

Development of a Gridded Ammonia Emission Inventory for the San Joaquin Valley of California

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ABSTRACT

In support of the California Regional PM₁₀/PM_{2.5} Air Quality Study (CRPAQS) a team of contractors consisting of ENVIRON International Corporation (ENVIRON) and E.H. Pechan & Associates, Inc. (Pechan) is developing a state-of-the-science ammonia emission inventory for the San Joaquin Valley (SJV). The primary goal of the project is to develop a draft, ground-level, gridded ammonia emission inventory for use in data analysis and grid-based aerosol modeling for the CRPAQS. The ammonia inventory has 1-hour temporal resolution and 1-kilometer spatial resolution. The inventory uses the best available ammonia emissions information for the study domain, including several ongoing studies in California. Improvements to the characterization of important ammonia source categories in the SJV have been accomplished through incorporation of information from these and other new studies. In particular, significant improvements will be made in temporal and spatial allocation of emissions for livestock operations, biomass burning, and on-road mobile sources. Ammonia emissions for fertilizer application and natural soil/plant canopy systems are estimated using an emission model developed by researchers at NASA Ames Research Center and the California State University for the California Air Resources Board.

A secondary goal of the project is the development of an ammonia-capable geographic information system (GIS) based emission modeling system. Emission estimates for many ammonia source categories are intimately linked to land use/land cover (LULC) characteristics and environmental variables. Hence, a modeling system which combines the GIS data on LULC distributions with LULC-specific emission factors and activity indicators can calculate gridded emissions in a single processing step and is ideally suited to development within a GIS framework. A GIS-based emission model was developed to provide an accurate and efficient tool for inventory processing, particularly the spatial allocation and gridding of the emission inventory. The emission model uses Arc/INFO GIS software and Access databases and makes use of local, high resolution LULC data for the development of gridding surrogates. The user-friendly, menu-driven graphical user interface (GUI) facilitates efficient inventory generation, revisions and future updates with minimal processing effort and resources.

INTRODUCTION

The California Regional PM₁₀/PM_{2.5} Air Quality Study (CRPAQS) is a multi-year program to study particulate matter (PM) air pollution in Central California and includes

meteorological and air quality monitoring, emissions inventory development, data analysis, and air quality modeling. The primary objectives of the study are to:

- Provide an improved understanding of emissions and atmospheric processes that influence particle formation and transport;
- Develop methods useful to planning agencies in formulating and assessing candidate control strategies for attaining the federal and state PM standards in Central California; and
- Provide reliable tools for estimating the impacts of control strategies for PM on visibility, air toxics, and acidic aerosols and on attainment strategies for other pollutants, specifically ozone.

The primary goal of the current project is to develop a draft, ground-level, gridded ammonia emission inventory for use in data analysis and grid-based aerosol modeling for the CRPAQS. The ammonia inventory is developed at a spatial resolution of 1-km by 1-km with a temporal resolution of 1-hour using the best available emission source data and processing methodologies. The geographic extent of the gridded inventory covers the San Joaquin Valley (SJV) study area, although where available, data were collected for the entire state of California. In addition, a standard input data library and processing procedures were developed to facilitate future refinements or revisions in a programmatic way.

A secondary goal of the study is the development of an ammonia capable GIS-based emission modeling system. Since for many ammonia emission source categories, emission estimates are intimately linked to land cover/land use (LULC) characteristics, an emissions model which combines the GIS data on LULC distributions with LULC specific emission factors to calculate gridded emissions in a single processing step would be ideal. In addition, the increased efficiency with which the inventories are generated within the GIS-based emission model will facilitate future updates and revisions with minimal processing effort.

The CRPAQS ammonia emission model has been designed to handle new and emerging issues in ammonia emission inventory development, including:

- the relationship of ammonia emissions to environmental variables (e.g., temperature, relative humidity);
- the incorporation of highly-resolved spatial data (LU/LC databases, geo-coded point sources); and
- detailed source classification schemes for improved spatial/temporal resolution, control strategy assessment.

METHODS AND DATA SOURCES

Calendar year 2000 emission estimates have been prepared for the CRPAQS domain (see Figure 1). The eight county SJV portion of the CRPAQS domain is an agriculturally-intensive area which includes:

- Over 2.2 million dairy cattle;
- About 650,000 beef cattle;

- Over 26 million broiler chickens;
- Other Confined Animal Operations (CAOs) - hogs, horses, goats; and
- Over 5.3 million acres of crop land.

The results of a previous ammonia inventory of the CRPAQS domain showed that livestock were responsible for about 44% of the annual ammonia emissions (STI, 1998)¹. Excluding emissions from natural soils (42% of annual emissions); livestock operations contributed about 76% of the annual total. Confined animal operations (CAOs), particularly dairies, contribute the bulk of the livestock operations emissions in the SJV. Hence, an effort was made to characterize emissions from this source sector to the greatest degree possible. A focus of this paper is in describing this work. Additional inventory work is summarized briefly.

