CONTRACT NO. 93-334
FINAL REPORT
FEBRUARY 1995

# Atmospheric Deposition to Agricultural Soil

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

# Atmospheric Deposition to Agricultural Soil

Final Report

Contract No. 93-334

*Prepared for:*

California Air Resources Board
Research Division
2020 L Street
Sacramento, California 95814

*Prepared by:*

Randall Mutters
Principal Investigator

Statewide Air Pollution Research Center
University of California
Riverside, California 92521

February 1995

## DISCLAIMER



## ACKNOWLEDGEMENTS

The author wishes to thank all those who contributed to this project. Among these are Brent Takemoto, California Air Resources Board; Stuart Pettygrove, University of California, Davis; Marty Martino, IMPACT Weather Database, University of California, Davis; and Justin Greene, Statewide Air Pollution Research Center. This final report was submitted in partial fulfillment of Research Division Contract Number 93-334 titled "Atmospheric Deposition to Agricultural Soil" by the University of California, Riverside, under the sponsorship of the California Air Resources Board. The report was completed as of February, 1995.

ABSTRACT

Atmospheric deposition of acidic air pollutants is widely recognized as an important environmental process. Most available data indicate that current levels of acidic deposition in California are below the levels required to adversely effect the yield of agricultural crops. However, excessive deposition of nutrient ions to soil may predispose plants to injury from other abiotic and biotic stresses. It was unknown whether current levels of acidic deposition exceed the growth requirements for any essential plant nutrients. Therefore, the objective of the study was to equate annual fluxes of dry and wet deposition to the nutritional requirements of major crops.

Aerometric data from a previously completed Air Resources Board (ARB) project (No. A132-149) were used to calculate atmospheric inputs and estimate regional-scale deposition flux across selected agricultural production areas in the state. Mean annual depositions of wet and dry acidic compounds from all monitoring stations were included in the data. Average fertilizer application rates were determined for 16 selected crops by agricultural region based on information from the University of California, Cooperative Extension Service. Typical amounts of nutrients taken up in the aboveground biomass on a seasonal basis were determined from published experimental results. Deposition fluxes were determined by using published specie-specific deposition velocities for dry compounds and using precipitation data for wet compounds. For those agricultural counties where monitoring stations were present, acidic deposition data were used to calculate: (1) Total Annual Deposition (TAD) of nitrogen (N), sulfur (S), and calcium (Ca); (2) TAD as a percentage of the fertilizer applied; and (3) TAD as a percentage of nutrients taken up during the growing season. Dry deposition data were available from only two stations near agricultural areas, Sacramento and Bakersfield. In those counties, dry deposition was included in the seasonal totals.

The TAD of N ranged < 1 to 14.4 kg $ha^{-1}$ on a county basis statewide. The highest deposition occurred in Kern county and the lowest in the coastal counties of Monterey and San Luis Obispo. Atmospheric deposition of N as a percentage of the fertilizer applied by growers ranged from 0.2% to 28% for lemon in San Luis Obispo county and for grape in Kern county, respectively. In contrast, TAD represented only 0.2% to 16% of seasonal N uptake by crops. Where dry deposition data were available, it represented approximately 8% to 15% of the TAD. The TAD of S ranged from 0.4 kg $ha^{-1}$ in Contra Costa county to a high of 2.4 kg $ha^{-1}$ in Kern county. This represented as much as 18% of the seasonal nutrient uptake of S by lettuce in Kern county. Sulfur is not routinely added as a fertilizer by California growers. Therefore, TAD as a percentage of applied fertilizer was not calculated. Similarly, California soil generally do not require amendment with Ca. The TAD of Ca represented < 2% of the seasonal nutrient uptake of the selected crops in all counties. Of those species typically measured in dry and wet deposition, only N at a few locations may represent a potential contributor to excessive nutrient loading to soil in California.

TABLE OF CONTENTS

LIST OF TABLES

## INTRODUCTION

Atmospheric deposition of acidic air pollutants is widely recognized as an important environmental process. Depending on meteorological conditions, these pollutants are transported from a few to hundreds of kilometers from sources to receptors (Legge, 1990). Primary and secondary pollutants which emanate from natural and anthropogenic sources are deposited on the Earth's surface by precipitation (rain and fog) or through dry deposition. Although the adverse effects of ozone and other air pollutants (e.g., sulfur dioxide) on crop yields are well-established, the effects of existing levels of acidic deposition on agricultural productivity are less well understood. The effects of acidic deposition, potentially beneficial or adverse, are thought to occur along two primary pathways: (1) direct effects on crop vegetation which may adversely affect yield or quality; and (2) indirect effects through the interactions with soil properties, climatic conditions, pests, or other air pollutants (Shriner and Johnston, 1985).

Most available data support the hypothesis that current levels of acidic deposition in California are below that predicted to lead to direct effects on growth and yield reductions in the major agricultural crops. This conclusion is supported by the fact that: (1) rain events with pH values below 3.5 (level for foliar injury) are rare in California (ARB, 1992); (2) experimental plants, from which response functions are frequently derived, grown under controlled conditions are generally more susceptible to injury than field-grown plants; and (3) experimental results repeatedly demonstrate the ability of plants to recovery from injury and/or compensate for initial growth reductions (Jacobson et al., 1985). The potential direct effects of acidic deposition on crop productivity in California were recently reviewed in the context of California Acid Deposition Monitoring Program (CADMP) data (Mutters, 1992).

The indirect effects via soil-related reactions are not well-documented. Acidic deposition (wet and dry) can have beneficial effects by supplying nitrogen (N), sulfur (S), and other nutrients to the foliage and soil. Conversely, the deposition of hydrogen ions ($H^+$) and acidifying compounds to the soil may cause long-term detrimental effects under certain conditions. In the latter case, much of what is known comes from the study of forest soil response to acidic deposition (Foster, 1989). One concern is N saturation, where the supply of atmospheric plus mineralized organic N exceeds the capacity of the ecosystem to assimilate it. Nitrogen saturation lends itself to acidification processes and to groundwater contamination via leached nitrates. Generally, the concern is that if acidification continues over long periods of time and the natural buffering capacity of the soil will eventually be fully titrated leading to a serious decline in soil pH. A decline in soil pH results in an increase in solubility of potentially toxic ions, such as aluminum and manganese (Stein and van Breemen, 1993). Soil high in aluminum ions may prove toxic to plants at a soil pH of 4.5 or less. Toxic levels of aluminum induce calcium (Ca) or iron toxicity symptoms, in addition to disrupting ATP-induced transmembrane transport functions (Liskens et al., 1989). Although a required nutrient, manganese has a narrow optimum pH range and is toxic if the range is exceeded (Tisdale and Nelson, 1975).

primary sources of acidic wet deposition. Once on the leaf surface, the pollutant may be taken up by the plant directly, chemically react with the surface of the leaf or be washed off by subsequent precipitation onto the soil (Marshall and Cadle, 1989). In the soil environment, acidic deposition may alter essential nutrient levels and influence soil pH. Soil may be exposed to frequent episodes of acidic fog or rain during the cool crop growing season. The pH of fog and rain in southern California may be as low as 2.0 and 3.0, respectively (Jacob et al., 1985, Hoffman, 1984). In contrast, the pH of precipitation in Tulare county during 1990 ranged from 4.8 to 7.0 (NADP, 1990).

