Ammonia Emissions and Fertilizer Applications in California's Central Valley

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ABSTRACT

Ammonia is the dominant gaseous base in the atmosphere and a principal neutralizing agent for atmospheric acids. NH_3 and alkaline soil dust in the atmosphere may control the acidity of precipitation. Volatilized NH_3 may react to form ammonium nitrate or ammonium sulfate and thereby contribute to airborne particulate matter ($PM_{2.5}$). NH_3 remains one of the most poorly characterized atmospheric trace compounds as a result of several factors such as: experimental difficulties associated with NH_3 measurements, rapid gas-to-particle conversion of NH_3 in the atmosphere, capacity of soils, organic matter, and vegetation to act as both sources and sinks for atmospheric NH_3, and variability in nitrogen fertilizer management and related NH_3 emissions.

The objective of this study was to determine atmospheric ammonia emissions in the Central Valley of California related to applications of various nitrogen fertilizers. Identification of fertilizer sources depended on estimating NH_3 emissions as the fraction of the applied fertilizer nitrogen lost from the soil as NH_3 to the ambient atmosphere. An active denuder sampling methodology was selected because it represented an established procedure in air quality studies and it satisfied the requirement for continuous sampling. Denuders and anemometers were co-located at 1, 2, 5, 10 and 18 meters above the soil surface on a portable tower. Nineteen sites were sampled and complete data sets are available for fourteen of those. At each site for which data are available an increase in atmospheric NH_3 was measured compared to the levels sampled both before and after the fertilizer application. The NH_3 emissions from the sampled sites ranged from 0.1 to 0.7 g N- NH_3 m^{-2}. The estimated emission factor values range from 0.1% to 6.6% with the average at about 3.2%. It appears the sites with low emission factors were those where fertilizer was applied in a manner that placed the fertilizer material several cm below the soil surface. Soil pH below about 7.4 was also correlated with low emission percentages.

The field data from the fourteen sites was used at the NASA Ames Research Center, Moffett Field, CA to produce a state-wide database of NH_3 emissions related to crop fertilization. The emission factors were correlated with crop acreage, soil data and fertilizer application information to model NH_3 emissions from the various agricultural regions of California. The total, annual emission of NH_3 from fertilizer applications was estimated as 12 X 10^6 kg NH_3 from all agricultural fertilizer applications. The average emission factor for fertilizer applications statewide was calculated to be 2.38%.

INTRODUCTION

Ammonia is the dominant gaseous base in the atmosphere and a principal neutralizing agent for atmospheric acids. The NH3 in the atmosphere, along with alkaline soil dust, may control the acidity of precipitation. Volatilized NH3 may react to form ammonium nitrate or ammonium sulfate and thereby contribute to airborne particulate matter (PM). National standards in the United States for PM apply to the mass concentrations of particles with aerodynamic diameters less than 2.5 microns ($PM_{2.5}$) and less than 10 microns (PM_{10}). Estimated patterns of nitrogen deposition suggest that, for California locations close to photochemical smog source areas, concentrations of oxidized forms of N dominate, while in areas near agricultural activities the importance of reduced N forms may increase significantly according to Bytnerowicz and Fenn[1].

NH_3 remains one of the most poorly characterized atmospheric trace compounds in terms of overall sources. This situation persists as a result of several factors such as; experimental difficulties associated with NH_3 measurements, rapid gas-to-particle conversion of NH_3 in the atmosphere, the capacity of soils, organic matter, vegetation to act as both sources and sinks for atmospheric NH_3, and variability in nitrogen fertilizer management and related NH_3 emissions (Langford et al.[2]). Consequently, there is a limited amount of published information from which to develop direct emissions estimates of NH_3 for the state of California in general, and the state's Central Valley in particular. Preliminary measurements of NH_3 background concentrations in the San Joaquin Valley by Fitz et al.[3] estimated February levels of 3-16 $\mu g\ m^{-3}$ near alfalfa fields. The magnitude and distribution (both regionally and seasonally) of current NH_3 emissions from fertilizer and other agricultural sources is still largely undetermined for the state of California and many other large regions where agriculture is a major land use (Matthews[4]).

The main objective of this study was to measure and characterize rates of ammonia emissions related to applications of N fertilizer to commercial fields in the Central Valley of California. Identification of fertilizer sources requires an estimation of NH_3 emissions in terms of the percentage of the applied fertilizer nitrogen lost as NH_3 to the ambient atmosphere. Estimations of emission factors for NH_3 related to commonly practiced fertilizer application methods in California's Central Valley combined with estimates of annual fertilizer applications could be used to produce a new statewide inventory from the NH_3 volatilization fluxes measured in this field study. This inventory information will ultimately assist the state in evaluating the important, but sometimes conflicting needs of maintaining both good air quality and a vital California agricultural industry.

