DISSERTATION

A SOCIAL-ECOLOGICAL APPROACH TO MANAGING AGRICULTURAL AMMONIA EMISSIONS AND NITROGEN DEPOSITION IN ROCKY MOUNTAIN NATIONAL PARK

Submitted by

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Graduate Degree Program in Ecology

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2017

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ABSTRACT

A SOCIAL-ECOLOGICAL APPROACH TO MANAGING AGRICULTURAL AMMONIA EMISSIONS AND NITROGEN DEPOSITION IN ROCKY MOUNTAIN NATIONAL PARK

Atmospheric nitrogen (N) deposition is harmful to nutrient-limited mountain ecosystems. Annual wet deposition of total inorganic N in Rocky Mountain National Park (RMNP) is dominated by ammonium, which primarily comes from agricultural sources. The most wet N deposition events between 1980 and 2015 occurred during summer months. The confluence of summertime mountain meteorology and the location of pollution sources are a perfect combination that leads to high values of wet N deposition in RMNP. In Chapter 2, we tested the importance of convection as a N transport mechanism in addition to large-scale east winds, typically associated with the summertime mountain-valley circulation on the eastern plains of Colorado. We characterized the meteorological transport by using the Weather Research and Forecasting model at 4/3-km horizontal resolution. We used passive tracers as a simplified representation of emissions from a single agricultural source in eastern Colorado during three summer precipitation events where wet N deposition values in RMNP were among the highest recorded in all summers between 1980 and 2015. In all three cases, anticyclones in north-central United States and monsoonal flow associated with the North American Monsoon brought together the necessary conditions for deep convection over RMNP. Output from our simulations suggested large-scale winds were responsible for slow and steady transport whereas convection was a rapid and intermittent form of transport. This chapter showed two scales of transport had

an additive effect that led to high deposition of N in RMNP during the afternoon/evening hours of three case studies.

Chapter 3 discusses the development of a pilot early warning system (PEWS) for agricultural operators to voluntarily and temporarily minimize emissions of NH_3 during periods of upslope winds. The PEWS was created using trajectory analyses driven by outputs from an ensemble of numerical weather forecasts together with the climatological expertise of human forecasters. In this study, we discuss the methods for the PEWS and offer a preliminary analyses of 21 months of the PEWS based on deposition data from two sites in RMNP as wells as voluntary responses from agriculture managers and producers after warnings were issued. Results from this study showed that the PEWS accurately predicted 5 of 7 high N deposition weeks at the lower-elevation observation site, but only 3 of 8 high N deposition weeks at the higher-elevation observation site. With the higher-elevation site receiving pollution from sources both west and east of the Continental Divide, sources west of the Continental Divide would need to be included in the PEWS to capture all of the sources leading to deposition at the higher-elevation site. Sixty agricultural producers and managers from 39 of Colorado's agricultural operations volunteered for the PEWS, and a two-way line of communication between the producers and the scientists was formed. An average of 21 voluntary responses (s.d. 4.9) per warning occurred, with over 75% of the PEWS participants altering their practices after an alert. Solving a broad and complex social-ecological problem requires both a technological approach, such as the PEWS, and collaboration and trust from all participants, including agricultural producers, university researchers, and environmental agencies.

Chapter 4 applies a systems approach that explores the actors involved in a complex social-ecological problem that deals with the competing interests of an unadulterated environment and the contribution towards feeding the global population. Agricultural operations in northeastern Colorado are among the densest in the world. The demand of a growing global population has put pressure on the agricultural community to provide large quantities of food in a short amount of time. The cost for higher yields means more water, nutrients, and energy, and the result is environmental degradation in the forms of atmospheric and water pollution. The problem becomes more complex when we mix bottom-up and top-down management approaches. That is, agricultural producers are asked to work together with state and federal agencies on reducing emissions from their operations. A pilot early warning system employed in Colorado since 2014 helped bring together the actors to work towards the common goal of reducing nitrogen deposition in Rocky Mountain National Park. Our goal in this chapter was to organize the problem using a conceptual, social-ecological framework. The case studies and pilot early warning system from Chapters 1 and 2 document starting points for how institutional decisions can incorporate agricultural stakeholders in a mix of bottom-up and top-down management approaches under current and future climatic conditions.

ACKNOWLEDGEMENTS

This paper is based upon work supported by National Science Foundation IGERT Grant No. DGE-0966346 "I-WATER: Integrated Water, Atmosphere, Ecosystems Education and Research Program" at Colorado State University, National Park Service under award P13AC00599, project CSURM-273, and by the National Science Foundation Science and Technology Center for Multi-Scale Modeling of Atmospheric Processes, managed by Colorado State University under Cooperative Agreement No. ATM-0425247.

National Centers for Environmental Prediction (NCEP) NARR data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. Stage IV radar data was provided by NCAR/EOL under sponsorship of the National Science Foundation.

Thanks to Matthew Paulus for his help on data processing for the automated portion of the early warning system. Thank you to Jorge Perez Garcia for the illustrations used in Chapter 4. I want to give huge thanks Brian Wee for his mentorship (including countless editorial comments) through the dissertation process.

The Pilot Early Warning System would not have been possible without the tireless efforts of William Brock Faulkner. Rest in peace.

DEDICATION

“The music ignites the night with passionate fire…feel the heat of the future’s glow.”

— Jonathan Larson

“Imagine that you enter a parlor. You come late. When you arrive, others have long preceded you, and they are engaged in a heated discussion, a discussion too heated for them to pause and tell you exactly what it is about. In fact, the discussion had already begun long before any of them got there, so that no one present is qualified to retrace for you all the steps that had gone before. You listen for a while, until you decide that you have caught the tenor of the argument; then you put in your oar. Someone answers; you answer him; another comes to your defense; another aligns himself against you, to either the embarrassment or gratification of your opponent, depending upon the quality of your ally's assistance. However, the discussion is interminable. The hour grows late, you must depart. And you do depart, with the discussion still vigorously in progress.”

— Kenneth Burke

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CHAPTER 1

INTRODUCTION

Aquatic and terrestrial ecosystems in the Rocky Mountains have evolved in a nutrient-limited environment. The granitic soils are poor in nutrients, namely phosphorus and nitrogen, conducive for vegetative growth (Baron et al. 1992). Historically, there have been low levels of atmospheric deposition of these nutrients (Baron et al. 2000).

Though nitrogen is the most abundant gas in our atmosphere, a strong triple bond that often prevents it from becoming part of a bioavailable compound. High-energy processes are required to break the triple bond, called “fixing”, and create reactive forms of N. Naturally-occurring fixation processes include lightning and microbial activities. Microbial activities dominated the role in fixing N until the 20th century (Vitousek et al. 1997). Over the last 50 years, atmospheric deposition of reactive nitrogen (N_r) have increased in Rocky Mountain National Park (RMNP) associated with the economic development the Colorado Front Range, the proximity to power plants, and the growth of industrialized agricultural operations in eastern Colorado (Baron et al. 2000; Benedict et al. 2013a).

In the United States, nitrogen oxide (NO_x) emissions, from fossil fuel combustion, are regulated as criteria pollutants from the Clean Air Act Amendments of 1990. Title IV of the Amendments was aimed to reduce acid rain (N and sulfur (S) deposition), especially in the northeastern United States.

In the early 20th century, the Häber-Bosch process was developed to create ammonia (NH_3), a key ingredient in fertilizer, from atmospheric nitrogen (N_2). This process revolutionized the agriculture industry (and likely Earth's carrying capacity for humans) as fertilizers were able to increase yields of crops. Due to the limited capacity of crops to uptake N, fertilizer that is not taken up by crops can be transported away via runoff and volatilization. Ammonia in fertilizers becomes airborne through volatilization (liquid to gas) and transport with wind and water to ecosystems that have not historically received large amounts of N input. In the mid-20th century, livestock farming in the U.S. transformed from small-scale, local community-based businesses to large-scale, highly formalized operations where tens of thousands of head of livestock are raised and harvested in confined feeding operations. In open fields, livestock excrement, rich with NH_3 would be naturally cycled in the system, often leading to an enrichment of soils. However, the soils under the concentrated livestock are not able to keep up with the thousands of kilograms of daily excrement. Therefore, the NH_3 contained within the surface of the slurry volatilizes into the atmosphere.

NH_3 has yet to be classified as a regulated pollutant, despite its potential harmful impacts to ecosystems far-removed from its source. Since the 1980s, deposition of reduced N species (NH_y) is increased, consistent with increases in NH_3 emissions (Li et al. 2016).

Deposition of N_r to RMNP is highly dependent on the local meteorology. Upslope winds carry Front Range pollutants towards the natural and fragile subalpine/alpine ecosystems (Baron and Denning1993; Benedict et al. 2013a). A number of studies have helped to understand source, transport, and fate of N_r reaching alpine and subalpine ecosystems in RMNP (Baron et al. 2000; Malm et al. 2009; Benedict et al. 2013b; Bowman et al. 2012; Gebhart et al. 2014; Thompson et al. 2015).

Currently, in alpine and subalpine regions across the globe, N deposition has mostly led to an increase in primary productivity in terrestrial ecosystems (Baron et al. 2000; Bobbink et al. 2010; Baron et al. 2011; Bowman et al. 2012). N deposition threatens not only terrestrial biota but also aquatic life. The western United States has just under 16,000 high-elevation lakes (Bahls et al. 1992). These high-elevation lakes are oligotrophic, meaning they offer few nutrients to the aquatic environment (Fenn et al. 2003). Small inputs of N can have large effects to the aquatic ecosystem.

One of the studies, the Rocky Mountain Atmospheric Nitrogen and Sulfur (RoMANS) study by Malm et al. (2009), occurred during two sampling periods in 2006. Primary findings were that N deposition was a factor of two higher in the summer than in the spring, due to the difference in meteorology. Additionally, higher concentrations of reduced and oxidized N were found to be in northeastern Colorado with a strong west-to-east gradient. Interestingly, the study also found about half of the N reaching Rocky Mountain National Park originates from east of the park. Deposition of reduced N has also increased in RMNP since the 1980s (NADP 2016).

In 2007, discussions between the U.S. National Park Service, the U.S. Environmental Protection Agency, Colorado Department of Public Health and the Environment, agricultural producers and managers, and other interest groups (e.g. Trout Unlimited) reviewed deposition and sources along the Colorado Front Range that led to increased N_r deposition in RMNP. The result of the discussions led to the Rocky Mountain Nitrogen Deposition Reduction Plan (NDRP). The Clean Air Act Amendments of 1990 helped reduce emissions of NO_x, which leads to wet deposition of NO_3^-. However, unregulated emissions of NH_3 have resulted in an increase of NH_4^+ in RMNP since the 1980s.

Recent technological advances in atmospheric modeling have provided more accuracy with regards to the transport of N. Chapter 2 of this dissertation looks at the mechanisms by which N is transported from cattle feedlots in eastern Colorado into Rocky Mountain National Park. We chose three high N deposition events using data from the National Atmospheric

Deposition Program's National Trends Network. We then ran weather simulations at high spatial and temporal resolution to study the transport of simulated pollutants from the location of a cattle feedyard near Greeley, CO.

Chapter 3 discusses the methods and preliminary findings of a pilot early warning system (PEWS) that aims to minimize N emissions from agricultural operations during periods where the weather conditions are conducive for upslope transport into Rocky Mountain National Park. The PEWS began in April 2014 and continues to the present. There were 94 individuals who signed up to receive alerts. Although the PEWS is not part of the Rocky Mountain National Park Nitrogen Reduction Plan that aims to reduce the wet deposition of inorganic N to below the critical threshold of an alpine lake in RMNP, it is an integral part of the objectives to reduce N deposition in RMNP.

Chapter 4 is an overview of the challenges in managing agricultural practices to minimize N emissions and deposition to RMNP. The topics of this dissertation are highlighted in red.

Chapter 5 includes concluding remarks, future work, and policy implications of this work.

CHAPTER 2

ATMOSPHERIC TRANSPORT OF AGRICULTURAL NITROGEN EMISSIONS FROM EASTERN COLORADO INTO ROCKY MOUNTAIN NATIONAL PARK: THREE CASE STUDIES

1. Introduction

Reactive nitrogen (N_r) deposition as a result of human activities is threatening the health of ecosystems around the world (Rockström et al. 2009; Erisman et al. 2013). In the southern Rocky Mountains, increased N_r deposition from fossil-fuel combustion (e.g. nitrate (NO_3^-)) and agricultural operations (e.g. ammonia (NH_3), ammonium (NH_4^+); Nichols et al. 2001; Elser et al. 2009; Malm et al. 2009) has led to a concern about pollutant transport into Rocky Mountain National Park (RMNP; CDPHE 2007). Generally, RMNP is upwind of the pollution sources in eastern Colorado because prevailing winds are from west to east. However, near the Rocky Mountains, the combination of a diurnal mountain circulation, monsoon-moisture flow, and synoptic circulation patterns can bring emissions in eastern Colorado into biogeochemical contact with ecosystems in RMNP. At one site in RMNP, the five-year averaged ratio of NH_4^+ wet deposition to total inorganic N (NO_3^- + NH_4^+) deposition has increased from ~40% in 1987 to just under 60% in 2015 (NADP 2016).

a. Pollution sources

Infrequent east winds bring the highest concentrations of reduced N into RMNP (Malm et al. 2009; Gebhart et al. 2014). Thompson et al. (2015) found over 60% of reduced N from Colorado sources comes from east of the Continental Divide, with the highest contributions from counties along the central and northern Front Range.

Counties in eastern Colorado have many concentrated animal feeding operations (CAFOs), which include dairy, beef cattle, poultry, swine, and sheep operations. Weld County, CO is permitted for over 500,000 head of beef cattle (Vilsack and Clark 2012) and has the highest population of livestock units compared with other counties in Colorado. Though there are many gaseous and particulate emissions from CAFOs, this study focused on NH_3 emissions and transport into RMNP. Volatilized NH_3 is highly soluble in water and converts to particle-phase NH_4^+ in cloud water through an acid-base reaction (Jacob 1999). Together, NH_3 and NH_4^+ are referred to as reduced N or NH_y.

b. Pollution effects in mountain ecosystems

RMNP has two National Atmospheric Deposition Program National Trends Network (NADP, hereafter) sites that measure wet deposition dating back to the early 1980s. From here forward, we discuss deposition data from the Beaver Meadows site (CO19; 2477 m ASL) because it experiences most meteorological influence from the east side of the Continental Divide during summers while Loch Vale (CO98; 3159 m ASL) experiences meteorological influence from both east and west sides of the Continental Divide (Baron et al. 1992). Beaver Meadows experienced an increasing trend in wet total inorganic N deposition between 1980 and 2012 (Morris et al. 2014). The increasing trend was dominated by the increasing trend in wet NH_4^+ deposition (Morris et al. 2014; NADP 2016), providing motivation for this study to look at transport from agricultural operations in eastern Colorado.

Nitrogen is a limiting nutrient for the growth of sensitive aquatic and terrestrial flora found in the Rocky Mountains (Baron et al. 2000; Bowman et al. 2006). Excess N_r from chronic deposition of atmospheric N can lead to nutrient enrichment or even acidification of ecosystems, which can lead to changes in primary productivity and a loss of biodiversity (Baron et al. 2000;

Baron et al. 2011). With N being a limiting nutrient in the Rocky Mountains, subalpine and alpine ecosystems are currently experiencing nutrient enrichment (i.e. plant growth) as a result of depositing N_r (Baron et al. 2000).

c. Summer transport mechanism

Though winds in counties just east of the Colorado Front Range are predominately from the west, east winds from midlatitude cyclones and a mountain-valley circulation are occasionally observed. East winds from mid-latitude cyclones occur mostly during spring months (MAM) and are major contributors to the annual N deposition in RMNP. However, source apportionment studies suggest summer transport patterns over complex terrain are more difficult to capture than spring transport patterns (Gebhart et al. 2011; Gebhart et al. 2014; Thompson et al. 2015).

Thermally-induced east winds during summers result from a mountain-valley circulation on the lee side of the Rocky Mountains in conditions with little-to-no synoptic forcing (Markowski and Richardson 2011). After sunrise, convection results from higher temperatures on the mountain slopes at a given pressure level relative to the plains, inducing a buoyancy-driven wind from the plains westward toward the mountains (Markowski and Richardson 2011). This east (upslope) wind carries agricultural emissions westward toward the mountains during the daytime. In the presence of moisture, convection over the mountains precipitates pollutants that were entrained into clouds onto the mountains (Baron and Denning 1993; Benedict et al. 2013b). These thermally induced winds can also be enhanced in response to transient shortwave troughs over the western United States during the summer. Malm et al. (2009) noted the largest deposition events of N-containing particulate matter and gases occurred during flow with a predominant easterly component.

Higher episodes of wet N_r deposition associated with east winds during summers motivated this study, which examined the meteorology surrounding three high N_r deposition events during summers between 1980 and 2015. In past studies, deposition in RMNP during summers was thought to have been solely influenced by the confluence of moisture transport and urban pollutants along the Colorado Front Range via a mesoscale mountain-valley circulation (Baron and Denning 1993; Malm et al. 2009; Benedict et al. 2013b). In this study, we tested the hypothesis that emissions from the largest feedlot in Weld County, CO are transported through the combination of a mesoscale mountain-valley circulation and convection into RMNP.

In the following sections, we discuss the methods for characterizing the meteorology surrounding three high wet N_r deposition events followed by a results section. The last section discusses implications of our findings and offers concluding suggestions for future studies.

2. Methods

We analyzed three test cases, chosen from data collected and sampled by the NADP, to identify different scales of transport. To test our hypothesis, we characterize the meteorology surrounding the high deposition events using the North American Regional Reanalysis for synoptic patterns and the Weather Research and Forecasting model for mesoscale and cloud-scale patterns.

a. National Atmospheric Deposition Program National Trends Network

The NADP records daily precipitation and weekly concentrations for over 350 rural sites across the United States to monitor trends and geographic distribution of precipitation chemistry (NADP 2016). We analyzed 36 summers (1980-2015) of available weekly precipitation and concentrations of total inorganic N from Beaver Meadows in RMNP. The Beaver Meadows NADP site is surrounded by grassland meadows, sagebrush, lodgepole and ponderosa pine, and

Douglas fir (Snyder 2006). Weekly wet inorganic N deposition, in mg N m^{-2} wk^{-1}, was calculated by multiplying weekly precipitation (mm wk^{-1}), the concentrations of N species (NH_4^+ or NO_3^-; mg L^{-1}), and the N-to-ion ratio of molecular masses, shown in equation 2.1. Because this study focused solely on wet deposition of inorganic N, we use "deposition" to represent "wet deposition of inorganic N" hereafter, unless otherwise noted.

$$Wet\ deposition_{N_i} = precipitation \cdot N_i \cdot \frac{M_N}{M_{N_i}} \qquad (2.1)$$

As seen in Figure 2.1, Beaver Meadows had a primary precipitation maximum in the spring and a secondary maximum in the summer. During summers, the combination of longer hours of sunlight, higher frequencies of east winds, and higher volatilization efficiencies of NH_3 results in higher concentrations of NH_4^+ in RMNP (Baron et al. 1992; Hargreaves et al. 2004; Grant et al. 2013).

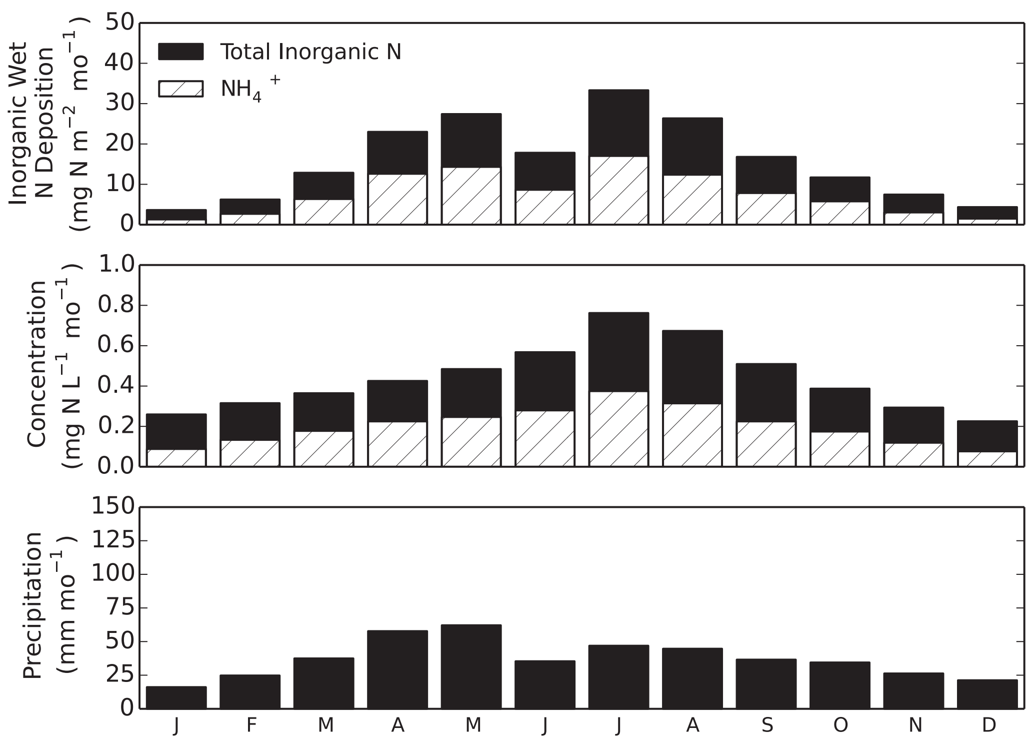

Figure 2.1. Monthly-averaged total inorganic N deposition, total inorganic N concentration, and precipitation for Beaver Meadows from 1980-2015.
Data source: NADP (2016).