Table 1. Seasonal Nitrogen and Sulfur Uptake* (kg $ha^{-1}$) of Important Non-nitrogen Fixing Crops in California.**

| *Crop* | *N* | *S* |
|---|---|---|
| Cotton | 180 | 28 |
| Grape | 125 | 20 |
| Tomato | 180 | 22 |
| Orange | 265 | 24 |
| Corn | 240 | 44 |
| Lettuce | 95 | 13 |
| Rice | 110 | 26 |
| Sugar beet | 255 | 50 |
| Peach | 95 | 17 |
| Wheat | 175 | 31 |

* Western Fertilizer Handbook, 1985 and Munson, 1982

** Total uptake in harvested portion of the crop. Reported uptake values may vary slightly depending on the source of the information

The properties of a particular soil are important to determine how it will chemically react to acidic deposition. Heavily weathered soil such as those found in the southeastern U.S. are initially acidic, often containing large amounts of exchangeable aluminum. The less weathered 'younger' soil formed from sedimentary material, typical of soil in the valleys of California, tend to be basic in reaction. They contain greater amounts of exchangeable cations. These exchangeable cations represent a pH buffer. Such basic soil with high exchangeable cation content are less likely to become acidified than highly weathered soil of the eastern U.S. Thus, the more relevant consequences of acidic deposition to soil in California may be the near time changes in soil fertility levels, rather than long-term acidification.

Among the plant nutrients present in both wet and dry acidic deposition in California, N species are taken up in the greatest quantities. Nitrogen is an essential component of chlorophyll, amino acids, and proteins. The amount of N (as nitrate ($NO_3^-$), ammonia ($NH_3$), and ammonium ($NH_4^+$)) from deposition varies temporally and spatially. The demand for N varies between crop and soil type. Approximate N demands for several crops important to California agriculture are listed in Table 1. To date no estimates exist of the nutritional demands supplied by acidic deposition processes in California.

Sulfur, a major component of both wet and dry deposition, is a minor macronutrient essential for plant growth. Sulfur requirements of selected crops are shown in Table 1. Two major sources of supplemental S to crop plants are atmospherically supplied S and incidental S as a component of N and phosphorus fertilizers. The increased use of high analysis, low-S fertilizers reduced the amount of incidental S applied and increased the occurrence of deficient soil in several areas (Adrilenas, 1984). Estimates of deposited atmospheric S across the U.S. range from 2 to 12 kg $ha^{-1}$ (NADP, 1990). Nonetheless, S-deficient soil is found in many states, particularly in the southeast (Martini and Mutters, 1985). Sulfur deficiencies, however, are uncommon in California (personal communication, Harry Andris, University of California, Cooperative Extension Service).

Dry deposition is the turbulent transport and sedimentation of gases and particles to the boundary layer close to the leaf or soil surface. The pollutant is then chemically or physically captured on the surface by processes of diffusion, convection, or inertial impaction (Legge and Krupa, 1986). Limited information is available on the consequences of acidic deposition to agricultural lands. In the agriculturally-rich San Joaquin Valley, dry deposition is an important means by which airborne acidic pollutants enter the agroecosystem during the summer growing season (ARB, 1988). The principal chemical species found in dry deposition in California are presented in Table 2. Only the N and S species form acidic compounds. The remaining elements are deposited unmodified to the soil surface. The bulk of the agricultural sales are generated from crop production during the summer months. Therefore, the potential consequences of dry deposition are of particular concern.

Wet deposition is the removal of suspended particles from the atmosphere by precipitation events. During the autumn and winter when cool season crops are grown, rain and fog are the

## STATEMENT OF PROBLEM

During the past decade several acidic deposition monitoring networks were established in the U.S. that provided data on a regional basis (Blanchard and Tonnessen, 1993). Several studies have addressed the regional deposition of acidic compounds in California (Lawson and Wendt, 1982; Liljestrand and Morgan, 1981; McColl et al., 1982). However, none provided data as extensive as that from the California Acid Deposition Monitoring Program (CADMP; Blanchard and Tonnessen, 1993). To date, the statewide wet and dry deposition data remain unevaluated in the context of soil nutrient requirements for agriculture. It is proposed to use the CADMP data to equate the annual flux of dry and wet deposition to the nutritional requirements of commercially-important crops in California.

Table 2. Principal Chemical Species in Dry and Wet Deposition in California.*

| *Mode of Deposition* | *Species* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dry | $NO_2$ | $NO_3^-$ | $HNO_3$ | $NH_3$ | $SO_2$ | $SO_4^{2-}$ | | |
| Wet | $NO_3^-$ | $NH_4^+$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$** | $Cl^-$ |

* Blanchard and Tonnessen (1993), and ARB (1992)

** Not an essential plant nutrient

## PROJECT OBJECTIVES

(1) Use deposition data from the Air Resources Board (ARB) sponsored CADMP to estimate the annual input of nutrient ions from wet and dry deposition to agricultural lands throughout the state.

(2) Evaluate the input in terms of nutritional requirements for major crops grown in the principal agricultural production zones of California.

## MATERIALS AND METHODS

Deposition Data: Processed and quality-assured data presented in an ARB sponsored report by Blanchard and Michaels (1994) were used for nutrient loading calculations. The authors used precipitation-chemistry data from the CADMP to estimate the flux of acidic species. Wet and dry deposition data gathered from stations located in or near agricultural production zones were used

| Table 4. Mean Annual Wet Deposition (kg $ha^{-1}$) Measured at Monitoring Stations near Agricultural Areas | | | | |
|---|---|---|---|---|
| *County* | *Site* | *N* | *S* | *Ca* |
| Orange | Anaheim | 1.1 | 0.6 | 0.4 |
| Kern | Bakersfield | 1.3 | 0.6 | 0.4 |
| Contra Costa | Bethel Island | 1.3 | 0.4 | 0.4 |
| San Diego | Escondido | 1.0 | 0.8 | 0.8 |
| Lake | Lakeport | 1.2 | 0.6 | 0.4 |
| Tulare | Lindcove | 2.4 | 0.5 | 0.5 |
| Siskiyou | Montague | 0.6 | 0.2 | 0.3 |
| Napa | Napa | 1.5 | 1.1 | 0.5 |
| San Luis Obispo | Nipomo | 0.4 | 0.6 | 0.4 |
| Sacramento | Sacramento | 2.5 | 0.7 | 0.4 |
| Monterey | Salinas | 0.8 | 0.5 | 0.3 |
| San Bernardino | San Bernardino | 2.5 | 0.7 | 0.7 |

