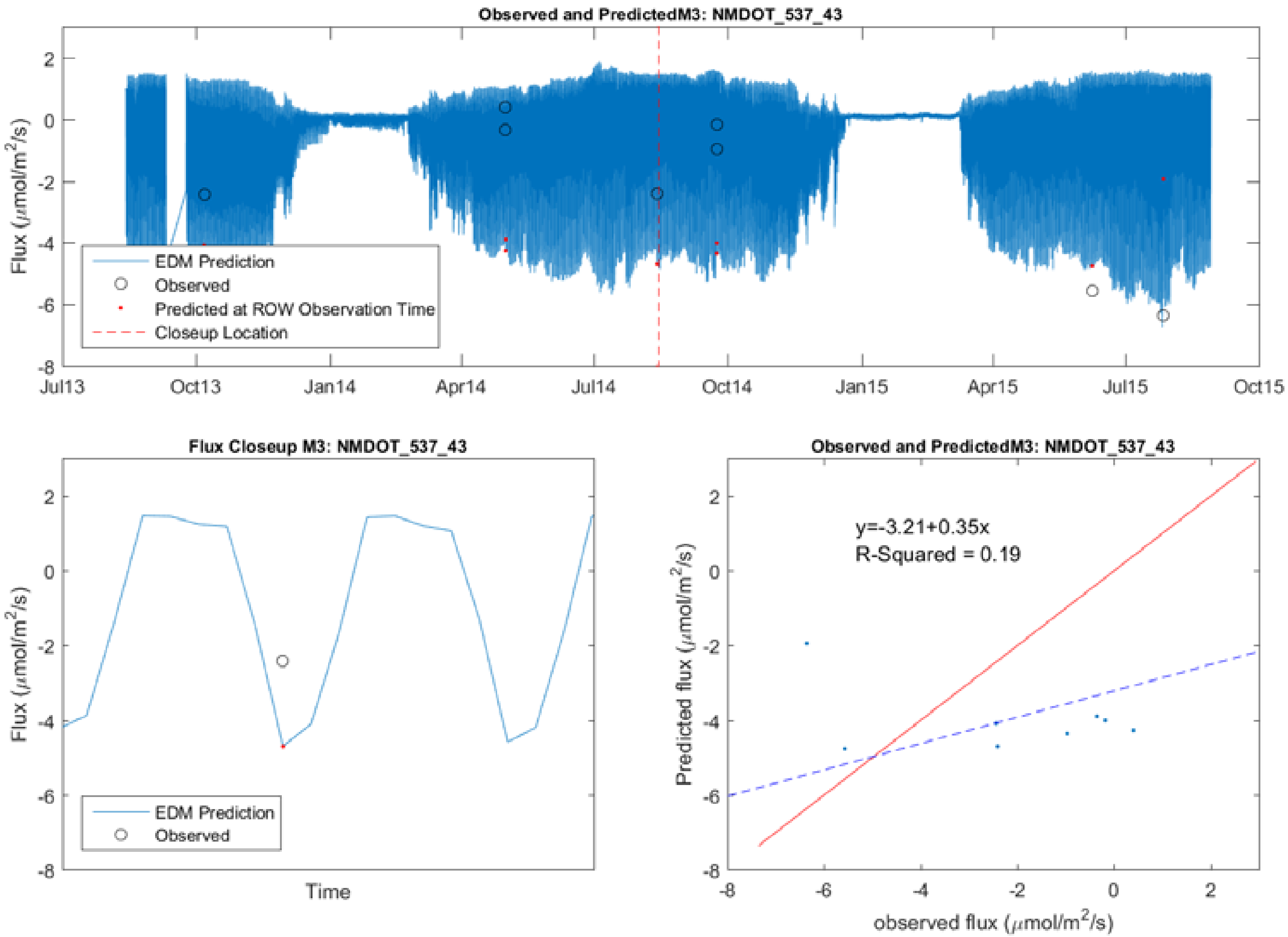


Figure D-27. Detailed predicted versus observed NEE at 537-43 for N1 treatment.