Methods and Data Sources for Important Non-Livestock Source Sectors.

Brief descriptions of methods and data sources for the largest source sectors are provided below:

- *On-Road Mobile Sources* – gridded VMT data developed for the Central California Ozone Study (CCOS) were used along with a fleet-based ammonia emission factor derived from recent tunnel studies in California;
- *Fertilizer Application* – emission estimates from fertilizer application obtained using the CAL/CASA model developed by researchers at NASA Ames Research Center and the California State University (Potter et al., 2001)² were incorporated into the CRPAQS inventory;
- *Natural Soils* – emission estimates for natural soils were also obtained from the CAL/CASA model;
- *Municipal Solid Waste Landfills* – due to a lack of any U.S. ammonia emissions data for landfills, emissions were estimated using the same methods as in the previous inventory (STI, 1998). This involved the use of an ammonia to methane emissions ratio (0.007). Methane emissions were taken from the year 2000 emissions data submitted to the California Air Resources Board (CARB) by the local districts. Emissions were allocated to specific geo-coordinates of active landfills from the California Integrated Waste Management Board's Solid Waste Information System;
- *Prescribed Burns and Wildfires* – emissions are being estimated using an emissions ratio of ammonia to carbon monoxide (CO). CARB's year 2000 inventory is serving as the source of CO emissions data;
- *Agricultural Burns* – emissions are being estimated in a similar manner to prescribed burns and wildfires;
- *Residential Wood Combustion* – due to a lack of ammonia test data from this source sector, emissions are also being estimated using an ammonia to CO emissions ratio;
- *Industrial Sources* – ammonia emissions from industrial sources were obtained from the California Emission Inventory Data and Reporting System (CEIDARS) maintained by CARB; and
- *Sewage Treatment Plants* – emission and activity data for Publicly Owned Treatment Works (POTWs) were obtained from the California State Water Resources Control Board

(SWRCB) database. Facility locations were geo-coded and spatially allocated as point sources.

Methods and Data Sources for Livestock Operations

Emission factors for livestock are given in Table x1. In addressing the livestock categories, we recognize the importance of characterizing the livestock populations in confined operations. Confined operations produce much higher ammonia emissions than non-confined operations (i.e., grazing). This is mainly important for beef cattle. The primary data source for livestock populations is the U.S. Department of Agriculture's Census of Agriculture and associated publications (NASS, 2000³, 2001a⁴, 2001b⁵; CASS, 2000⁶; USDA, 2001⁷). These publications provide either state or county level population data for most livestock categories. County level data are often not included where data are considered confidential (e.g., disclosure would provide facility-specific data).

Improvements were needed in both spatial and temporal allocation of livestock emissions in the SJV counties. Therefore, we performed a survey of state and local agencies for information on herd-level populations. The results of this survey yielded:

- Geo-coded herd-level populations for 577 dairies in the 5 southern SJV counties;
- Geo-coded herd-level populations for 155 feedlots in Tulare and Imperial counties (estimated to contain over 75% of the >1000 head feedlot herd in California); and
- Geo-coded herd-level populations for 92 other CAOs (poultry, hogs, goats, and horses & ponies) in Tulare, Fresno, and Kings counties.

Figure 2 shows the locations of dairies and PM monitoring sites in the southern SJV. In the current inventory, we have attempted to incorporate a higher level of disaggregation of source categories. For example, the source categories used for beef and dairy cattle are shown in Table 2. This higher level of source resolution allows for: improved spatial allocation (e.g., geo-coding of point sources, allocation of manure spreading to specific crop land cover data); temporal allocation (e.g., month or season of manure spreading); emission estimation (e.g., use of more livestock-specific emission factors as they become available); and better control strategy analysis (e.g., control strategies tailored to the specific sources of interest).

We reviewed available test results and surveyed local agricultural experts to improve the temporal allocation of CAO emissions (both diurnal and seasonal). Unfortunately, we could not identify test data for dairies and feedlots of sufficient robustness to develop an algorithm for temporally allocating emissions using important environmental parameters (e.g., ambient temperature, relative humidity). Therefore, monthly temporal allocation factors were assigned to feedlots and dairies based on the seasonal differences found by Schmidt et al⁸ (1996) during their tests of southern California dairies (emissions during the winter months are approximately half of that during the months of other seasons). Diurnal temporal allocation for dairies and feedlots was assigned based on the dairy and feedlot testing of Flocchini et al⁹ (2001). This temporal allocation was also assigned to hog and pig operations. This testing showed an order of magnitude higher emission rate during the daytime hours (227 lb/hd-yr) compared to night-time hours (24 lb/hd-yr). Monthly allocation factors for hog and pig operations were assigned based

on test data from Aneja et al¹⁰ (2000). These data showed much higher emissions during the summer than the winter months and more moderate emission rates during the fall and spring. No temporal allocation factors were assigned to other livestock operations due to a lack of information.