Frequency of weekly summer deposition between 1980 and 2015 (n=344 weeks) at Beaver Meadows (Figure 2.2) showed a secondary deposition peak in the tail of the distribution (deposition greater than 20 mg N m^{-2} wk^{-1}). NH_4^+ constituted an average of 54.2% (s.d. 10.0%) of the total inorganic N deposition in this secondary peak compared with an average of 42.7% (s.d. 14.6%) for all summer weeks (1980-2015). A cumulative distribution (not shown) showed the bulk of the deposition occurred in the few tail events of the frequency distribution—25.0% of the total summer deposition between 1980 and 2015 occurred from the highest 24 weekly N deposition events (7.0% of all weeks). We, therefore, chose to analyze three recent and representative cases within the secondary deposition peak in Figure 2.2: 1. The highest amount of weekly deposition, 13-20 July 2004; 2. A recent event which experienced the third-highest weekly deposition, 3-10 July 2012; and 3. The median week of the secondary peak, 15-22 August 2006. Combined, the three weeks accounted for ~4.6% (2.0%, 1.4%, and 1.2%, respectively) of all summer deposition between 1980 and 2015 at Beaver Meadows. From daily precipitation measurements by NADP, we were able to identify which days within these weeks had the highest wet deposition and focused our simulations on these periods with precipitation.

b. North American Regional Reanalysis

The North American Regional Reanalysis (NARR) was used to examine synoptic conditions that preceded and likely primed the high summer deposition events. The NARR is a combined model and assimilation dataset, providing 32-km meteorological analyses over North America (Mesinger et al. 2006). We used the NARR 3-hour analysis to look at mean sea level pressure (MSLP), 850-hPa winds, 700-hPa relative humidity (RH), and precipitable water surrounding the three events.

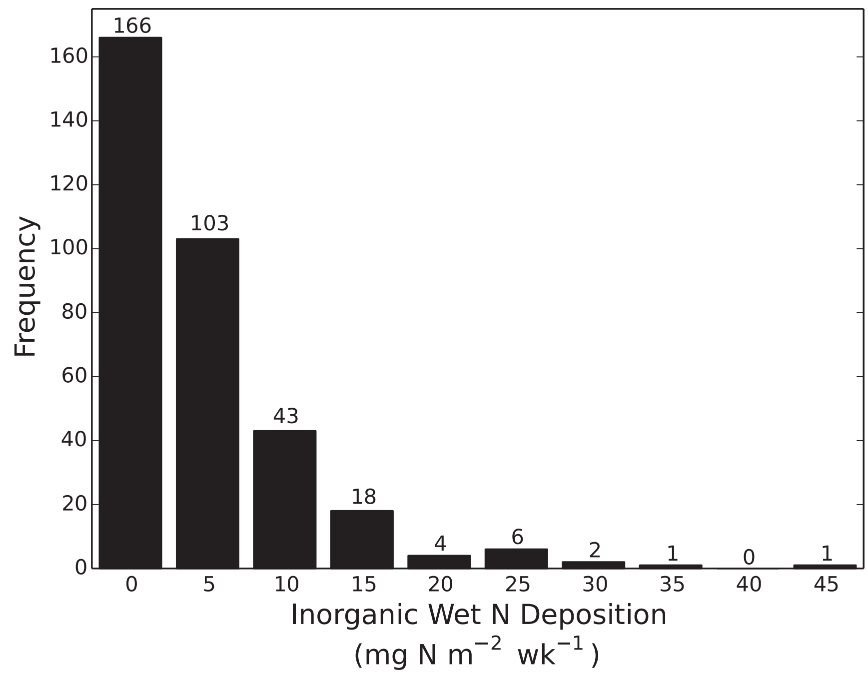

Figure 2.2. Frequency distribution of wet deposition of inorganic N at Beaver Meadows for summer (JJA) weeks between 1980 and 2015 (n = 344 weeks).
Data source: NADP (2016).

c. Weather Research & Forecasting Model

The Advanced Research core of the Weather Research and Forecasting (WRF, hereafter) model, version 3.4.1 (Skamarock et al. 2008) was used to simulate the meteorology at a high time-and-space resolution for the progression of the upslope events that led to high deposition values in RMNP. Specifically, wind direction and speed along with precipitation adjacent to the Colorado Front Range were of interest. WRF was configured with one-way boundary conditions between three domains (shown in Figure 2.3) at a 3:1 parent-to-nest ratio. The outer domain had grid spacing set to 12 km with a time-step of 36 s. The vertical grid had 45 layers with a ceiling at 10 hPa. The choices of model parameterizations were similar to those used by Nehrkorn et al. (2010) and are shown in Table 2.1. The NCEP Operational Model Global Tropospheric Final Analyses (NCEP 2000) were used for the model initial and outermost lateral boundary conditions. Each simulation was 48 hours with an output interval of 10 minutes for the 4/3-km domain. We initialized WRF at least 12 hours prior to hours of interest to avoid erroneous spin-up meteorological features (Weiss et al. 2008): Case 1 was initialized at 1200 UTC 15 July 2004, Case 2 was initialized at 1200 UTC 18 August 2006, and Case 3 was initialized at 1200 UTC 6 July 2012. The NCEP Stage IV precipitation analysis (Lin and Mitchell 2005), which includes manual quality control, was used to compare with simulated precipitation.

Table 2.1. WRF physics schemes used in this study.

Physical parameter	*Scheme*	*Domains applied*
Microphysics	Lin et al. (1983)	All
LW Radiation	RRTMG (Iacono et al. 2008)	All
SW Radiation	New Goddard (Chou et al. 1999)	All
PBL	Yonsei University (Hong et al. 2006) with Noah Land Surface Model and MM5 similarity theory-based surface layer scheme	All
Cumulus	Grell 3D (Grell and Devenyi, 2002)	1

We activated a passive tracer option discussed by Barth et al. (2012) in an area of 2x2 grid points over the location of a feedlot in Weld County, CO in domain 3, denoted by the black dot in Figure 2.3. The feedlot is one of the largest CAFOs in the United States, and therefore world. We assumed that if emissions from this area of land reaches RMNP, emissions from surrounding feedlots would also reach RMNP. The unitless and massless passive tracer was initialized at every time step (dt = 4 s) from the lowest model level. At each time step, the lowest model level of the location of the simulated feedlot was set to a tracer value of 1. Tracer concentrations downwind of the feedlot were normalized to the release concentration. It should be noted the purpose of exposing a massless tracer to transport (and dispersion) and not interact with the model's thermodynamics was to observe the atmospheric flow during upslope conditions.

Realistically, the tracer emitted from the feedlot would have been water-soluble NH_3 and would either have been entrained into the cloud or scavenged by falling rain droplets. Any collocation of the tracer with a cloud extending to the surface suggested wet deposition. It should be noted this study did not attempt to reproduce the deposition amounts from NADP data; we used the tracer as a tool to observe advection and convection.

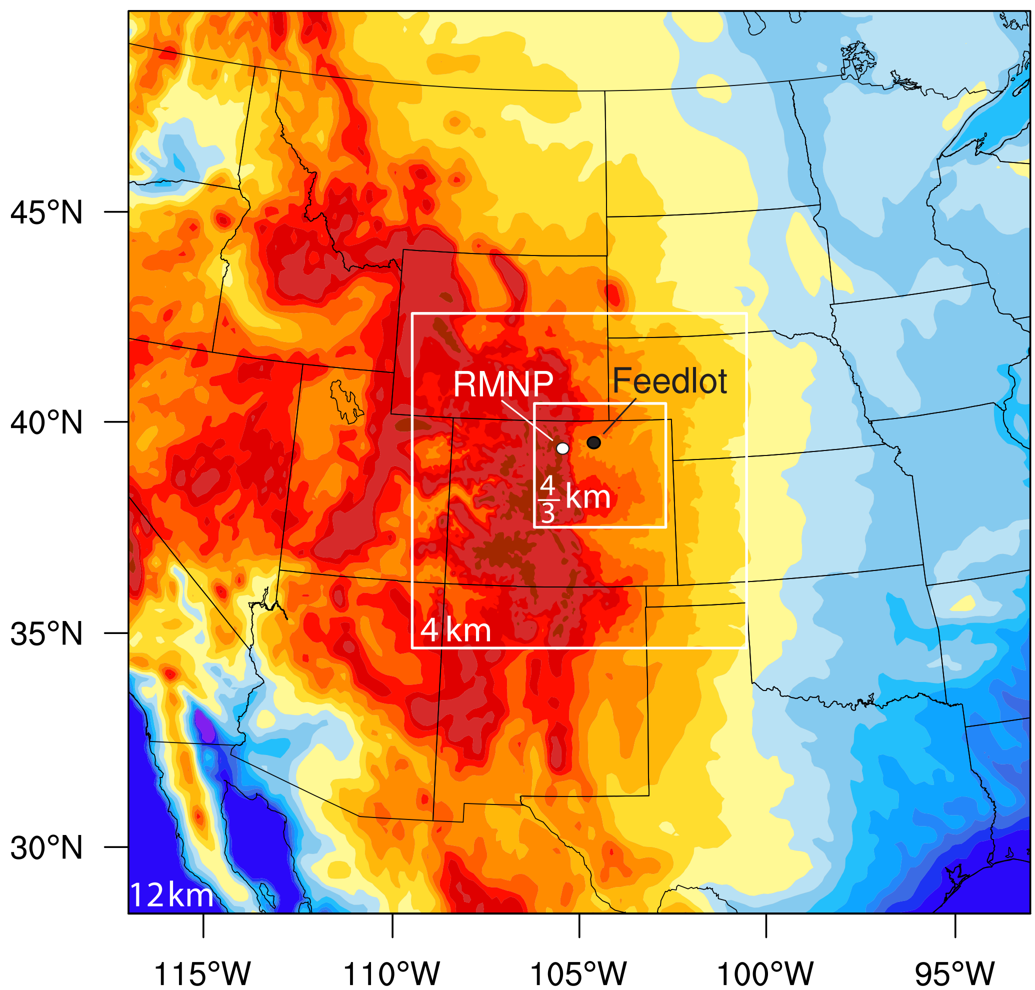

Figure 2.3. WRF domains with grid-spacing of 12 km, 4 km, and 4/3 km for domains 1, 2, and 3, respectively, overlaid on terrain maps from the WRF simulations.
Cool colors represent lower elevations and warm colors represent higher elevations, with the warmest color being the 3000 m ASL contour. Locations of the simulated feedlot in Weld County, Colorado and Rocky Mountain National Park are shown by the black and white dots, respectively.

3. Results

Figure 2.4 shows that, although there are errors in the precise magnitude and placement of precipitation in the model simulations, all three simulations replicate the general pattern of precipitation along the Front Range of the Rocky Mountains and near RMNP in particular. One should note replicating exact precipitation quantities in order to quantify wet deposition was not the intention of the comparison of Stage IV analysis with WRF output. The intention was to verify the model output had precipitation over RMNP around the time of simulated deposition, and that the spatial distribution of precipitation was approximately consistent with observations.

a. North American Regional Reanalysis

1) CASE 1: 16 JULY 2004

The large-scale meteorological pattern at 1800 MDT 16 July 2004 (0000 UTC 17 July) during the period of high deposition was characterized by a surface anticyclone was located over Saskatchewan and Manitoba, with an associated pressure ridge extended southward from that anticyclone into northern Colorado. Easterly (upslope) flow along the southern flank of the pressure ridge caused moist air to be transported westward along the Front Range in northern Colorado (Figure 2.5c). Both the easterly component of winds and the precipitable water values were anomalous for July 2004 (Figure 2.5d).

2) CASE 2: 18 AUGUST 2006

Figure 2.6 shows a reanalysis snapshot on 18 August 2006 at 2100 MDT (0300 UTC 19 August). Similar to the 2004 event, there was an anomalous large-scale surface anticyclone over southern Canada with a pressure ridge extending southwestward into northern Colorado (Figures 6a and 6b). Northern Colorado experienced northeasterly (upslope) flow associated with the southern flank of the pressure ridge (Figure 2.6c). The easterly component of winds and the precipitable water values were anomalous for August 2006 (Figure 2.5d).

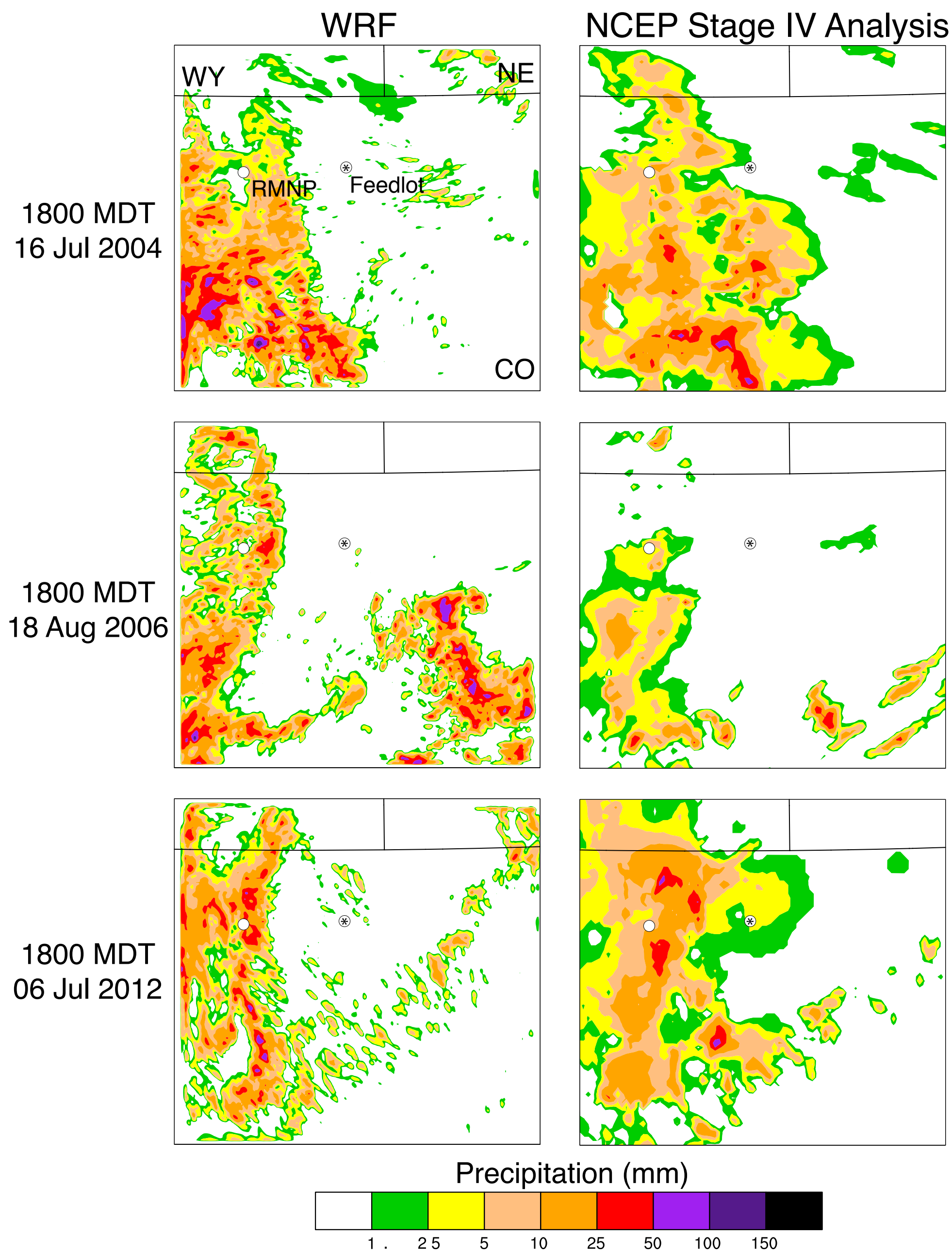

Figure 2.4. Comparison of 6-hour WRF simulated precipitation with the NCEP Stage IV precipitation analysis in domain 3 (northern CO, southeastern WY, and western NE) for 3 high N deposition events.

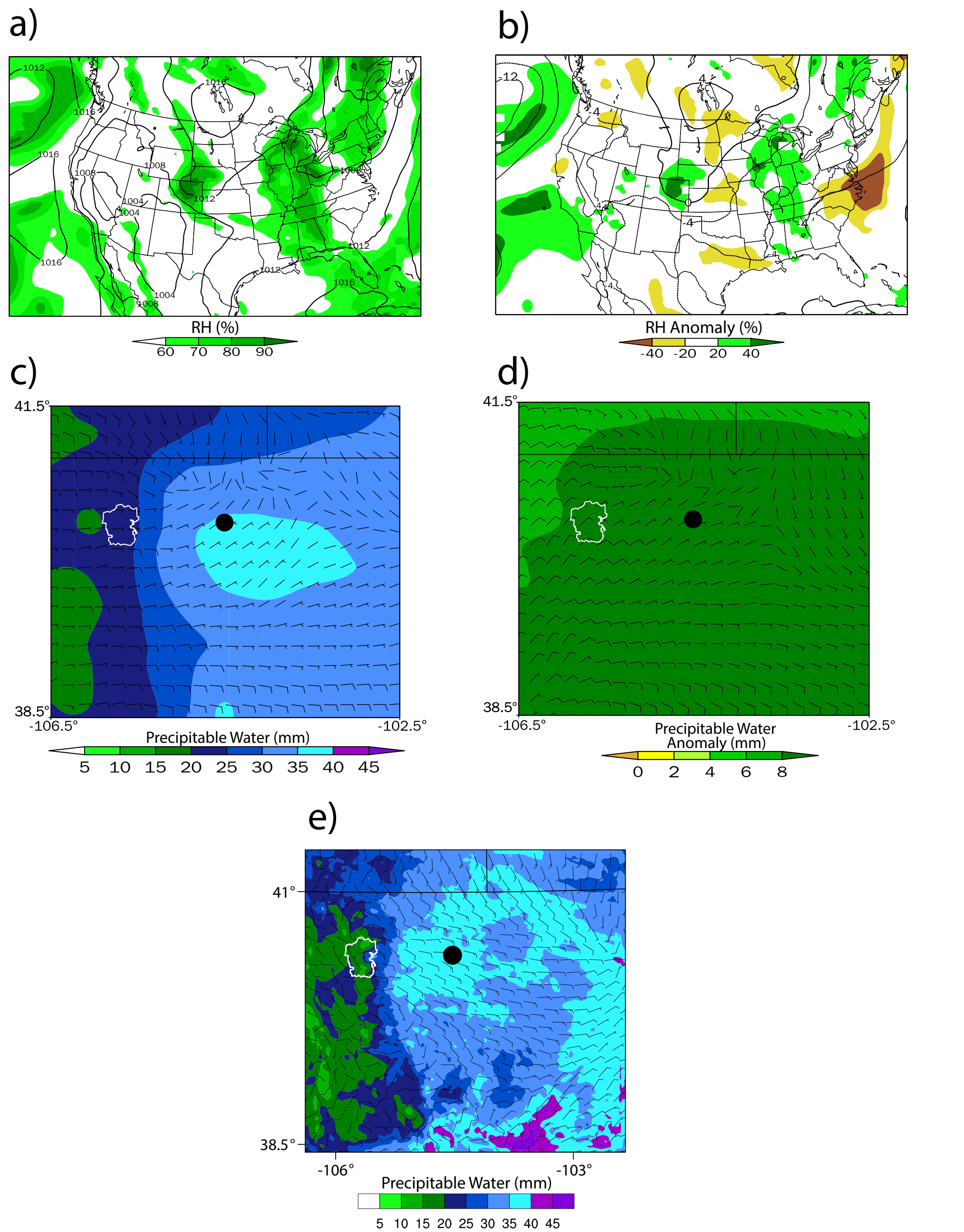

Figure 2.5. NARR output (a-d) and WRF output (e) for Case 1.
1800 MDT 16 July (0000 UTC 17 July) 2004: a. shaded 700-hPa relative humidity (%) and contoured MSLP (hPa); b. fields from map a. subtracted from the corresponding monthly-averaged values from July 2004 (solid for positive and zero values, dashed for negative values); c. shaded precipitable water (mm) and 850-hPa winds (kts) with RMNP boundary and location of feedlot; d. fields from map c. subtracted from the corresponding monthly-averaged values from July 2004; e. a replicate of map c. using WRF output.

3) CASE 3: 6 JULY 2012

The reanalysis maps in Figure 2.7, shown for 6 July 2012 at 1800 PM MDT (0000 UTC 7 July 2012), closely resemble the reanalysis maps from 2004 and 2006 with an anomalous surface anticyclone over southern Canada (Figures 7a and 7b). Similar to the high deposition events in 2004 and 2006, the northeasterly flow and precipitable water in northern Colorado were anomalous (Figures 7c and 7d). Interestingly, this precipitation event was largely responsible for extinguishing the High Park Fire northeast of RMNP and led to flash flooding around the High Park Fire burn scar.

