Nitrogen Emissions Along the Colorado Front Range: Response to Population Growth, Land and Water Use Change, and Agriculture

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While N emissions are not commonly linked to land use change, the production of fixed nitrogen is strongly related to activities associated with urbanization, such as construction, production of energy, and development and use of transportation corridors. Agricultural intensification, brought about by application of synthetic N fertilizers and industrial-scale animal feeding operations, is another land use change that increases N emissions. The Colorado Front Range region experienced rapid population growth from 1980 (1.9 million) to 2000 (2.9 million). Emissions from point (power plants and industry) and mobile (highway and off road vehicles) sources were responsible for most of the increase in emissions since 1980. Agriculture (cropped and grazed land and livestock) was the other important source of N emissions. Soil emissions from cropped and grazed lands remained stable while livestock emissions increased slightly due to more cattle and hogs in feedlots. Although cause and effect relationships between increased N emissions and eutrophication of particular ecosystems are difficult to establish, higher N deposition has been observed at alpine sites near the headwaters of the South Platte River commensurate with the rise in emissions. The ecosystem responses of alpine systems to N deposition are likely to be the result, albeit an indirect one, of land use change.

INTRODUCTION

The South Platte River Basin, home to 68% of Colorado's residents, is a region that has experienced rapid population growth and land use change over the past several decades. The population in the 16 county region of the South Platte River basin grew from 1.9 million to 2.9 million people from 1980–2000, a gain of 33% (Table 1; U.S. Census Bureau, http://www.census.gov/prod/cen2000/doc/sf3.pdf). Coincident land conversion from agricultural and non-federal forest lands resulted in the growth of urban, suburban, and exurban land cover in the State of Colorado from 3,650 km^2 to 12,785 km^2 over the period 1960–1990 [Table 2; *Theobald*, 2000]. In addition to urban sprawl, there have been large changes in agricultural practices and land use in this region. Along with an overall decrease in total farmland, harvested drylands, and rangelands between 1959 and 1997, there was intensification of irrigated agriculture and an overall increase in irrigated croplands. The area of irrigated lands in Eastern Colorado—the Arkansas River basin, South Platte River basin, and above the Ogallala Aquifer—increased by 76% [*Parton et al.*, 2003]. The two major irrigated crops, corn and alfalfa hay, support an equally dramatic increase in the number of animals (e.g., cattle and hogs) in confined animal feeding operations throughout the region (CASS, Colorado Agricultural Statistics Service, 2003, http://www.nass.usda.gov/co/).

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Table 1. Population by county, South Platte Basin.

County	Area (km^2)	1980	1990	2000	20-yr % Change
Adams	3087	245,944	265,038	363,857	32
Arapahoe	2080	293,621	391,511	487,967	40
Boulder	1924	189,625	225,339	291,288	35
Clear Creek	1026	7,308	7,619	9,322	22
Denver	396	492,365	467,108	554,636	11
Douglas	2176	25,153	60,391	175,766	86
Elbert	4794	3,516	9,646	19,872	82
Gilpin	389	1,320	3,070	4,757	72
Jefferson	1999	371,753	438,430	527,056	29
Larimer	6737	149,184	186,136	251,494	41
Logan	4763	19800	17,509	20,404	3
Morgan	3331	22,498	21,923	27,171	17
Park	5701	2,740	7,174	14,523	81
Sedgewick	1419	3,266	2,690	2,747	-19
Washington	6529	2,701	4,770	4,926	45
Weld	10342	123,438	131,821	180,936	32
All South Platte	58,474	1,954,232	2,240,175	2,936,822	33
All Colorado	269,600	2,819,893	3,294,394	4,301,261	34

Food and energy production and transportation byproducts emit reactive nitrogen species, nitrogen oxides (NO_x) and ammonia (NH_3), to the atmosphere. Increased atmospheric deposition of NO_x and NH_3 can lead to enrichment

Table 2. Changes in land use, numbers of building permits, and commute time to work for counties of the South Platte Basin. Conversion of agricultural to urban land use data 1982–1992 are from Theobald (2000), numbers of building permits 1985-1995 are from the Colorado Division of Local Affairs (2003, http://www.dola.state.co.us/demog/Housing.htm), and travel time for work in 2000 are from the 2000 Census (http://www.census.gov/prod/cen2000/doc/sf3.pdf). % pop 30 minutes represents the proportion of working age population that commute more than 30 minutes per day one way.

County	Ag to urban conversion (km^2)	No. building permits 1985	No. building permits 1995	Ave. Commute (min)	% Pop 30 min
Adams	50-115	2741	2944	25.4	41.7
Arapahoe	50-115	5069	3408	23.7	37.8
Boulder	20-50	1953	2938	19.9	26.1
Clear Creek	0-5	53	83	27.9	49.2
Denver	0-5	1272	786	22.5	32.4
Douglas	50-115	2160	4785	25.6	43.5
Elbert	0-5	184	494	35.8	65.8
Gilpin	0-5	36	67	30.9	51.0
Jefferson	50-115	4909	5102	24.7	40.3
Larimer	50-115	2619	2797	19.1	22.4
Logan	0-5	12	85	13.4	12.6
Morgan	0-5	33	98	16.3	16.1
Park	5-10	228	452	37.3	62.7
Sedgewick	0-5	0	0	13.3	16.5
Washington	0-5	3	12	16.0	22.6
Weld	10-20	878	1469	21.0	28.5

and acidification of terrestrial and aquatic communities, and adversely affect human health [*Galloway et al.*, 2002]. Atmospheric N deposition to high mountain ecosystems along the Colorado Front Range has influenced lake nutrient status, aquatic algal communities, and increased soil N cycling [*Baron et al.*, 2000]. We trace here the history of land use in a rapidly changing region and describe how land use change and associated human activities have altered NO_x and NH_3 emissions.