Field Sampling

The field sampling methods were designed to measure the magnitude of volatile NH_3 loss and its duration as a result of an actual commercial fertilizer application. The percentage loss for a specific N application would be influenced by several factors that could be identified in a statewide database. These factors were developed into a matrix from which representative combinations could be selected to monitor in the field. The first factor identified was crop type. The statewide database for this study utilized county-based crop maps from the California Department of Water Resources (DWR[5]). This database included ten crop types with several sub-divisions in each type. The second factor was soil. A simple separation of the state soils into four categories based on %clay was used for the initial database development. The most subjective selections for the sampling matrix were the fertilizer forms and application methods. Six combinations of a basic fertilizer material and application method were chosen as common to many of the crops and soils for the completion of the sampling matrix. The ten crops, four soils and six fertilizers resulted in a matrix of 240 cells. The sampling period for this study was the calendar year 2000. Therefore, it was planned to sample 15 - 20 representative applications during that time period. Sites were selected based on matching the matrix, site accessibility, and available personnel in that order of priority. The sites were sampled from December, 1999 to December, 2000 and are shown in Table 1. Fertilizer types and application amounts are shown in Table 2, and soil conditions at the point of fertilizer application are in Table 3.

Once the sampling matrix had been determined, the next step was to develop and evaluate a field sampling procedure that would characterize the emission factor for each site in a manner suitable for the needs of the statewide database. The magnitude and duration of the volatile losses must be measured to establish an emission factor. Duration could be characterized as long as a continuous sampling method was used. The initial plan was to sample for two days prior to an application to determine background levels. Sampling would proceed through the application of the fertilizer and continue for five days afterward to monitor the expected spike of atmospheric NH_3 from the application. This sampling schedule was used through the year and proved to be adequate to establish the duration of the NH_3 emission.

The sampling device selected for the project was an active denuder. It represented an established method in air quality studies and it satisfied the inventory development requirement for continuous sampling of emissions over relatively long time periods and large plot areas. The denuder is a medium through which an air stream is passed in a manner similar to a filter for particulates. In the case of NH_3 it is a fibrous material, usually glass, treated with a substance (citric acid) that will react with NH_3 to form a solid. The denuder is usually an active sampler utilizing a pump to pull a known flow of air through a disk of the treated material in a filter holder located at the point of measurement. Passive denuders, using wind to move air through the medium, were tested along with the active units at three of the sampling sites but only data from the active denuders was used to develop the emissions inventory.

For this study, a 47 mm disk of glass fiber filter paper was treated with citric acid (5% in 95% ethanol) and dried. A commercially available, 12 volt air sampling pump with a flow regulator was used to pull air through the denuder disk at a rate of about four liters per minute. Air flow was monitored by a rotameter accurate to 0.1 liters/minute and the flow was recorded at the beginning and end of each sampling period. Previous work suggested differences in day and night levels of NH_3 in the air, so the sampling was diurnal with the denuders changed at dawn and dusk. Samples were refrigerated and taken to the Graduate Laboratory of the CSU-Fresno, College of Agricultural Science and Technology for analysis. The NH_4-citrate was extracted from the denuder with distilled water and analyzed with a spectrophotometer. The amount of ammonia on the denuder disk was reported in $\mu g\ NH_3$. The concentration of NH_3 in the air at the sampling point could be determined by dividing the amount of ammonia on the disk by the volume (m^3) of air pumped through the denuder in the sampling period to derive the concentration in units of $\mu g\ N\text{-}NH_3\ m^{-3}$ air at the sampling point.

The concentration of NH_3 at a particular sampling point is not sufficient to determine the emission factor for a particular field site. The amount of NH_3 in the atmosphere depends not only on the concentration but also the flow of air at the sampling point. The value necessary to characterize the sampling point was the flux in $\mu g\ N\text{-}NH_3\ m^{-2}\ s^{-1}$. The initial assumption during the planning of the project was to monitor ammonia flux at several elevations above the field surface to characterize the gradient between the soil surface and the ambient atmosphere. Denuders and anemometers were co-located at 1, 2, 5, 10 and 18 meters above the soil surface

Initially, it was assumed that a positive NH_3 flux gradient from the soil surface, decreasing as the elevation increased would be found and could be used to determine the magnitude of the emission factor for the sampling period. Prior to the fertilizer application, it was suspected that negative gradients, with higher flux rates in the atmosphere, decreasing at elevations closer to the soil surface, might be found due to ammonia absorption by foliage and/or a moist soil surface. The stomata and internal structure of the leaf that functions to absorb CO_2 from the air should also effectively absorb NH_3 from the atmosphere near the foliage. Alternatively, the sampling at a site might well exhibit what appears to be a negative gradient, as NH_3 in air from nearby point sources (such as livestock or other fertilizer applications) moves over the field and is sampled. The actual results varied somewhat from the initial assumption in that the gradient of NH_3 was almost always from the ambient atmosphere to the soil/vegetation surface over the elevation range that was sampled. The magnitude of the NH_3 fluxes increased following the fertilizer application but the gradient almost always remained negative.