Discussions with state and local agricultural experts and the California Agricultural Statistical Service (CASS; part of the USDA), revealed that large feedlots (>1000 head) are concentrated in just a handful of the state's counties. About three quarters of these are located in Imperial county (within the CRPAQS domain, but outside of the SJV). Information on herd level populations was obtained from the California Regional Water Quality Control Board. In previous efforts, the state-level feedlot cattle populations were generally distributed to counties based on county-level beef cattle populations. Hence, the new information resulted in significant changes in the distribution of feedlot cattle in the new CRPAQS inventory.

Information Leading to Changes in the Distribution of Range Cattle

Consultations with CASS staff gave us a better understanding of the distribution of range cattle for the CRPAQS inventory. One of the categories for beef cattle in California is referred to as stocker inshipments. These cattle are brought in from out of state during the months of November through May to graze on California rangelands. These rangelands are generally in the foothills of the state, and not in the valley or mountainous areas (and obviously, urban areas). A listing of counties was developed where stocker inshipments are grazed and the state-level estimate was allocated based on county-level range cows (a separate population).

DEVELOPMENT AND IMPLEMENTATION OF A GIS-BASED EMISSIONS MODEL

The development of ammonia emission inventories for several source categories is directly related to the underlying land use and land cover and is therefore ideally suited to a GIS-based application. The ammonia model developed for this study focuses on the San Joaquin Valley within the state of California although it is general enough to treat any region for which LULC and activity data are available. The resulting inventories are high resolution (1 kilometer) gridded and have hourly temporal resolution. Activity and emission factor data are based on the most recent literature and local survey efforts, as discussed above, and described in detail in ENVIRON (2001)¹¹. The model developed for this study, the California Gridded Ammonia Inventory Modeling System (CalGAIMS) is designed to be flexible, user friendly and easily updated with revised land cover data, activity data and emission factors.

The successful development and implementation of a comprehensive GIS-based ammonia emission inventory model application capable of the accurate and efficient spatial allocation of ammonia emissions sources depends on a number of factors, including the necessary or desired processing capabilities and resource requirements. However, any model application should provide certain key features including:

- Comprehensive treatment of applicable emission source categories
- Accurate spatial allocation
- Fast and efficient processing capabilities (CPU and memory)

- Intuitive and user-friendly interface
- Support for temporal allocation
- Variable spatial scales and resolution
- Flexible input data sources and formats
- Flexible output data formats
- Easy modification of input tabular data (including activity data, emission factors, and spatial surrogate relationships)
- Well designed data storage facility (e.g. current database technologies)
- Extensive quality assurance and quality control
- Modularity
- Expandable and scaleable
- Extensive visualization capabilities

A well designed system which can be easily enhanced and expanded upon as resources or processing requirements increase, was an important consideration in the model application design, as well as one of the goals of the study.

The model is based on the Arc/INFO GIS, linked with an Access Database and designed to take advantage of the benefits of a GIS to construct the required LULC- and population-based gridding surrogates. Accurate inventory development and spatial allocation is possible with a minimum of user interaction. For a given modeling grid, activity and emission factor data can be updated without the need for resource intensive re-calculation of gridding surrogates, allowing the generation of an updated inventory quickly with a minimum of effort. This technique is accomplished through the development of a number of inter-related tables which store the data and are managed within the Access database. These data tables include cross-reference relationships between emission source categories and land use characteristics, specification of relationships between source categories, activity data and emission factors with regional, or county boundaries, and relationships between source categories and temporal allocation profiles. Arc/INFO's ability to link spatial attributes directly with the data stored within the database tables increases the efficiency of the model application. The model is designed to be general and flexible enough to easily incorporate additional source categories, vary spatial allocation relations and to include various relationships between emission estimates, temporal allocation and environmental parameters, including soil characteristics and meteorological parameters, where available. Figure 3 displays a conceptual design flow-chart for the modeling system. Input and output data are represented by rectangular shapes while data processing steps are represented by elliptical shapes.

The model is designed with a user-friendly menu-driven graphical user interface (GUI), in order to minimize the need for a user to be an expert in GIS software applications. All required processing steps are developed as Arc/INFO scripts using the ARC Macro Language (AML) and controlled and implemented through user selections within the GUI. In addition, users have the option of performing the emission inventory calculations from within the GIS or the Access Database model. This allows the most resource intensive procedures, definition and development of LULC data, modeling grid development and computation of gridding surrogates, to be performed with the GIS at a preliminary inventory development stage, while the final estimation and temporal allocation of the gridded inventory can be performed quickly and

efficiently within either model. Emission sensitivity scenarios can be generated simply by altering emission factor and activity data through modification of tabulated data without the need to re-calculate LULC-based gridding surrogates. The various processing steps required for the development of an ammonia inventory include the preparation of LULC coverages, definition and creation of a gridded modeling domain, calculation of the gridding surrogates, and the final computation of emission estimates and their spatial and temporal allocation. Separate modules are available to allow display and visualization capabilities as well as QA/QC and reporting utilities. Figure 4 displays the main menu interface for the GIS model.