Seasonal dry deposition of an acidic specie was determined as the product of its ambient concentration and deposition velocity. Deposition velocity is analogous to a gravitational falling speed (Legge and Krupa, 1990; Allen et al., 1991). Using a simplified model, the flux of acidic compounds may be estimated from air concentrations as a simple product.

$$-F = C \times V_d$$

where: $F$ = Flux away from the surface
$V_d$ = Deposition velocity for species

Deposition velocity ($V_d$) depends on surface characteristics and meteorological conditions that are site-specific. It is parameterized by the sum of the resistance's ($r_t$) to pollutant transfer ($r_a + r_b + r_s$), where $r_a$ is the aerodynamic resistance, $r_b$ is the boundary layer resistance, and $r_s$ is the resistance associated with the chemical and biological reactivity of the particles with the surface (Allen et al., 1991; Voldner et al., 1986). Blanchard and Michaels (1994) used an expanded version of the model developed at Oak Ridge National Laboratory (Hicks et al., 1991), which included stomatal, cuticular, and soil resistances, as well as key meteorological statistics for calculations presented in the current report (Table 3). Principal productions zones with monitoring stations were defined as the San Joaquin Valley, Sacramento Valley, Salinas Valley, and portions of Orange, San Bernardino, and Siskiyou counties.

| Table 3. Monitoring Stations Located In or Near Agricultural Production Areas | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *--- Latitude ---* | | | *-- Longitude --* | | | |
| *Site* | *Station No.* | *Deg* | *Min* | *Sec* | *Deg* | *Min* | *Sec* | *Elevation (m)* |
| Anaheim | 30-194 | 33 | 49 | 53 | 117 | 55 | 6 | 45 |
| Bakersfield | 15-203 | 35 | 21 | 28 | 119 | 1 | 6 | 120 |
| Bethel Island | 07-442 | 38 | 0 | 38 | 121 | 38 | 29 | 0 |
| Escondido | 80-115 | 33 | 7 | 29 | 117 | 4 | 1 | --- |
| Lakeport | 17-713 | 39 | 1 | 52 | 122 | 55 | 32 | 412 |
| Lindcove | 54-578 | 36 | 21 | 0 | 119 | 4 | 30 | 140 |
| Montague | 47-870 | 41 | 45 | 30 | 122 | 29 | 0 | 816 |
| Napa | 28-783 | 38 | 18 | 40 | 122 | 17 | 41 | 12 |
| Nipomo | 40-834 | 35 | 2 | 30 | 120 | 30 | 0 | 100 |
| Sacramento | 34-282 | 38 | 34 | 25 | 121 | 29 | 41 | 34 |
| Salinas | 27-544 | 36 | 41 | 50 | 121 | 37 | 57 | 13 |
| San Bernardino | 36-194 | 34 | 6 | 26 | 117 | 16 | 34 | 317 |

Aerometric wet and dry deposition data from a previously completed ARB sponsored project (Blanchard and Michaels, 1994; No. A132-149) were used to evaluate annual acidic deposition in terms of fertility requirements of major crops grown in selected agricultural production areas in the state. Procedures for determining quantities annually deposited and the associated uncertainties are described in detail in the report. Briefly, seasonal wet deposition was calculated based on observed precipitation chemistry and daily precipitation data gathered at appropriately located meteorological stations. The concentrations of key precipitation ions at various locations, together with precipitation depth, were use to compute ion deposition (kg $ha^{-1}$; Table 4). Chemical composition of rain water from the CADMP database multiplied by the amount of rainfall on a monthly basis (National Weather Service; IMPACT Weather Database, Davis, CA) yielded volume-weighted wet deposition. Monthly volume-weighted values were summed to give annual wet deposition.

| Table 6b. Monitoring Station Location, County, and Major Crops | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Location* | *County* | *Lemon* | *Lettuce* | *Orange* | *Peach* | *Rice* | *Tomato* | *Wheat* |
| Anaheim | Orange | X | X | X | | | X | |
| Bakersfield | Kern | X | X | X | X | X | X | X |
| Bethel Island | Contra Costa | | | | X | | X | X |
| Escondido | San Diego | X | | X | | | | |
| Lakeport | Lake | | | | | | | X |
| Lindcove | Tulare | X | | X | X | | | X |
| Montague | Siskiyou | | | | | | | X |
| Napa | Napa | | | | | | | |
| Nipomo | San Luis Obispo | X | X | X | | | | X |
| Sacramento | Sacramento | | X | | | X | X | X |
| Salinas | Monterey | | X | | | | X | X |
| San Bernardino | San Bernardino | X | X | X | | | | |

Statewide average fertilizer use for crops of concern is presented in Table 7 (Rauschkolb and Mikkelsen, 1978; personal communication, Dr. S. Pettygrove, Department of Land, Air and Water Resources, University of California, Davis). California soil is generally not amended with Ca and magnesium (Mg), therefore, no application rates are presented. Organic Matter (OM) is frequently applied to fields in close proximity to animal husbandry operations. The amount of OM-applied plant nutrients is relatively small compared to the amount of chemically-formulated fertilizer applied. Consequently, nutrients derived from OM were not considered in the calculations. Furthermore, the statewide average values presented in Table 7 do not reflect local differences in agronomic practices or industry-wide changes adopted since the original survey. For example, semi-dwarf varieties of rice replaced taller statured predecessors throughout most of the rice production area by the mid-1980's. The shorter statured varieties are more heavily fertilized with N; sometimes at rates as high as 150 kg $ha^{-1}$ (personal communication, Dr. J. Hill, Agronomy Department, University of California, Davis). Estimates of nutrient loading in terms of fertilizer requirements presented herein, should be considered conservative.

which may modify flux. Annual dry flux of N and S at the two applicable sites were calculated assuming a cover of 15% grass, 15% tree, and 70% bare soil (Table 5). The $V_d$ of $HNO_3$, which accounted for 40 to 70% of the total N deposition (Blanchard and Michaels, 1994), is insensitive to surface type (Hicks et al., 1991).

| Table 5. Mean Annual Dry Deposition (kg $ha^{-1}$) Measured at Monitoring Stations Near Agricultural Areas | | | |
|---|---|---|---|
| *County* | *Site* | *N* | *S* |
| Kern | Bakersfield | 14.4 | 1.7 |
| Sacramento | Sacramento | 8.6 | 0.8 |

Nutritional Requirements for Major Crops: Major crops grown in each production area were chosen based on 1992 production statistics provided by the Agricultural Commissioner's Office in each county (Tables 6a, 6b).

| Table 6a. Monitoring Station Location, County, and Major Crops | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Location* | *County* | *Alfalfa* | *Bean* | *Corn* | *Cotton* | *Grape* | *Grapefruit* |
| Anaheim | Orange | | X | | | | X |
| Bakersfield | Kern | X | X | X | X | X | X |
| Bethel Island | Contra Costa | X | | X | | X | |
| Escondido | San Diego | | | | | X | X |
| Lakeport | Lake | X | | | | X | |
| Lindcove | Tulare | X | X | X | X | X | X |
| Montague | Siskiyou | X | | | | | |
| Napa | Napa | | | | | X | |
| Nipomo | San Luis Obispo | X | | | | X | |
| Sacramento | Sacramento | X | X | X | | X | |
| Salinas | Monterey | X | X | | | X | |
| San Bernardino | San Bernardino | X | | | | X | X |

Calculations: All nutrient quantities are presented on an elemental basis. For example, deposition of N-containing compounds ($HNO_3$, $NH_3$, $NH_4^+$, $NO_3^-$) were converted to N content and summed. Sulfurous compounds were treated in a similar fashion. Atmospheric deposition of N was not considered in relation to legume crops, because N is infrequently applied, and if so, only in small quantities. Because Ca is not generally applied as a fertilizer in California, atmospheric deposition was analyzed only in the context of nutrient content in the aboveground biomass.