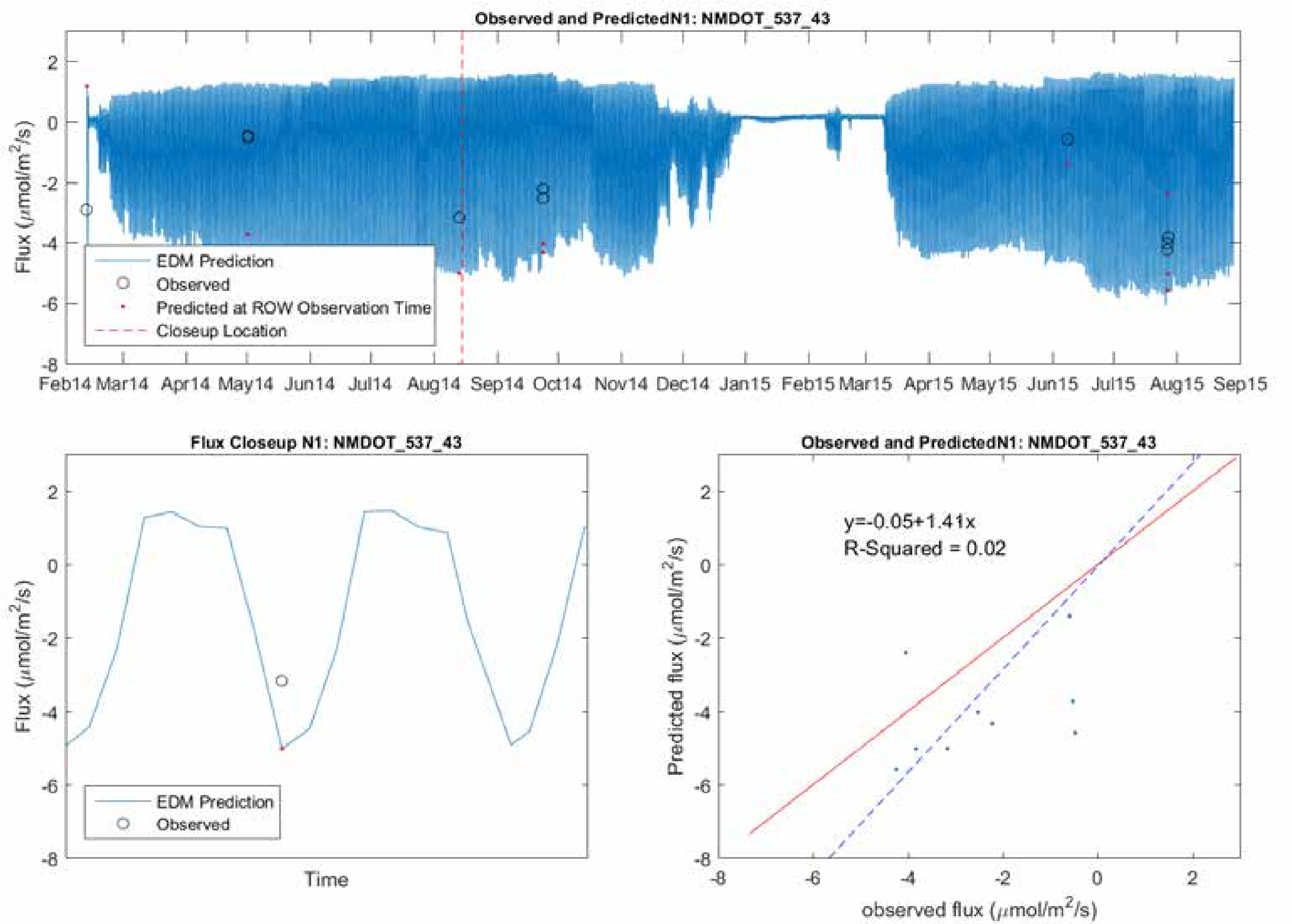


Figure D-28. Detailed predicted versus observed NEE at 537-43 for N3 treatment.