Field Sampling Results

Measurement results confirm that field sampling by the micrometeorological mass balance method can detect volatile NH_3 from an application of N fertilizer. In each of the applications for which data is available; an increased level of atmospheric NH_3 was measured compared to the levels sampled both before and after the application. The expected positive gradient of NH_3 fluxes from the surface toward the ambient atmosphere was apparent at only one of the sites, the pasture fertilized with effluent from a dairy shown in Figure 1. The traditional fertilizer applications at the other sites exhibited the increase in NH_3 flux that indicated a positive emission factor but the gradient of the fluxes remained lower at the soil/vegetation surface as shown in Figures 2 and 3. The line in Figures

1, 2 and 3 labeled "Application" is the average of 2 to 5 sampling periods during which the N application was actually occurring. The lines labeled "Pre-application" and "Post-application" were the averages of 2 to 10 samples taken prior to and after the application. The "Application" values were greater than those before and after in each of the sites analyzed. This is the basis for the conclusion that the methodology can detect volatile NH_3 resulting from a fertilizer application.

Standard mass balance micrometeorological techniques (Denmead[6]) were used to estimate the integrated NH_3 flux by combining measurements of wind speed and NH_3 air sample concentrations from height-dependent sampling locations mounted on the portable mast.

The surface flux density of a gas can be calculated according to equation 1.

Equation (1) $F = {}_0{}^{z} U \ (\rho_g - \rho_b) \quad z$

where

F = the surface flux density of a gas

$U(z)$ = the horizontal wind speed at sampling height z

ρ_g = the atmospheric gas concentration at the height of the sampler

ρ_b = the background atmospheric gas concentration from upwind of the field plot

Previous field tests (Leuning et al.[7]) suggest that this equation tends to overestimate true fluxes due to turbulent diffusive flow in the opposite (upwind) direction. Therefore, following the recommendation from Denmead[8], emissions calculated from this equation were reduced by 15%.

To describe the NH_3 emission resulting from the fertilizer application, integration calculations were made using a fourth-order polynomial fit to the height-dependent horizontal flux points for each sampling period. Integration under the time series curves and adjustment for fetch distance were made to determine the total N-NH_3 emitted as vertical fluxes over the entire time period sampled, beginning at the time of the first fertilizer application. To compute the site emission factor, the total N- NH_3 emitted was divided into the total kg N applied m^{-2} area for that site sampling period.

One assumption worth noting for the calculations of NH_3 vertical fluxes is that, for sampling from the middle of a typical commercial field plot, any samples collected from greater than 10 m probably do not provide any reliable information on soil surface emission of gases. It is generally assumed that there are too many other possible sources of contamination from upwind background air at such heights. Therefore, we adopted the general guideline that the ‘effective fetch’ is equal to about ten times the highest sampling point (Denmead[6]), an assumption which establishes the effective fetch (over a circular plot footprint) for these vertical flux calculations (1 m - 10 m samples) at a consistent value of 100 m. Under this assumption, the samples taken at the 18 m height were used to determine upwind background fluxes of NH_3 for our sites.

Emission flux totals of NH_3 for all fertilized sites analyzed to date show a notable consistency of emission factor estimates among the different crop types and fertilizer amounts applied as shown in Table 4. While total NH_3 nitrogen losses ranged from 0.01 to 0.7 g N- NH_3 m^{-2}, the estimated emission factor values for the sites analyzed range from 0.05% to 6.6% with the average at about 3.2%. It appears the sites that produced lower emission factor estimates were primarily those sites where fertilizer was applied in a manner that placed the fertilizer material below the soil surface. Data collected from sites A, C and P was incomplete due to equipment problems, site N did not include a fertilizer application and site O was the dairy lagoon that supplied effluent to site L. Those sites were not included in Table 4.

Although few comparable measurements exist for crop emission sources of NH_3 flux at locations outside of California, we found the range of total NH_3 losses listed in Table 4 to be similar to the total NH_3 losses (0.32 g N m^{-2}) reported by Ryden and McNeill[9] for a period of several days in grazed ryegrass sward at the Grassland Research Institute, Hurley, UK. The Site L pasture measurements also generated a total NH_3 loss estimate of 0.32 g N m^{-2} associated with organic fertilizer application. Both studies used the micrometeorological mass balance method for determination of ammonia loss to arrive a nearly identical emission estimates.