Table 8. Nutrient Uptake (kg $ha^{-1}$) by Various Crops During the Growing Season

| *Crop* | *N* | *$P_2O_5$* | *$K_2O$* | *Ca* | *Mg* | *S* |
|---|---|---|---|---|---|---|
| Alfalfa | 480 | 95 | 480 | 100 | 20 | 41 |
| Bean (Snap) | 175 | 40 | 200 | 100 | 20 | 17 |
| Corn (Grain) | 240 | 100 | 240 | 20 | 26 | 44 |
| Cotton | 180 | 65 | 125 | 150 | 53 | 28 |
| Grape | 125 | 45 | 195 | --- | --- | 20 |
| Lettuce | 95 | 30 | 200 | --- | --- | 13 |
| Orange | 265 | 55 | 330 | --- | --- | 24 |
| Rice | 110 | 60 | 150 | 20 | 9 | 26 |
| Peach | 95 | 40 | 120 | --- | --- | 17 |
| Tomato | 180 | 50 | 340 | --- | --- | 22 |
| Wheat | 175 | 70 | 200 | 20 | 9 | 31 |

Yearly deposition flux of the various nutrients were used in the following manner:

(1) Total Annual Deposition (TAD) = Wet Deposition + Dry Deposition

(2) Deposition as a Portion of Applied Fertilizer (AF) = (TAD ÷ AF) * 100

(3) Deposition as a Portion of Crop Uptake = (TAD ÷ Nutrients in Aboveground Biomass) * 100

(4) Portion of Applied Fertilizer Supplied by Dry Deposition = (Dry Deposition ÷ AF) * 100

The latter calculation was included to provide the reader information on the relative contribution of the contrasting pathways of deposition to soil nutrient loading. Obviously, the amount of wet deposition in relation to applied fertilizer can be obtained by difference between 2 and 4.

| Table 7. Statewide Average Annual Fertilizer Application Rates (kg $ha^{-1}$) to Selected Crops in California* | | | | |
|---|---|---|---|---|
| *Crop* | *N* | *$P_2O_5$* | *$K_2O$* | *OM* |
| Alfalfa | 20 | 76 | 19 | 3 |
| Bean (Dry) | 51 | 28 | 8 | < 1 |
| Corn | 170 | 53 | 29 | 3 |
| Cotton | 109 | 42 | 100 | 7 |
| Grape -- Raisin | 58 | 19 | 21 | 4 |
| Grape -- Table | 56 | 19 | 25 | 6 |
| Grape -- Wine/Juice | 53 | 20 | 112 | 2 |
| Grapefruit | 154 | 43 | 29 | 2 |
| Lemon | 166 | 34 | 99 | 2 |
| Lettuce | 159 | 93 | 48 | 4 |
| Orange | 123 | 38 | 31 | 2 |
| Peach | 129 | 21 | 78 | 1 |
| Rice | 86 | 37 | 10 | --- |
| Tangerine | 142 | 33 | 17 | 2 |
| Tomato | 142 | 80 | 55 | 2 |
| Wheat -- Irrigated | 104 | 33 | 3 | 3 |
| Wheat -- Unirrigated | 42 | 33 | 1 | 1 |

* Ca is not generally applied to soil in California

Seasonal Nutrient Uptake in the Aboveground Biomass of Selected Crops: Total amount of nutrients taken up by crops of interest during the growing season are presented in Table 8 (Kardos, et al., 1977; Eaton and Ergle, 1957; Western Fertilizer Handbook, 1985). Uptake (kg $ha^{-1}$) was determined based on typical planting densities used on California farms. The bulk nutrient uptake in excess of applied quantities are supplied by elemental fixation by the plant, and mineralization, decomposition, and weathering processes in soil.

## RESULTS AND DISCUSSION

Annual wet deposition of N ranged from 0.8 to 2.5 kg $ha^{-1}$ in Monterey and Sacramento counties, respectively (Table 9). In contrast for the two counties considered, dry deposition added 8.6 kg N $ha^{-1}$ to the soil in Sacramento county and 14.4 kg N $ha^{-1}$ in Kern county. The TAD was substantially less in counties where dry deposition data were unavailable. The large difference may be attributable to the seasonal anthropomorphic activities and factors influencing airborne particulate matter. Wet deposition occurs predominantly from November to April in much of state. Moist conditions generally minimize airborne particulate matter. The amount of $PM_{10}$ associated acid particles would thus be less during the winter.

In rural areas, agricultural activity is at a low during the wet season. Dry deposition occurs in the summer growing season, when agricultural activity is at a peak. Volatilization of N fertilizers may significantly contribute to atmospheric concentrations of $NH_3$ and $NH_4^+$ in localized areas. Depending on wind conditions and associated transport patterns, dry deposition could conceivably represent a recycling of N which originated from local area soil. Under such circumstances, estimates of N loading in relation to agricultural operations may be an overestimate, because the dry deposition originated initially from the fertilizer application.

The previous point aside, acid deposition represented from 0.2% to about 28% of the N typically applied as fertilizer to lemon in San Luis Obispo and to grape in Kern counties, respectively. This exemplifies a reoccurring pattern throughout the data set where inland areas experience high levels of deposition, while levels remain low in the coastal counties. The TAD was proportional to only 0.4% of N uptake by tomato in Monterey county. However in Kern county, N deposition was equivalent to over 14% of N taken up by lettuce.

Sulfur is seldom applied as a fertilizer in California. Consequently, acidic deposition was considered only in the context of crop uptake (Table 10). Similar to N, annual dry deposition of S (1.7 kg S $ha^{-1}$) was considerably higher than wet deposition (0.6 kg S $ha^{-1}$). The TAD (2.4 kg S $ha^{-1}$) corresponded to as little as 0.7% of wheat uptake in Siskiyou county and as much as 18% of S uptake by lettuce in Kern county.

The TAD of Ca was substantially less than either N or S (Table 11). The TAD ranged from 0.3 to 0.7 kg Ca $ha^{-1}$ in Monterey and San Bernardino counties, respectively. Atmospheric deposition of Ca represented less than 3% of plant uptake for all crops in all counties. In terms of plant nutrition or as a potential soil pH buffer, Ca appeared to be inconsequential. No environmental consequences would be expected.