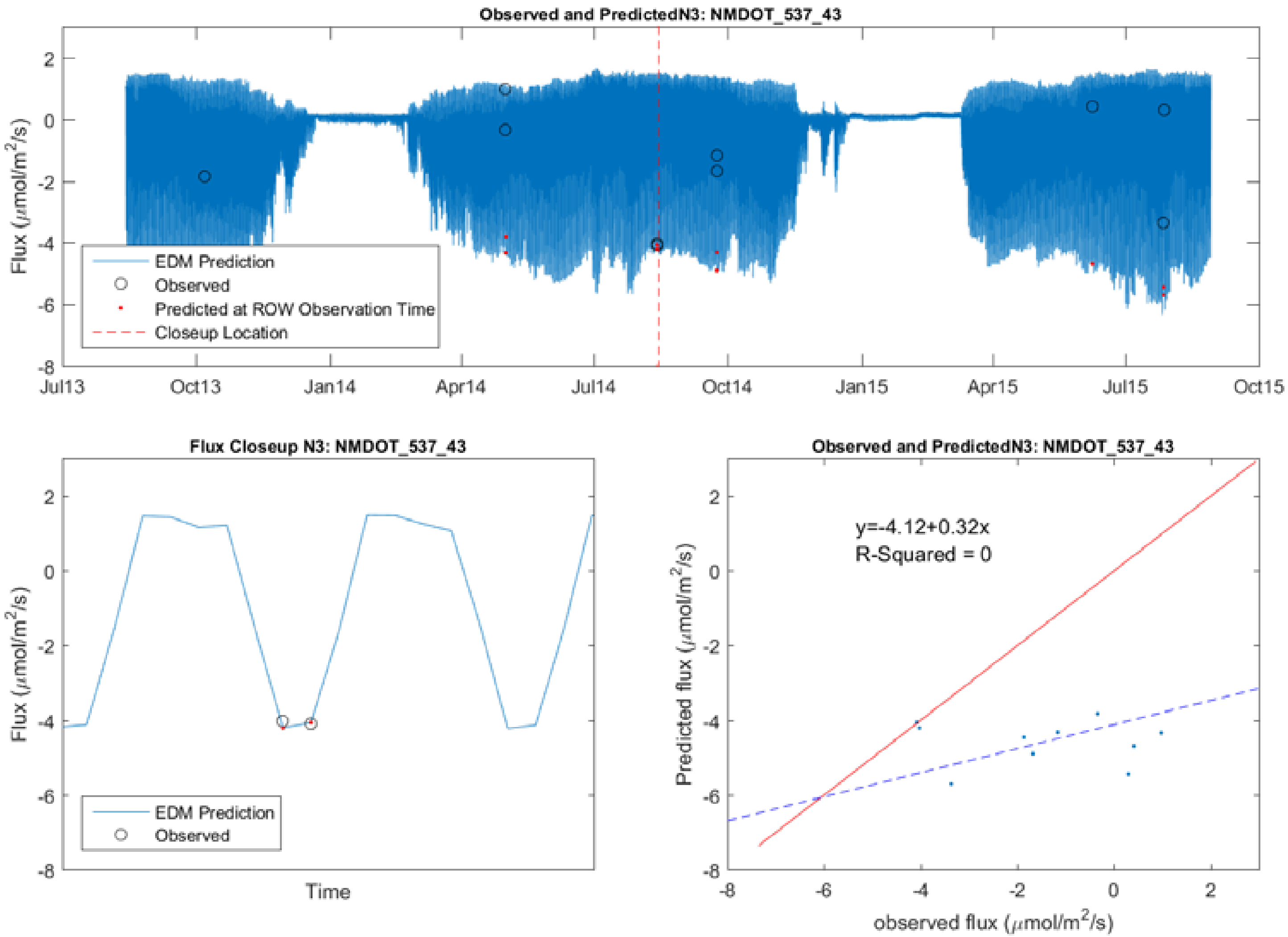


Figure D-29. Detailed predicted versus observed NEE at 555-12 for M1 treatment.