Statewide Ammonia Emission Estimates From Fertilized Crops

The emission factors estimated from the field data, shown in Table 4 were used with correlating data from several sources to build a database for an atmospheric model used at the Ames Research Center - NASA. This database included crop acreage and locations by counties, soil information, and fertilizer application amounts and methods. The crop acreage data was obtained from the California Department of Water Resources. Fertilizer applications were not available from any public source so data was estimated by questioning farmers, fertilizer industry members, county farm advisors and other crop specialists. The practices varied across the state, as expected but could be correlated with the county based crop acreage data. The database was used to estimate the application of the various types of N fertilizer to the crops of the state. These estimates, shown in Table 5, were checked by comparing them with the public records of fertilizer sales from the California Department of Food and Agriculture[10]. Though county by county comparisons did not correlate well, the estimates for the regions of the state, the Central Valley, Imperial Valley and Central Coast, were within 10% of the recorded fertilizer sales. The poor correlation on a county by county basis was explained, by members of the fertilizer industry; as sales recorded at a regional outlet in one county and actually used on crops in several other, nearby counties. The recorded sales also included commercial landscape and other, non-agricultural uses of fertilizer that were not included in the estimated fertilizer applications calculated from the DWR crop data. The fact that the recorded sales are greater than the estimated applications is due, at least in part, to these other fertilizer sales.

The estimated fertilizer applications over the state were then matched with ammonia emission factors from the most similar site monitored during the field study. The soil pH and textural data from the Natural Resources Conservation Service was used along with the rest of the database in a rule-based atmospheric model at the Ames Research Center - NASA to estimate the distribution of ammonia emission across the state from fertilizer applications to agricultural land. The rule-based model was used to assign NH_3 emission factors, together with the county level fertilizer application rates (Table 5) to create the statewide inventory estimate for emissions of NH_3 directly from fertilizer applications shown in Table 6. The total of these emissions is estimated to be 11.7×10^6 kg N- NH_3 annually. The leading counties for annual emissions of NH_3 directly from fertilizer sources are Imperial, Fresno, Kern, Tulare, and Kings. Overall, the San Joaquin Valley area accounts for more than one-half of the state’s total annual emissions of NH_3 directly from fertilizer sources. The Imperial Valley accounts for a higher proportion of the state’s total annual emissions of NH_3 from fertilizer sources than would be predicted from crop area alone, primarily due to the high proportion of soils with pH above 8 and a major portion of the total fertilizer applied to the soil surface.

As a follow-on to this study, fertilizer application schedules can be added to the inventory analysis to generate daily NH_3 emissions directly from chemical fertilizer applications, with timing throughout the year on a county-by-county, crop-by-crop scheduling basis. We anticipate from initial analyses that the highest NH_3 emission rates directly from fertilizer applications would be predicted during periods between February and September. However, as improved information becomes available for timing and amounts of fertilizer application rates in DWR crop types and the geographic distribution of fertilizer application methods, a refined model for daily NH_3 emissions from fertilizer applications can be generated.

SUMMARY AND CONCLUSIONS

Emission flux totals of NH_3 for fertilized sites in California's Central Valley shows consistency of emissions factor estimates, regardless of the crop types and fertilizer amounts. Total measured NH_3 losses for the fertilizer applications ranged from less than 0.1 to 0.7 g N-NH_3 m^{-2} (equal to 0.9 to 6.2 lbs. N-NH_3 emitted per acre). The estimated NH_3 emission factor values for the field sites analyzed to date range from 0.05% to 6.6% of total applied N fertilizer with an average at about 3.2% of applied nitrogen.

Field flux measurements imply that the single most important factor affecting the NH_3 emission rates from cropped sources in the Central Valley is the amount of chemical fertilizer applied. Field flux measurements suggest that other significant limiting factors of NH_3 emission rates from fertilizers include soil pH and the method of N fertilizer application. When the fertilizer ammonia emission factors developed through this research are used to calculate statewide ammonia emissions for fertilizer application, the average fertilizer NH_3 emission factor for California is 2.4% of the total applied N fertilizer.

Statewide emissions of NH_3 directly from chemical fertilizer applications are computed to total nearly 12×10^6 kg N- NH_3 annually. The San Joaquin Valley accounts for just over one-half of the state's total annual emissions of NH_3 directly from agricultural application of fertilizers. On the basis of DWR crop types, it appears that the generalized categories of field crops and truck crops each account for about one-third of the state's total annual emissions of NH_3 directly from chemical fertilizer sources. Grain, pasture grass, and rice crop categories also contribute large fractions of the state's total annual emissions of NH_3 directly from chemical fertilizer sources.