Table 9. Total N from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *N in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | % | | |
| Contra Costa | Corn | 170 | 240 | 1.3 | --- | 1.3 | 0.8 | 0.6 | --- |
| Contra Costa | Grape | 56 | 125 | 1.3 | --- | 1.3 | 2.4 | 1.1 | --- |
| Contra Costa | Peach | 129 | 95 | 1.3 | --- | 1.3 | 1.0 | 1.4 | --- |
| Contra Costa | Tomato | 142 | 180 | 1.3 | --- | 1.3 | 0.9 | 0.7 | --- |
| Contra Costa | Wheat | 104 | 175 | 1.3 | --- | 1.3 | 1.3 | 0.8 | --- |
| Kern | Corn | 170 | 240 | 1.3 | 14.4 | 15.7 | 9.2 | 6.5 | 8.5 |
| Kern | Cotton | 109 | 180 | 1.3 | 14.4 | 15.7 | 14.3 | 8.7 | 13.2 |
| Kern | Grapefruit | 154 | --- | 1.3 | 14.4 | 15.7 | 10.2 | *** | 9.3 |
| Kern | Grape | 56 | 125 | 1.3 | 14.4 | 15.7 | 27.9 | 12.5 | 25.7 |
| Kern | Lemon | 166 | --- | 1.3 | 14.4 | 15.7 | 9.4 | *** | 8.7 |
| Kern | Lettuce | 159 | 95 | 1.3 | 14.4 | 15.7 | 9.9 | 16.5 | 9.0 |
| Kern | Orange | 123 | 265 | 1.3 | 14.4 | 15.7 | 12.7 | 5.9 | 11.7 |
| Kern | Peach | 129 | 95 | 1.3 | 14.4 | 15.7 | 12.1 | 16.5 | 11.1 |
| Kern | Rice | 86 | 110 | 1.3 | 14.4 | 15.7 | 18.2 | 14.2 | 16.7 |
| Kern | Tomato | 142 | 180 | 1.3 | 14.4 | 15.7 | 11.0 | 8.7 | 10.1 |
| Kern | Wheat | 104 | 175 | 1.3 | 14.4 | 15.7 | 15.1 | 8.9 | 13.8 |
| Lake | Grape | 56 | 125 | 1.2 | --- | 1.2 | 2.2 | 0.9 | --- |
| Lake | Wheat | 104 | 175 | 1.2 | --- | 1.2 | 1.2 | 0.7 | --- |

Table 9 (Continued). Total N from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *N in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | % | | |
| San Bernardino | Lemon | 166 | --- | 2.5 | --- | 2.5 | 1.5 | *** | --- |
| San Bernardino | Lettuce | 159 | 95 | 2.5 | --- | 2.5 | 1.5 | 2.6 | --- |
| San Bernardino | Orange | 123 | 265 | 2.5 | --- | 2.5 | 2.0 | 0.9 | --- |
| San Diego | Grapefruit | 154 | --- | 1.0 | --- | 1.0 | 0.7 | ** | --- |
| San Diego | Grape | 56 | 125 | 1.0 | --- | 1.0 | 1.8 | 0.8 | --- |
| San Diego | Lemon | 166 | --- | 1.0 | --- | 1.0 | 0.6 | *** | --- |
| San Diego | Orange | 123 | 265 | 1.0 | --- | 1.0 | 0.8 | 0.4 | --- |
| San Luis Obispo | Grape | 56 | 125 | 0.4 | --- | 0.4 | 0.7 | 0.3 | --- |
| San Luis Obispo | Lemon | 166 | --- | 0.4 | --- | 0.4 | 0.2 | *** | --- |
| San Luis Obispo | Lettuce | 159 | 95 | 0.4 | --- | 0.4 | 0.2 | 0.4 | --- |
| San Luis Obispo | Orange | 123 | 265 | 0.4 | --- | 0.4 | 0.3 | 0.1 | --- |
| San Luis Obispo | Wheat | 104 | 175 | 0.4 | --- | 0.4 | 0.4 | 0.2 | --- |
| Siskiyou | Wheat | 104 | 175 | 0.6 | --- | 0.6 | 0.6 | 0.3 | --- |
| Tulare | Corn | 170 | 240 | 2.4 | --- | 2.4 | 1.4 | 1.0 | --- |
| Tulare | Cotton | 109 | 180 | 2.4 | --- | 2.4 | 2.2 | 1.3 | --- |
| Tulare | Grapefruit | 154 | --- | 2.4 | --- | 2.4 | 1.6 | *** | --- |
| Tulare | Grape | 56 | 125 | 2.4 | --- | 2.4 | 4.3 | 1.9 | --- |
| Tulare | Lemon | 166 | --- | 2.4 | --- | 2.4 | 1.4 | *** | --- |

| Table 9 (Continued). Total N from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *County* | *Crop* | *Added as Fertilizer** | *N in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
| | | kg $ha^{-1}$ | | | | | % | | |
| Monterey | Grape | 56 | 125 | 0.8 | --- | 0.8 | 1.4 | 0.7 | --- |
| Monterey | Lettuce | 159 | 95 | 0.8 | --- | 0.8 | 0.5 | 0.8 | --- |
| Monterey | Tomato | 142 | 180 | 0.8 | --- | 0.8 | 0.5 | 0.4 | --- |
| Monterey | Wheat | 104 | 175 | 0.8 | --- | 0.8 | 0.8 | 0.4 | --- |
| Napa | Grape | 56 | 125 | 1.5 | --- | 1.5 | 2.7 | 1.2 | --- |
| Orange | Grapefruit | 154 | --- | 1.1 | --- | 1.1 | 0.7 | ** | --- |
| Orange | Lemon | 166 | --- | 1.1 | --- | 1.1 | 0.7 | ** | — |
| Orange | Lettuce | 159 | 95 | 1.1 | --- | 1.1 | 0.7 | 1.2 | --- |
| Orange | Orange | 123 | 265 | 1.1 | --- | 1.1 | 0.9 | 0.4 | --- |
| Orange | Tomato | 142 | 180 | 1.1 | --- | 1.1 | 0.8 | 0.6 | --- |
| Sacramento | Corn | 170 | 240 | 2.5 | 8.6 | 11.1 | 6.5 | 4.6 | 5.0 |
| Sacramento | Grape | 56 | 125 | 2.5 | 8.6 | 11.1 | 19.8 | 8.8 | 15.3 |
| Sacramento | Lettuce | 159 | 95 | 2.5 | 8.6 | 11.1 | 6.9 | 11.6 | 5.4 |
| Sacramento | Rice | 86 | 110 | 2.5 | 8.6 | 11.1 | 12.9 | 10.1 | 9.9 |
| Sacramento | Tomato | 142 | 180 | 2.5 | 8.6 | 11.1 | 7.8 | 6.1 | 6.0 |
| Sacramento | Wheat | 104 | 175 | 2.5 | 8.6 | 11.1 | 10.6 | 6.3 | 8.3 |
| San Bernardino | Grapefruit | 154 | — | 2.5 | — | 2.5 | 1.6 | *** | — |
| San Bernardino | Grape | 56 | 125 | 2.5 | — | 2.5 | 4.4 | 1.9 | — |

## CONCLUSIONS

Atmospheric N appeared to contribute as much as 28% of the traditionally applied fertilizer in Kern county. The complexities of N cycling, however, between the soil and atmosphere in agricultural areas are not well-understood. Estimated N flux may in fact represent the redeposition of volatilized N originating from applied fertilizers. Therefore, recommendations to reduce current fertilizer application rates are premature until the localized N cycling is better quantified. Regardless, based upon the current analyses, only N among nutrient elements present in acidic deposition may pose a potential for excessive nutrient loading to the agricultural soil of California.