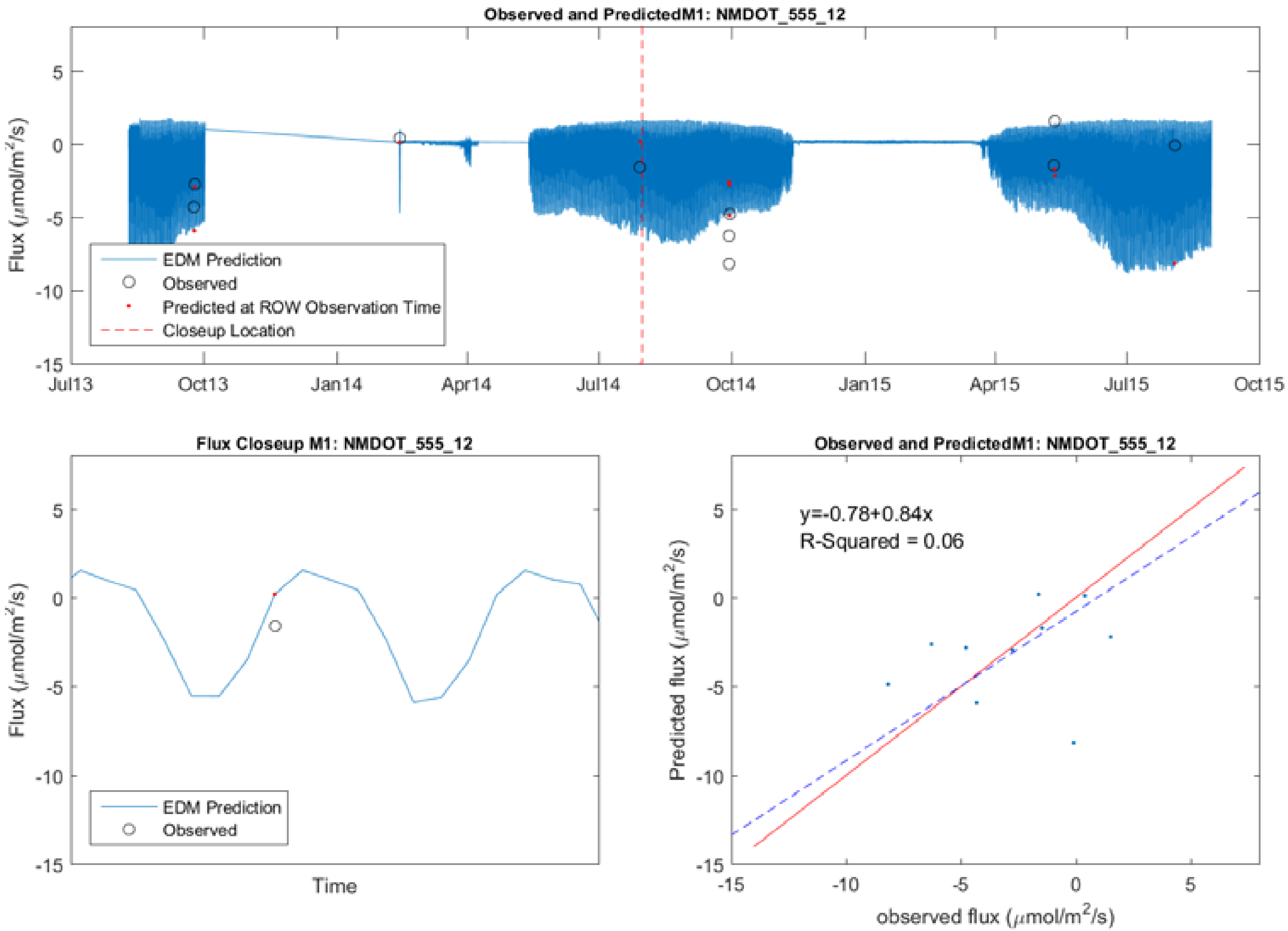


Figure D-30. Detailed predicted versus observed NEE at 555-12 for M3 treatment.

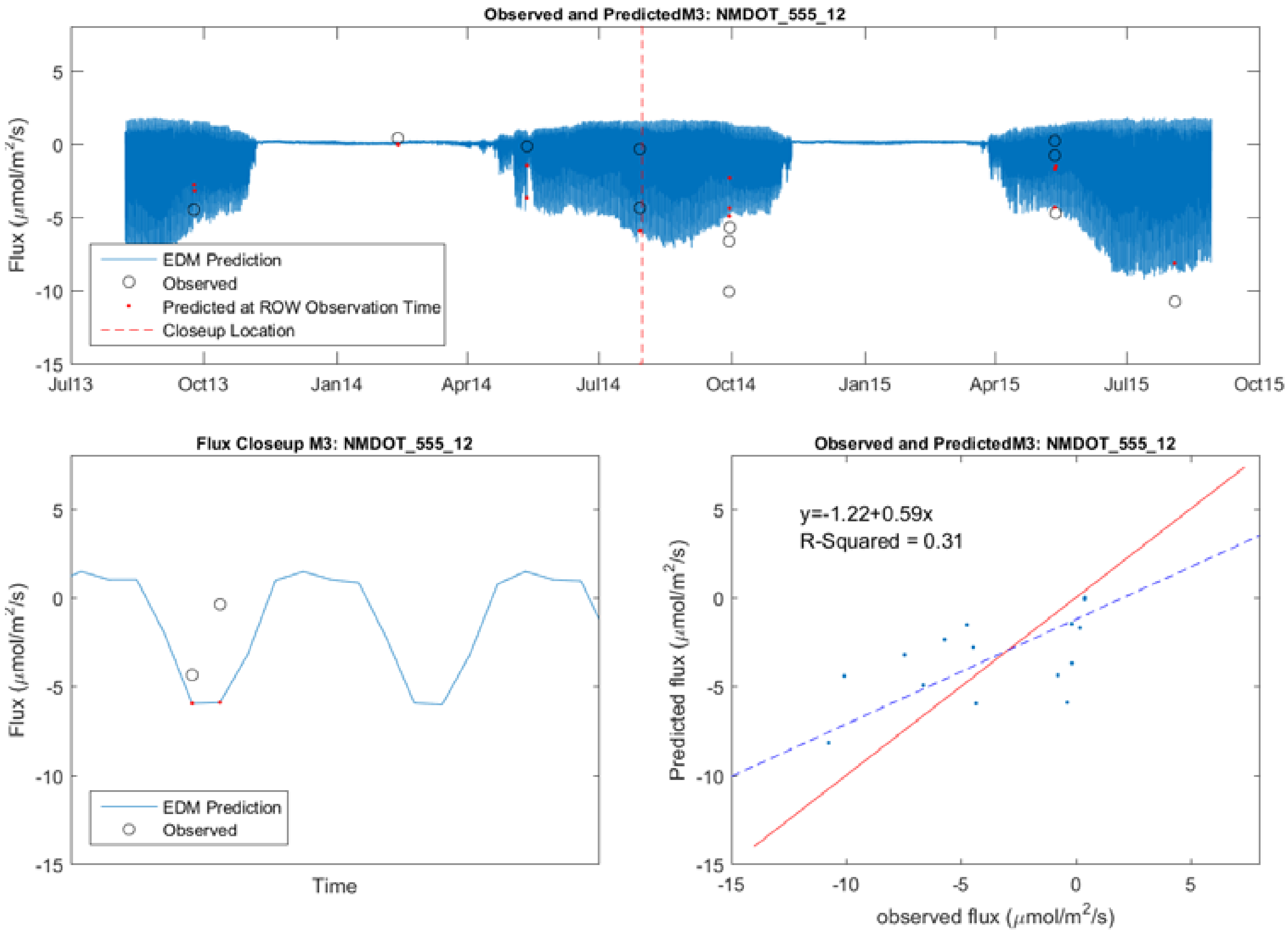


Figure D-31. Detailed predicted versus observed NEE at 558-12 for N1 treatment.