Figures 5e, 6e, and 7e were compared with Figures 5c, 6c, and 7c, respectively, to empirically assess the consistency between the reanalysis and model wind fields. Overall, the model results (Figures 5-7e) produced easterly winds over northern Colorado along with high precipitable water values, consistent with the NARR. Similar patterns in precipitation, precipitable water values, and wind flow between Stage IV analysis/NARR and WRF (Figures 4-7) allowed us to use the WRF output with confidence to investigate the small-scale/convective transport of simulated N into the Rocky Mountains from an eastern Colorado feedlot. Additionally, a time series (not shown) of surface wind in RMNP matched the timing of upslope winds with simulated winds from the WRF simulations.

b. Weather Research & Forecasting Model

1) CASE 1: 16 JULY 2004

From the right column in Figure 2.8, surfaces easterlies east of the Rocky Mountains associated with the mountain-valley circulation extended from the surface to about 1.5 km above the surface in the afternoon. At 1420 MDT (2020 UTC; Figure 2.8a), a plume released from the feedlot towards RMNP was just west of a large convective shower. Fifty minutes later, at 1510

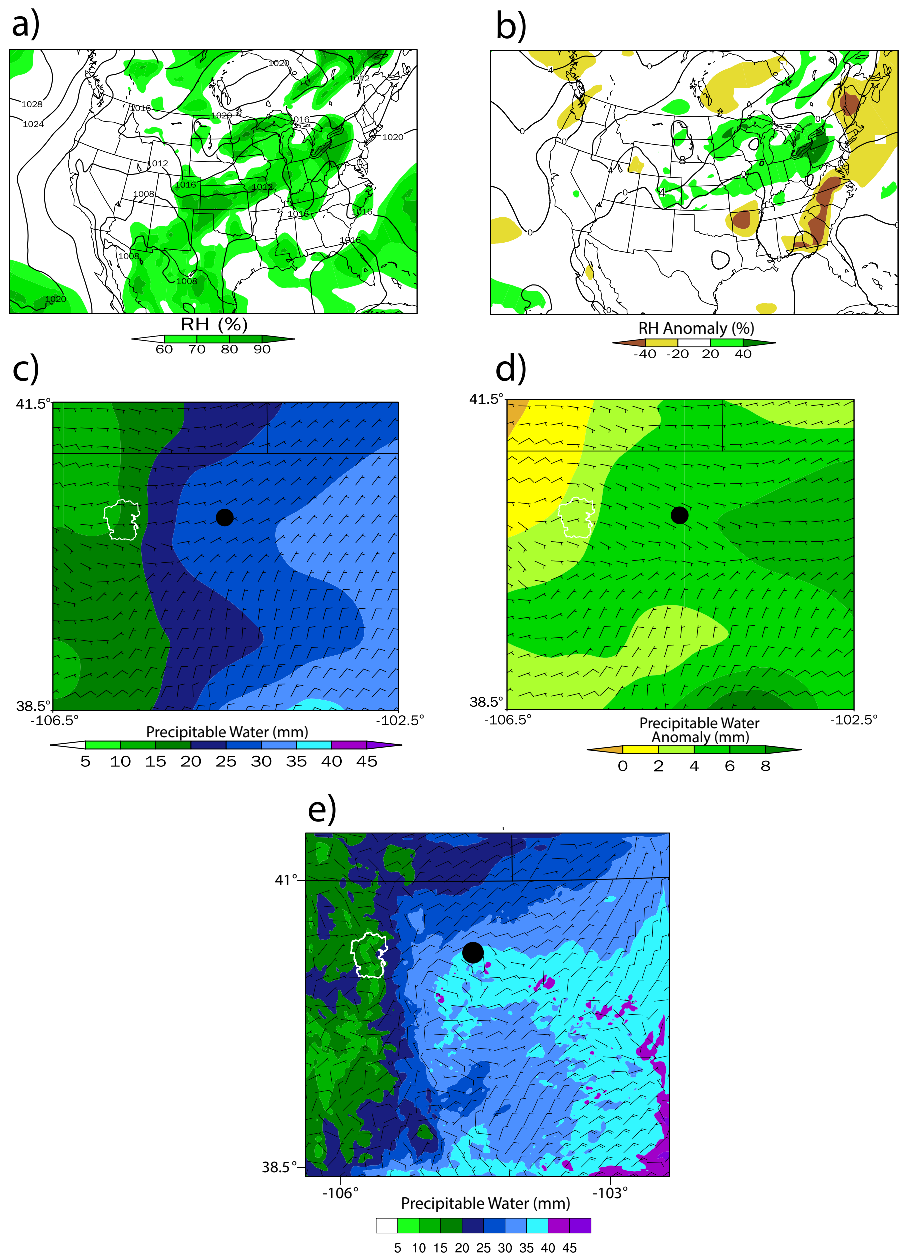

Figure 2.6. NARR output (a-d) and WRF output (e) for Case 2.
2100 MDT 18 August (0300 UTC 17 August) 2006: a. shaded 700-hPa relative humidity (%) and contoured MSLP (hPa); b. fields from map a. subtracted from the corresponding monthly-averaged values from August 2006 (solid for positive and zero values, dashed for negative values); c. shaded precipitable water (mm) and 850-hPa winds (kts) with RMNP boundary and location of feedlot (black dot); d. fields from map c. subtracted from the corresponding monthly-averaged values from August 2006; e. a replicate of map c. using WRF output.

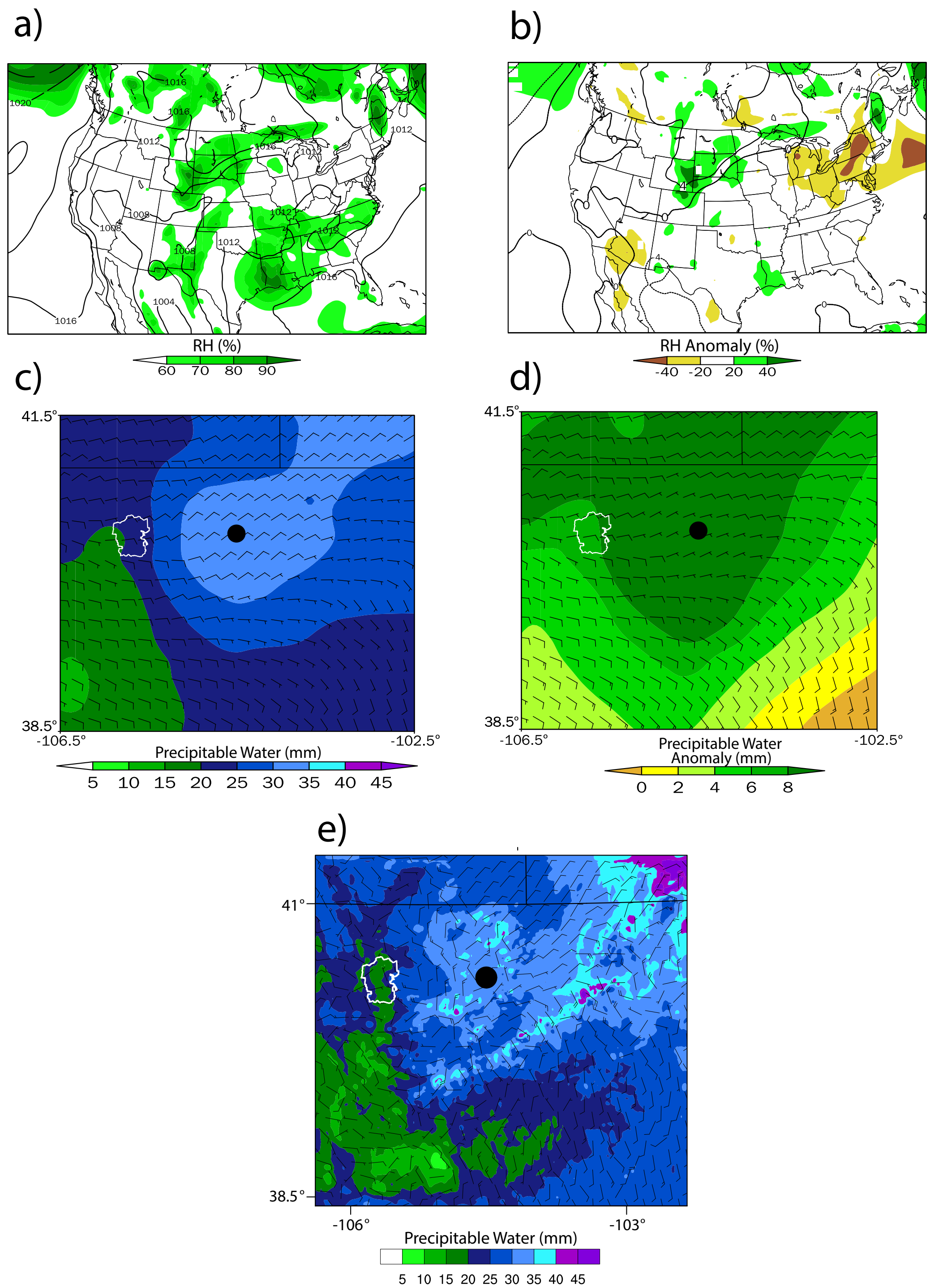

Figure 2.7. NARR output (a-d) and WRF output (e) for Case 3 1800 MDT 6 July (0000 UTC 7 July) 2012: a. shaded 700-hPa relative humidity (%) and contoured MSLP (hPa); b. fields from map a. subtracted from the corresponding monthly-averaged values from July 2012 (solid for positive and zero values, dashed for negative values); c. shaded precipitable water (mm) and 850-hPa winds (kts) with RMNP boundary and location of feedlot (black dot); d. fields from map c. subtracted from the corresponding monthly-averaged values from July 2012; e. a replicate of map c. from WRF output.

MDT (2110 UTC; Figure 2.8b), the plume was vertically transported to nearly the height of the mountains. Vertical transport, on the order of tens of minutes (not shown), is much quicker than the horizontal transport, which takes on the order of hours for air initialized from the feedlot to reach RMNP. By 1750 MDT (2350 UTC; Figure 2.8c), high concentrations were over the east side of RMNP. From the corresponding cross section, there was also precipitation over both sites in RMNP. Collocation of tracer and precipitation reaching the ground suggested wet deposition. The lateral transport, which sums the tracer concentration from the ground to 10 km, is shown in the left column of Figure 2.8.

2) CASE 2: 18 AUGUST 2006

The right column of Figure 2.9 shows surface easterlies occurred into the late evening hours, atypical of the diurnal mountain-valley circulation, indicating an influence from large-scale winds. The deep easterlies are consistent with those shown in Figure 2.6c. A volume of tracer released from the feedlot was directed towards RMNP at 2110 MDT (0310 UTC; Figure 2.9a). At 2220 MDT (0420 UTC; Figure 2.9b), the large volume of the tracer was ingested into a cloud's updraft well above mountaintops at a time scale on the order of tens of minutes (not shown). This area of high tracer concentration grew much more quickly in the vertical than the horizontal, suggesting convection played a key role in the N transport. The tracer-filled cloud, emulating particle-phase NH_4^+, then slowly advected westward towards the mountains before precipitating over RMNP around 0000 MDT (0600 UTC; Figure 2.9c) on August 19, shown in Figure 2.9c.

3) CASE 3: 6 JULY 2012

Similar to Case 2, the right column of Figure 2.10 shows deep easterlies on the eastern plains, influenced by large-scale winds. From Figure 2.10a, a volume of tracer was advected in the direction of RMNP at 1640 MDT (2240 UTC). At 1750 MDT (2350 UTC; Figure 2.10b), a cloud vertically transported the tracer well above the simulated mountaintops. The deep easterlies then slowly (on the order of hours) directed the vertically stretched volume towards the mountains before the tracer-filled cloud precipitated out over RMNP around 1920 MDT (0120 UTC; Figure 2.10c).

4. Discussion and conclusions

We isolated three anomalously high wet deposition events of inorganic N in RMNP based on N deposition data in RMNP. We identified large-scale circulations over the north-central United States as drivers for deep, east winds over northern Colorado. The simulations of all three cases showed increased precipitation in northern Colorado occurred after a push of cold air during monsoon season, consistent with Wallace (1975) and Riley et al. (1987). From WRF simulations, we noted all three deposition events began with an emitted plume of tracer in the lowest portion of the atmosphere moving westward towards the mountains (Figures 8a, 9a, and 10a). Within an hour, convection drew the plumes upward, above mountaintops. In subsequent hours to the emissions getting lofted to above mountaintop heights, the plume slowly advected horizontally towards the mountains carried by winds associated with the mountain-valley circulation (Case 1) or large-scale pressure gradients (Cases 2 and 3). Modeled tracer and precipitation in Figures 8-10 showed small-scale processes are equally important as large-scale processes for N transport into RMNP. Small-scale processes (e.g. convection) are responsible for quick, intermittent forms of transport while the large-scale processes (e.g. synoptic-scale easterlies midlatitude cyclones) bring slow and steady transport.

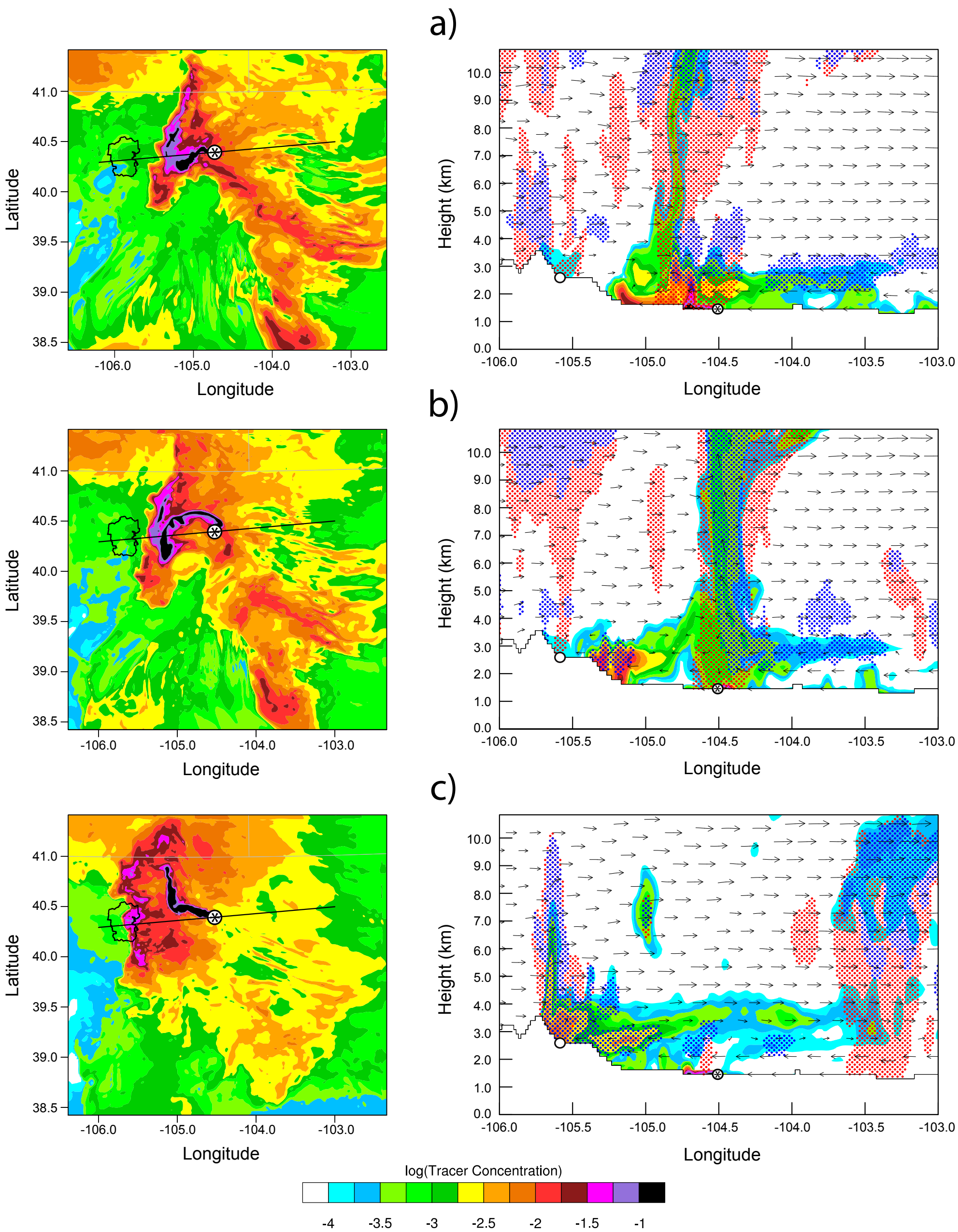

Figure 2.8. WRF output for Case 1.
Left column: shaded logarithm of passive tracer concentrations (integrated surface to 10 km ASL) in the 4/3-km domain with the RMNP boundary and an asterisk-filled dot indicating the location of the simulated feedlot. Right column: Cross section through Rocky Mountain National Park and the representative feedlot in Weld County, CO, shown by the line segment in the left panel. The times for each row during this 16 July 2004 event are a) 1420 MDT (2020 UTC), b) 1510 MDT (2110 UTC), and c) 1750 MDT (2350 UTC). Dots along the terrain surface of the cross sections (right column) are the locations of Beaver Meadows (white) and the approximate location of the Weld County feedlot (asterisk-filled dot). The cross section shows wind vectors, stippled clouds (blue), stippled precipitation (red), and the shaded logarithm of passive tracer concentrations. Cloud and precipitation concentration thresholds were 2.5E-6 g kg-1 and 1.0E3 g kg-1, respectively.

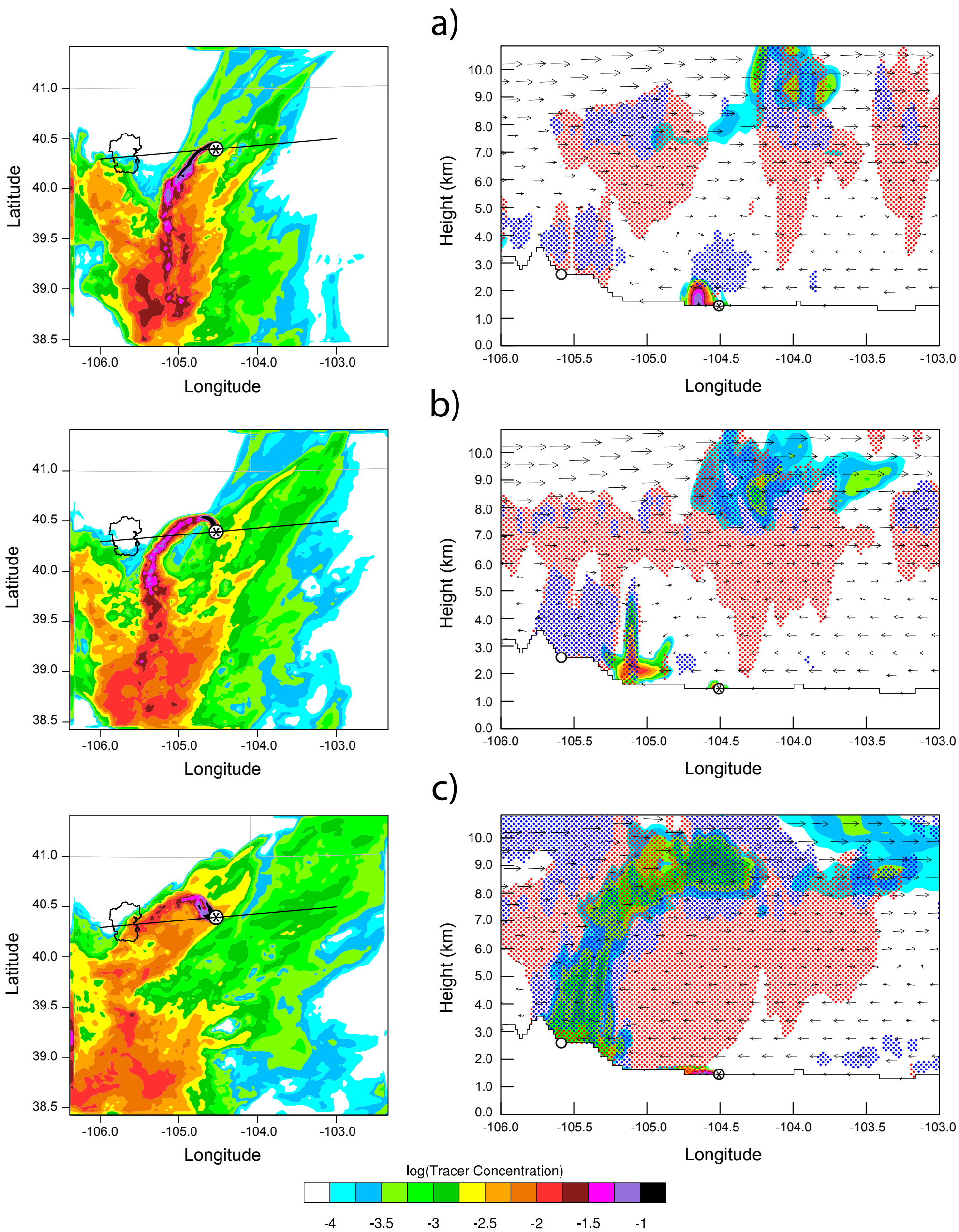

Figure 2.9. WRF output for Case 2.
Left column: shaded logarithm of passive tracer concentrations (integrated surface to 10 km ASL) in the 4/3-km domain with the RMNP boundary and an asterisk-filled dot indicating the location of the simulated feedlot. Right column: Cross section through Rocky Mountain National Park and the representative feedlot in Weld County, CO, shown by the line segment in the left panel. The times for each row during this 18 August 2006 event are a) 2110 MDT (0310 UTC on 19 August), b) 2220 MDT (0420 UTC on 19 August), and c) 0000 MDT (19 August; 0600 UTC). Dots along the terrain surface of the cross sections (right column) are the locations of Beaver Meadows (white) and the approximate location of the Weld County feedlot (asterisk-filled dot). The cross section shows wind vectors, stippled clouds (blue), stippled precipitation (red), and the shaded logarithm of passive tracer concentrations. Cloud and precipitation concentration thresholds were 2.5E-6 g kg-1 and 1.0E3 g kg-1, respectively.