DESCRIPTION OF THE REGION

The South Platte Basin occupies the northeastern fifth of the State of Colorado (with small portions in Wyoming and Nebraska that are not addressed here). Its 58,474 km^2 include extremely diverse topography, ranging from mountains greater than 4,000 m elevation to 850 m where the South Platte River joins the North Platte River (Figure 1). The western mountainous part of the basin, including Park, Clear Creek, and Gilpin Counties, is a mixture of sparsely inhabited public and private land, although foothills counties such as Jefferson have seen rapid population gains since 1980. The western third of Boulder and Larimer Counties are also mountainous, but the eastern portions include many cities and towns and are considered urban. A densely populated urban corridor is found at the boundary between mountains and plains, stretching from Denver and its suburbs north to Fort Collins. It includes Denver, Douglas, Jefferson, Arapahoe, Boulder and Larimer Counties. This metropolitan area had 2.9 million inhabitants in the 2000 census, or 68% of the state population (Table 1). Parton et al. [2003] define Weld, Adams, and Elbert Counties as Urban Fringe Counties, where there are large towns, but also large areas that are rural and agricultural in character. Rural areas east of the metropolitan areas are sparsely populated, but support a stable agricultural economy based on wheat, irrigated corn and alfalfa hay, and intensive livestock operations [*Parton et al.*, 2003]. Rural counties of the South Platte Basin are Morgan, Logan, Washington, and Sedgewick Counties.

Land use has been dynamic in the region especially since 1950, but not only as a result of immigration. Denver is a fully urban county in the region (the City and County of Denver are the same). All other urban counties have lost extensive rangeland to urban and suburban development, with absolute

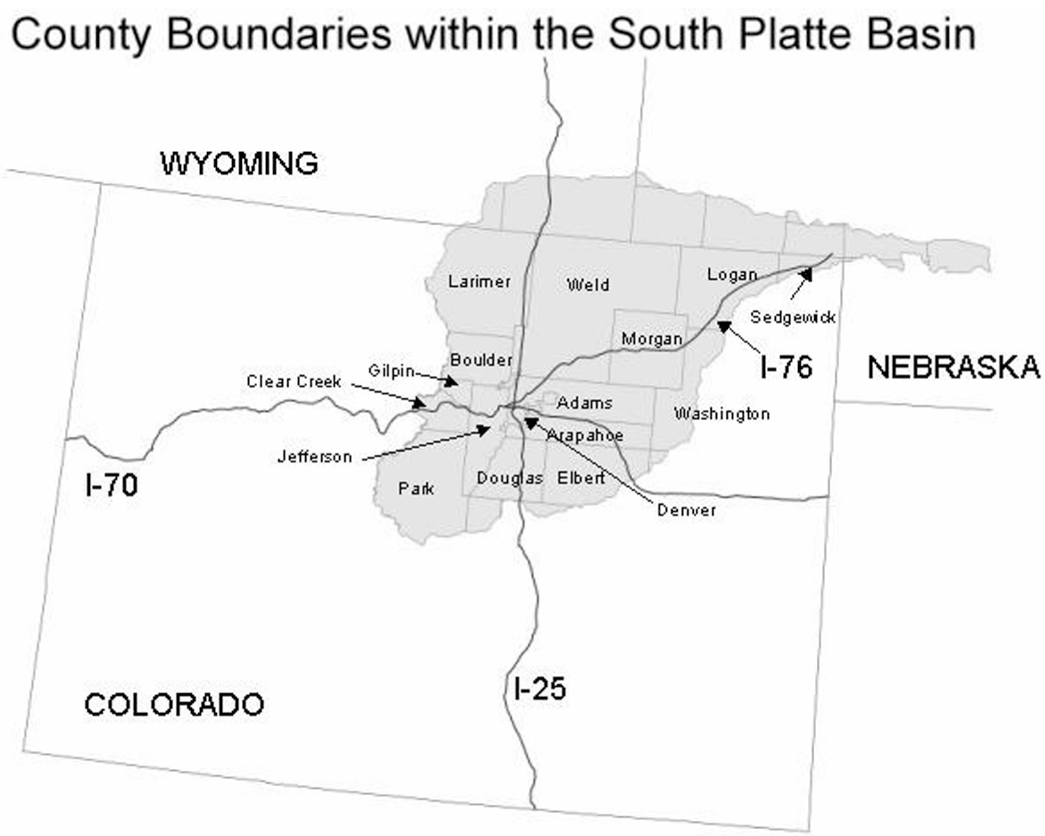

Figure 1. Map of South Platte Basin, CO.

Table 3. Livestock numbers in the South Platte Basin, 1985 and 1995.

Livestock	1985	1995	Percent Change (%)
All cattle	1,174,000	1,291,500	9
Hogs	173,590	278,132	38
Sheep	337,675	327,082	-3
Poultry	3,029,565	2,887,049	-5

losses between 50–115 km^2 since 1982 in Larimer, Jefferson, Adams, Arapahoe, and Douglas Counties, and 20–50 km^2 lost in Boulder County [Table 2; *Theobald,* 2000]. Ten to 20 km^2 of agricultural land has been converted to urban uses in Weld County.