## RECOMMENDATIONS

The soil fertility-related statistics derived from this project are complementary to the statewide digital soil database archived at the Statewide Air Pollution Research Center (SAPRC). The continued development of a Geographic Information System (GIS) soil data management system strengthens the ability of administrators and researchers to access, critically analyze, and visualize soil related information as it relates to air quality.

| Table 10. Total S from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *County* | *Crop* | *Added as Fertilizer** | *S in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
| | | ---------- kg ha$^{-1}$ ---------- | | | | | ---------- % ---------- | | |
| Contra Costa | Alfalfa | 0 | 41 | 0.4 | --- | 0.4 | ** | 1.0 | --- |
| Contra Costa | Corn | 0 | 44 | 0.4 | --- | 0.4 | ** | 0.9 | --- |
| Contra Costa | Grape | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Contra Costa | Peach | 0 | 17 | 0.4 | --- | 0.4 | ** | 2.4 | --- |
| Contra Costa | Tomato | 0 | 22 | 0.4 | --- | 0.4 | ** | 1.9 | --- |
| Contra Costa | Wheat | 0 | 31 | 0.4 | --- | 0.4 | ** | 1.3 | --- |
| Kern | Alfalfa | 0 | 41 | 0.7 | 1.7 | 2.4 | ** | 5.8 | *** |
| Kern | Bean | 0 | 17 | 0.7 | 1.7 | 2.4 | ** | 13.9 | *** |
| Kern | Corn | 0 | 44 | 0.7 | 1.7 | 2.4 | ** | 5.4 | *** |
| Kern | Cotton | 0 | 28 | 0.7 | 1.7 | 2.4 | ** | 8.5 | *** |
| Kern | Grapefruit | 0 | --- | 0.7 | 1.7 | 2.4 | ** | ** | *** |
| Kern | Grape | 0 | 20 | 0.7 | 1.7 | 2.4 | ** | 11.9 | *** |
| Kern | Lemon | 0 | --- | 0.7 | 1.7 | 2.4 | ** | ** | *** |
| Kern | Lettuce | 0 | 13 | 0.7 | 1.7 | 2.4 | ** | 18.2 | *** |
| Kern | Orange | 0 | 24 | 0.7 | 1.7 | 2.4 | ** | 9.9 | *** |
| Kern | Peach | 0 | 17 | 0.7 | 1.7 | 2.4 | ** | 13.9 | *** |
| Kern | Rice | 0 | 26 | 0.7 | 1.7 | 2.4 | ** | 9.1 | *** |

Table 10 (Continued). Total S from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *S in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | ------------ kg ha$^{-1}$ ------------ | | | | | ------------ % ------------ | | |
| Kern | Tomato | 0 | 22 | 0.7 | 1.7 | 2.4 | ** | 10.8 | *** |
| Kern | Wheat | 0 | 31 | 0.7 | 1.7 | 2.4 | ** | 7.6 | *** |
| Lake | Alfalfa | 0 | 41 | 0.6 | --- | 0.6 | ** | 1.4 | --- |
| Lake | Grape | 0 | 20 | 0.6 | --- | 0.6 | ** | 2.8 | --- |
| Lake | Wheat | 0 | 31 | 0.6 | --- | 0.6 | ** | 1.8 | --- |
| Monterey | Alfalfa | 0 | 41 | 0.5 | --- | 0.5 | ** | 1.1 | --- |
| Monterey | Bean | 0 | 17 | 0.5 | --- | 0.5 | ** | 2.6 | --- |
| Monterey | Grape | 0 | 20 | 0.5 | --- | 0.5 | ** | 2.3 | --- |
| Monterey | Lettuce | 0 | 13 | 0.5 | --- | 0.5 | ** | 3.5 | --- |
| Monterey | Tomato | 0 | 22 | 0.5 | --- | 0.5 | ** | 2.1 | --- |
| Monterey | Wheat | 0 | 31 | 0.5 | --- | 0.5 | ** | 1.5 | --- |
| Napa | Grape | 0 | 20 | 1.1 | --- | 1.1 | ** | 5.7 | --- |
| Orange | Bean | 0 | 17 | 0.6 | --- | 0.6 | ** | 3.6 | --- |
| Orange | Grapefruit | 0 | --- | 0.6 | --- | 0.6 | ** | ** | --- |
| Orange | Lemon | 0 | --- | 0.6 | --- | 0.6 | ** | ** | --- |
| Orange | Lettuce | 0 | 13 | 0.6 | --- | 0.6 | ** | 4.8 | --- |
| Orange | Orange | 0 | 24 | 0.6 | --- | 0.6 | ** | 2.6 | --- |
| Orange | Tomato | 0 | 22 | 0.6 | --- | 0.6 | ** | 2.8 | --- |

Table 10 (Continued). Total S from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *S in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | % | | |
| Sacramento | Alfalfa | 0 | 41 | 0.7 | 0.8 | 1.5 | ** | 3.7 | *** |
| Sacramento | Bean | 0 | 17 | 0.7 | 0.8 | 1.5 | ** | 8.9 | *** |
| Sacramento | Corn | 0 | 44 | 0.7 | 0.8 | 1.5 | ** | 3.5 | *** |
| Sacramento | Grape | 0 | 20 | 0.7 | 0.8 | 1.5 | ** | 7.6 | *** |
| Sacramento | Lettuce | 0 | 13 | 0.7 | 0.8 | 1.5 | ** | 11.7 | *** |
| Sacramento | Rice | 0 | 26 | 0.7 | 0.8 | 1.5 | ** | 5.8 | *** |
| Sacramento | Tomato | 0 | 22 | 0.7 | 0.8 | 1.5 | ** | 6.9 | *** |
| Sacramento | Wheat | 0 | 31 | 0.7 | 0.8 | 1.5 | ** | 4.9 | *** |
| San Bernardino | Alfalfa | 0 | 41 | 0.7 | --- | 0.7 | ** | 1.7 | --- |
| San Bernardino | Grapefruit | 0 | --- | 0.7 | --- | 0.7 | ** | ** | --- |
| San Bernardino | Grape | 0 | 20 | 0.7 | --- | 0.7 | ** | 3.5 | --- |
| San Bernardino | Lemon | 0 | --- | 0.7 | --- | 0.7 | ** | ** | --- |
| San Bernardino | Lettuce | 0 | 13 | 0.7 | --- | 0.7 | ** | 5.3 | --- |
| San Bernardino | Orange | 0 | 24 | 0.7 | --- | 0.7 | ** | 2.9 | --- |
| San Diego | Grapefruit | 0 | --- | 0.8 | --- | 0.8 | ** | ** | --- |
| San Diego | Grape | 0 | 20 | 0.8 | --- | 0.8 | ** | 3.8 | --- |
| San Diego | Lemon | 0 | --- | 0.8 | --- | 0.8 | ** | ** | --- |