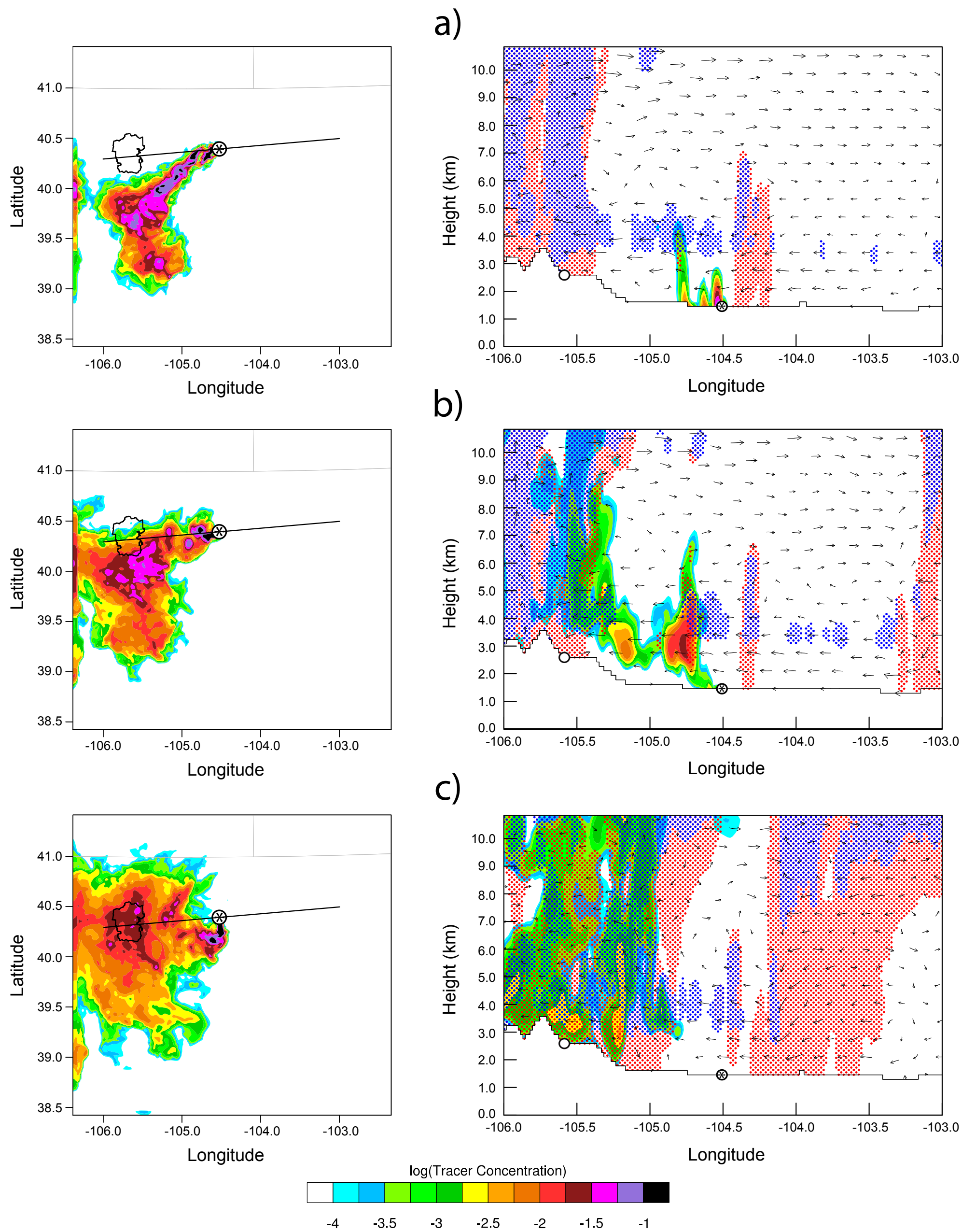

Figure 2.10. WRF output for Case 3.
Left column: shaded logarithm of passive tracer concentrations (integrated surface to 10 km ASL) in the 4/3-km domain with the RMNP boundary and an asterisk-filled dot indicating the location of the simulated feedlot. Right column: Cross section through Rocky Mountain National Park and the representative feedlot in Weld County, CO, shown by the line segment in the left panel. The times for each row during this 6 July 2012 event are a) 1640 MDT (2240 UTC), b) 1750 MDT (2350 UTC), and c) 1920 MDT (0120 UTC on 7 July). Dots along the terrain surface of the cross sections (right column) are the locations of Beaver Meadows (white) and the approximate location of the Weld County feedlot (asterisk-filled dot). The cross section shows wind vectors, stippled clouds (blue), stippled precipitation (red), and the shaded logarithm of passive tracer concentrations. Cloud and precipitation concentration thresholds were 2.5E-6 g kg-1 and 1.0E3 g kg-1, respectively.

As seen from the left panels of Figure 2.8, the tracer distribution for Case 1 covers a much larger horizontal area with higher domain-averaged concentrations compared with Cases 2 and 3. The July 2004 deposition event (Case 1) had the highest deposition of wet inorganic N of all 344 summer weeks between 1980-2015. Of the total wet inorganic N, 62% was NH_4^+. Observations and reanalyses from this period showed multiple days of easterly winds and precipitation, further suggesting eastern Colorado is a large source of reduce N, consistent with Thompson et al. (2015). This study showed only one of the periods from the July 2004 deposition event in which there was transport between the simulated feedlot and RMNP.

Due to the reliability of buoyancy-driven upslope winds and presence of moisture associated with the North American Monsoon each year, high deposition during summer months was expected. However, synoptic circulations during summers, which were responsible for deep easterlies in northeastern Colorado, were key to pollution transport over northern Colorado during weeks of high N deposition in RMNP. High precipitable water values from the Gulf of Mexico and eastern Pacific Ocean transported by large-scale circulations enhanced convective activity during high N deposition events of 2004, 2006, and 2012. This study found that convection, primed with moisture advection, in addition to winds from the mountain-valley circulation or large-scale pressure gradients played a significant role in the transport of N.

Findings from our study exemplify the need to explicitly resolve convection when simulating pollution transport over complex terrain as shown by Gebhart et al. (2011). A natural follow-on study would be to use the WRF output from this study with the time-inverted lagrangian transport model from Nehrkorn et al. (2010) and compare with source apportionment studies such as Gebhart et al. (2011), Gebhart et al. (2014), and Thompson et al. (2015). Despite resolving convection in their simulations, the meteorological models used in all three of these source-apportionment studies did not adequately capture the strength or frequency of upslope winds that would carry emissions from eastern Colorado all the way to RMNP. Two major differences in our simulations that would influence other simulations are the number of vertical levels--45 (this study) versus 35 (Gebhart et al. 2011)/34 (Gebhart et al. 2014; Thompson et al. 2015)—and the horizontal grid spacing on the finer grid—4/3 km (this study) versus 4 km (Gebhart et al. 2011; Gebhart et al. 2014; Thompson et al. 2015). Increases in vertical levels and horizontal grid spacing are computationally more expensive but may better represent small-scale processes over complex terrain.

From the predictable nature of upslope events associated with large-scale circulations, our next steps include working with livestock producers in eastern Colorado and creating an early warning system that will alert producers when a potentially high-N-deposition event might occur. To reduce atmospheric N_r deposition, we must decrease the amount of N_r created or emitted. The agricultural community could alter their manure or feed management practices that temporarily reduce ammonia emissions (e.g. loading out manure onto croplands) during periods of upslope winds. This mitigation strategy would not be enough to solve the entire N_r deposition problem in RMNP, but it would reduce contributions from agricultural practices. Communication and cooperation between scientists, policy makers, and feedlot managers over the next decade will be vital for reducing the amount of N_r that reaches the RMNP.

CHAPTER 3

REDUCING WET AMMONIUM DEPOSITION IN ROCKY MOUNTAIN NATIONAL PARK: THE DEVELOPMENT AND EVALUATION OF A PILOT EARLY WARNING SYSTEM FOR AGRICULTURAL OPERATIONS IN EASTERN COLORADO

1. Introduction and background

Across most of the United States, wet deposition of nitrate (NO_3^-) has decreased as a result of the 1990 Clean Air Act Amendments that targeted NO_x emissions (Li et al. 2016). Wet deposition of ammonium (NH_4^+), an unregulated pollutant, has increased across the U.S. since the 1980s (Du et al. 2014; Li et al. 2016). Emissions of ammonia (NH_3) are increasing globally (Xing et al. 2013) and are expected to increase through the 21st century (Van Vuuren et al. 2011). Sources of atmospheric NH_3 include emissions from landfills and wastewater treatment plants, mobile sources, biomass burning, and emissions from wild and domestic animals, crop fertilizers, and especially from dairies and concentrated animal feeding operations (CAFOs; Vitousek et al. 1997 and Anderson et al. 2003). Sources from livestock waste contribute 56% of the U.S. NH_3 budget according to the 2014 National Emissions Inventory (https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data).

a. History of nitrogen management policy for Rocky Mountain National Park

Eastern Colorado processes more than one million head of cattle, sheep and hogs through CAFOs each year; conventional dairies support an additional 100,000 head of dairy cattle (USDA NASS 2015). NH_3 is a byproduct of the metabolic process in most animals and when exposed to air at warm temperatures, will volatilize into the atmosphere. In Colorado, the contribution of NH_3 from livestock waste to the state NH_3 budget is 72% (EPA 2014). However, with NH_3 being an unregulated pollutant and areal sources being difficult to measure, the uncertainty around the NH_3 emissions from agricultural operations is very large.

The east side of Rocky Mountain National Park (RMNP) has experienced an increase in wet NH_4^+ deposition and a decline in wet NO_3^- deposition since measurements began in the early 1980s (Morris et al. 2014). Both wet and dry deposition of inorganic N and its impacts on RMNP ecosystems have been studied for over three decades (Baron et al. 1992; Baron et al. 2000; Baron 2006; Malm et al. 2009; Bowman et al. 2012; Benedict et al. 2013 a,b; Morris et al. 2014). Reactive N (N_r) acts as a fertilizer in the N-limited Rocky Mountains (Bowman et al. 2006; Fenn et al. 2008). Chronic inputs of N_r can lead to acidification of aquatic and terrestrial mountain ecosystems (Vitousek et al. 1997; Fenn et al. 1998; Baron et al. 2000; Bowman et al. 2006). Baron (2006) found the critical load, the threshold for ecosystem response, of an alpine lake in Loch Vale Watershed, RMNP to be 1.5 kg N ha^{-1} yr^{-1}.

A Memorandum of Understanding (MOU) was signed in 2007 by the U.S. Environmental Protection Agency, National Park Service, and Colorado Department of Public Health and the Environment to reduce total wet inorganic N deposition in RMNP, known as the Rocky Mountain Nitrogen Deposition Reduction Plan (NDRP; NPS, EPA, CDPHE 2007). The goal for the NDRP is to reduce the wet deposition of inorganic N to 1.5 kg N ha^{-1} yr^{-1} by 2032, which is the critical load adopted for alpine lakes in RMNP (Baron 2006).

The NDRP began when the 5-year wet N deposition average value was 3.12 kg N ha^{-1} yr^{-1} (2003-2007). At the Loch Vale site (NADP CO98), 2013 was an anomalous year for high wet N deposition which dominated the 5-year-averaged values through 2015 (Figure 3.1).

Measurements from part two of the Rocky Mountain Atmospheric Nitrogen and Sulfur (RoMANS II) study found that NH_y was the largest contributor to the total N deposition budget

(56% NH_y, 26% NO_3^-, and 18% organic N) from November 2008 through December 2009 (Benedict et al. 2013a). In this study, we focused on wet NH_4^+ deposition because it made up 63% of the total NH_y deposition (Benedict et al. 2013a) and it is the primary value used to track the progress of the NDRP.

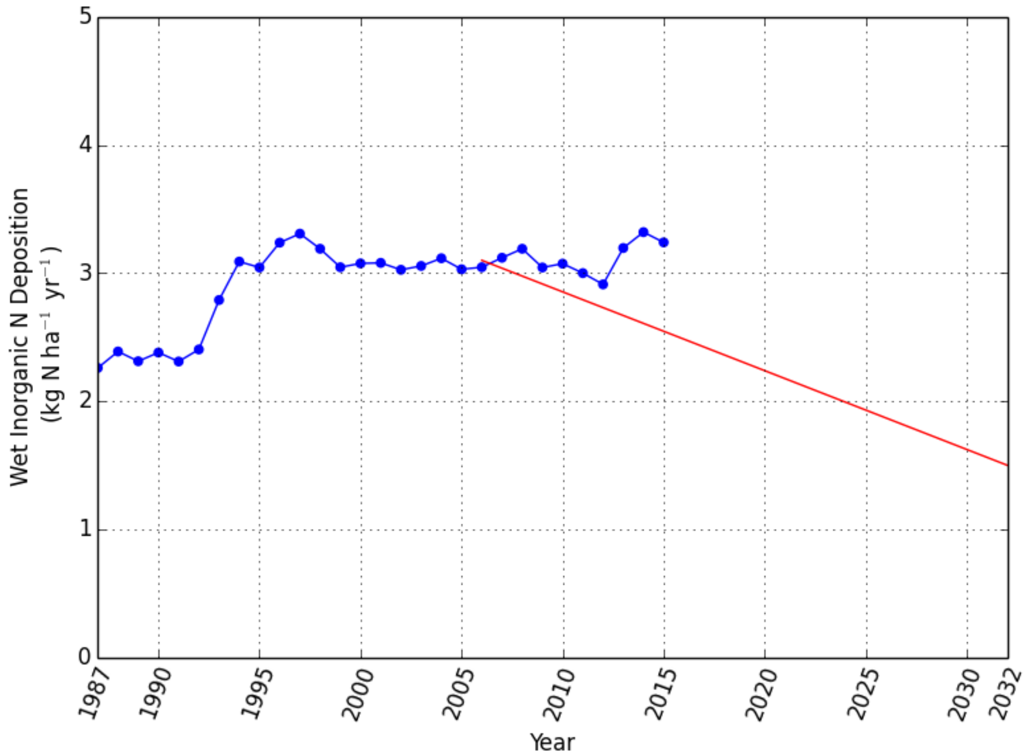

Figure 3.1. Five-year aveaged wet deposition of total inorganic N at Loch Vale (NADP CO98) between 1987 and 2015 (blue) and the Nitrogen Deposition Reduction Plan glide path from 2006 to 2032 (red).

b. Characterizing the source and meteorological conditions that transport reduced N to Rocky Mountain National Park

Annually averaged NH_3 emissions in eastern Colorado contributed more to wet deposition of NH_3 and NH_4^+ in RMNP than NH_3 sources west of the (Thompson et al. 2015). Thompson et al. (2015) also found that within Colorado, sources east and west of the divide contributed 61% and 26%, respectively, to the NH_y concentration at the receptor site in RMNP while sources within the park contributed 13%. Regions to the east occasionally contributed to

NH_y deposition in RMNP, but they have larger impacts due to their proximity and total emissions (Gebhart et al. 2014; Thompson et al. 2015).

Based on a N deposition climatology from the National Atmospheric Deposition Program National Trends Network (NADP hereafter), spring and summer have weeks with high wet N deposition more frequently than fall, and high deposition very rarely occurs in winter (Figure 3.2). Meteorologically characterizing these occasional episodes during spring, summer, and fall and determining their predictability will offer insight to potential leverages points that could minimize NH_3 emissions with an ultimate goal of reducing N deposition in RMNP. High values of wet NH_4^+ deposition in RMNP require NH_3 emissions, winds that transport emissions toward RMNP, and conditions that lead to precipitation in RMNP.

1) EMISSIONS

Ammonia is formed when nitrogen from urea in urine and urease enzymes in feces combine and hydrolyze (Davis et al. 2007). Emissions can be controlled or, at the very least, be temporarily minimized during short periods of time. Beyond factors not immediately controlled by humans (e.g. temperatures and pH of soils), Anderson et al. (2003) found NH_3 emissions are often highest during times of transport of fertilizer and livestock effluent (e.g. hauling manure away from livestock pens or applying fertilizers to crops).

2) WINDS

Easterly winds are responsible for transporting Front Range emissions, including those from agriculture, industry, and municipalities, into RMNP. Though winds on the leeside of the Colorado Rocky Mountains are primarily from the west, there are two mechanisms that lead to easterly (i.e. upslope) winds. The first is a synoptic meteorological pattern that brings notable springtime snowstorms to the Colorado Front Range. The centers of large-scale low-pressure

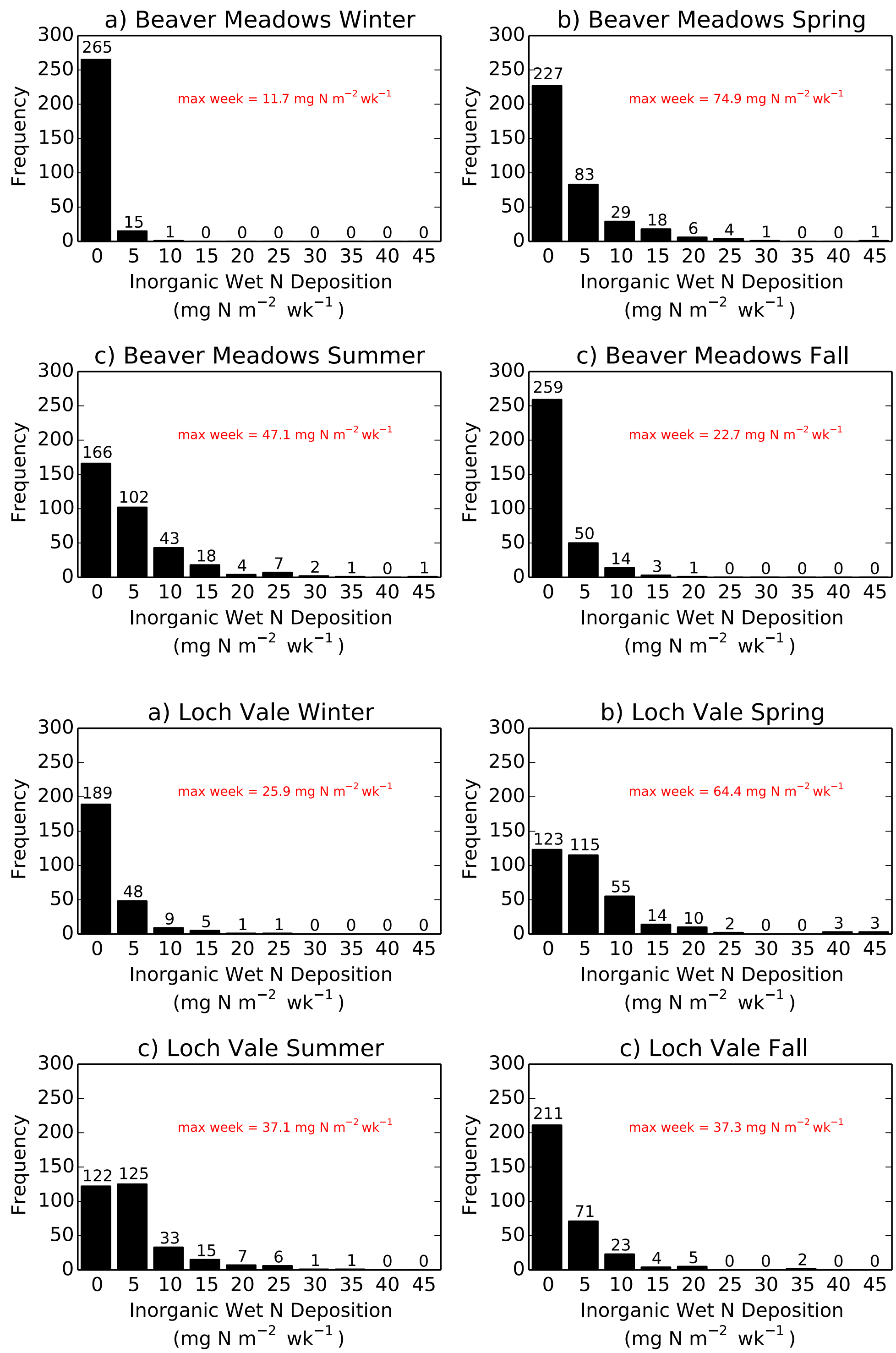

Figure 3.2. Frequency of seasonal wet inorganic N deposition at Beaver Meadows and Loch Vale. Histograms of weekly wet N deposition (mg N m-2 wk-1) at Beaver Meadows and Loch Vale for (a) winter, (b) spring, (c) summer, and (d) fall over the period 1980-2015 at Beaver Meadows and 1983-2015 at Loch Vale. Also shown are the overall maximum weekly deposition for each respective season.

systems, which rotate counterclockwise and are associated with cold fronts, typically move across the four-corners region (AZ, UT, CO, and NM) and towards southeastern Colorado. The counterclockwise winds indicate that in the northern Colorado, east or northeast winds transport airborne agricultural emissions into the mountains. The second is a summertime mountain-plains circulation that occurs on days when the jet stream is too far north for its associated large-scale winds to influence Colorado. With dynamics similar to a sea-breeze circulation near a coastline, this mechanism is much smaller in scale compared with the first mechanism. The daytime heating of the high-elevation land surface along the mountain slopes is much greater than the heating of the air over the adjacent plains at the same pressure level, resulting in localized low densities over the mountains at a given pressure level compared with the plains (Markowski and Richardson 2011). With relatively higher densities at a given pressure level over the plains, sinking air leads to surface winds that blow Front Range emissions westward towards the mountains (Baron and Denning 1993; Benedict et al. 2013b). Both mechanisms are important for transporting Front Range N (Chapter 1).

3) PRECIPITATION

As easterly winds advect and lift pollutants up the east slope of the Rocky Mountains, the air cools and condenses to form clouds in the presence of moisture. Precipitation maxima in northern Colorado are associated with easterly winds and occur most frequently in spring and summer (Baron et al. 1992; Benedict et al. 2013a). During precipitation events, clouds entrain Front Range pollution and deposit the pollutants over the mountains with precipitation.

In this study, we discussed the development and evaluation of a piloted early warning system (PEWS). Other environmental warning systems have been developed and used to reduce risks regarding human health (Imen et al. 2015) and food security (Otkin et al. 2015). This warning system was designed to temporarily mitigate NH_3 emissions from eastern Colorado agricultural operations during periods of upslope winds that will lead to wet deposition of NH_4^+ in RMNP. Because there are multiple sources of ammonia inside and outside Colorado (Thompson et al. 2015), it should be noted minimizing NH_3 emissions from Colorado agricultural operations alone will not solve the N deposition problem in RMNP. Further, we did not expect to see reductions on the NDRP glide path as a result of the pilot phase of the early warning system.