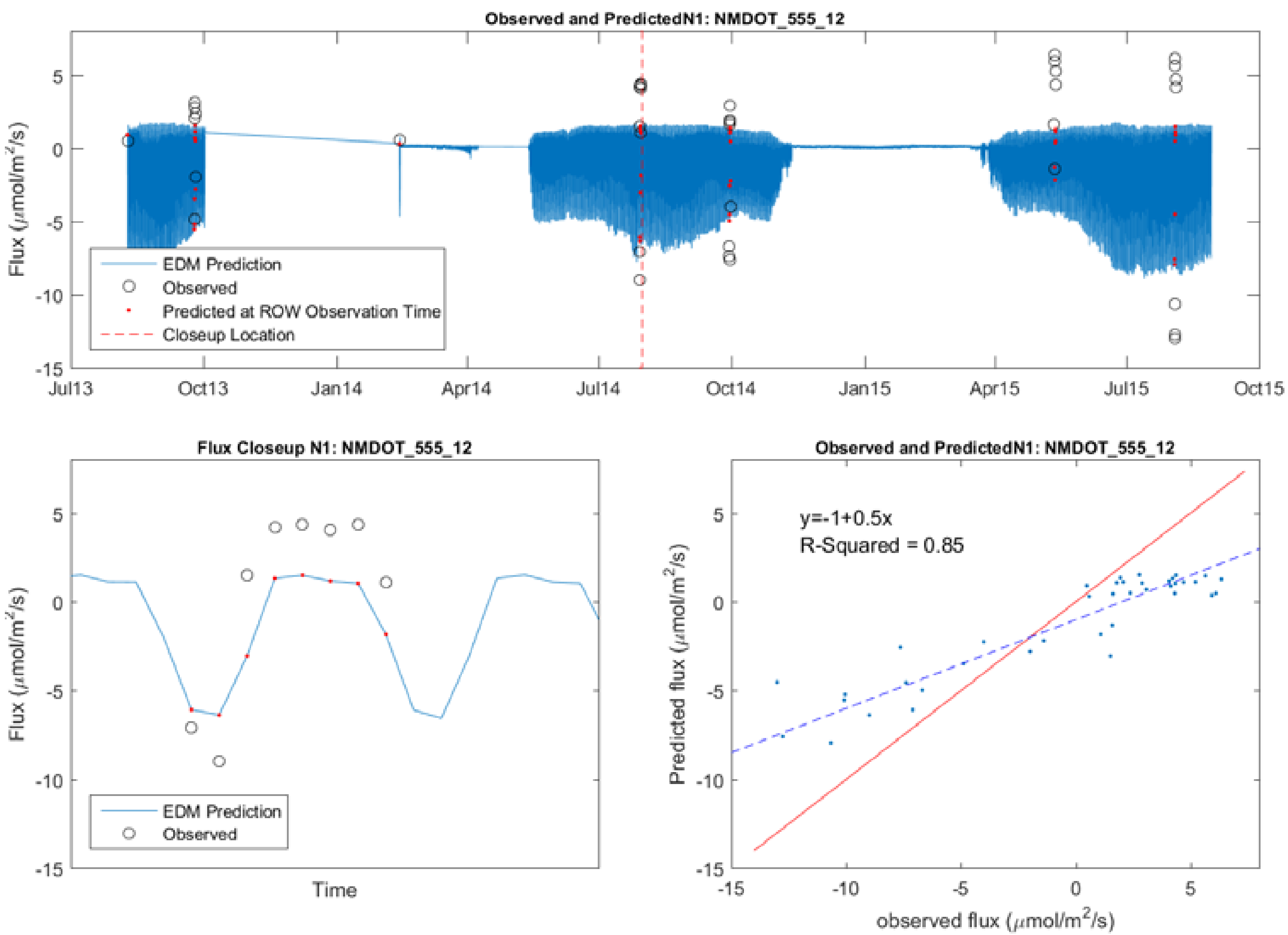
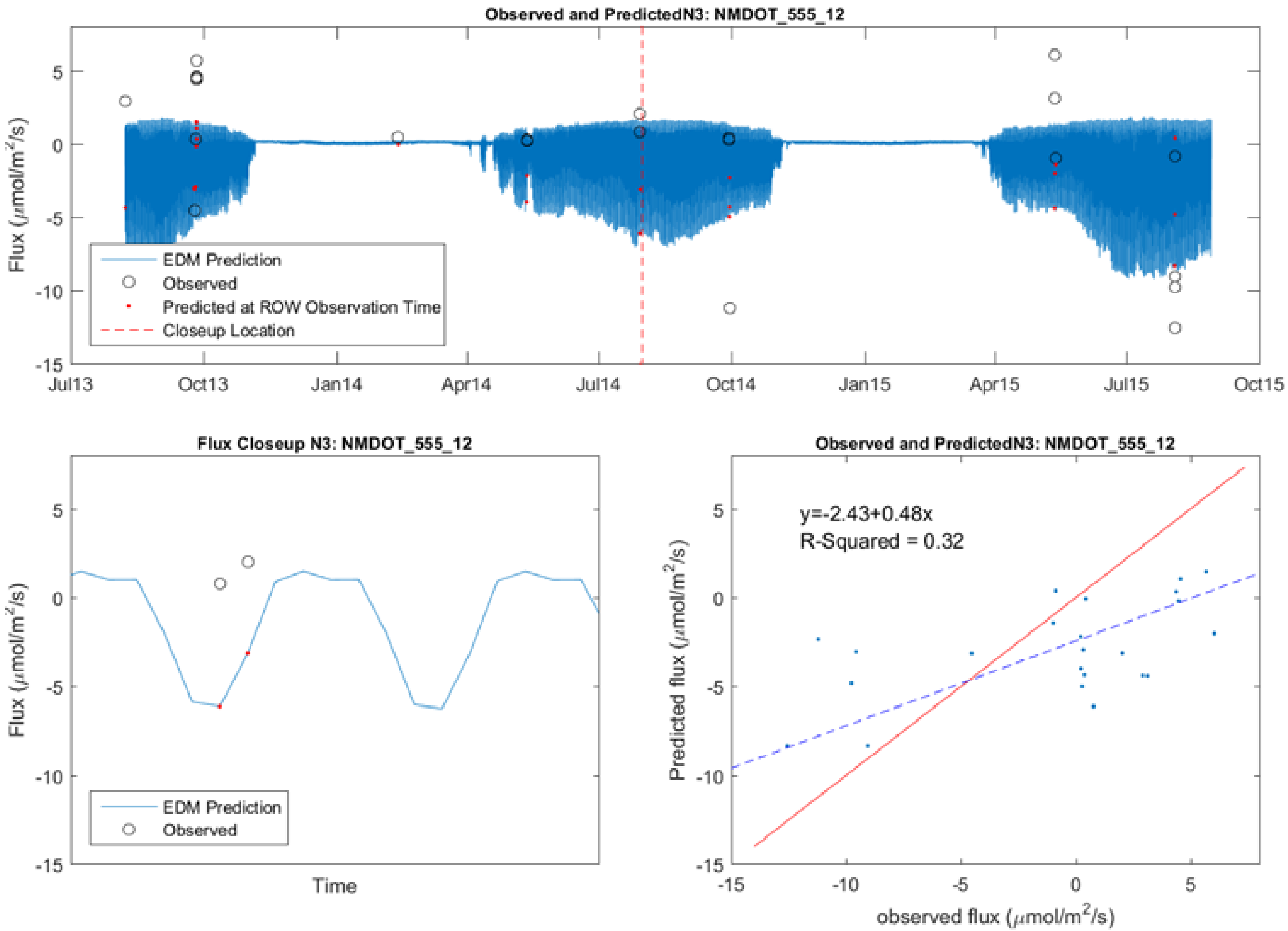