Table 10 (Continued). Total S from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *S in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | ---------- kg ha$^{-1}$ ---------- | | | | | ---------- % ---------- | | |
| San Diego | Orange | 0 | 24 | 0.8 | --- | 0.8 | ** | 3.2 | --- |
| San Luis Obispo | Alfalfa | 0 | 41 | 0.6 | --- | 0.6 | ** | 1.4 | --- |
| San Luis Obispo | Grape | 0 | 20 | 0.6 | --- | 0.6 | ** | 2.9 | --- |
| San Luis Obispo | Lemon | 0 | --- | 0.6 | --- | 0.6 | ** | *** | --- |
| San Luis Obispo | Lettuce | 0 | 13 | 0.6 | --- | 0.6 | ** | 4.4 | --- |
| San Luis Obispo | Orange | 0 | 24 | 0.6 | --- | 0.6 | ** | 2.4 | --- |
| San Luis Obispo | Wheat | 0 | 31 | 0.6 | --- | 0.6 | ** | 1.8 | --- |
| Siskiyou | Alfalfa | 0 | 41 | 0.2 | --- | 0.2 | ** | 0.6 | --- |
| Siskiyou | Wheat | 0 | 31 | 0.2 | --- | 0.2 | ** | 0.7 | --- |
| Tulare | Alfalfa | 0 | 41 | 0.5 | --- | 0.5 | ** | 1.3 | --- |
| Tulare | Bean | 0 | 17 | 0.5 | --- | 0.5 | ** | 3.1 | --- |
| Tulare | Corn | 0 | 44 | 0.5 | --- | 0.5 | ** | 1.2 | --- |
| Tulare | Cotton | 0 | 28 | 0.5 | --- | 0.5 | ** | 1.9 | --- |
| Tulare | Grapefruit | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |
| Tulare | Grape | 0 | 20 | 0.5 | --- | 0.5 | ** | 2.7 | --- |
| Tulare | Lemon | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |

Table 10 (Continued). Total S from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *S in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | ---------- kg $ha^{-1}$ ---------- | | | | | ---------- % ---------- | | |
| Tulare | Orange | 0 | 24 | 0.5 | --- | 0.5 | ** | 2.2 | --- |
| Tulare | Peach | 0 | 17 | 0.5 | --- | 0.5 | ** | 3.1 | --- |
| Tulare | Wheat | 0 | 31 | 0.5 | --- | 0.5 | ** | 1.7 | --- |

* In California, S is only applied as a trace contaminant in other fertilizers

** S in the harvested portion of the crop (Western Fertilizer Handbook, 1985)

*** Insufficient data

--- Not applicable

Table 11. Total Ca from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *Ca in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | % | | |
| Contra Costa | Alfalfa | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Contra Costa | Corn | 0 | 20 | 0.4 | --- | 0.4 | ** | 1.8 | --- |
| Contra Costa | Grape | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Contra Costa | Peach | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Contra Costa | Tomato | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Contra Costa | Wheat | 0 | 20 | 0.4 | --- | 0.4 | ** | 1.8 | --- |
| Kern | Alfalfa | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Kern | Bean | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Kern | Corn | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Kern | Cotton | 0 | 150 | 0.4 | --- | 0.4 | ** | 0.3 | --- |
| Kern | Grapefruit | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Kern | Grape | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Kern | Lemon | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Kern | Lettuce | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Kern | Orange | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Kern | Peach | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Kern | Rice | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Kern | Tomato | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |

Table 11 (Continued). Total Ca from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *Ca in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | % | | |
| Contra Costa | Alfalfa | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Lake | Alfalfa | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Lake | Grape | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Lake | Wheat | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Monterey | Alfalfa | 0 | 100 | 0.3 | --- | 0.3 | ** | 0.3 | --- |
| Monterey | Bean | 0 | 100 | 0.3 | --- | 0.3 | ** | 0.3 | --- |
| Monterey | Grape | 0 | --- | 0.3 | --- | 0.3 | ** | *** | --- |
| Monterey | Lettuce | 0 | --- | 0.3 | --- | 0.3 | ** | *** | --- |
| Monterey | Tomato | 0 | --- | 0.3 | --- | 0.3 | ** | *** | --- |
| Monterey | Wheat | 0 | 20 | 0.3 | --- | 0.3 | ** | 1.7 | --- |
| Napa | Grape | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |
| Orange | Bean | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Orange | Grapefruit | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Orange | Lemon | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Orange | Lettuce | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Orange | Orange | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Orange | Tomato | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Sacramento | Alfalfa | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |

Table 11 (Continued). Total Ca from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *Ca in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | ---------- kg $ha^{-1}$ ---------- | | | | | ---------- % ---------- | | |
| Sacramento | Bean | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |
| Sacramento | Corn | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Sacramento | Grape | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Sacramento | Lettuce | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Sacramento | Rice | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Sacramento | Tomato | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| Sacramento | Wheat | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| San Bernardino | Alfalfa | 0 | 100 | 0.7 | --- | 0.7 | ** | 0.7 | --- |
| San Bernardino | Grapefruit | 0 | --- | 0.7 | --- | 0.7 | ** | *** | --- |
| San Bernardino | Grape | 0 | --- | 0.7 | --- | 0.7 | ** | *** | --- |
| San Bernardino | Lemon | 0 | --- | 0.7 | --- | 0.7 | ** | *** | --- |
| San Bernardino | Lettuce | 0 | --- | 0.7 | --- | 0.7 | ** | *** | --- |
| San Bernardino | Orange | 0 | --- | 0.7 | --- | 0.7 | ** | *** | --- |
| San Diego | Grapefruit | 0 | --- | 0.8 | --- | 0.8 | ** | *** | --- |
| San Diego | Grape | 0 | --- | 0.8 | --- | 0.8 | ** | *** | --- |
| San Diego | Lemon | 0 | --- | 0.8 | --- | 0.8 | ** | *** | --- |
| San Diego | Orange | 0 | --- | 0.8 | --- | 0.8 | ** | *** | --- |
| San Luis Obispo | Alfalfa | 0 | 100 | 0.4 | --- | 0.4 | ** | 0.4 | --- |