When the PEWS was triggered by the potential for pollutant transport to RMNP, agricultural operators volunteered to minimize activities that increased NH_3 emissions. Though livestock waste in northeastern Colorado is not the only source of NH_3 (Malm et al. 2009; Thompson et al. 2015), it makes up roughly 72% of the statewide NH_3 emissions (EPA 2016). Without feedlot-scale emission measurements at sites across eastern Colorado, it was impossible to calculate what impact the PEWS will have on N deposition values in RMNP. This pilot study was not intended to significantly mitigate wet NH_4^+ deposition originating from agricultural sources. Rather, we explored the feasibility of operational prediction of the meteorological conditions that lead to deposition of agricultural pollution in RMNP, and the willingness of producers to address the problem through altering or curbing management practices that lead to higher NH_3 emissions.

The study was designed to address the following questions:

1. How effective were operational meteorological models at predicting high wet NH_4^+ deposition events at two sites in RMNP?
2. Of those who participated in the PEWS, what fraction altered their management practices? What were the main barriers for those who did not alter their practices?

3. What is the potential effectiveness of reducing wet NH_4^+ deposition in RMNP by implementing the PEWS?

In section 2 of this manuscript, we discussed the methods of the PEWS. In section 3, we evaluated the PEWS using deposition data from the NADP to address question 1 above. Also in section 3, we discussed survey results from producers and managers of agricultural operations after warnings to address question 2 above. In section 4, we calculated and discussed the potential effectiveness of the PEWS. In section 5, we concluded by discussing the challenges and successes of getting agricultural producers to volunteer their time and efforts to minimize emissions during warning periods, policy implications of the early warning system, and improvement needs for the PEWS.

2. Methods for the design of a pilot early warning system

The PEWS was designed to provide Colorado agriculture producers and managers with information about the timing of upslope winds carrying N emissions from their localities towards RMNP. First, we produced a daily forecast that estimated the likelihood of N-containing precipitation over RMNP using the Weather Research and Forecasting (WRF) model. During warnings, agricultural operators voluntarily opted to reduce or halt certain manure management activities. We then used deposition-monitoring programs to evaluate the accuracy of the meteorological forecasts.

a. The Weather Research and Forecasting Model

The Weather Research and Forecasting (WRF) model is a widely used numerical weather prediction model used for both operational forecasting and research purposes (Skamarock et al. 2008) with a well-supported user community. Using version 3.3.1 of the Advanced Research WRF model (WRF, hereafter), daily forecasts were produced by the Precipitation Systems

Research Group at Colorado State University. The goal was to make use of existing operational forecasts to minimize computational costs. Daily output was used to forecast the likelihood that emissions from eastern Colorado plains reached RMNP and for predicting precipitation over RMNP. The daily forecasts include a 5-member ensemble simulation and are run for 60 hours with a horizontal grid spacing of 36 km and a 12-km nested grid (Figure 3.3). The PEWS was based on meteorological outputs from the 12-km grid. The 5-member ensemble includes members initialized from the National Centers for Environmental Prediction Global Forecast System (GFS) and North American Mesoscale (NAM) models, as well as a variety of physical parameterization schemes. The details of the configuration of each ensemble member are shown in Table 3.1.

The Read/Interpolate/Plot (RIP; version 4.3; http://www2.mmm.ucar.edu/wrf/users/docs/ripug.htm) graphics tool for WRF output was used to calculate air parcel trajectories initialized from several locations in eastern Colorado. To capture the atmospheric flow at different vertical levels, the air parcel trajectories were initialized from two different heights. Initializing the air parcels over areas near Greeley, Fort Morgan, and Limon, Colorado provided statistics on how frequently air parcels from each of these locations would reach RMNP.

Thirty-two virtual particles in each simulation (160 for all five members) were initialized in a 4-by-4 grid (12 km apart) and at levels approximately 10 and 20 m above ground level. Air parcels were initialized every three hours and integrated six hours forward for 60-hour forecasts driven by winds from the WRF model. For every three hours, kernel density estimation (KDE) was applied to the location of all the virtual particles at the end of their six-hour integrations (endpoints hereafter) every three hours. Gridded KDE was used to both visualize the airflow and

Table 3.1. Five different initial/boundary conditions and physics options used in the WRF simulations.
Details for physics options can be found at http://www2.mmm.ucar.edu/wrf/users/docs/user_guide/users_guide_chap5.html.

Physical parameter	*Member* 1	*Member* 2	*Member* 3	*Member* 4	*Member* 5
Initial/Boundary Conditions	0.5 degree GFS, BCs updated every 3 hours	0.5 degree GFS, BCs updated every 3 hours	40-km NAM, BCs updated every 3 hours	40-km NAM, BCs updated every 3 hours	40-km NAM, perturbed with the perturbations from the ’m_p1 member of the 21Z SREF. BCs come from the em_p1 member of the 21Z SREF, updated every 3 hours
Cumulus	Kain-Fritsch	Grell-Devenyi 3	Betts-Miller-Janjic	Kain-Fritsch	Grell-Devenyi 3
Boundary layer	MYJ	YSU	MYJ	MYJ	YSU
Microphysics	WSM 6-class	Thompson	Goddard	Thompson	Goddard
Land surface	Noah	Noah	Noah	Noah	Noah
Shortwave radiation	Dudhia	Dudhia	Goddard	Dudhia	Goddard
Longwave radiation	RRTM	RRTM	RRTM	RRTM	RRTM

to identify time periods when air from the eastern Plains of Colorado would reach the RMNP airshed.

b. The Pilot Early Warning System

The PEWS was designed to predict conditions in which air that had been in close contact with agricultural operations would be located over RMNP during periods of precipitation. When at least one virtual particle was located within the boundary of RMNP and the 12-60 hour averaged model precipitation in RMNP was greater than 5 mm, an alert was issued to human forecasters. This low precipitation threshold was too low to produce significant deposition but is used to allow for uncertainties in precipitation forecasts. An example of the trajectory endpoints is shown in Figure 3.4. For reference, this example led to a successful warning, meaning a warning was issued and NADP measurements indicated a high wet N deposition event. After a heuristic assessment of the upcoming meteorological event by human forecasters, an email was sent to alert recipients of an upcoming N deposition event and asked that operators minimize management activities related to livestock waste and/or fertilizers during the period.

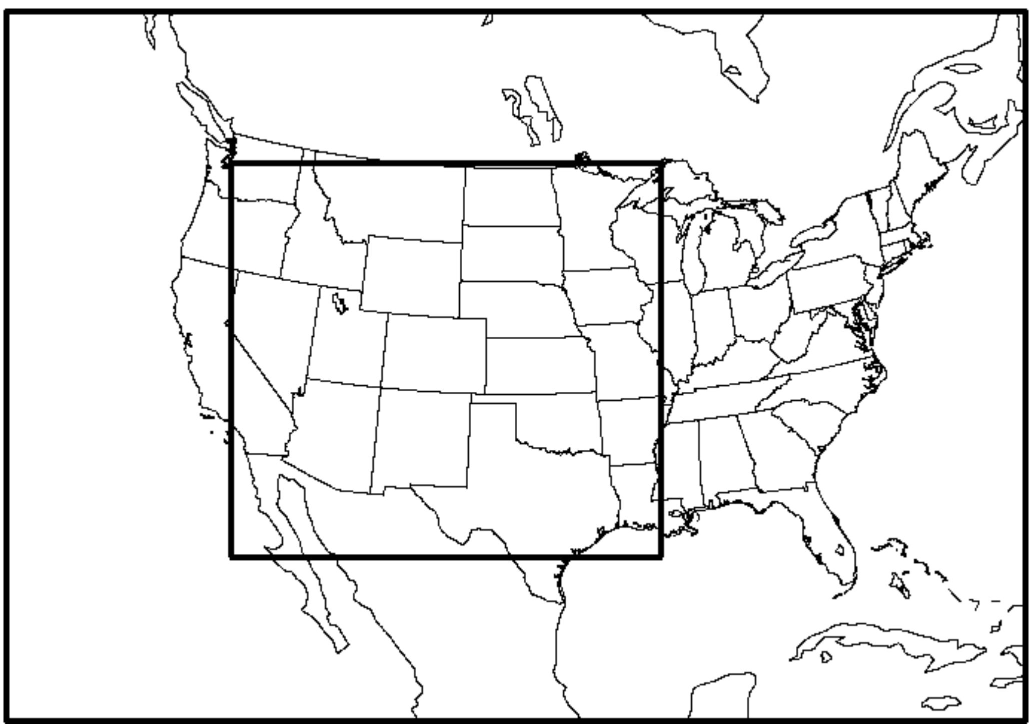

Figure 3.3. Domains for the WRF simulations.
Outer and inner grids have horizontal spacings of 36 and 12 km, respectively.

The participants of the PEWS included agriculture producers and managers who were recruited by entities such as the Colorado Livestock Association and Colorado Corn Growers Association. The participants elected to receive notifications via email and/or text messaging out of concerns that emissions from their respective operations may reach RMNP. Participants were alerted based on the counties of their operation(s). For example, Colorado counties located farther east of RMNP were only alerted for strong (and rather rare) upslope events. There were also recipients from the research community or other community members with a general interest in the PEWS.

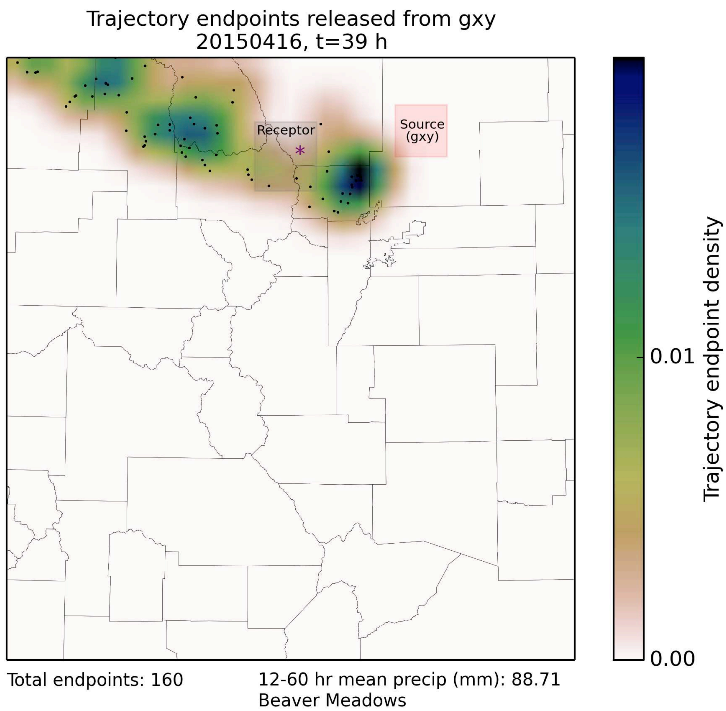

Figure 3.4. A figure of trajectory endpoints valid from a 39 hour forecast initialized at 00 UTC on 16 April 2015 over northern Colorado.
The trajectory points at hour 33 were in a two-layer 4x4 grid over the source box in the area of Greeley, CO (gxy). Five simulations resulted in a total of 160 endpoints. This map shows the location of endpoints after 6 hours along with the shaded kernel density, where cooler colors indicate higher concentrations of endpoints. The precipitation value for Beaver Meadows was calculated from the average of the 5 simulations.

c. Website and emails

The host server of the PEWS (www.rmwarningsystem.com) was designed to alert agricultural producers by SMS text message or email before an upslope event occurred. Alerts included the following: the period in which producers and managers are asked to halt activities that increase N emissions, the counties in eastern Colorado affected by the upcoming event, and occasionally a brief description of the weather forecast (Figure 3.5).

After an upslope event, PEWS participants were asked to complete a survey about alterations to manure management practices during the period of a warning. The responses included the producer's primary product, a 'yes' or 'no' to a no, partial, or full change to management practices, and a reason for no or partial changes. For confidentiality of the producers, no locations beyond the county from which a producer was responding were documented. Reasons for producers' inability to partake in reducing emissions for a particular event included: animal health concerns, biosolids incorporated immediately after application, labor availability, no manure management or fertilization activities were planned, other weather concerns, regulatory restrictions prevent changes (e.g. effluent ponds over-filling in the event of back-to-back warnings), or other reasons not listed.

There were times when producers and managers were only able to alter management plans for a portion of the warning period. When practices were changed for only a portion of the warning period, producers were asked the same questions as those who were unable to alter their management practices and to document their reasons accordingly.

There were 93 participants in eastern Colorado signed up to receive warnings (Table 3.2), 33 who are not directly involved with agriculture production (e.g. university researchers, interested parties, etc.). Many of the respondents are from some of the largest production areas in eastern Colorado. For anonymity, the producers were identified only by their counties.

An upslope event is expected to move air from over Adams, Arapahoe, Boulder, Broomfield, Denver, Jefferson, Larimer, Morgan and Weld counties towards Rocky Mountain National Park from 04/15/2015 through 04/17/2015. During these days, please minimize emissions of reactive nitrogen in these counties.

An upslope event is expected to move air from over Logan, Phillips, Sedgwick, Washington and Yuma counties towards Rocky Mountain National Park from 04/15/2015 through 04/17/2015. During these days, please minimize emissions of reactive nitrogen in these counties.

Warning Information:
Based on expected strong upslope flow, the warnings for more westerly counties has been extended farther east.

Figure 3.5. Screenshots of warnings issued to participants for the 15-17 April 2015 upslope event. Trajectory endpoints and precipitation for this event are shown in Figure 3.4.

Table 3.2. A breakdown of early warning system participants and operations. "Other" category includes livestock such as poultry and sheep.

Operation type	Participants	Operations
Feedyards	20	10
Dairies	11	9
Swine producers	8	5
Crop producers	9	9
Composters	5	5
Biosolids applicators	2	1
Other	5	0
"Non-responding" recipients	33	0
Total receiving warnings	**93**	**39**

After the summer of 2014, agriculture producers expressed a need for more lead time on the PEWS warnings. Instead of less-than 24 hours lead time, at least 48 hours of lead time was requested. This allowed producers to plan for appropriate management actions. Producers were prepared to accept the trade-off between the level of forecast uncertainty and the amount of lead-time.

d. Management changes

Agricultural managers and producers registered to receive alerts from the PEWS volunteered to change management practices during periods of an issued alert. These warnings would allow producers to implement strategic, short-term management practices that were not feasible to implement year-round. We therefore aimed to issue warnings less than 36 days (10%) per year. Specific best management practices (BMPs) for minimizing NH_3 emissions were discussed by leaders of the Colorado Livestock Association and Colorado Corn Growers Association and later agreed on by the rest of the agriculture community. The suggested BMPs to reduce agriculture emissions at both livestock and farming operations continue to change with new technologies and information. The top BMPs during periods of upslope winds are those that avoid transporting manure or spreading fertilizers, consistent with the top NH_3-emission factors noted in Anderson et al. (2003), and include: avoiding scraping of pens, sprinkling pens with water, adding bedding to open lot pens, avoiding manure loadout or opening mounds, avoiding turning compost piles, avoiding compost loadout, avoiding land application of manure or compost, shortening time between land application and incorporation of manure or compost, avoiding aeration of effluent impoundments, avoiding land application of effluent, and any other practice applied or avoided during the warning period to reduce NH_3 emissions.

e. Nitrogen deposition monitoring programs

The primary data source for identifying high N deposition events is the NADP. NADP is a long-term network that monitors precipitation chemistry at over 250 sites across the United States, including two in RMNP (Beaver Meadows, CO19 and Loch Vale, CO98). Samples are collected every Tuesday and sent to the Central Analytical Laboratory at the Illinois State Water

Survey for analysis, quality control/assurance, and data dissemination. The data are available at http://nadp.sws.uiuc.edu/data/NTN/.

We used weekly observations of precipitation and concentration (the product of which can be used to calculate deposition) of total inorganic N at two sites in RMNP: Beaver Meadows (NADP CO19; 2477 m) and Loch Vale (NADP CO98; 3159 m). Available data from Beaver Meadows goes back to 1980; available data from Loch Vale goes back to 1983, comprising over three decades of weekly data from each of these two sites.

The location of the two NADP sites are separated horizontally by only 11 km but the 700 m vertical difference brings different precipitation chemistry at the two sites (Baron and Denning 1993 and NADP2016). Beaver Meadows, the lower elevation site, is surrounded by montane forests. It experiences most meteorological influence mostly from east of the Continental Divide (Baron et al. 1992). The Loch Vale NADP site is in a subalpine forest located just below treeline near the Continental Divide. It has meteorological influences from west and east of the Continental Divide (Baron et al. 1992).

Using data from Beaver Meadows between 1980 and 2015 (n = 1321 weeks), 10% of weeks with the highest deposition (132 weeks) had deposition greater than 10 mg N m^{-2} wk^{-1} and accounted for about 40% of total wet N deposition (not shown; NADP 2016). We therefore use this value as a threshold for “high deposition”.

We calculated a potential reduction in NH_4^+ during weeks that contained warnings to show the potential effectiveness if all warnings were successful (with regards to dissemination of information on the forecasting side) and effective (with regards to the mitigation of emissions on the agricultural producer side). The calculation involved a linear product of deposition originating east of the Continental Divide (%), fraction of targeted NH_y in eastern Colorado (%), potential fraction of NH_3 emissions reduced by BMPs (%), fraction of deposition events forecasted correctly (%), and fraction of producers that comply (%), shown in equation 3.1.

$$\begin{aligned} \textit{Potential reduction in } NH_4^+ \textit{ deposition} = \; & F_{NH_y \, originating \, east \, of \, Continental \, Divide} \\ & x \, F_{targeted \, NH_y \, in \, eastern \, Colorado} \\ & x \, F_{BMP \, potential \, effectiveness} \\ & x \, F_{forecast \, accuracy} \\ & x \, F_{complying \, producers} \end{aligned} \tag{3.1}$$

The lower bound of what fraction of NH_y originated east of the Continental Divide was based on findings in Thompson et al. (2015), which was unable to produce strong upslope winds into RMNP. Weather simulations shown in Chapter 1 captured strong easterly transport of agricultural pollutants suggesting Thompson et al. (2015) underestimated the NH_y contribution from east of the Continental Divide. The upper bound was assumed to be 100% because during large deposition events, prevailing winds are from the east and the areal sources of NH_3 are all east of RMNP (Benedict et al. 2013a; Rodriguez et al. 2011). The lower bound of the fraction of targeted NH_y by the PEWS was determined by the permitted capacity of CAFOs in Colorado; the upper bound was the percentage of NH_3 in Colorado attributed to livestock waste, as reported by the U.S. Environmental Protection Agency's National Emissions Inventory from 2014. This category was the most uncertain in this calculation due to the values being estimated. The efficacy of BMPs was bounded by literature values from various peer-reviewed studies on best management practices (e.g. Rotz 2004; Embertson and Davis 2009; Carew 2010; Hristov et al. 2011; Rotz et al. 2011; Lee et al. 2012), which offered a large range of potential for reduction, indicative of large uncertainties. The lower bound of forecasting accuracy was determined in this study, and was the fraction of high deposition events correctly forecasted at Loch Vale; the upper bound was also determined in this study, and was the fraction of high deposition events correctly forecasted at Beaver Meadows. Lastly, the lower bound for the number of complying producers was determined in this study and was calculated by dividing the number of producers who responded with ‘Change’ to the total number of producers, including those who had ‘No response’ (Table 3.4); the upper bound was determined by this study and was calculated by dividing the number of producers who responded with ’Change’ to the total number of responding producers (‘Change’, ‘No change’, and ‘Partial change’).

We then modified the weekly wet N deposition during 2014 and 2015 for weeks that had warnings by reducing the NH_4^+ concentrations by the potential efficacy. Because there are no feedyard-/cropland-scale NH_3 emission studies from eastern Colorado, we assumed the emission and deposition concentrations were linearly related for this hypothetical scenario.

3. Results

a. Evaluation of the PEWS based on deposition monitoring programs

The PEWS issued 10 warnings in 2014 and 15 warnings in 2015. The duration of each warning was between one and three days, for a cumulative 51 days for the 25 total warnings between April 2014 and December 2015. The counties with the majority of the warnings were near the Front Range (Figure 3.6), so based on the warnings, winds rarely carried pollutants from the eastern border of Colorado into RMNP. Hence, it appeared the eastern side of RMNP received most of its NH_3 from agricultural sources closest to the Front Range of Colorado compared with sources in the eastern-most counties of Colorado, consistent with Thompson et al. (2015).

A tabular summary of the warning frequencies at Beaver Meadows and Loch Vale is shown in Table 3.3. The ideal distribution of warning frequencies would have had values of 0 in the “No high deposition, Warning" and "High deposition, No warning" cells. The Gilbert Skill Score (GSS; also known as the Equitable Threat Score) calculates the fraction of forecasted deposition events that resulted in high deposition in RMNP (Wilks 2006). Based on our results, the GSS for forecasts and observations at Beaver Meadows was 0.151 with a bias of 2.71 and the GSS at Loch Vale was 0.0188 with a bias of 2.88. There were weeks which contained warnings but had missing NADP data. Of the 25 weeks of high deposition between April 2014 and December 2015, Beaver Meadows had 8 weeks of missing data and Loch Vale had 4 weeks of missing data. Hence, the total number of deposition measurements at Beaver Meadows and Loch Vale do not add to the total number of 25 issued warnings. Four weeks showed high deposition at both sites.