Lands that have remained in agriculture have also changed in character, but total harvested cropland area has been fairly constant since 1950 [*Parton et al.,* 2003]. Dryland wheat crop area was taken out of production and enrolled in the Conservation Reserve Program beginning in 1986; 13% of total cropland was contracted to CRP by 1997 [*Parton et al.,* 2003]. The area in irrigated croplands increased rapidly after 1990 in both Urban Fringe counties and rural eastern counties. Throughout eastern Colorado total cropland decreased by ~2%, but irrigated areas increased ~73% since 1950. Irrigated corn and alfalfa hay accompanied the rise in demand for livestock feed, and animal feedlots constituted the other major change in agriculture in the South Platte Basin. Over the past 50 years, the South Platte Basin became a national center for confined animal feeding operations. The numbers of cattle and hogs increased between 1985 and 1995, while sheep and poultry numbers declined slightly (Table 3).

METHODS

We compiled information on NO_x and NH_3 emissions, land use, farming and livestock activities, human population and transportation patterns for the 16 Colorado counties in the South Platte River Basin. NO_x and mobile source NH_3 emissions were taken from the EPA TIERS database of point, highway, and off-road vehicle emissions (http://www.Epa.gov/air/data/). Data for the National Emissions Inventory (NEI) were submitted by the States to the Environmental Protection Agency in standard format and were quality-checked for format and content according to methods described in the 1999 National Emission Inventory Preparation Plan (revised February 2001; http://www.epa.gov/ttn/chief/et/nei_plan_feb2001.pdf). NO_x emissions for large stationary sources with emissions >100 tons yr^{-1} (point sources), other stationary sources (area sources), mobile sources on highways and roads (onroad) and other mobile sources such as construction vehicles, farm machinery, trains (non-road) were compared for 1985 and 1995. For this paper, all stationary sources (point and area) have been combined and labeled "point" sources. Highway NH_3 emissions were not reported in 1985, but were in 1995.

NH_3 and NO_x emissions from agricultural soils in the South Platte basin were estimated using the DAYCENT ecosystem model [*Del Grosso et al*., 2001; *Parton et al*., 1998]. DAYCENT is the daily time step version of the CENTURY biogeochemical model [*Parton et al.,* 1994]. Key submodels include plant production, organic matter decomposition, soil water and temperature by layer, and trace gas fluxes. DAYCENT is a process-based model of intermediate complexity, and the microbial processes that result in N gas emissions—nitrification and denitrification—are explicitly represented. Comparisons of model results with field observations show that DAYCENT reliably simulates crop yields, soil organic matter levels, and trace gas fluxes for various native and managed systems [*Del Grosso et al.,* 2002]. Daily maximum/minimum temperature and precipitation, vegetation cover, land management, and soil texture data are needed as model inputs. Climate and soil texture class data at the 0.5° grid scale from VEMAP [1995] were combined with county level land use data from the USDA NASS web site (http://www. nass.usda.gov:81/ipedb/) to drive DAYCENT. Four land uses were simulated: dryland winter wheat/fallow cropping, irrigated alfalfa cropping, irrigated corn cropping, and rangeland. For each county, we identified the 0.5° grid cell that covered most of the land area in that county and used climate and soils data from the appropriate cell to represent the entire county. DAYCENT output in units of N gas emissions per square meter per year were multiplied by reported land cover areas in each county to calculate annual N gas flux for each land use for each county. N gas emissions for each land use in each county were then summed to obtain annual basin-wide emissions. Annual emissions were used to calculate decadal mean N emissions for South Platte agricultural soils during each decade of the 20th century.

NH_3 emissions were calculated for cattle on feed, range cattle, hogs, sheep, and poultry using percentage of N lost from animal waste with calculations for animals in developed countries (Region I) from Bouwman et al. [1997]. Animal numbers for 1987 and 1997 came from the United States Census of Agriculture (http://www.nass.usda.gov/census/). Human population data were acquired from the US Census Bureau (http://www.census.gov/). Commuting statistics also came from the Census Bureau (Travel time to work, Summary File 3, US Census Bureau, 2003, http://www.census.gov/prod/cen2000/doc/sf3.pdf), and represent the working population (age 16 and older).