The required processing steps within the model are developed as separate modules to allow flexibility with respect to model application. This is particularly important since the most resource intensive and time consuming procedural steps involve the geospatial processing of land use and domain grid coverages which does not need to be repeated if the inventory is to be revised based on updated activity data and/or emission factors. In a similar way, the modeling grid can be modified without the need to reprocess LULC coverages since the modeling domain is essentially independent of the underlying LULC data. Another advantage of this approach is the ability to develop emission inventories using only the database component of the application, given the necessary GIS related geospatial data. The GIS model is applied to develop the required spatial surrogate data, which is then exported to the database model. Further processing and development of the inventory is then completed within the database, independent of the GIS.

Spatial Allocation Data and Surrogate Assignment

The spatial allocation of county-level ammonia emissions is accomplished with the aid of gridded spatial surrogate data for each emission source category or groups of source categories. Spatial surrogates are typically based on the proportion of a known region-wide characteristic variable which exists within the modeling domain grid cells (e.g. land use categories, population, socioeconomic data, etc.). The development of an accurate gridded ammonia emission inventory at a spatial resolution of 1-km by 1-km requires surrogate data at a comparable resolution. In addition, in the case of land use data, the ability to distinguish between various land cover characteristics is necessary to properly allocate the county-level emission estimates for certain source categories, particularly for fertilizer application and soil emissions. The development of the ammonia emission inventory for CRPAQS is based on LULC data from the USGS and the California Department of Water Resources. A detailed description of these data can be found in ENVIRON (2001).

USGS National Land Cover Data (NLCD)

The National Land Cover Data (NLCD) was developed as part of a cooperative project between the U.S. Geological Survey and the U.S. Environmental Protection Agency to produce a consistent land cover data layer for the entire conterminous U.S. based on 30-meter Landsat thematic mapper (TM) data. The NLCD was developed from TM data acquired from the Multi-Resolution Land Characterization (MRLC) Consortium, a partnership of federal agencies that produce or use land cover data. The NLCD datasets are available as flat generic raster image files which are easily imported into a GIS (e.g., Arc/INFO) and are provided in an Albers Conic Equal Area projection at a spatial resolution of 30-meters. The data can be obtained from the

following URL <http://edcwww.cr.usgs.gov/pub/edcuser/vogel/states/>.

Department of Water Resources Land Use Survey

The California Department of Water Resources (DWR) Land Use Survey databases are developed by the department's Division of Planning and Local Assistance in order to aid in DWR's efforts to continually monitor land use for the purpose of determining the amount of and changes in the use of water. The data are available at the county level and include detailed agricultural land use classifications, as well as less detailed urban and native vegetation land uses. The data was compiled from aerial photography with subsequent extensive field verification and are updated on a rotating basis by county approximately every seven years. Databases for each county are available in Arc/INFO shape file format employing a Transverse Mercator coordinate projection and can be obtained from the DWR's developing web site at <http://dplasp.water.ca.gov/landwateruse/>.

These LULC data were combined to provide a single complete coverage for the entire state. Figure 5 displays the combined LULC coverage for a portion of the southern SJV study area.

Spatial Surrogate Assignment

Point source emissions are spatially allocated using the appropriate coordinate projection system for the CRPAQS modeling domain. These include sources within certain categories previously modeled as area sources (e.g., livestock) where the study has identified information (e.g., dairy locations) to model the sources as point sources. The following emission source categories are treated as stationary point sources: dairy cattle, poultry operations, POTWs, composting, landfills and industrial sources. For area and mobile sources, emissions are spatially allocated based on the data sources presented in Table 3.

RESULTS

The year 2000 emission estimates are still being compiled and draft estimates should be completed in the spring of 2002. The importance of proper spatial and temporal characterization of ammonia emissions is exemplified in Figure 6. This figure shows the locations of two monitoring sites in and around Fresno, California. The monitoring results are from the winter of 2000. While the samples were not collected on the same day, the results show that the ammonium content of PM_{2.5} (PMNH₄) can vary dramatically even over fairly short distances. The downtown Fresno sample (First Street) shows a relatively low PMNH₄ reading, while the Clovis site shows a considerable PMNH₄ content (possibly influenced by the nearby dairy or other local source).

Figure 7 displays an example of gridded ammonia emissions from domestic sources. Note that the emission estimates shown in the figure are based on preliminary data and are presented to illustrate the spatial allocation and gridding capabilities of the model.

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Figure 1. The CRPAQS modeling domain. (Coordinates are LCP with reference origin of 120.5 degrees west longitude, 37 degrees north latitude and true parallels of 30 and 60 degrees north latitude).