One goal of the PEWS was to evaluate if the warning system could capture the highest deposition events. Figure 3.7 shows frequency distributions of weekly values of wet inorganic N deposition at Beaver Meadows (NADP CO19) and Loch Vale (NADP CO98) between April 2014 and December 2015. As seen from Table 3.3, warnings were issued for 5 of the 7 highest deposition events for Beaver Meadows. These 7 weeks above 10 mg N m^{-2} wk^{-1} accounted for 40.9% of the April 2014-December 2015 total inorganic N deposition at Beaver Meadows. It should be noted that a large number of warnings were also issued for weeks with low deposition values, which were considered as false-positives (14 at Beaver Meadows and 20 at Loch Vale). Many of these false-positives occurred due to the precipiation totals being lower than forecasted, which prompted an increase in the preciptation threshold (5 mm) for the PEWS. The range of precipitation depth at both sites during high deposition events was 20-90 mm. Near treeline on the Continental Divide, Loch Vale (NADP CO89/98) experienced 8 events above 10 mg N m^{-2} wk^{-1}. These 8 weeks above 10 mg N m^{-2} wk^{-1} accounted for 33.8% of the April 2014-December

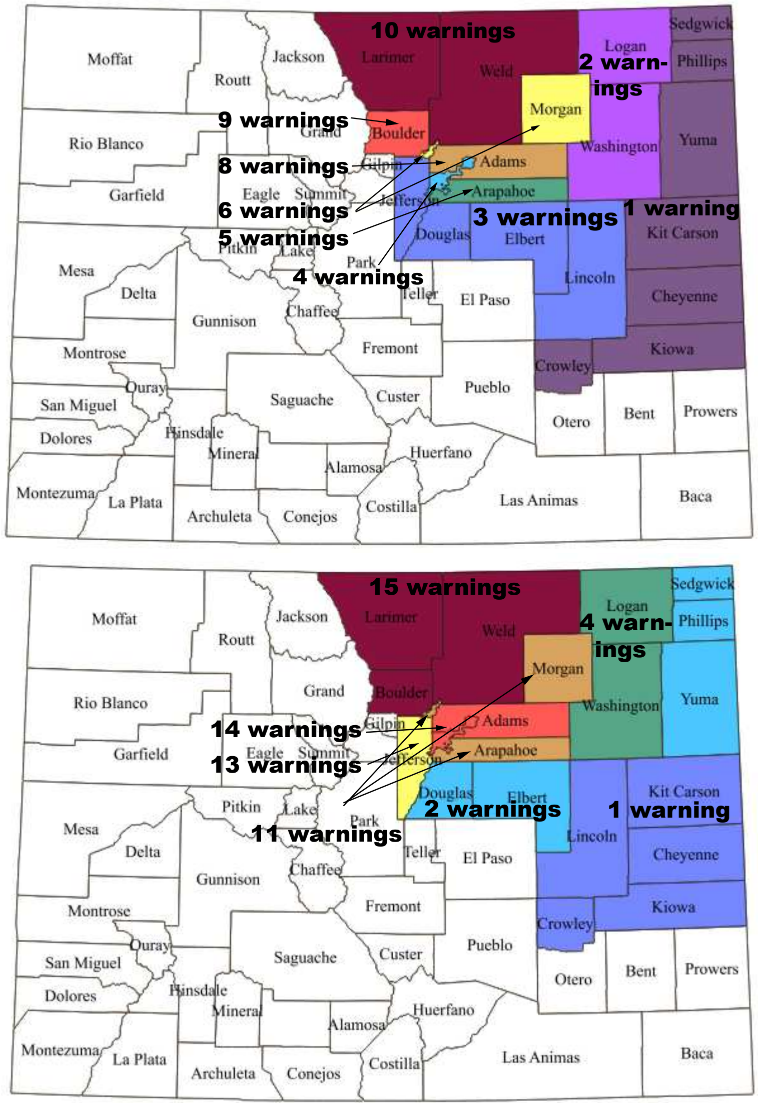

Figure 3.6: Colorado county map with shaded warnings for 2014 (top) and 2015 (bottom).

Table 3.3. Weekly deposition at Beaver Meadows (n = 62 weeks) and Loch Vale (n = 73 weeks) that occurred during periods of warning and resulted in high or low deposition.

Beaver Meadows (*NADP CO*19)	No high deposition (< 10 mg N m^{-2} wk^{-1})	High deposition (> 10 mg N m^{-2} wk^{-1})
Warning	14	5
No warning	41	2

Loch Vale (*NADP CO*98)	No high deposition (< 10 mg N m^{-2} wk^{-1})	High deposition (> 10 mg N m^{-2} wk^{-1})
Warning	20	3
No warning	45	5

2015 deposition at Loch Vale. Of these 8 events, only 3 warnings were issued, suggesting Beaver Meadows and Loch Vale have different sources of N. Ratios of ammonium to total inorganic N were over 60% during weeks when high deposition occurred at both sites, suggesting sources of deposition at both sites were mostly from agriculture. Loch Vale experiences meteorological transport from both west and east of the Continental Divide whereas sources of deposition at Beaver Meadows come primarily from east of the Continental Divide (Baron et al. 1992). As previously stated, the PEWS was designed to capture only emissions from eastern Colorado.

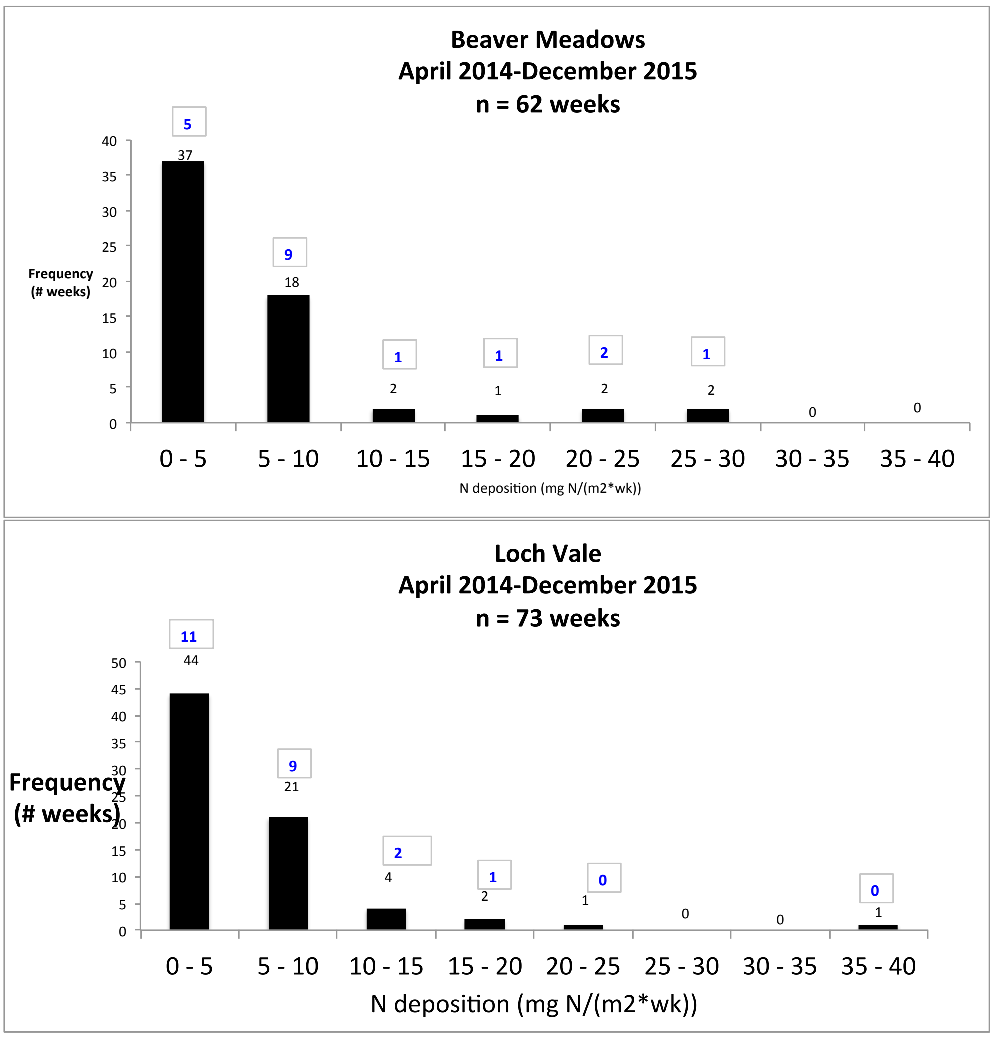

Figure 3.7. Frequency distribution of weekly wet deposition of inorganic N at Beaver Meadows (top) and Loch Vale (bottom) for the period of the pilot early warning system (April 2014 - December 2015).
Blue numbers indicate the number of warnings issued per bin.

b. Post-warning survey results

There was an average of 21 responses (s.d. 4.9 responses) per event for the 25 events between April 2014 and December 2015, for a total of 529 responses (Table 3.4). “No Response” dominated the responses, which contributed to a confounding factor: it was impossible to distinguish between no response and no mitigation. One solution was to encourage producers to respond to the surveys at the end of a warning period. However, a more dire challenge was motivating producers to take mitigatory action in the first place. For some producers, there was insufficient incentive for them to change their operations if their sole objective was to reduce emissions. A more conducive incentive structure, such as financial support to help implement the most time- and cost-effective BMPs, might help producers of smaller operations. Getting producers to volunteer to take part in the PEWS a difficult task, and sustaining momentum over a period of years was and continues to be a challenge.

Table 3.4. A breakdown of responses on whether or not practices were changed by producers/managers as part of the PEWS (n = 529).
Categorical reasons for no and partial changes are further broken down in Figure 3.8.

Response	*Number*
Change	136
No Change	58
Partial Change	42
No response	293

Of the respondents who made no or partial changes during a warning, “no activities were planned”, “labor availability”, and “animal health concerns” dominated the reasons (Figure 3.8). The high frequency of "no activities were planned" and “labor availability” occurred during warnings that occurred over weekends.

4. Potential effectiveness of the PEWS

We calculated the range of potential effectiveness of the PEWS based on a range of source apportionment values, fraction of targeted N based on the number of volunteer producers, BMP efficacies, the fraction of deposition events forecasted correctly, and the number of complying producers based on surveys (Table 3.5). We then applied the calculated potential effectiveness values to NH_4^+ concentrations from NADP data and reduced those values during weeks warnings occurred. Because the lower bound was nearly zero, we reduced wet deposition of NH_4^+ during weeks where warnings were issued by the upper bound value of 33%. The purpose of this hypothetical scenario was to evaluate the impact the PEWS would potentially have on annual deposition if management changes during a warning led to a reduction in NH_3 emissions and thus wet NH_4^+ deposition in RMNP.

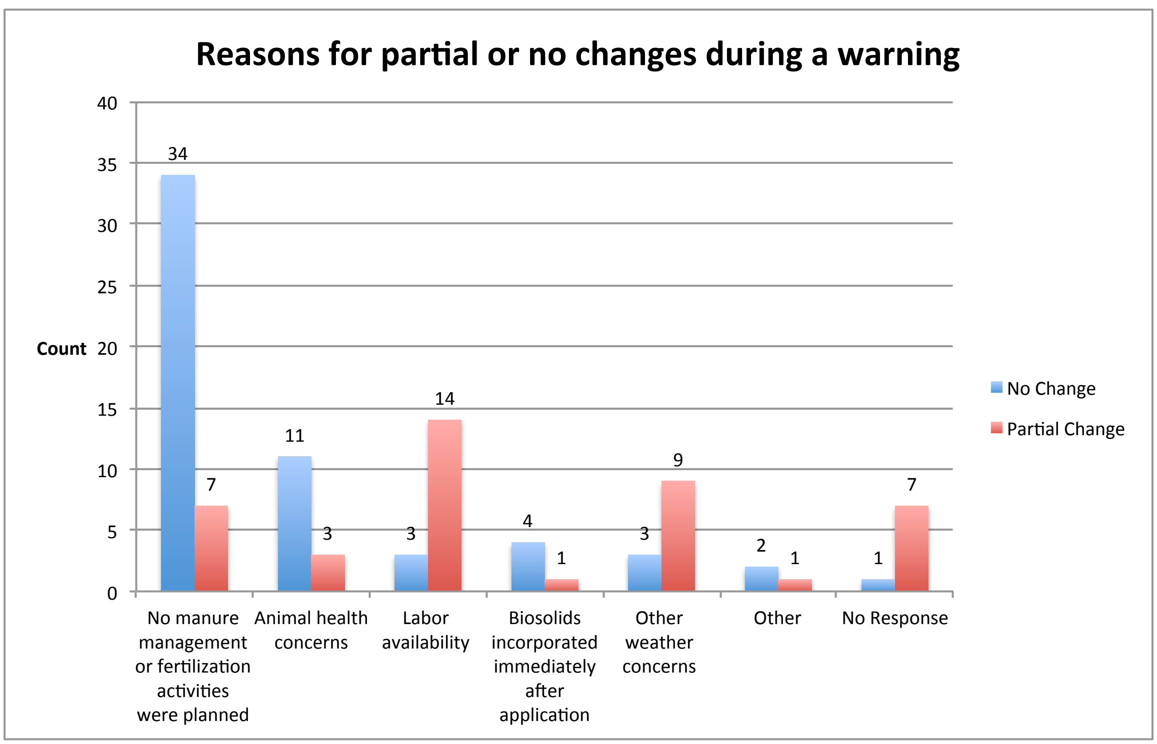

Figure 3.8. Categorization of the reasons for no/partial changes to management practices from Table 3.4.

The calculations using Beaver Meadows NADP data showed a potential of 13.6% (0.47 kg N ha^{-1}) reduction in cumulative inorganic N deposition over 21 months if the PEWS resulted in 33% reduction of wet NH_4^+ deposition during weeks where a warning was issued (Figure 3.9a). The calculations using Loch Vale NADP data showed a potential of 6.2% (0.26 kg N ha^{-1}) reduction in cumulative inorganic N deposition over 21 months if the PEWS resulted in 33% reduction of wet NH_4^+ deposition during weeks where a warning was issued (Figure 3.9b). From these hypothetical calculations, Beaver Meadows experienced greater reductions as a result of the PEWS. This was expected because, as shown above, the PEWS performed better at Beaver Meadows than at Loch Vale.

Table 3.5. Range of potential effectiveness of the pilot early warning system Calculations are based on a number of factors impacting emissions, meteorological transport, and deposition.

Factor	Lower bound (%)	Upper bound (%)
Average NH_y deposition originating east of Continental Divide	45	100
Fraction of targeted NH_y in CO	26	72
Efficacy of BMPs	20	85
Fraction of deposition events forecasted correctly	38	71
Fraction of complying producers	34	75
Total	**0.30**	**33**

5. Discussion and conclusions

The PEWS was developed to temporarily minimize NH_3 emissions from eastern Colorado agricultural operations during certain meteorological events that would ultimately lead to wet N deposition in RMNP. We also discussed developing criteria for warnings, forecasting by automated systems and human meteorologists, disseminating warnings, the intended recipients of the warning, and BMPs used on agricultural operations. BMPs were not part of this research but a study on the most effective BMPs in eastern Colorado would greatly inform the potential for reducing NH_3 emissions.

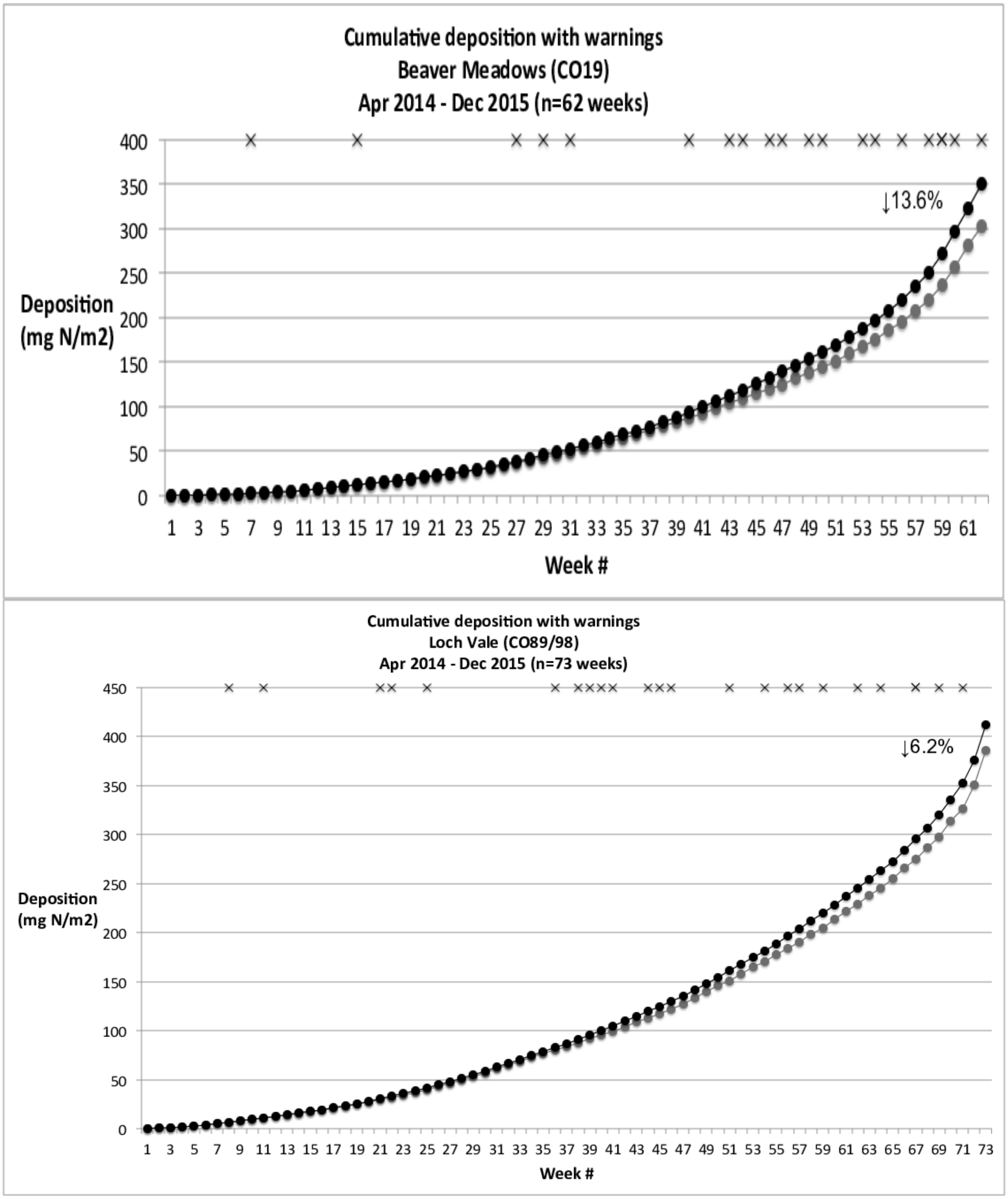

Figure 3.9. Hypothetical reductions in cumulative wet deposition.
Cumulative wet deposition of inorganic N (black) and a hypothetical 33% reduction (dark gray) in NH4+ during warned periods (Xs) for the duration of the pilot early warning system from Beaver Meadows (top) and Loch Vale (bottom). The percentages refer to the cumulative hypothetical reduction.

The pilot early warning system began in April 2014 and continues to operate. Through time, open communication between the agriculture community and the forecasters helped change the timing of issued forecasts. A one-day forecast is more accurate than longer-range forecasts but resulted in little time for managers and producers to prepare for changing operations. We found through trial and error that a two-day forecast was the best compromise for both the forecasters and the agricultural producers to ensure more accurate forecasts and to better prepare for management changes. Additionally, though policy decisions were made by the MOU agencies based off 5-year averaged values, presenting annual deposition values were preferred by agricultural operators to continue their motivation to voluntarily reduce emissions.

Based on deposition data from two NADP sites in RMNP, the PEWS was able to capture high deposition events ($\geq$ 10 mg N m^{-2} wk^{-1}) more often at Beaver Meadows (the lower elevation site) than at Loch Vale. Two possible reasons for the PEWS performing better at the lower elevation site were: 1. Front Range NH_3 was precipitated out before it reached the higher elevation site due to the high efficiency of scavenging by clouds and rain drops (Saylor et al. 2010), and 2. the higher elevation site has sources from both the Colorado Front Range and west of the Continental Divide, including out-of-state sources (Gebhart et al. 2014, 2011; Thompson et al. 2015; Malm et al. 2016). From reason 2, reductions of total NH_4^+ as a result of the PEWS may not be noticed based on measurements from Loch Vale, which is the official monitoring station for wet deposition of inorganic N used by the NDRP. Our results suggest a different framework would be needed to mitigate all of the emissions depositing in RMNP, especially at Loch Vale. The current meteorological modeling framework, which utilizes the weather simulations for other purposes, initializes emission sources directly related to agriculture in eastern Colorado. Therefore, the new framework would require long-range transport modeling from high NH_3-emitting regions in the western U.S. such as the Uintah Basin in Utah, California, and the Snake River Valley (Thompson et al. 2015).

For this pilot study, we asked if producers and managers of Colorado agricultural operations would volunteer to mitigate emissions if they were given information on the timing of upslope events that lead to N deposition in RMNP. Many of the largest agricultural operations in Colorado volunteered to receive warnings. Though not all agricultural producers were included in the PEWS, the number of individual operators and operations that volunteered to be part of the pilot PEWS was encouraging. The primary incentive for agricultural operators to voluntarily reduce their NH_3 emissions was to avoid regulatory mandates, at the federal and/or state level, on emissions from agriculture.

Agricultural managers and producers who did not volunteer to receive warnings either did not believe the project will help the agriculture community from regulations regarding emissions, believed they were already doing everything possible to reduce their emissions, or have not yet heard of the PEWS (Justin Miller, JBS Five Rivers, 2016, personal communication). The PEWS has gained media attention through National Public Radio (when we saw a jump in the number of operators who signed on to the PEWS), local news articles, and even the Union of Concerned Scientists.