Figure D-32. Detailed predicted versus observed NEE at 555-12 for N3 treatment.



APPENDIX E

Implementation Plan

Assessing the Potential to Sequester Carbon within State Highway Rights-of-Way in New Mexico
Phase 2: Development of a
Right-of-Way Carbon Sequestration Program

IMPLEMENTATION PLAN

The purpose of this implementation plan is to provide detailed guidelines and instructions to the project's technical panel regarding the application of the project's results as described in the final report. The document serves as a concise guide to provide recommendations to senior NMDOT management relating to departmental roadside vegetation maintenance procedures that have the potential the enhance carbon sequestration in ROWs. Further, we describe the components of an ecological research program to answer questions as to how roadside vegetation sequesters carbon in response to mowing. Finally, we suggest a more national effort to examine the eligibility criteria of a highway ROW vegetation management carbon offset protocol. Such a protocol has the potential to provide not only an environmental benefit to address climate change, but financial benefit to state DOTs who might wish to manage ROWs to sequester carbon and qualify for carbon offsets that could be sold in a cap-and-trade carbon market.

Modification of Standard Mowing Operations for State Highways

Mowing the ROW is a necessary maintenance operation used to clear sight lines, prevent woody plant encroachment, control invasive plants, reduce the potential for wildlife-vehicle collisions, prevent wildfires and manage snowdrifts. Unlike other states that receive more precipitation, only a single mowing pass per year may be needed along many New Mexico state highways. Yet, data from NMDOT's Highway Maintenance Management System (1998–2011) showed that mowers were deployed on average more 1.5 times a year, with Districts 1, 2 and 4 averaging over 2 visits per year (EMI 2013). While some mowing occurs during the non-growing season, more than 50 percent of the mowing is done from July through September when the roadside vegetation is actively growing (EMI 2013).

Mowing operations are initiated when herbaceous vegetation immediately adjacent to the road is deemed "too high" by NMDOT road patrols. Each patrol yard may have slightly different height standards based on the ROW plant communities within their area of responsibility, but in general roadside vegetation above 18 inches often triggers mowing. Maintenance crews may also mow regardless of plant height during the summer months to keep themselves busy when other responsibilities are light.

Given paved roads shed water to the shoulder, vegetation immediately adjacent to the roadside may reach 18 inches early in the growing season (i.e. mid-July or early August) half way through the monsoon summer precipitation season. Plants in mid-summer are near their maximum potential to capture CO_2 from the atmosphere through the photosynthetic process. Our research suggests that mowing the ROW in mid-summer can severely reduce the ability of plants to absorb CO_2 and can even lead to releases of CO_2 to the atmosphere in the days and weeks after mowing. Mowing essentially halts the carbon sequestration process and turns what would be a CO_2 sink into a source while the plants recover from the defoliation.