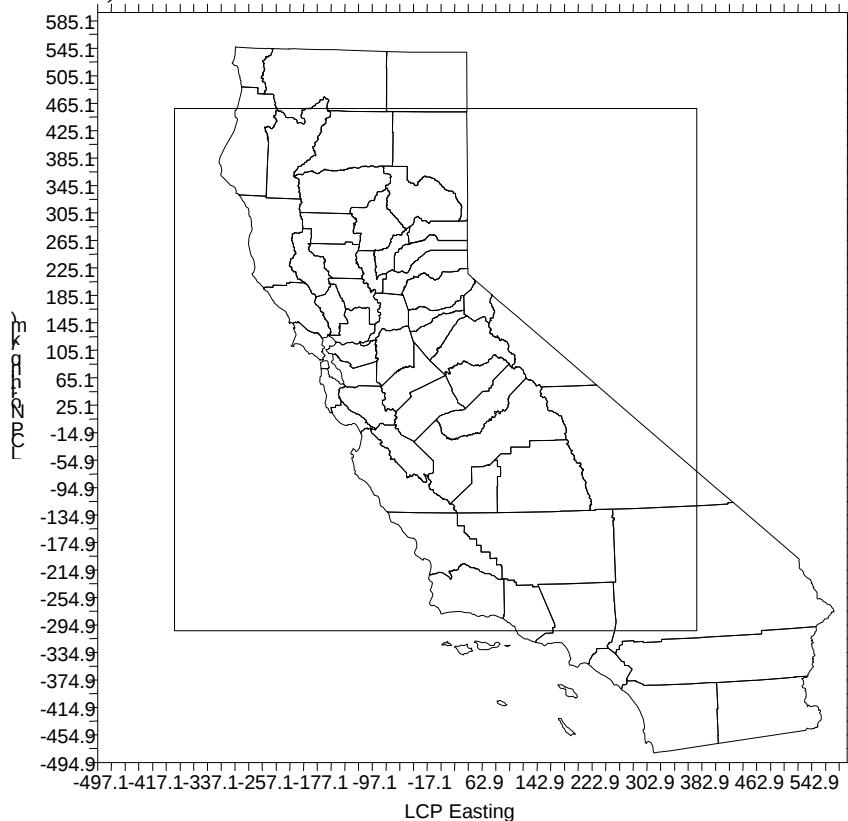


Table 1. Livestock emission factors.

Livestock	Emission Factor, lbs/animal/yr	Emission Factor Source
Beef Cows (confined operations)	74	James et al. ¹² (1997)
Milk Cows (confined operations)	74	James et al. (1997)
Dairy Calves (confined operations)	11.5	Battye et al. ¹³ (1994)
Manure Spreading	5.6	Battye et al. (1994)
Range Cattle	1.54	Battye et al. (1994)
Hogs and Pigs	20.3	Battye et al. (1994)
Sheep and Lambs	7.43	Battye et al. (1994)
Layers and pullets	1.00	Battye et al. (1994)
Broilers and other meat type chickens	0.37	Battye et al. (1994)
Horses	26.90	Battye et al. (1994)
Mules, Burros and Donkeys	26.9	Battye et al. (1994)
Goats	1.28	Bouwman, et al. ¹⁴ (1997)
Rabbits	0.37	Gharib and Cass ¹⁵ (1984)

Table 2. Source categories for beef and dairy cattle.

Category	EIC	Description
Cattle – Confined Beef Operations	630-618-0262-0002P	Point Source Cattle Feedlots
Cattle – Confined Dairy Operations	630-618-0262-0001P	Point Source Dairies
		Point Source Dairy Replacement Operations
Cattle – Dairy calves	630-618-0262-0005P	
Cattle – Confined Beef Operations	630-618-0262-0002A	Area Source Cattle Feedlots
Cattle – Range calves	630-618-0262-0003A	Area Source Range Calves
Cattle – Stocker inshipments	630-618-0262-0009A	Area Source Range Stocker Inshipments
Cattle – Range cows	630-618-0262-0010A	Area Source Range Cows
Cattle – Dairy cows	630-618-0262-0006A	Area Source Dairy Cows
Cattle – Dairy heifers	630-618-0262-0007A	Area Source Dairy Heifers
Cattle – Dairy bulls	630-618-0262-0008A	Area Source Dairy Bulls
Cattle - Confined beef operations, dry manure spreading	630-618-0262-0004A	Area Source Confined Beef Operations, Dry Manure Spreading
Cattle – Dairy operations, dry manure spreading	630-618-0262-0011A	Area Source Dairy Operations, Dry Manure Spreading
Cattle – Dairy operations, liquid manure spreading	630-618-0262-0012A	Area Source Dairy Operations, Liquid Manure Spreading

Table 3. Spatial surrogates for area and mobile sources.

Source Category	Spatial Surrogate
On-Road Mobile Sources	Allocated based on existing gridded VMT.
Fertilizer Application	Crop coverages developed by Potter et al (2001)
Soils and Plant Canopy Systems	Crop coverages developed by Potter et al (2001)
Agriculture Burning	NLCD LULC and DWR Crop coverages
Prescribed Burns/Wildfires	NLCD LULC and DWR Crop coverages
Residential Wood Burning	DWR and NLCD LULC and census data
Livestock: Beef Cattle	NLCD LULC and DWR Crop coverages
Livestock: Hogs, Rabbits, Sheep, Goats	NLCD LULC and DWR Crop coverages
Livestock: Horses, Mules, Donkeys, Burros	NLCD LULC and DWR Crop coverages
Native Animals	NLCD LULC coverages
Domestic Sources Human	DWR and NLCD LULC coverages and census data

Figure 2. Locations of dairies and PM monitoring stations in the southern SJV.