Additional sampling of NH_3 emissions in cropped systems should be carried out with experimental manipulations on the primary emission regulators (method of fertilizer application and soil pH) to determine the importance of soil texture, temperature, and moisture management on NH_3 emission factors.

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KEYWORD

ammonia volatilization
nitrogen fertilizers
cropland soils
GIS
California

Table 1. Field sampling site locations for the ammonia emissions from fertilizer applications.

Site	Crop	Latitude N deg.	Latitude min.	Longitude W deg.	Longitude min.	General Location
A	Almond	36	55.594	120	13.955	15 m West of Madera
B	Almond	36	56.693	120	15.697	16 m West of Madera
C	Almond	36	49.341	119	44.078	CSUF Farm
D	Citrus	36	46.708	119	33.217	5 m North of Sanger
E	Almond	36	47.039	119	33.656	7 m North of Sanger
F	Onions	36	23.820	120	7.320	3 m South of Five Points
G	Tomato	36	23.818	120	6.255	3 m SW of Five Points
H	Garlic	36	23.169	120	6.506	4 m SW of Five Points
I	Cotton	36	24.471	120	7.437	2 m SW of Five Points
J	Cotton	36	26.416	120	7.284	4 m West of Five Points
K	Almond	36	49.263	119	43.528	CSUF Farm
L	Pasture	36	48.874	119	44.241	CSUF Farm
M	Broccoli	36	40.971	120	29.491	8 m SW of Mendota
N	Cotton	36	13.599	119	56.942	5 m South of Lemoore NAS
O	Lagoon					CSUF Farm
P	Broccoli	36	40.971	120	29.491	8 m SW of Mendota
Q	Lettuce	36	22.301	120	7.791	3 m SW of Five Points
R	Cotton	36	22.712	120	9.378	4 m SW of Five Points
S	Tomato	36	24.073	120	7.216	2 m South of Five Points

Table 2. Fertilizer applications at field sampling sites for the ammonia emissions.

Site	Crop	Fertilizer	N applied lb./Ac	Application Method	Application Point Depth (cm)
A	Almond	UAN-32	100	surface band, watered in	Surface
B	Almond	$(NH_4)_2SO_4$	100	surface band, watered in	Surface
C	Almond	Urea liquid	15	foliar with bloom spray	Foliar
D	Citrus	NH_4NO_3	50	Broadcast - rained in	Surface
E	Almond	UAN-32	100	Water Run-buried drip	50
F	Onions	UAN-32	40	Water Run-sprinkler	Water-run
G	Tomato	UAN-32	100	Side dressed	10
H	Garlic	UAN-32	50	Water Run-furrow	Water-run
I	Cotton	NH_3	100	Injected, 15cm shank	15
J	Cotton	NH_3	100	Injected, 15cm shank	15
K	Almond	21%N liquid	9	Water Run-microspray	Water-run
L	Pasture	effluent	100	Flood	Water-run
M	Broccoli	NH_4NO_3	60	Surface for weed control	Foliar
N	Cotton	defoliant	0	Aerial Spray	Surface
O	Lagoon	effluent	NA	Ponded	Water-run
P	Broccoli	UAN-32	75	Water Run-buried drip	15
Q	Lettuce	UAN-32	60	Water Run-furrow	Water-run
R	Cotton	NH_3	80	Injected, 15cm shank	15
S	Tomato	NH_3	100	Injected, 10cm shank	10

Notes: Depth at application point refers to the placement of the fertilizer by the application method. Surface indicates fertilizer applied to soil surface, Water-run indicates fertilizer applied in irrigation water. Foliar indicates direct application to vegetation

Table 3. Soil conditions at field sampling sites for the ammonia emissions.

Site	Crop	Soil Name	Soil pH	Clay Content.	Moisture Content
A	Almond	Grangeville f sandy loam	6.7	9%	high
B	Almond	Fresno/ElPeco loam (sl alk)	8.1	9%	high
C	Almond	Hanford sandy loam	6.4	9%	high
D	Citrus	Atwater sandy loam	6.1	4%	low
E	Almond	San Joaquin loam (shallow)	6.4	15%	high
F	Onions	Panoche clay loam (sl alk)	8.5	23%	high
G	Tomato	Panoche clay loam	7.9	23%	medium
H	Garlic	Panoche clay loam	7.9	23%	high
I	Cotton	Oxalis silty clay (sl alk)	8.5	30%	medium
J	Cotton	Lethent silty clay (mod alk)	7.8	30%	medium
K	Almond	Delhi loamy sand	6.4	4%	high
L	Pasture	Hanford sandy loam	6.6	9%	high
M	Broccoli	Panoche loam	7.9	18%	low
N	Cotton	Panoche clay loam (sal alk)	8.5	23%	NA
O	Lagoon	Greenfield sandy loam	6.6	9%	high
P	Broccoli	Panoche loam	7.9	18%	high
Q	Lettuce	Oxalis silty clay (sl alk)	7.8	30%	high
R	Cotton	Panoche clay loam	7.9	23%	medium
S	Tomato	Panoche silty clay (mod alk)	8.5	32%	medium

Notes: Soil pH refers to the soil pH at the depth of fertilizer placement. Soil pH may be different at other depths. Percent of soil particles smaller than 0.005 mm is used to classify the clay fraction of soil texture. Moisture content is a relative evaluation of the soil moisture content at the point and time of fertilizer application: ‘High’ is approximately Field Capacity, ‘Low’ would be near or below the irrigation point.