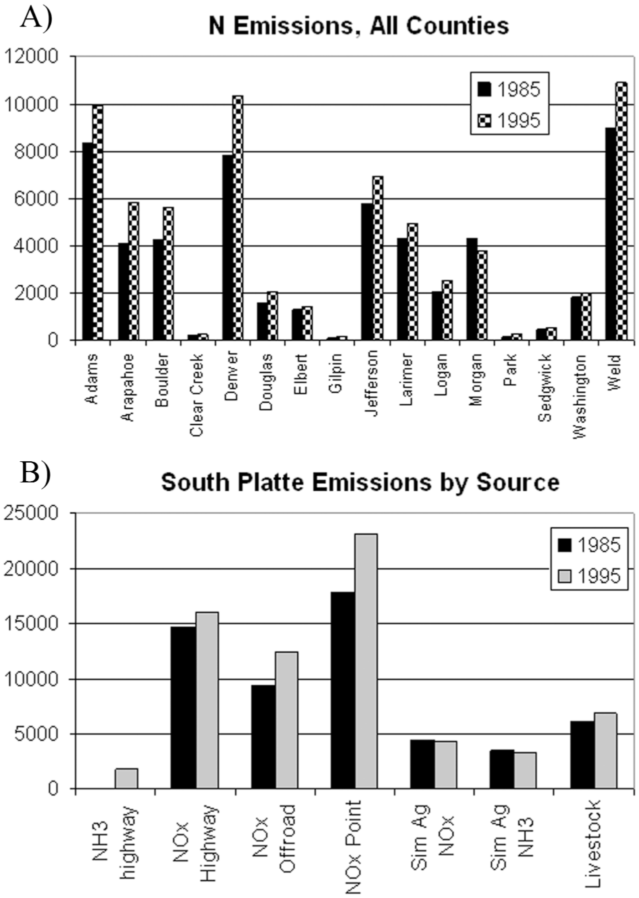

Figure 2. A) Nitrogen (NO_x–N and NH_3–N) emissions by A) county, and B) by emissions source for 1985 and 1995 for the South Platte Basin, Colorado.

RESULTS

County comparisons. Three counties had significantly higher N emissions than the remaining 13 counties (Figure 2a). Weld County is the largest of all South Platte counties (Figure 1, Table 1), at 10,342 km^2, and had the highest N emissions of all South Platte counties in 1985 (8,974 Mg N) and again in 1995 (10,907 Mg N; Figure 2a). Denver is the second smallest county in the Basin but had the second highest N emissions of all counties. N emissions from Denver increased 25% over the 10-yr period, to 10,376 Mg N. Adams County was the other county with N emissions greater than 8,000 Mg N in 1995; emissions from these three counties alone made up 46% of the total N emissions for the Basin. Seven counties fell into a group of N emissions between 2,000 and 6,000 Mg N. Of these, Arapahoe, Boulder, Douglas, Jefferson, Larimer and Logan all showed strong increases in N emissions from 1985 to 1995, while emissions decreased 15% in Morgan County over this time period (Figure 2a). Douglas County emissions increased 25% from 1985 to 1995, to 2,075 Mg N. The remaining counties—Clear Creek, Elbert, Gilpin, Park, Sedgwick, and Washington—had N emissions less than 2,000 Mg N, and showed little change over the 10-yr period. The counties with the highest N emissions were either entirely urban, such as Denver, or a mixture of urban, agricultural, and industrial. All high N emitting counties were located in counties along Interstate 25 or Interstate 70 in the Front Range urban corridor. Low N emitting counties were farther from the urban centers of Denver, Boulder, Longmont, Fort Collins and Greeley, and were either eastern agricultural counties (Elbert, Sedgewick, Washington) or western mountain counties (Park, Clear Creek, Gilpin).

Point sources. Point sources were the largest single type of N emissions in both 1985 and 1995. Point sources included large electrical generating plants and other industrial manufacturing and processing facilities, as well as many smaller stationary facilities. Emissions from point sources increased from 17,827 Mg N in 1985 to 23,128 Mg N in 1995 (Figure 2b).

Mobile sources. Mobile sources were divided in the EPA emissions inventories as highway and offroad sources. Highway sources included passenger cars and trucks, buses, and transport vehicles. The reported NO_x emissions from this sector were 14,719 Mg N in 1985 and 16,010 Mg N in 1995 (Figure 2b). Emissions from highway mobile sources were the second highest sources of N after point sources for the South Platte Basin. Offroad sources included trains, construction and farm machinery. Emissions from this sector ranked third in magnitude, and were 9,369 Mg N in 1985 and 12,428 Mg N in 1995. While highway NO_x emissions were 61% of the total in 1985, they made up only 53% of the total mobile source emissions by 1995. Ammonia emissions from vehicles, which were not reported in the 1985 EPA database, were 6% of the total vehicle emissions in 1995, with a value of 1,858 Mg N.

Commuting times can be subjectively related to mobile source emissions, because there is a direct relationship between time spent driving and automobile emissions. Counties with less than 20 minutes average commuting time were Boulder, Larimer, Logan, Morgan, Philips, Sedgewick, and Washington (Table 2). Even in these counties, however, between 13% and 26% of the population spent one or more hours per day in the vehicle. Fifty percent or more of the populations of Park, Gilpin, Elbert, and Clear Creek Counties commuted more than 1 h per day roundtrip.

Agricultural emissions. Emissions of NO_x in the South Platte Basin from 1900–2000 were indicative of settlement and abandonment patterns through mid-century, and then