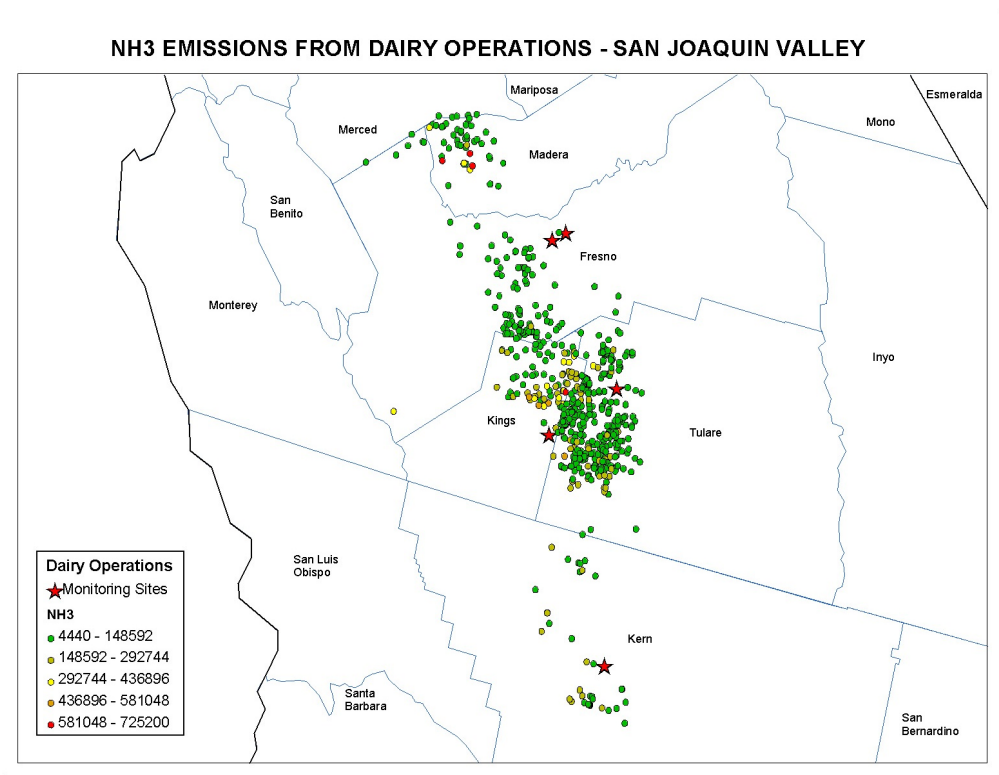


Figure 3. Conceptual design of GIS-based ammonia emission model.

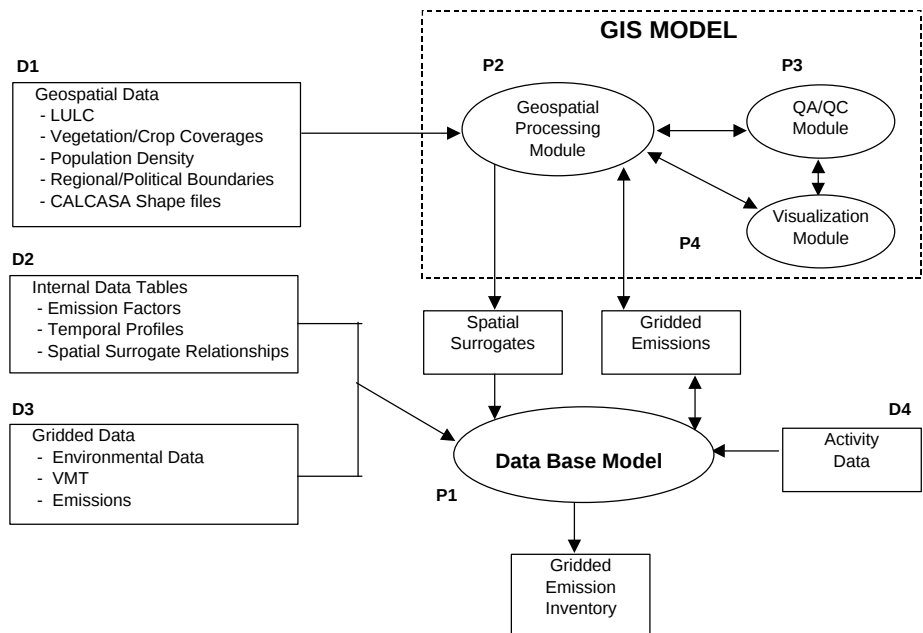


Figure 4. Main menu interface for GIS model.