We then asked which management strategies could and would be implemented to reduce N emissions. While the answer to this question is still part of ongoing efforts with the agriculture community, the PEWS as part of the NDRP was a great platform to test BMP ideas. Different BMPs worked better for certain operations than others. For example, BMPs employed at a small-scale dairy operation would not work at a large-scale beef operation. While the PEWS targeted NH_3 emissions, certain activities such as anaerobic stacking of manure can lead to other environmental concerns such as the release of methane, nitrous oxide, hydrogen sulfide (Amon et al. 2001).

For the PEWS, short-term changes (e.g. halt bulldozing manure stacks, delay fertilizing croplands, etc.) were suggested during periods of upslope. While these methods did not reduce the overall emissions, they aimed to reduce emissions while winds were from the east and were likely to deposit with precipitation in RMNP. A more sustainable practice would be to reduce total emissions from agricultural operations. One example, though more costly yet more effective, would be to focus on feed management as opposed to manure management by working with animal nutritionists and veterinarians (Carew 2010; Hristov et al. 2011; Lee et al. 2012). The benefit of feed management versus manure management is that feed management is applied throughout the operation while manure management is applied to as many as 3 pens (of up to 300 pens for the largest operations) per day (Justin Miller, JBS Five Rivers, 2016, personal communication). Additionally, reducing NH_3 emissions from livestock manure and crop production systems benefited livestock and crop producers by keeping valuable nitrogen in places where it was be used to produce food, fiber, and fuel. It also benefited RMNP by reducing undesirable ecosystem changes.

We also showed that there would be reductions to wet deposition of inorganic N change in RMNP under the hypothetical assumption that mitigated NH_3 emissions during periods of warning led to reductions in wet NH_4^+ deposition. Due to the lack of feedlot-scale emission measurements, it is impossible to determine what impact the PEWS had on annual deposition values in 2014 and 2015.

Lastly, it is important to acknowledge the necessary collaborative efforts to successfully implement a PEWS. From the first ideas of the PEWS, the project could not have been possible without collaboration and communication between the agricultural managers and producers, the MOU agencies (NPS, EPA, and CDPHE), and the university researchers at Colorado State University and Texas A&M University.

CHAPTER 4

AGRICULTURAL MANAGEMENT PRACTICES IN NORTHEASTERN COLORADO: A SOCIAL-ECOLOGICAL PROBLEM

1. Introduction

The intersection of agriculture and environment poses one of the most important social-ecological problems of our time. Environmental issues often find scientists, stakeholders, regulators, and policy makers at odds with each other over strategies to reduce environmental degradation and development of social-economic goals. A difficulty in finding common solutions to environmental issues is often related to the inability to finding a common language to express ideas, difficulty to develop and share a set of common values, or to be able to listen to each other to improve the dialogue. These difficulties exist when, in fact, there a number of areas where a shared sense of values exist, a set of common goals can be identified, and scientific and management actions can be taken to lessen the burden on the environment and maintain livelihoods of communities being impacted.

Social-ecological system perspectives in assessing and co-designing of solutions have proven to be a useful framework in developing strategies to mitigate environmental problems (Cowie and Borrett 2005; Imen et al. 2015). A social-ecological system approach provides an integrated perspective of ecological and societal processes which can enable management actions that reduce the impact on the environment while maintaining social-economic aspects of the land management system under scrutiny.

Agriculture is one of Colorado's primary economic sectors (Colorado Department of Labor and Employment, 2016). Of the agricultural commodities in the state, cattle and calves account for almost half of the state total agricultural income (Ojima et al. 2015). The number of livestock in Colorado increased substantially between the 1870s and 1900, and the proportion of nondairy cattle began dominating the livestock population in the 1940s (Parton et al. 2015). Livestock operations are water- and nutrient-intensive and are the source of agricultural pollution, impacting other ecosystems near the Front Range of Colorado, especially those in the Rocky Mountains (Baron and Denning 1993; Baron et al. 2000).

In the Colorado Front Range, a “wicked” problem (Churchman 1967) has emerged between the amount of ammonia (NH_3) emissions coming from the confined animal feed operations (CAFOs) and the environmental quality of Rocky Mountain National Park (RMNP). It has come to light through decades of monitoring nitrogen deposition in the RMNP that emissions from the CAFOs are altering the sensitive aquatic and terrestrial ecosystems of the Park. Though no one solution will solve the problem, a transdisciplinary approach will allow for multiple pathways to implement possible solutions to the problem. These intervention points should be designed so that the ecological health of RMNP is maintained or improved with little-to-no impact on the agriculture sector of Colorado’s economy.

During the past decade of discussion of this issue, a voluntary approach was developed and emerged as a co-designed effort to reduce impacts of ammonium deposition in the Park while maintaining CAFO operations with manageable impacts on their operational and economic activities. Though not designed from the onset as a social-ecological system, the emerging system of monitoring, early warning, and management modifications is developing into a case study of social-ecological system thinking toward the development of feasible strategies to reduce the impact on the environment.

These efforts came about in 2007 when researchers, policy-makers, feedlot managers, and federal and state agencies came together and co-designed a set of best management practices that incorporated aspects of the economics for feedlot management, cattle for food safety, and the fragile ecosystems impacted by emissions from feeding operations. In 2007, the National Park Service (NPS), the Environmental Protection Agency (EPA), and Colorado Department of Public Health and the Environment signed a memorandum of understanding (MOU) to reduce N deposition in RMNP (NPS, EPA, CDPHE 2007). This agreement is known as the Rocky Mountain Nitrogen Deposition Reduction Plan (NDRP). In 2014, a pilot early warning system (PEWS) was launched (Chapter 2), not formally part of NDRP, but with the intent to reduce agriculture's contribution to N deposition in Rocky Mountain National Park (RMNP). The PEWS was introduced to help mitigate nitrogen (N) emissions from agricultural operations that would ultimately deposit N compounds over RMNP. Specifically, the aim of the PEWS was to curb NH_y emissions from agricultural operations– industrialized croplands and concentrated animal feeding operations (CAFOs)–in eastern Colorado by alerting feedlot operators when conditions for high-deposition of ammonium in RMNP are imminent. A forecast favoring high deposition in RMNP would give operators the option to halt activities that increase ammonia emissions.

In this paper, we discuss the relations of social components of the agriculture industry with the biophysical impacts the agricultural emissions have on the environment. We then asked: What adaptive management approaches are needed for the future? The PEWS was developed as a platform for actors to look at impacts the dialogue between the actors. How can this be retained to inform dialogue in other management scenarios?

Before we answer these questions, it is important to start by viewing the social-ecological system from a distance (i.e. looking at the big picture). Figure 4.1 shows connections and interactions between social and ecological components of the PEWS. In this paper, we discuss CAFO-scale occurrences that require management decisions. Historically, the population of livestock was governed by food demand, income growth, and urbanization (Thornton 2010). Emissions from the livestock excrement could be prevented through dietary changes or by changing post-excrement husbandry practices (Rotz 2004; Embertson and Davis 2009; Rotz et al. 2011; Lee et

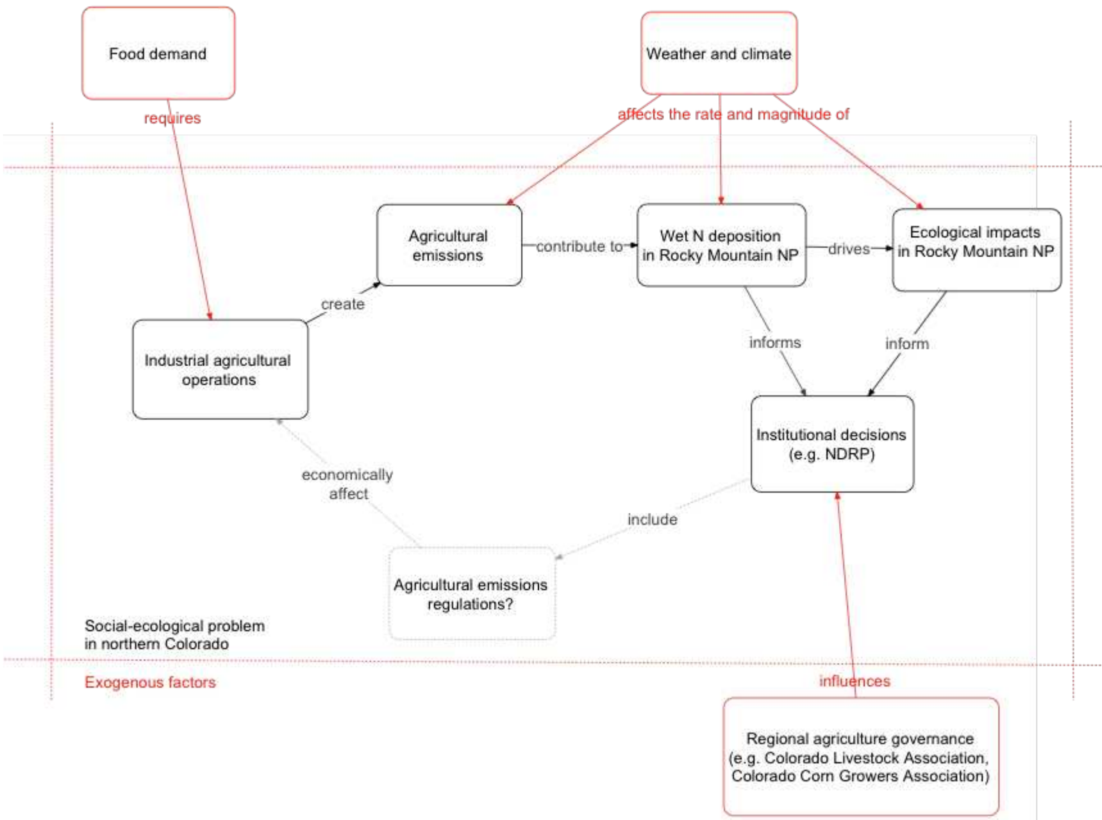

Figure 4.1. A social-ecological diagram applied to agriculture management in northeastern Colorado.
Outside the red rectangle are exogenous controls to the presented social-ecological system. The gray arrows denote a potential future decision that would have social-economic impacts on industrial agricultural operations.

al. 2012). Choosing the type of management changes affects the emissions and therefore concentrations of atmospheric ammonia (Anderson et al. 2003). Additionally, there are exogenous controls that influence variables within the system, such as energy, food demand, weather and climate, and regional governance systems (Figure 1; Chapin III et al. 2009). The connections within these systems inform decisions, which affect how management of livestock waste is in northern Colorado. One decision that would impact agricultural operations would be the regulation of emissions from agricultural operations.

In section 2, we outline an institutional framework for the pilot early warning system described in Piña et al. (2017b, Chapter 2). We then discuss, in section 3, the participation of integrated management in northeastern Colorado and future needs for managing agricultural operations in a changing climate. We close with concluding remarks in section 4.

2. Institutional framework for participation in the pilot early warning system

Institutions are social constructs that influence and constrain decisions (Gunderson et al. 1995; Chapin III et al. 2009). Decision makers, or actors, include individuals, intra-agency departments, interagency programs, and even unincorporated stakeholders. The power from institutional decisions is that they can inform policy driven by scientific findings—they are the bridge from natural capital to social capital.

The NDRP was an institutional decision, written and executed by MOU agencies, to reduce wet deposition of inorganic N in RMNP. The MOU agencies along with leaders of the agricultural community initiated the PEWS in order to provide the agricultural community a chance to voluntarily reduce their N emissions to avoid regulations. Though the PEWS is not formally part of the NDRP, the PEWS was introduced with the intent of temporarily decreasing N emissions that led to the wet deposition of reduced N in RMNP. The MOU agencies worked together with researchers from Colorado State University (CSU) and stakeholder interest groups, such as the Colorado Livestock Association (CLA) and Colorado Corn Growers Association, to reduce agriculture's contribution to N deposition in RMNP (Table 4.1).

Table 4.1: Management structure of early warning system in eastern Colorado.

Position	*Authority*
MOU agencies	
Environmental Protection Agency	Regulatory
National Park Service	Advisory
Colorado Department of Public Health and the Environment	Advisory
Agricultural operators	
Colorado Livestock Association	Decision-making
Colorado Corn	Decision-making
University partners	
Colorado State University	Advisory or consultative
Texas A&M University	Consultative

From Figure 4.2, reduction in ammonia emissions are a result of feed and manure management. It is known there are certain meteorological events that bring emissions from agricultural operations in eastern Colorado into the RMNP airshed (Piña et al 2017a, Chapter 1). In fact, Thompson et al. (2015) showed that 40% of the reduced N in RMNP comes from northeastern Colorado while winds in RMNP are from the east only 20% of the year (Benedict et al. 2013a). To help reduce emissions from these agricultural sources in NE CO during occasional meteorological events, the PEWS was created. In the following sections, we describe the actors associated with the PEWS, the institutional arrangements, the who and how of participation, and potential outcomes of participation.

a. Actors and their role in the social-ecological framework

Many approaches for natural resource management would classify actors as managers, coordinators, and officials at agencies of different levels of governance (e.g. local, state, federal, international). In the case of the PEWS, actors made decisions based on deposition data and ecosystem changes in RMNP. The approach of the PEWS was voluntary (versus regulatory) and introduced decisions that were not equally feasible for all agricultural operators responsible for N emissions.

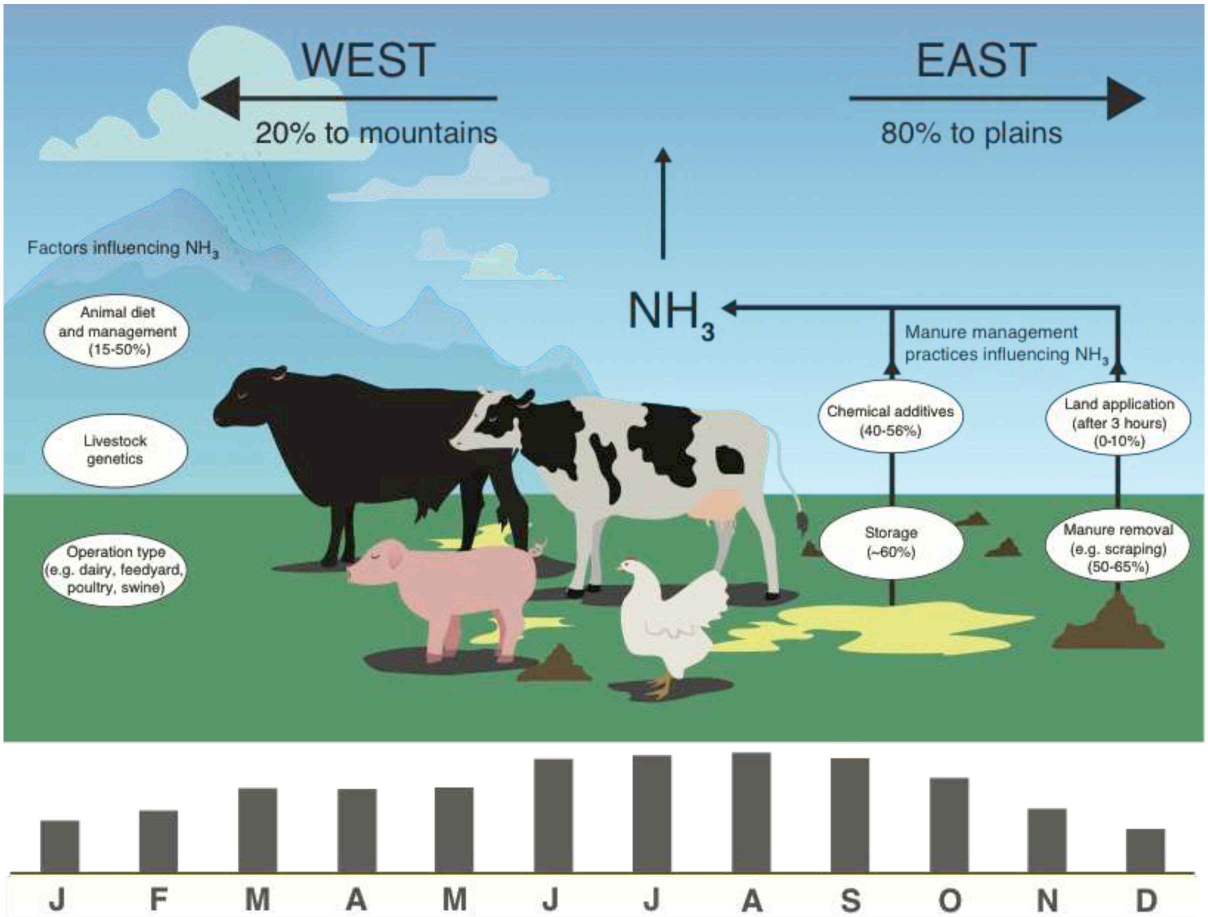

Figure 4.2. A time-space diagram of factors influencing ammonia emissions from livestock operations.
Monthly averaged ammonia emissions (histogram) were based on temperature records in Greeley, CO (GXY), which is highly correlated with ammonia emissions (Grant et al. 2013); frequency of horizontal transport was based on Benedict et al. (2013a) and climate records for GXY. This frequency is represented as the percentage of ammonia that is advected east and west of eastern Colorado agricultural operations. The percentages each bubble represents the potential reduction in ammonia emissions if the corresponding management practice was enacted.

Here, we include PEWS participants as decision-making actors, creating a two-way information exchange as opposed to regulatory approach or a bottom-up, grassroots effort. It should be noted the ammonia emissions of PEWS participants are not currently regulated, but multiple years of non-compliance with the NDRP could lead to regulations.

Therefore, the PEWS is a motivational practice that reflects producers' preferences that agricultural emissions do not become regulated. With the participants included as actors, the feasibility for institutional decisions was easy to agree upon. Additionally, many decisions are based on quantitative measures from measurement networks (e.g. National Atmospheric Deposition Program). By including the PEWS participants, we were able to understand the immeasurable changes such as "What fraction of PEWS participants change their manure management practices during a warning?" or "For what reasons are volunteers unable to alter their management practices?". Additionally, it was not possible to measure emissions from individual urine patches at feedyards or the economics behind each implemented management practice.

The MOU agencies of the NDRP—the National Park Service, Environmental Protection Agency, and Colorado Department of Public Health and the Environment—work for the public and towards the mission of the National Park Service Organic Act to adaptively manage and preserve the beautiful air, aquatic and terrestrial ecosystems, and mountains so that future generations may enjoy what our ancestors enjoyed (54 U.S. Code §100101(a)). In addition to preserving the natural ecosystems for future generations of people, it is also important to fragile habitats within RMNP that the air, water, and land remain undisturbed by human activities.

The MOU agencies are among the monitoring, coordinating, and regulatory actors. Collectively, they agreed to reduce the amount of wet N deposition in RMNP based on observations—gathered over 20 years—of N deposition data in Loch Vale Watershed, RMNP. Baron (2006) showed that deposition above 1.5 kg N ha^{-1} yr^{-1} would lead to undesirable changes to an alpine lake in Loch Vale Watershed. The United States Geological Survey (USGS) and the NPS monitor N deposition data at Loch Vale Watershed and provide this data to the MOU agencies. Scientists who work in RMNP observed increasing trends in N deposition since the 1980s (Morris et al. 2014). Based on the NDRP, wet N deposition values in RMNP were (and are) evaluated every five years (known as “milestone years”). There has only been one milestone year (2012) since the MOU was agreed in 2007.

The MOU agencies worked with agricultural operators and managers to identify points of intervention for temporarily reducing agricultural N (NPS, EPA, CDPHE 2007). Agricultural producers were asked to take part in the institutional decisions so that their concerns and management feasibilities could be factored into the decision-making process. The agricultural entities included producers that are part of the CLA and Colorado Corn Growers Association. Ammonia is a nitrogen-containing compound that comes from livestock effluent and fertilizers applied to croplands. Producers from both the CLA and Colorado Corn formed and continue to manage the RMNP Agriculture Subcommittee to help ensure the needs by other institutional actors are met.

Researchers from CSU co-developed and operated the meteorological aspect of the PEWS which identified periods in which winds would carry agricultural emissions into RMNP (Piña et al. 2017b, Chapter 2). During these periods, operators were alerted to enact management practices that reduced N emissions from their operations. Agricultural producers relied on the alert system developed at CSU. The two-way communication between the CSU researchers and the agricultural producers has helped to alleviate needs from both sides. For instance, to ensure management practices could be implemented, the agricultural producers asked that weather forecasts be issued at least 48 hours ahead of the time management practices should be changed to mitigate ammonia emissions. The trade-off for more planning time at the agricultural operations was that weather forecasts would not be as accurate as a 24-hour forecast.

At the end of milestone years (e.g. every five years from 2007 through 2032), the MOU agencies will aggregate all the N deposition reduction efforts since the last milestone report.

Future regulatory decisions will be made based on wet N deposition values and trends at measurement sites in and near RMNP.

b. Institutional arrangements

Institutional decisions are designed so that actors co-develop actions and plans that work towards a common goal (Chapin III et al. 2009). In the case of the PEWS, the signed MOU between the NPS, EPA, and CDPHE serves as a formal institution that works towards mitigating N deposition in RMNP. The NDRP was signed to reduce wet deposition of total inorganic N, which includes nitrate (NO_3^-) plus ammonium (NH_4^+), in RMNP. The 1990 Clean Air Act Amendments were incorporated to reduce acid rain over the eastern United States. As a result, NO_3^- became regulated and emissions as well as deposition decreased (Li et al. 2016). Ammonia emissions, however, have never been controlled by regulatory agreements. The Rocky Mountain Atmospheric Nitrogen and Sulfur (ROMANS) study was conducted in the spring and summer seasons of 2006 and identified source areas of N that contributed to wet N deposition in RMNP (Malm et al. 2009). The ROMANS II study was conducted for an entire year in 2009, and a NH_3 source budget showed agricultural operations in north central Colorado were a large contributor to reduced N deposition in RMNP (Thompson et al. 2015).