In grassland communities, up to 80 percent of the total biomass of a grass plant exists as root tissues and nearly 50 percent of those roots die and are replaced over the course of a year. Annual senescence of grass roots directly contributes organic compounds to the soil and leads to the formation of soil organic matter. The accumulation of soil organic carbon in grasslands is directly related to root growth where highly product grasslands in temperate climates can store in the soil. Removing a large proportion of aboveground biomass during the growing season by mowing leads to reallocation of energy reserves from the roots to regrow stems and leaves. The net result is mowing effectively prunes the plant's root systems, resulting in less carbon being sequestered into ROW soils.

Applying our understanding of a plant's tolerance and physiological response to a significant defoliation could allow NMDOT to manage ROWs to sequester soil carbon. Our research strongly suggests that modifying NMDOT's mowing operations by either removing less plant tissue (raising the mower height) or adjust the timing of mowing to when plants are not growing (October through April) would maintain the ability of managed portions of the ROW to absorb CO_2 sink throughout the growing season. Both modified mowing regimes would have less of an impact on root growth and likely lead to eventual increases on soil carbon as compared to the current mowing regime.

While still being attentive to the public safety needs to maintain a clear zone along a highway, NMDOT could implement new standards for mowing operations that essentially manages for root growth and enhances the capacity of roadside vegetation communities to sequester carbon. The new standards would allow mowing with a raised blade or deferring mowing to the end of the growing season. The implementation costs for such a program would be effectively zero as mowing is already a required annual practice. We believe this recommendation is aligned with FHWA's Eco-logical approach which works to implement efficient/cost-effective measures to avoid/minimize ecological impacts associated with transportation infrastructure.

Follow-on Research

The research proposed below is a continuation of the NMDOT ROW Carbon Sequestration Project to further refine our technical understanding of plant responses to ROW vegetation management and to advance a ROW carbon offset protocol. The implementation plan provides scopes of work for three tasks to be considered by the project's technical panel to advance the technical basis for a ROW carbon sequestration greenhouse gas offset project at state, regional and national levels.

Research Scopes of Work

Task 1: Evaluation of CO_2 Flux above Grassland Ecosystems under Different Mowing Regimes

Greater understanding of plant responses to defoliation by mowing is needed. In particular, more specific information is required to appreciate the dynamics of ecosystem CO_2 exchange associated with plants' physiological reaction to the removal and regrowth photosynthetic tissues. This information is necessary to optimize mowing operations in shortgrass ecosystems to maximize soil carbon sequestration. Due to the sophisticated and expensive equipment necessary to measure CO_2 flux in the field, the research project was only able to deploy a portable survey CO_2 flux chamber while field staff were on a test plot. Thus, only a limited number of discrete flux measurements were made over a very short period of time, especially following the mowing operations.

We consider a more controlled field experiment with replicated clipping treatment to simulate different mowing operations. The field experiment would be located in an ungrazed pasture with limited public access. The secure setting would allow for more continuous CO_2 monitoring to determine net ecosystem exchange (NEE) responses to simulated mowing over time. We recommend replicating the treatments at a minimum of two sites and the field work to extend over no less than two growing seasons.

Potential sites to implement the research could be at NMSU Agricultural Science Centers that focus on rangeland and grazing-related research. The primary rangeland research centers are located in Tucumcari, Clovis, and Clayton. There may also be opportunities at the John T. Harrington Forestry Research Center at Mora and the Corona Range and Livestock Research Center east of Corona, NM. We would recommend considering partnerships or project sites outside the state that have similar botanical and climatic characteristic to the eastern New Mexico shortgrass prairie. For example Colorado State University has several grassland long-term ecological research site where NEE has been evaluated for decades. There may also be opportunities to work with the US Department of Agriculture at the US Forest Service Kiowa National Grasslands or the Agricultural Research Service, Rangeland Research Sites in Akron and Ft. Collins, Colorado or Brushland, Texas.

We envision deploying portable flux chambers or constructing more permanent ecosystem respiration chambers to measure CO_2 flux over plants throughout the growing season with the specific intent to monitor NEE as plants recover from clipping. The permanent flux chambers could be automated to open the tops and allow for normal air circulation and rainfall during periods when flux measurements are not being taken. Methods to measure CO_2 flux in open-top chambers should also be considered. Additional instrumentation would be required including soil moisture and temperature sensors, a rain gage, and quantum sensors or light meters to measure photosynthetically active radiation. We also recommend the use of specialty instrumented cameras fitted infrared sensors so that a Normalized Difference Vegetation Index (NDVI) for each treatment can be determined. Post processing images to obtain real-time NDVI would alleviate the need to estimate plant cover and simplify ecosystem modeling to predict NEE responses to mowing.

Treatments would include various mowing regimes including delayed and dormant season mowing. Potentially a few treatments could include also legumes to evaluate whether increasing nitrogen can enhance productivity and increase the rate CO_2 sequestration. Table 1 presents the potential mowing treatments with a preliminary clipping schedule.