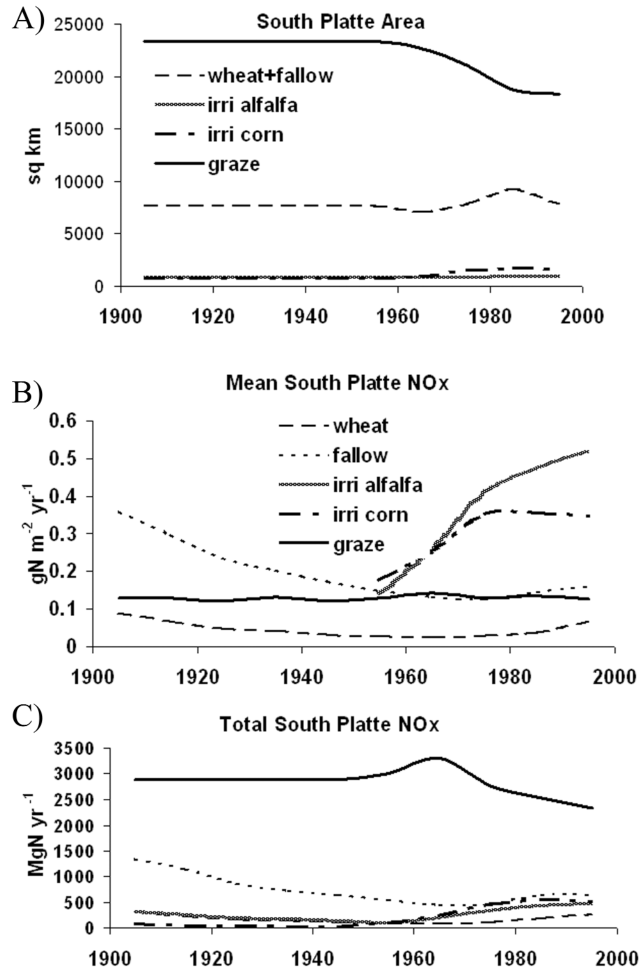

Figure 3. Trends in agricultural land area and NO_x–N emissions in South Platte Basin, 1900–2000. A) Area by agricultural crop, in km^2; B) NO_x–N emissions by crop, g N m^{-2} yr^{-1}; C) aerially-weighted NO_x–N emissions for entire basin, in Mg N yr^{-1}. Irri, irrigated. Legends for B) and C) are the same.

reflected increased applications of synthetic N fertilizers on irrigated crops beginning in the late 1950s (Figure 3a). Nitrogen oxide (and NH_3, data not shown) emissions from soils declined with loss of the original soil organic matter with tillage for wheat/fallow cropping, while rangeland emissions held steady around 0.16 g N m^{-2} yr^{-1}. N emissions from irrigated corn, as did the area planted to irrigated corn, increased greatly between 1955 and 1980 with the advent of inexpensive synthetic nitrogen fertilizers. Nitrogen emissions from irrigated alfalfa also increased beginning in the late 1950s and continued to increase linearly through 2000. Total NO_x–N emissions from rangelands were far greater than all croplands combined due to the large area of land in the Basin that was grazed (>30,000 km^2), so the dynamics of N emissions from croplands, while interesting, did not account for most of the agricultural N emissions. Total cropland area in the South Platte Basin was around 7,000 km^2 (Figure 3b). The combined agricultural NO_x–N and NH_3–N emissions for the South Platte Basin changed very little between 1985 (7,870 Mg N) and 1995 (7,576 Mg N, Figure 3c).

The number of cattle in the Basin increased by 10% between 1985 and 1995, and many, if not all, of these animals spent at least part of their lives in confined feeding operations (Table 3). The number of hogs increased 38%, from 174,000 to 278,000 during this period. Sheep and poultry numbers declined slightly. NH_3–N emissions from livestock for the South Platte Basin were greater than other agricultural emissions, at 6,094 Mg N and 6,955 Mg N for 1985 and 1995, respectively (Figure 2b). Combined agricultural emissions were 13,647 Mg N in 1985 and 14,174 Mg N in 1995.

DISCUSSION

Basin-wide. Power plants and industry, or point sources, were the major sources of N emissions for the South Platte Basin (32% and 34% of total emissions for 1985 and 1995, respectively), although the combined highway and offroad mobile sources emissions (24,088 Mg N emissions in 1985, 30,296 Mg N emissions in 1995) exceeded point sources to make up 43% of total in 1985, and 45% of total in 1995. Point source emissions were proportionally twice as important in the South Platte Basin as in the 11 contiguous Western states (including Colorado), where they made up only 21% of total N emissions in a 1996 evaluation [*Fenn et al.,* 2003]. Highway and offroad emissions were proportionally similar in the South Platte and the Western states, with 27% and 18% of total N emissions in the South Platte, compared with 29% and 20% of the total for the West, respectively. All agricultural N emissions in the South Platte Basin made up 21% of total N emissions, compared with 30% for the 11 contiguous states [*Fenn et al*., 2003]. Fenn and colleagues note considerable uncertainty in the NH_3–N values derived from the EPA database, and a shift in the proportion of agricultural N emissions would affect all other proportions. Nearly half of all emissions in the Western states came from California; Colorado was the second most important source of NH_3–N and third for NO_x–N [*Fenn et al*., 2003].

Nitrogen oxide emissions increased from most sources in the South Platte Basin between 1985 and 1995. In this they followed a pattern shown by all other U.S. states except California, whose emissions decreased by at least 5% [*Fenn et al*., 2003]. Emissions of NO_x and NH_3 from crop- and rangelands were essentially unchanged over the time period. The largest absolute increase in emissions of 5,301 Mg N (23%) was from point sources, while the largest proportional