The PEWS was designed to help reduce a fraction of the wet N deposition in RMNP. It should be noted that, owing to the relatively small number of producers participating in the pilot part of the project, the PEWS was not expected to reduce the annual N deposition in RMNP to below the targeted levels set by the NDRP glidepath. The metrics of success outlined for the pilot phase were that high N deposition events in RMNP were accurately predicted and that many agricultural producers from the largest operations in Colorado volunteered to mitigate ammonia emissions (Chapter 2). If the early warning system were to move beyond the pilot phase, a future metric of success might be measurable reductions of N deposition in RMNP. For now, agricultural producers came together and agreed on best management practices (BMPs) that would help cut NH_3 emissions. Some of these BMPs included not applying fertilizers, not bulldozing manure stacks, and using precision feeding with livestock (i.e. cutting extra N-containing protein in feed that cannot be utilized in the metabolic processes). The BMPs were chosen based on literature values and the low costs of implementation by members of the CLA, Colorado Corn Growers Association, and researchers at Texas A&M University.

On a quarterly basis, the RMNP Agriculture Subcommittee convened to discuss BMPs that were implemented, to show further findings and understanding by scientific researchers, and to provide a platform for questions from the MOU agencies to the producers and vice versa. Because of multiple interests between each of the actors, meetings became contentious. Much of the contentiousness stems from producers feeling as if they did as much as possible to reduce emissions. They felt they were using the latest technologies, implementing the latest BMPs, and heeding alerts issued by the PEWS. These are measures that were not able to be quantitatively measured, but were considered to be encouraging aspects of the PEWS.

c. The ’who’ and ’how’ of the pilot early warning system participation

The PEWS included meteorologists and agricultural producers from farming and livestock operations. CSU meteorological forecasters were responsible for the deciding if and when warnings are issued while BMPs were implemented by agricultural producers. Participation in the PEWS were voluntary actions taken by agricultural producers to temporarily minimize emissions during a warning period.

1) THE 'WHO'

Meteorologists at CSU run weather simulations daily and use these forecasts to identify periods of east winds in the Colorado Front Range. These east winds carry pollutants, including reduced N, across the Front Range into the Rocky Mountains and deposit N compounds with precipitation. If conditions were ripe for high wet N deposition in RMNP, warnings were issued to PEWS volunteers in eastern Colorado. It should be noted N deposition was not forecasted for the PEWS.

Farmers manage croplands that require large amounts of water as well as nutrients. The focus of the PEWS is to halt practices that release large amounts of ammonia during occasional meteorological events. One of these practices is the application of fertilizers to croplands. Liquid and dry fertilizers contain nitrogen. Nitrogen from liquid fertilizers are volatilized into the atmosphere and are carried with winds, especially during warm days (Grant et al. 2013). If fertilizers were applied only while winds were not from the east, there would be much less contribution from croplands to N deposition in RMNP.

Livestock operators, especially those that run concentrated animal feeding operations (CAFOs) tend to raise cattle at high densities and keep animals within a limited area. As a result, cattle excrement accumulates in these pens and represent large sources of reactive N. When cattle within a pen are harvested, the pen is cleaned and prepared for a new batch of cattle. The cleaning process includes scraping pens with bulldozers, which exposes effluent to the air and volatilization is increased. Any exposure of effluent to the atmosphere, especially during high temperatures, increases the likelihood of ammonia volatilization (Grant et al. 2013). With the PEWS, husbandry activities can be temporarily halted until winds would carry the emissions away from RMNP.

Without the efforts and cooperation of the agricultural producers, the PEWS would not have been possible. Although discussions amongst researchers in regards to how much agricultural sources contribute to N deposition in RMNP are not in consensus, the efforts to change practices by the agriculture community is noteworthy.

2) THE ‘HOW’

To connect the forecasters with the PEWS participants, a communication system was created (www.rmwarningsystem.com). PEWS participants opted to receive an email or SMS text message for each alert. These emails from forecasters included the duration of a warning in which participants were asked to minimize activities that led to high emissions, the affected counties, and a brief description of the meteorology.

In addition to the alert, a survey was issued to the participants so that changes are documented. The BMPs that were implemented during each warning were noted, or if no action was taken, the reason(s) for no change(s) were documented. Results from the surveys were used to track the frequency of reasons for no management changes.

d. Potential outcomes of participation

Ecosystems in RMNP are already changing as a result of N deposition. Ecosystems in RMNP are experiencing increases in primary productivity as a result of increases in N availability, which acts as a fertilizer for N-limited soils (Mast et al. 2014, Baron et al. 2000). In other locations across the globe, where N deposition has been taking place for multiple years (or even decades), soil health is deteriorated and acidification can occur (Ulrich 1986). Reducing emissions that lead to N deposition will help ecosystems such as those in RMNP. Currently, agriculture-related emissions are not regulated and reduced N deposition is increasing (Li et al. 2016; NADP 2016).

The motivation for the agriculture community to volunteer for the PEWS is primarily to prevent regulation from state and federal agencies that monitor air pollution (personal communication, JBS Five Rivers, 2016). Any evidence showing the agricultural producers took steps to reduce emissions help the agricultural producers' cases in the event agricultural pollution becomes regulated in the future.

Though it is not expected for changes in agricultural practices to result in a large percentage-change of total inorganic N deposition in RMNP, emission reductions can have impacts on systems closer to the sources, including at the sources themselves. Even if no regulations on emissions are enacted, a reduction in ammonia emissions could help with operating costs of an agricultural operation. Nitrogen, either as protein in livestock feed or as fertilizer for crops, is one of the most expensive inputs to agricultural operations. Therefore, it is imperative to use only the amount of nitrogen that is able to be used by livestock or plants so that excess N is not lost to the environment. These nitrogen use efficiency techniques are co-benefiting both operating costs and the RMNP ecosystems.

The PEWS provided a short-term solution for minimizing N emissions during periods where forecast winds were expected to carry agricultural pollution into RMNP. For future sustainability, there needs to be long-term solutions that minimizes agricultural emissions, regardless of whether the efforts are voluntary or mandated. It is likely that the majority of the ammonia emissions come from urine patches and fertilized croplands. Studies such as Carew (2010), Hristov et al. (2011), and Lee et al. (2012) suggest feed management (versus manure management) is more effective way of reducing ammonia emissions. Therefore, one such long-term solution that a volunteer of the PEWS provided was the utilization of livestock veterinarians and nutritionists to reduce the amount of concentrated protein in the feed or rumen that would otherwise be excreted by livestock (Stackhouse-Lawson et al. 2013).

3. Discussion

a. Participation of integrated management in northeastern Colorado

Agriculture has played a major role in the growth of Colorado since the 1860s (Parton et al. 2007, Ojima et al. 2015). Since the 1950s, livestock operations transitioned from operations that relied on pastoralized methods to more concentrated, large-scale, and industrialized operations (Parton et al. 2015). While efficient for growing food in small areas of land, CAFOs have caused environmental problems related to air and water pollution around them. At temperatures above 10ºC, more than 50% of the total ammoniacal nitrogen is volatilized into the atmosphere as ammonia (Anderson et al. 2003). Additionally, the high concentration of animals does not allow for natural nutrient cycling, which means the waste solidifies onto the surface. This hardened ground is an impermeable surface and is much different from a grassland that can convert nutrients from excrement and promote healthy soils. At a CAFO, the manure either hardens or runs off towards effluent ponds, usually with the help of rain. In either case, the waste exposed to the atmosphere where volatilization is likely to occur, leading to concerns for air and water quality around CAFOs (Montes et al. 2009, Rotz et al. 2014).

Food, water, and energy goes into quickly growing a head of beef cattle to over 1000 pounds– the average weight at which beef cattle are harvested–in 18-24 months. Water and energy are required to grow food for livestock. In eastern Colorado, agricultural operations subsist off of surface and subsurface water sources. Energy is consumed by the Haber-Bösch process that creates ammonia used for crop fertilizers. To meet the food demands of a quickly-growing global population, energy, water, and food is consumed along the way by livestock, which inevitably bring waste that threaten both air and water quality.

Recently, concerns that agricultural emissions from non-point sources, and subsequently wet deposition of reduced N, has been increasing over the last three decades across the midwestern US (Li et al. 2016). In Colorado, wet deposition of reduced N is increasing, where sources come from inside and outside of the state (Malm et al. 2009; Benedict et al. 2013b; Thompson et al. 2015). Because emissions of ammonia from livestock operations are not regulated, they are not measured. Therefore, it should be noted that the rise in reduced N deposition cannot be attributed to only agricultural sources in northeastern Colorado.

Preliminary results from a 20-month study (April 2014 - December 2015) were documented in Piña et al. (2017b, Chapter 2). Prelimary results showed that the forecasters were able to predict the events that led to high wet deposition of inorganic N. The most active months for N deposition in RMNP corresponded with higher values of temperature and rainfall over northern Colorado.

One of the most important successes of the PEWS was the number of participants in the agriculture industry who volunteered to minimize emissions that would potentially reach and harm RMNP. There were 59 individual respondents from 39 of the largest agricultural operations who volunteered to temporarily curb their emissions. It is important to remember that although the livestock operations are for-profit businesses, the operators are stewards of the land and are still part of the public that wants to preserve the fragile ecosystems in RMNP.

b. Future needs

When framing the problem of agricultural N reaching RMNP in the context of a social-ecological system, it is important to look at the exogenous variables that are expected to change, such as land cover change in northeastern Colorado, a warming climate, and a growing global population that needs to be fed. These exogenous variables are not directly influenced by the agriculture industry, but they will have impacts on food, energy, and water that drive CAFOs and industrialized farming operations.

A warming climate will lead to more evapotranspiration, requiring more water to grow crops. The increased temperatures with more frequent droughts are also expected to reduce yields (Melillo et al. 2014). More pertinent to the issue of the emissions from agricultural operations, warmer temperatures increase the volatilization efficiencies of ammonia (Grant et al. 2013). The US High Plains states, which include eastern Colorado, are in a transition zone where temperatures and precipitation amounts are not high nor low, and their expected trends are uncertain (Figure 4.3; Melillo et al. 2014). From Figure 1a, we can see weather and climate plays an important role as an exogenous variable to emissions, wet N deposition in RMNP, and ecological impacts in RMNP. Hence, it is difficult for agricultural producers and mangers in these transition zones to prepare for future management.

To compound water stresses associated with climate change, the human population of the Colorado Front Range is expected to double by 2050 (Colorado Water Conservation Board 2015). With the conversion of grasslands to cityscapes, the regional climate is expected to warm. Additionally, more people in Front Range cities will drive up the water demand, which will lead to a water battle between the municipalities and the agriculture communities who predominantly hold the rights to water in Colorado.

The PEWS was an agreement on how actors with competing interests solve a problem. On one side, state and federal agencies act on behalf of the public to reduce N emissions that lead to N deposition in RMNP. On the other side, agricultural operators are helping to supply the demands of a growing global population using the most efficient methods for growing and distributing food while minimizing their emissions.

Further studies are still needed to identify which management practices are the most effective in terms of cost, emissions reductions, and resources (e.g. water and energy). For

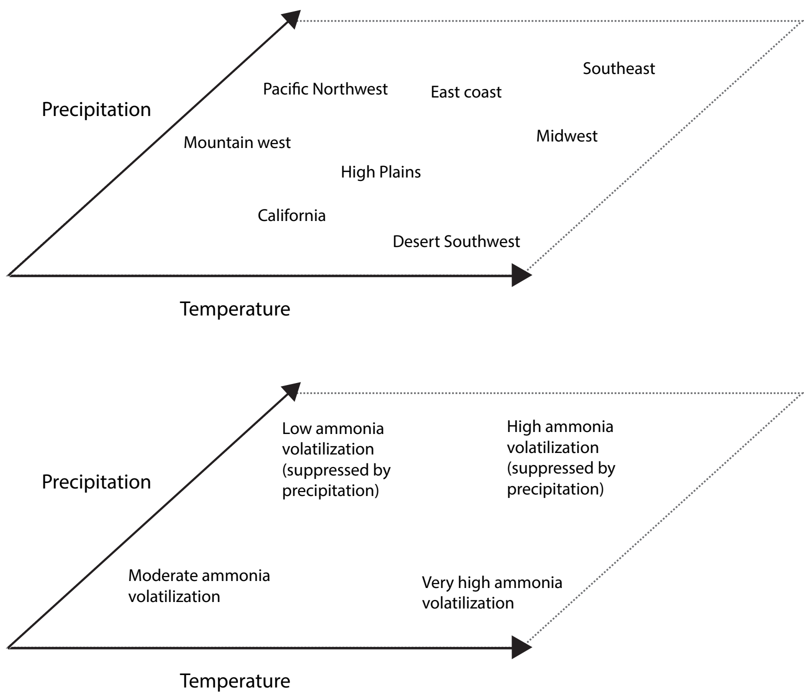

Figure 4.3. A multi-level concept diagram for climate regions across the contiguous U.S. and the associated ammonia volatilization potential.

instance, the values for the effectiveness of reducing ammonia emissions by manure management (Figure 4.2) is misleading because those practices can only be applied to a small part of the operation. Feed management, on the other hand, could be applied to the entire operation. Ractopamine hydrochloride (RAC) is a feed supplement that helps cattle increase muscle mass but decreases urea excretion (Walker and Douillard 2010) and, therefore, ammonia volatilization. Incorporating RAC into the PEWS and comparing ammonia emissions with a comparable feedyard that uses manure management practices would be a useful study that would benefit participants in the PEWS. Another management practice is to spray water over an entire livestock operation hours before winds are forecasted to be in the direction of RMNP (personal communication, Jay Ham, Colorado State University). It is important to keep in mind other environmental costs associated with these practices. For the use of RAC, the production of CH_4, a potent greenhouse gas, increases (Walker and Douillard 2010). Spraying water over entire operations–up to 4 km^2 for operations in Colorado–would be highly water intensive. Therefore, it is important to weigh costs versus benefits when it comes to environmental decision-making.

4. Conclusion

In this paper, we conceptualized, organized, and framed the complex problem of air pollution from agricultural sources into a social-ecological system using the context of the early warning system. Emissions from agricultural operations is a prime example of a social-ecological issue facing northeastern Colorado.

We outlined the the many social and ecological aspects. For the social components, agricultural producers and managers rely on profits for improved livelihoods culture of helping to supply the demand for food and energy whereas recreationalists visit Rocky Mountain National Park with expectations of natural beauty brought by geology, biology, and hydrology. Air pollution, not only from industrialized agricultural operations but from the quickly-expanding Front Range of Colorado (Thompson et al. 2015), has adverse impacts on the biology and even visibility in and around RMNPk. Changes to vegetation have already been documented (Baron et al. 2000; Baron 2006; Bowman et al. 2012).

The two-way communication between researchers at CSU, the MOU agencies, and the agricultural community should go beyond the PEWS. With respect to adaptive management and the entire social-ecological system, scientists should be helping with best management practices for altering animal husbandry practices as global temperatures continue to warm, as water becomes less and less available, and as feedlot operations continue to consolidate and increase the density of livestock.

CHAPTER 5

CONCLUSION

In this dissertation, we studied the interconnectedness of industrial agricultural in the Colorado eastern plains with the fragile mountain ecosystems via meteorology. The dissertation was divided into three major chapters: the transport mechanisms for which agricultural emissions are carried into the mountains, the development and analysis of a pilot early warning system that would warn agricultural operators when meteorological conditions were ripe for their emissions to likely impact Rocky Mountain National Park (RMNP), and a synthesis that explains the human-environment interactions in eastern Colorado using a social-ecological framework.

High-energy processes introduced in the 20th century helped grow the world's human population and the world's gross domestic product while compromising the ecological integrity, biodiversity, and resilience of natural terrestrial, cryospheric, and marine ecosystems. Rockström et al. (2009) suggested the globe has crossed its boundary of a safe space when it comes to interference with the nitrogen cycle. Moving forward, special consideration must be given with reduction efforts to avoid inadvertent impacts on other issues, such as the fertilization of mountain ecosystems.

Improved efforts to understand the source N emissions are important to reduce N deposition. By the end of the 21st century, N emissions from combustion of NO_x and oceanic NH_3 outgassing are the only two sources expected to decrease (Fowler et al. 2015). The study found the largest increases will be from terrestrial N_2O and NH_3 emissions. These increased emissions will only lead to increased N deposition.

NH_3 emissions are not regulated. Additionally, N deposition in RMNP has been shown to come from sources inside and outside of Colorado (Malm et al. 2009; Benedict et al. 2013a).

This necessitates a reduction of the uncertainty associated with ammonia emissions in the national emissions inventory. It also might require multi-state/regional agreements to monitor/reduce NH_3. For instance, parts of RMNP experience N deposition from western sources of NO_x emissions. Because NO_x is regulated as a criteria pollutant by the EPA, coal-fired power plants may get cited for their role in NO_x emissions reaching RMNP. This may be difficult with NH_3 because of the difficulties in attributing NH_3 emissions (e.g. one animal feeding operation may not be emitting enough NH_3 to impact the park, but aggregating the emissions from 15 operations and 20 croplands will lead to high concentrations of NH_3). To complicate matters even more, two of those operations may be in Nebraska and six of the croplands are split between Nebraska and Kansas. Without an accurate inventory, it cannot be assumed which animal feeding operations and croplands contribute the most to NH_3 emissions.

The uncertainties associated with estimating how much N deposition RMNP is receiving, coupled with challenges in attributing N from buildings, surfaces of feedlots/croplands, or motor vehicles in Colorado and neighboring states, and other sources, makes it challenging to prioritize investments in efforts for reducing N deposition in RMNP.

What we must do is sustainably reduce the amount of emitted N into ecosystems. That is, we must answer engineering questions such as: how can we reduce N volatilization/runoff while keeping up with the increasing global demands for food? N-use efficiency will help down-wind/-stream ecosystem health as well as agriculture expenditures on fertilizers. A desirable method for N-use efficiency would be to optimize the applied fertilizers as opposed to over-applying fertilizers. From a livestock production standpoint, reducing N emissions would require a change in diets for livestock that reduce excreted N-containing compounds. Another possibility would be to go back to old practices and have free-range cattle, which would allow for more biogeochemical cycling of the excrement with the soils. Lastly, a more drastic move would be to relocate the entire operations to a more moist climate, where soils can cycle the nutrients much quicker than those in a semi-arid climate.

Semi-arid regions around the globe do not experience large amounts of annual moisture, with the exception of land adjacent to surface streams/rivers. For instance, in eastern Colorado, croplands not immediately drawing from the South Platte River rely on subsurface waters. In addition to N transport from agricultural lands, water availability has placed many strains on semi-arid regions. We must figure out ways to provide the same yields while cutting water and nitrogen costs, or completely change the global trajectory of food, energy, and water, consumption.

As pessimistic as the picture may sound, it is important to protect minimally disturbed ecosystems like those found in Rocky Mountain National Park. Efforts like the RMNP N Deposition Reduction Plan (NDRP) appear to be useful only with mandates. Voluntary efforts since the inception of the NDRP, such as the Rocky Mountain Early Warning System, attempt to reduce agriculture emissions of ammoniacal N. However, without emissions data, there are difficulties in quantifying the impact of the early warning system.

1. Future outlooks

In addition to increased demand for food production, agricultural producers are also battling the rapid growth of the Colorado Front Range, which will increase the demands of water in a water-limited east slope. Municipalities are buying-and-drying agriculture producers to meet the demands of the growing Front Range populations.

The population of the Front Range of Colorado is expected to more-than double by 2050 (Colorado Water Conservation Board 2010). This will undoubtedly bring social and ecological changes to the Front Range. For instance, the extent to which the mountain-valley circulation is impacted depends on the increase in impermeable surfaces (e.g. roads, buildings, sidewalks) versus landscaped surfaces (e.g. golf courses, residential lawns, parks).

If the temperature gradient between the plains and the urbanizing Front Range increases, the Front Range would expect stronger upslope winds (Segal et al. 1989). If the gradient decreases, the Front Range would expect weaker upslope winds (Wolyn and Mckee 1994). Areas of growth along the Front Range do not necessarily suggest an increase in impermeable surfaces, which would lead to greater heating nearest the mountain slopes. Aside from temperatures and wind changes, it would be necessary to estimate a N budget on Colorado based on current population and climate. The budget could have multiple variables that would change the N budget including future scenarios regarding population, land-cover, and climate change. The work would require detailed N emission fluxes from urban and agricultural sources. Additional, N from wildfires and oil-and-gas exploration would need to be included.

2. Future of NDRP

The NDRP's glide path of achieving 1.5 kg N ha^{-1} yr^{-1} by 2032 was created based off a study from Loch Vale (Baron 2006). The critical threshold value for Loch Vale is applied to all of RMNP, including alpine, subalpine, and montane ecosystems.

We found in the analysis of the early warning system that more high N deposition events occurred during warnings at Beaver Meadows (NADP CO19) than Loch Vale (NADP CO98). This suggests the source regions we used for the EWS in eastern Colorado had more of an influence on deposition Beaver Meadows than Loch Vale. Loch Vale, located just below treeline near the Continental Divide, is influenced meteorologically from both west and east of the

Contintental Divide while Beaver Meadows is mostly influenced by sources east of the Divide (Baron et al. 1992).

Since the NDRP was outlined 9 years ago, there have been more studies on ecosystem thresholds (Bowman et al. 2012) as well as advances in computing (Skamarock et al. 2008). The NDRP would benefit from a reformulation that reflects current science. The revised NDRP should then be peer-reviewed to ensure objective scientific integrity. Additionally, with studies on N deposition in RMNP being published each year, it is also advisable the NDRP should be revised every 5-7 years so that policy can be based on the latest science. Each subsequent release of the NDRP should be accompanied by a carefully designed stakeholder engagement plan. The approach utilized with the EWS demonstrated the value of engaging stakeholders as active contributors to a shared objective. A constituency that may have resisted changing livestock management practices were instead involved as stakeholders that actively contributed to a shared policy objective.

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