Figure 1. Ammonia flux profiles for dairy lagoon effluent applied to irrigated, sheep pasture on the CSU Fresno farm-laboratory June, 2000 (site L).

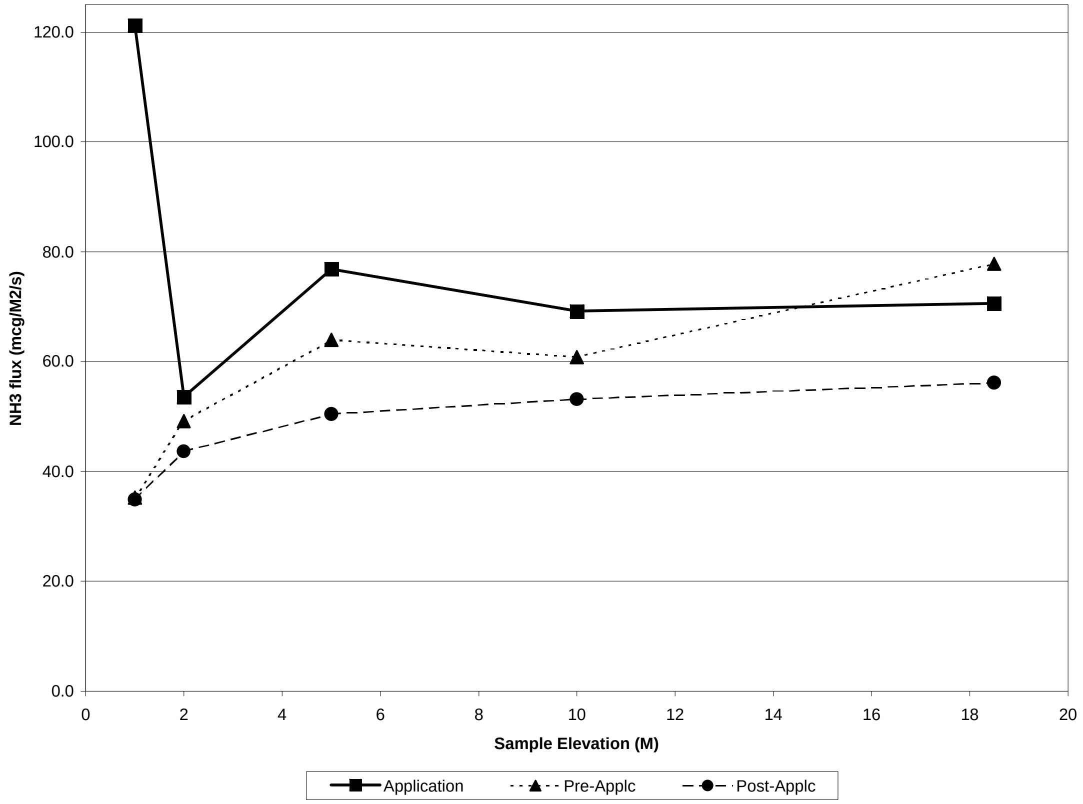

Figure 2. Ammonia flux profiles for NH_4NO_3 broadcast on the soil surface of an orange grove near Sanger, California, February, 2000 (Site D).