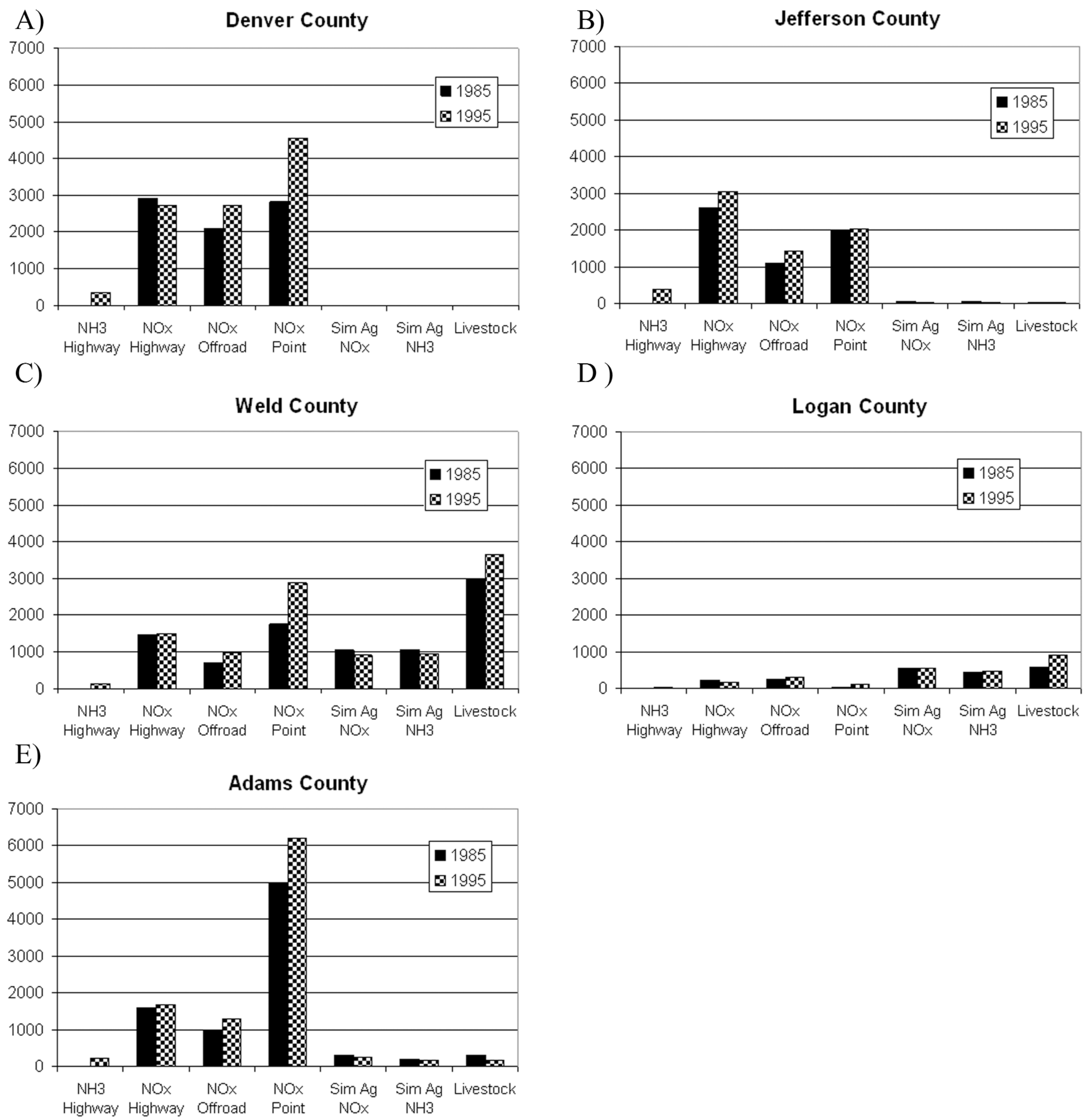

Figure 4. Five county comparison of N emissions from major sources in 1985 and 1995. A) Denver County; B) Jefferson County; C) Weld County; D) Logan County; E) Adams County.

increase was in offroad machinery emissions, where the absolute value was 3,059 Mg N (25%). Highway vehicle NO_x emissions increased by 8% and livestock NH_3 emissions increased by 12%.

Relation of emissions to land use. We selected five counties as examples of urban, agricultural, or industrial land use (Figure 4). Denver and Jefferson Counties are urban, and while population increased in both counties over the period 1980–2000, it increased by 29% in Jefferson County compared to only 11% for Denver. The number of building permits in each county illustrates rapid land use change and construction activity. Jefferson County granted 4,909 building permits in 1985 and an additional 5,102 in 1995 (Colorado State Division of Local Affairs, 2003; http://www.dola.state.co.us/demog/Housing.htm). The number of building permits in Denver declined from 1,272 in 1985 to 786 in 1995.

Highway N emissions were the dominant source of N to the atmosphere in Jefferson County (Figure 4). The average commute for residents of Jefferson County was 25 minutes, and 40% of Jefferson County residents commuted 30 or more minutes one way each day, which is equal or less than most other counties in the Basin (Table 2). While some mobile source emissions can be attributed to resident populations of commuters, I-70 is a heavily trafficked corridor for transportation to mountain resorts and across the state. Denver had the next highest highway mobile source emissions, and emissions decreased slightly from 1985 to 1995. The average commute for Denver residents was 22.5 minutes, and 32% of the Denver population spent more than an hour per day commuting.

Agricultural emissions declined from small to barely detectable for Jefferson County (Figure 4). Offroad highway emissions reflected construction of buildings, roads, and infrastructure in Jefferson County, and increased from 1,087 Mg N to 1,420 Mg N from 1985 to 1995. Denver offroad mobile source emissions were even greater, increasing from 2,077 Mg N to 2,730 Mg N over the 10-yr period. Denver County has no agricultural land, and the area of harvested land in Jefferson County declined 50–115 km^2 (2–6%) between 1982 and 1992. While the time periods for which data are available are not exactly coincident, they illustrate land use change in a rapidly urbanizing part of the South Platte Basin [*Theobald,* 2000].