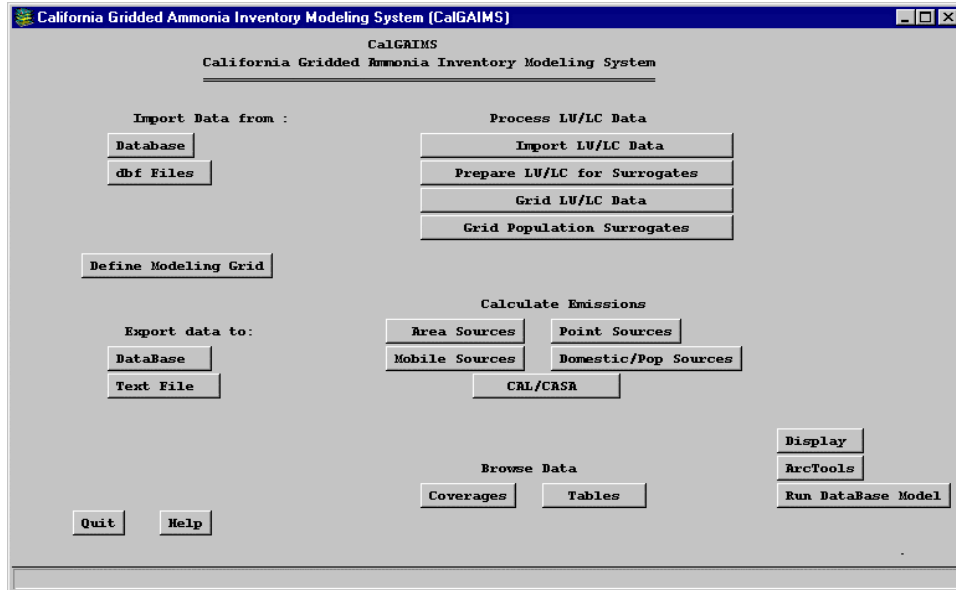


Figure 5. Sample LULC coverage for southern SJV study area.

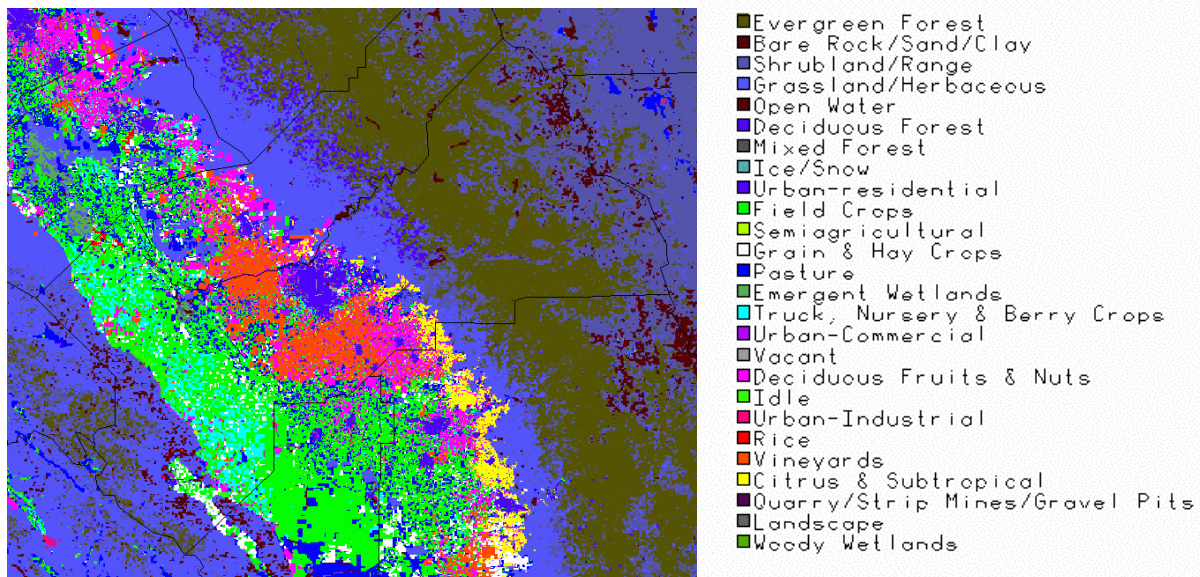


Figure 6. Ammonium content of winter PM_{2.5} at two Fresno area monitoring sites.