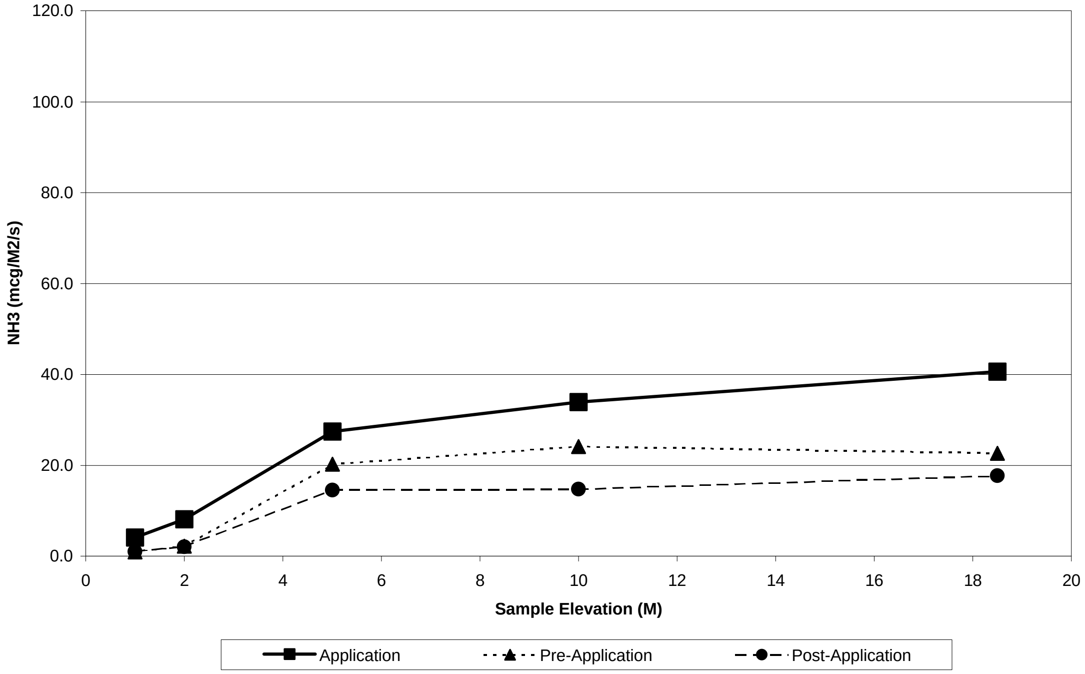

Figure 3. Ammonia flux profiles for NH_3 injected 15cm below the soil surface of a cotton field near Five Points California, April, 2000 (Site I).

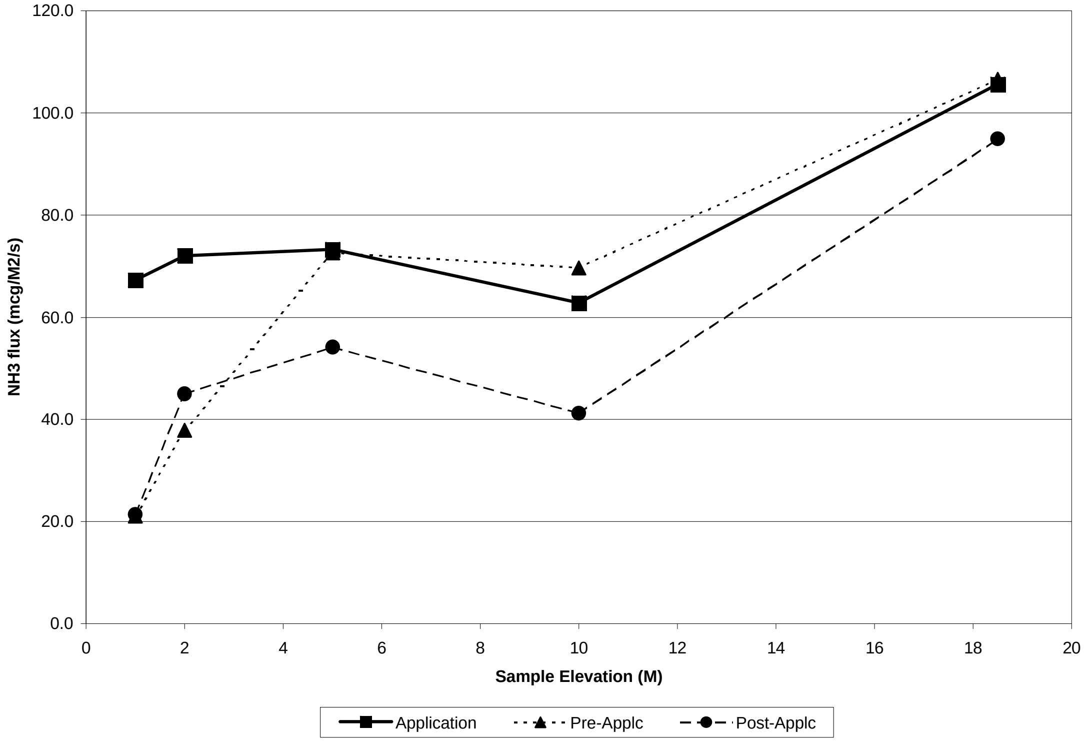

Table 4. Summary of field sampling sites with fertilizer, irrigation and emission factor estimates.