While there were significant N emissions from point and mobile sources, Weld County N emissions were dominated by agriculture. The agricultural counties in the South Platte Basin are among the most productive in the state, and Weld County is the third most productive county in the entire United States (CASS, 2003; http://www.nass.usda.gov/co/).

In 2003, Weld County ranked fifth in Colorado for wheat and corn production, first for alfalfa hay, and first for numbers of cattle and calves. There were significant emissions from agricultural crops, although these values declined slightly between 1985 and 1995. The largest source of N came from confined livestock operations, whose NH_3–N emissions increased from 2,983 to 3,645 Mg N yr^{-1} between 1985 and 1995, due to a large increase in the numbers of cattle and hogs. The hog population throughout the South Platte increased by more than 100,000 over this time period, up to 278,000 in 1995, while cattle numbers increased by a modest 9% (CASS, 2003; http://www.nass.usda.gov/co/). Weld County is home to more than half the cattle in Colorado, and this constituted an increase from 580,000 to 602,000, maintaining Colorado's strong ranking of fourth in the United States for production of cattle on feed. There were 260,000 sheep in Weld County in 1995, unchanged from 1985, and nearly 2.4 million chickens in 1995, up nearly 300,000 from 1985. N emissions reflected this strong agricultural base.

Weld and Logan Counties have strong agricultural economies, and Weld is also rapidly gaining population and industry. Weld County was identified by Parton et al. [2003] as an Urban Fringe County because of its proximity to metropolitan urban areas to the west. There were more than 57,000 newcomers to Weld County since 1980. An increase in residents that commute to work in neighboring counties was not reflected in emissions from highway mobile sources (Figure 4), but the average commute for a Weld County resident was 21 minutes, and 28% of the population spent an hour or more commuting each day (Table 2). The number of building permits in Weld County increased from 878 in 1985 to 1,469 in 1995, and construction could explain an increase in offroad mobile sources. Weld County increased its point source emissions by nearly one third between 1985 and 1995 with addition of power generators, industrial facilities, oil and gas wells.

The bulk of Logan County's emissions were also agricultural, but it had only one third of the cattle and one quarter of the hogs found in Weld County. Nevertheless, Logan County ranks fourth in Colorado for alfalfa and ties with Morgan County for a third place ranking for numbers of cattle and calves. Other livestock were not important, and Logan County's low human population and distance from urban centers was reflected in low highway, offroad, and point sources. Fully agricultural Logan County lost little or no agricultural land to urbanization from 1985–1995 [*Theobald*, 2000; *Parton et al*., 2003]. Logan County residents spent only 13 minutes per day commuting, on average, and only 12% of residents commuted an hour or more daily for work. Logan County granted 12 building permits in 1985 and 85 in 1995.

Adams County, like Weld County, had mixed land use that was reflected in emissions from most major sources. Cropland emissions were about one third those from Logan County, and there were only 7% of the basin total head of cattle in Adams County (CASS, 2003; http://www.nass.usda.gov/co/). Adams County N emissions were dominated by industry, however, and this shows in the more than 5,000 Mg N point source emissions in 1985 that increased 19% to more than 6,000 Mg N in 1995. Electricity generation, oil refineries, and a large airport contributed NO_x–N to the atmosphere. Adams County human population increased 32% since 1980, and at 364,000 people, ranked fourth in population in the South Platte Basin, after Denver, Jefferson, and Arapahoe Counties. Building permits in Adams County remained fairly high, with 2,741 permits in 1985, and 2,944 in 1995. Parton et al. [2003] describe Adams County as part of the Urban Fringe, where there was a loss of cropland, especially corn and wheat since 1985. Theobald [2000] also reported a loss of cropland, and found that 50–115 km^2 or between 2% and 4% of county area, were converted in Adams County from agricultural to urban land use between 1982 and 1992.

The total N emissions from all sources in the South Platte Basin were 67,598 Mg N in 1995, or 23.0 kg N per person per year (using 2000 census numbers). The emissions per capita were not very different from the calculated value for 1985 of 25.0 kg N (using 1990 census numbers). Emissions per unit area are 1.16 g m^{-2} for the entire Basin. There is great disparity in the geographic concentrations of emissions, however, as one would expect, with the highest N emissions per unit area occurring in Denver, at 26.18 g m^{-2}. Emissions per area were one to two orders of magnitude lower for all other counties, with metropolitan area counties having emissions of ~1–3 g m^{-2}, and distant mountain or agricultural counties having emissions <1 g m^{-2}. Exceptions were Larimer County, with lower emissions per area than other metropolitan counties, and Morgan County, with higher emissions per area than other agricultural counties (Table 4).

Prior to the 1960s, the economy of the South Platte Basin, as with the rest of the U.S. Great Plains, was dominated by agriculture [*Parton et al.,* 2003]. There were about 800,000 residents. Denver County was urban, but all other plains counties were agricultural, while mountain counties would have been sparsely populated. Weld, Adams, Elbert, Morgan, Washington, Logan, and Sedgewick were still either partially or primarily agricultural in 2000, and with the exception of Sedgewick County, had stable or increasing populations. Sedgewick County, with a decline of nearly 20% population from 1980 to 2000 might represent other Great Plains counties where farm abandonment and emigration of young people have been given media attention in light of creating a "buffalo commons" [*Popper and Popper*, 1987]. Nitrogen emissions from the South Platte Basin prior to the 1960s, would have been dominated by agricultural sources, and would have been substantially lower than current values because synthetic nitrogen fertilizers were not widely used, nor were there extensive confined animal feeding operations.