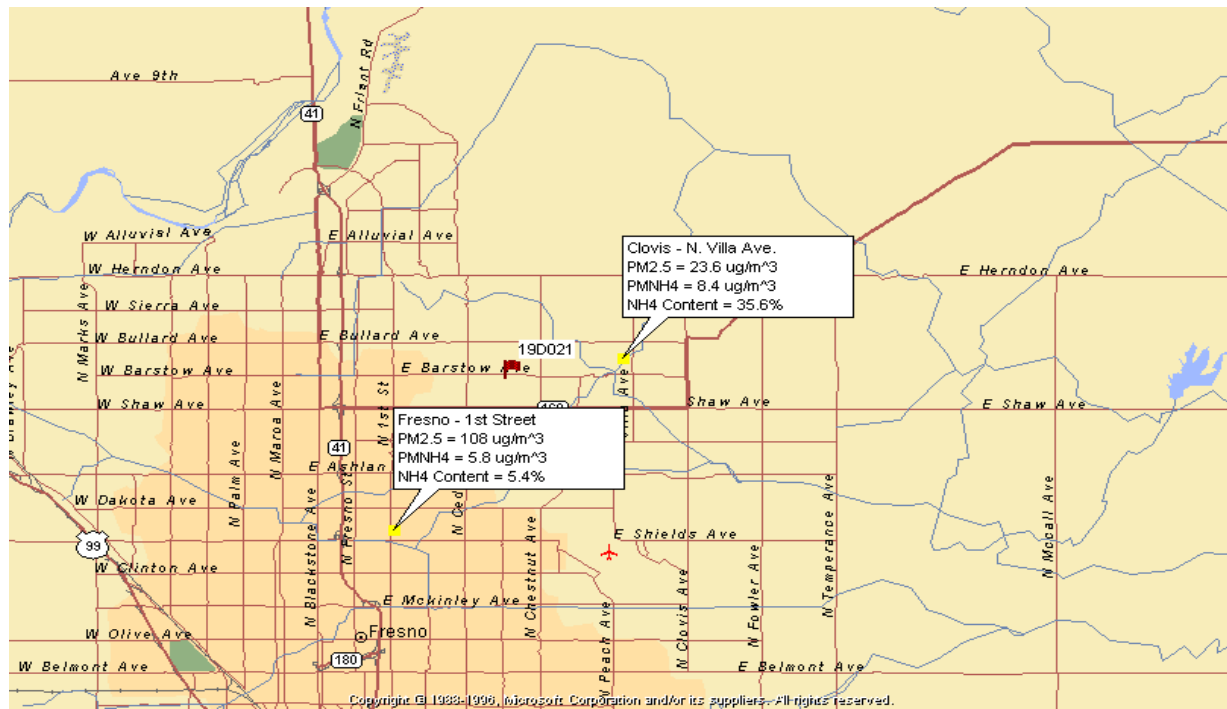
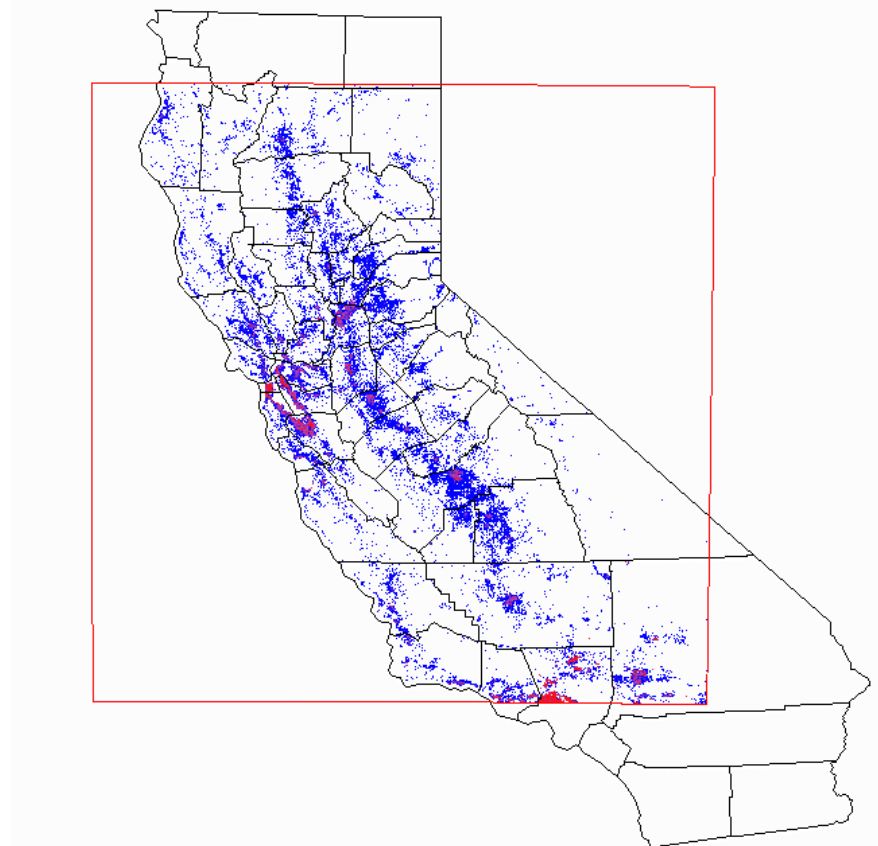


Figure 7. Example gridded annual emission estimates for domestic sources.



KEYWORDS

ammonia
emission inventories
spatial allocation
emissions modeling
GIS
database
CRPAQS