Table 1. Potential Field Trial Mowing Treatments

Treatment	Clipping Date
Control	None
Standard (6”)	August 1
High (10-12”)	August 1
Standard/Legume	August 1
High/Legume	August 1
Standard/Delayed	September 1
High/Delayed	September 1
Dormant Season	October 15

Task 2: Assessment of Greenhouse Gas Sources, Sinks and Reservoirs

Protocol development requires an offset project boundary which delineates and assesses all GHG sources, sinks and reservoirs (SSR’s) in order to determine the net change in emissions. The GHG assessment boundary is not the same as an offset project physical boundary, rather it encompasses all SSRs, regardless of location or who controls or owns them, that could be significantly affected by a project activity. All SSRs within the GHG assessment boundary need to be included in the quantification of GHG reductions. GHG emission reductions are quantified by comparing project emissions against baseline emissions.

In the case of the NMDOT ROW project, the preliminary identification of sources identified that the same SSRs are present under both the baseline and the project case i.e. there are no additional GHG sources as a result of project activities. The ROW project quantified both baseline and project emissions based on an ecosystem modeling approach that considers site-specific biometric measurements, long-term ecological monitoring data and NDVI – a measure of 'greenness' derived from satellite collected data.

Other grassland type protocols (such as the Climate Action Reserve [CAR] grassland protocol) use a modeling approach to estimate baseline and/or project emissions and reductions. One such model DAYCENT, which simulates cycling of carbon, nitrogen and other nutrients in various ecosystems on a daily time step. In the case of the CAR grasslands protocol, a number of different scenarios were run using the DAYCENT model in order to develop simplified emission rates based on different soil types and climatic regions.

The measurement and ecosystem modeling approach developed to date is considered to quantify SSR's associated with soil organic carbon, belowground biomass, aboveground biomass and litter. Whether quantification of emissions related to soil nitrogen and soil inorganic carbon is required for a ROW protocol needs to be confirmed.

For this task, we recommend a modeling exercise to specifically simulate fluxes of carbon and nitrogen among the atmosphere, vegetation, and soil using DAYCENT. Key submodels include soil water content and temperature, plant production and allocation of net primary production (NPP), decomposition of litter and soil organic matter, mineralization of nutrients, N gas emissions from nitrification and denitrification, and CH_4 oxidation in non-saturated soils.

Task 3: Examination of the Eligibility Criteria for a ROW Protocol

Carbon offsets are sophisticated financial instruments that require substantial documentation, review, monitoring and verification before offset credits are issued. The process by which an offset is developed must be completely transparent, technically credible, compliant with regulatory guidelines and include stakeholder participation to give buyers complete confidence in the offset issued.

For this task, we recommend assembling a technical advisory committee to examine these issues in depth as they relate to ROWs and address the minimum expectations of carbon registries to develop a protocol. Specific topics that need resolution include project boundaries, ownership, additionality, permanence, leakages and monitoring/verification.

The committee should include individuals well-versed in carbon offset protocol development, transportation easements, realty, federal land policy, ROW maintenance and highway safety. We are concerned, however, that the level of interest in ROW CO_2 sequestration is limited within New Mexico. Interest in the topic is dispersed among various researchers and practitioners from Florida to Washington State, Montana, North Carolina, Minnesota, Virginia, Ohio and Colorado. There is also a significant initiative to preserve and enhance pollinator habitat in ROWs by employing integrative roadside vegetation management (reduced mowing and spraying). This group has yet to recognize the carbon sequestration benefits with the establishment of roadside plant communities comprised of native flowers and grasses that provide forage and cover to pollinators.

Convening a committee comprised of integrative experts would not garner much national attention for a ROW carbon offset protocol. Thus, we believe such a project is likely at least a regional effort if not national. It seems the most sensible that it be an undertaking by Transportation Research Board committees (i.e. Ecology and Transportation, Environmental Analysis in Transportation, Landscape and Environmental Design and the Special Task Force on Climate Change and Energy).

Issues that require resolution prior to the development of a Highway ROW Carbon Sequestration Protocol are discussed at length in Section 6 of the final report. At a minimum, the committee would need to address:

- Quantification of both baseline emissions and project removals for ROW practices (i.e. accurately defined current best management practices and project activities)
    - Account for changes to all GHG emissions (CO_2, CH_4, N_2O, NO_x, and NH_4).
    - Develop an audit system to demonstrate the new practice is implemented according to the protocol sequesters carbon, is different and meets verification requirements.
- Policy-related thresholds or issues common to most GHG offset programs
    - Additionality
        - Are the practices going above and beyond the industry standard?
    - Ownership of the Carbon Offset
        - ROWs cross private and public property. Who will own any revenue that is generated?
    - Permanence
        - How can an agency commit to a project's longevity specified in a protocol?
- Resolve constraints related to highway safety with modification of ROW mowing practices

New Mexico Department of Transportation
RESEARCH BUREAU
7500B Pan American Freeway NE
PO Box 94690
Albuquerque, NM 87199-4690
Tel: (505) 798-6740