SITE	CROP	N lb/Ac	g N m^{-2}	Fertilizer Type	Irrigation Type	Soil pH	Emission g NH_3 m^{-2}	Emission Factor
B	Almonds	100	10.9	C	G	8.1	0.72	6.6%
D	Citrus	50	5.5	C	G	6.1	0.24	4.3%
E	Almonds	100	10.9	D	M	6.4	0.51	4.7%
F	Onion	40	4.4	D	S	8.4	0.28	6.5%
G	Tomato	100	10.9	D	G	7.9	0.10	0.9%
H	Garlic	50	5.5	D	G	7.9	0.32	5.8%
I	Cotton	100	10.9	A	G	8.5	0.62	5.6%
J	Cotton	100	10.9	A	G	7.8	0.43	3.9%
K	Almonds	9	1.0	A	M	6.4	0.00	0.0%
L	Pasture	100	10.9	F	G	6.6	0.32	2.9%
M	Broccoli	60	6.5	C	S	7.9	0.10	1.6%
Q	Lettuce	40	4.4	D	G	7.8	0.02	0.5%
R	Tomato	80	8.7	A	G	7.9	0.01	0.1%
S	Cotton	100	10.9	A	G	8.5	0.14	1.3%
							Ave. Emission Factor	3.2%

Fertilizer Type Codes
A = anhydrous NH_3 or Urea-Ammonium Nitrate below the soil surface at 10-20 cm depth
C = dry Ammonium Nitrate/Sulfate applied to soil followed by irrigation
D = Urea-Ammonium Nitrate (UAN) liquid mixed into irrigation water
F = dairy lagoon effluent mixed in irrigation water

Irrigation Type Codes
G = gravity, surface/flood
S = sprinkler
M = microsprayer/drip

Table 5. Estimated Fertilizer N Used in Counties of California.

	DWR area total (hectares)	Metric Tons Nitrogen		% Difference
San Joaquin Valley		County Sales (CDFA, 1999)	Estimate from DWR Crop Maps	
San Joaquin	232,531	77,701	25,360	67
Stanislaus	158,549	16,169	15,233	6
Madera	145,660	4,540	10,835	-139
Merced	226,158	17,008	22,782	-34
Fresno	538,163	47,546	60,625	-28
Kern	398,140	41,296	41,108	0
King	236,465	22,983	26,420	-15
Tulare	307,772	20,144	31,877	-58
TOTAL	**2,243,437**	**247,386**	**234,240**	**5**
Sacramento Valley				
Butte	106,658	19,496	15,942	18
Colusa	130,851	21,577	21,482	0
Glenn	111,747	12,420	15,636	-26
Sacramento	80,029	24,078	8,422	65
Solano	83,183	7,764	9,118	-17
Sutter	119,301	23,580	18,436	22
Yolo	147,605	14,126	18,515	-31
TOTAL	**779,373**	**123,039**	**107,551**	**13**
Central Coast				
Monterey	107,251	13,171	13,468	-2
San Luis Obispo and Santa Barbara	125,976	13,270	14,125	-6
TOTAL	**233,227**	**26,440**	**27,592**	**-4**
Imperial Valley				
Riverside and San Bernadino	54,482	14,516	9,086	37
Imperial	211,559	51,220	44,088	14
TOTAL	**266,041**	**65,735**	**53,173**	**19**
STATE TOTAL	**3,522,079**	**462,601**	**422,556**	**9**

Table 6. Estimated NH_3-N emission directly from chemical fertilizer application in counties of California.

	DWR area total (ha)	NH_3-N Emission 10^6 kg	Ave. NH_3 Emission Factor
San Joaquin Valley			
San Joaquin	232,531	0.66	2.41%
Stanislaus	158,549	0.40	2.38%
Madera	145,660	0.27	2.30%
Merced	226,158	0.65	2.64%
Fresno	538,163	1.46	2.47%
Kern	398,140	1.14	2.71%
Kings	236,465	0.74	3.06%
Tulare	307,772	0.78	2.35%
TOTAL	**2,243,437**	**6.11**	**2.54%**
Sacramento Valley			
Butte	106,658	0.41	2.26%
Colusa	130,851	0.61	2.58%
Glenn	111,747	0.42	2.30%
Sacramento	80,029	0.22	2.34%
Solano	83,183	0.26	2.40%
Sutter	119,301	0.55	2.74%
Yolo	147,605	0.49	2.43%
TOTAL	**779,373**	**2.96**	**2.43%**
Central Coast			
Monterey	107,251	0.28	1.57%
San Luis Obispo and Santa Barbara	125,976	0.34	1.45%
TOTAL	**233,227**	**0.61**	**1.51%**
Imperial Valley			
Riverside and San Bernadino	54,482	0.31	2.33%
Imperial	211,559	1.70	2.53%
TOTAL	**266,041**	**2.01**	**2.43%**
STATE TOTAL	**3,522,079**	**11.7**	**2.38%**