Table 4. Emissions per unit area and per person for South Platte Basin. Emissions data are from 1995, and population data are from 2000 census.

County	Population/ Area	Emissions/ Area g/m^2	Emissions/ capita kg
Adams	118	3.22	27.35
Arapahoe	235	2.80	11.93
Boulder	151	2.93	19.39
Clear Creek	9	0.24	26.46
Denver	1,400	26.18	18.71
Douglas	81	0.95	11.81
Elbert	4	0.30	72.07
Gilpin	12	0.45	37.06
Jefferson	264	3.48	13.20
Larimer	37	0.74	19.76
Logan	4	0.53	123.97
Morgan	8	1.14	139.25
Park	3	0.04	16.70
Sedgewick	2	0.12	62.70
Washington	1	0.30	402.50
Weld	18	1.05	60.28
All South Platte	52	1.19	23.00

The transformation from the agricultural past to today's environment is striking, not only in the magnitude of N emissions increases, but in the complexity of social, cultural, and land use change. Agriculture is thriving in several South Platte counties, while others that had extensive cropland, such as Boulder, Larimer, Arapahoe, and Jefferson, have become completely or partially urbanized. Adams County has become the industrial hub of the Basin, in addition to contributing N emissions from agricultural and residential sources.

The mountain counties of Park, Clear Creek, Gilpin, and the partial mountain counties of Jefferson, Boulder, and Larimer, have seen urban, suburban, and exurban development. Urbanization has occurred throughout the Front Range counties adjacent to Denver, along with a large increase in mobile source N emissions. As these counties have urbanized, emissions have switched from agricultural sources to those dominated by urban and industrial sources. Nationally, driving activity, defined by the U.S. Department of Transportation as vehicle miles traveled (VMT), increased by 136% from 1970–1998, at least partly in response to suburban and exurban residences requiring greater commute time [*U.S. Department of Transportation*, 1999]. There was also an increase in the number of vehicle trips per person, average vehicle trip length, and number of motor vehicles per person; people are simply driving more [*U.S. Department of Transportation*, 1999]. Point, highway, and offroad mobile sources made up 79% of total emissions in 1995.

Ideally, one would like to link the amount and location of N emissions to N deposition as a way to fully attribute measured ecological responses to their original source. This is difficult to do because of complex atmospheric transport and transformation mechanisms. N deposition occurs throughout the Basin, and much of it is deposited close to the source of origin [*Mosier*, 2000]. Some N is blown east with prevailing winds, but N also moves against prevailing winds to be deposited in mountainous areas [*Parrish et al*., 1990; *Baron and Denning*, 1993]. Mean annual atmospheric N deposition to Loch Vale Watershed, a high elevation long-term study site on the western edge of the South Platte Basin, is 0.26–0.50 g m^{-2} [*Baron et al.,* 1995; *Baron et al*., 2000], or less than half the areally-weighted N emissions value for the Basin, and far less than emissions from the adjacent urban counties. Ecological effects in mountain environments have been observed, however, and their onset appears to be concurrent with the shifts from an agriculturally-dominated landscape to an urban landscape post 1950 [*Baron et al*., 2000; *Wolfe et al*., 2003].

Both the deposition of N and the concentration of N, particularly as ammonium, in wet precipitation have increased at two high elevation National Atmospheric Deposition Program (NADP) monitoring sites, Loch Vale and Niwot Ridge, over the past two decades [*Burns*, 2003; *NADP*, 2003]. Deposition has not increased at three other NADP sites in the Basin since the early 1980s, but neither has it decreased [*Burns*, 2003; *NADP*, 2003]. N concentrations at the high elevation monitoring sites were greatest during spring and summer months when there were upslope winds from the east [*Baron and Denning*, 1993]. While cause and effect relations cannot be drawn, the shift from an agriculturally-dominated N emissions to urban-dominated N emissions in the middle of the last century resulted in large increases of N within the South Platte Basin. Emissions are still increasing in most counties, as evidenced by comparison between emissions in 1985 and 1995.

Nitrogen emissions are very much a product of land use. Globally, the need to feed and provide energy for a growing world human population is driving the trend toward increasing fixed N emissions from intensively-farmed land and from combustion of fossil fuels to the atmosphere [*Mosier et al.*, 2002]. This can be seen regionally, as our study reported here, as well as in other parts of the world. In a compilation of total N budgets for 16 watersheds of the northeastern U.S.A., Boyer et al. [2002] found land use was a major determinant of the amount and sources of N cycling within each watershed. They and others [*Caraco and Cole*, 1999] found that while nitrogen inputs to rivers were strongly related to percent of catchment in agricultural land, catchments that were highly urbanized had even greater N inputs.

Urban and agricultural areas are loci for nitrogen-fixing activities: emissions from construction vehicles and other heavy machinery, automobile emissions, energy generation for heating and cooling, volatilization of fertilizers and manure from fields and feedlots. The myriad ways in which atmospheric N can be fixed become more abundant as population density increases and agricultural practices intensify. In the South Platte counties described here, similar patterns emerge: mountain counties with low population density and little agricultural activities had the lowest N emissions overall. High population (Denver, Arapahoe), intensive agricultural (Weld), and industrial (Adams) counties had the highest emissions overall. The ecosystem responses of alpine systems to N deposition are therefore very much a result, albeit an indirect one, of land use change.

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