| Table 11 (Continued). Total Ca from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *County* | *Crop* | *Added as Fertilizer** | *Ca in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
| | | ---------- kg ha$^{-1}$ ---------- | | | | | ---------- % ---------- | | |
| San Luis Obispo | Grape | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| San Luis Obispo | Lemon | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| San Luis Obispo | Lettuce | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| San Luis Obispo | Orange | 0 | --- | 0.4 | --- | 0.4 | ** | *** | --- |
| San Luis Obispo | Wheat | 0 | 20 | 0.4 | --- | 0.4 | ** | 2.1 | --- |
| Siskiyou | Alfalfa | 0 | 100 | 0.3 | --- | 0.3 | ** | 0.3 | --- |
| Siskiyou | Wheat | 0 | 20 | 0.3 | --- | 0.3 | ** | 1.3 | --- |
| Tulare | Alfalfa | 0 | 100 | 0.5 | --- | 0.5 | ** | 0.5 | --- |
| Tulare | Bean | 0 | 100 | 0.5 | --- | 0.5 | ** | 0.5 | --- |
| Tulare | Corn | 0 | 20 | 0.5 | --- | 0.5 | ** | 2.5 | --- |
| Tulare | Cotton | 0 | 150 | 0.5 | --- | 0.5 | ** | 0.3 | --- |
| Tulare | Grapefruit | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |
| Tulare | Grape | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |
| Tulare | Lemon | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |
| Tulare | Orange | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |
| Tulare | Peach | 0 | --- | 0.5 | --- | 0.5 | ** | *** | --- |

Table 11 (Continued). Total Ca from Atmospheric Deposition in Relation to Common Fertilization Practices and Plant Nutrient Content

| *County* | *Crop* | *Added as Fertilizer** | *Ca in Aboveground Biomass*** | *Annual Wet Deposition* | *Annual Dry Deposition* | *Total Deposition* | *Portion of Fertilizer Applied* | *Portion of Uptake* | *Portion of Applied Fertilizer Supplied by Dry Deposition* |
|---|---|---|---|---|---|---|---|---|---|
| | | $kg\ ha^{-1}$ | | | | | % | | |
| Tulare | Wheat | 0 | 20 | 0.5 | --- | 0.5 | ** | 2.5 | --- |

* Ca is not applied to soil in California

** Ca in the harvested portion of the crop (Western Fertilizer Handbook, 1985)

*** Insufficient data

--- Not applicable

## REFERENCES

Adrilenas, P. 1984. Inputs: Outlook and situation. Economic Research Service, USDA, IOS-3, p 25.

Allen, AG, RM Harrison, and KW Nicholson. 1991. Dry deposition of fine aerosol to a short grass surface. *Atmos. Environ.* 25A:2671-2676.

Air Resources Board (ARB). 1988. *The Health and Welfare Effects of Acidic Deposition in California: Technical Assessment.* Research Division, Sacramento, CA.

Air Resources Board (ARB). 1992. *The Atmospheric Acidity Protection Program: Annual Report to the Governor and Legislature, 1991.* Research Division, Sacramento, CA.

Blanchard, CL, and KA Tonnessen. 1993. Precipitation chemistry measurements from the California Acid Deposition Monitoring Program, 1985-1990. *Atmos.Environ.* 27A:1755-1763.

Blanchard, CL, and H Michaels. 1994. Regional Estimates of Acid Deposition Fluxes in California. Final report, California Air Resources Board, Contract No. A132-149.

Eaton, FM, and DR Ergle. 1957. Mineral nutrition of the cotton plant. *Plant Physiol.* 32(3):169-175.

Foster, NW. 1989. Acidic deposition: What is fact, what is speculation, what is needed? *Water Air Soil Pollut.* 48:299-306.

Hicks, BB, RP Hosker, TP Meyers, and JD Womack. 1991. Dry deposition inferential measurement techniques. I. Design and tests of a prototype meteorological and chemical system for determining dry deposition. *Atmos. Environ.* 25A(10): 2345-2359.

Hoffman, MR. 1984. Comment on acid fog. *Environ. Sci. Tech*nol. 18:51-64.

Jacob, DJ, JM Waldman, JW Munger, and MR Hoffman. 1985. Chemical composition of fogwater collected along the California coast. *Environ. Sci. Technol.* 19:730-736.

Jacobson, JS, J Troiano, and L Heller. 1985. Stage of development response and recovery of radish plants from episodic exposure to simulated acid rain. *J. Exp. Bot.* 36: 159-167.

Kardos, LT, CE Scarsbrook, and VV Volk. 1977. *Recycling Elements in Wastes Through Plant-Soil Systems.* Soil for Management of Organic Waste and Waste Waters. Soil Science Society of America, Madison, WI.

Lawson, DR, and JG Wendt. 1982. Acid deposition in California. *Soc. Auto. Eng., Technical Paper Series* No. 821246.

Legge, AH. 1990. Sulfur and nitrogen in the atmosphere. IN: Legge, AH, and SV Krupa. (eds) *1990. Acidic Deposition: Sulfur and Nitrogen Oxides.* Lewis Publishers, Chelsea.

Legge, AH, and SV Krupa. (eds) 1986. *Air Pollutants and Their Effects on the Terrestrial Ecosystem.* John Wiley and Sons, New York.

Legge, AH, and SV Krupa. (eds) 1990. *Acidic Deposition: Sulphur and Nitrogen Oxides.* Lewis Publishers, Chelsea.

Liljestrand, HG, and JJ Morgan. 1981. Spatial variations of acid precipitation in southern California. *Environ. Sci. Technol.* 15: 33-339.

Liskens, HF, FM Derks, and GF Schonenberg. 1989. The influence of artificial acid rain on the physiology and morphology of *Phaseolus vulgaris*, *Vicia faba*, and *Spinacia oleracea* after separate spraying of the shoots and soil. *Angew. Bot.* 63: 67-80.

Marshall, JD, and SH Cadle. 1989. Evidence for transcuticular uptake of $HNO_3$ vapor by foliage of eastern white pine (*Pinus strobus* L.). *Environ. Pollut.* 60: 15-28.

Martini, JA, and RG Mutters. 1985. Effect of liming and fertilization on sulfur availability, mobility, and uptake in cultivated soil of South Carolina. *Soil Sci.* 138: 403-410.

McColl, JG, LK Monette, and DS Bush. 1982. Chemical characteristics of wet and dry atmospheric fallout in northern California. *J. Environ. Qual.* 11: 585-590.

Munson, RD. 1982. Soil fertility, fertilizers, and plant nutrition. IN: Kilmer, KJ. (ed) 1982. *Handbook of Soil and Climate in Agriculture.* CRC Press, Boca Raton. p. 269-293.

Mutters, RG. 1992. Effects of acidic deposition on crops in the San Joaquin Valley. IN: Air Resources Board. 1992. *The Atmospheric Acidity Protection Program: Annual Report to the Governor and Legislature, 1991.* Research Division, Sacramento, CA.

National Atmospheric Deposition Program (NADP). 1990. *Annual Data Summary.*

Rauschkolb RS, and DS Mikkelsen. 1978. *Fertilizer Use in California.* USDA Cooperative Extension Bulletin No. 1887.

Shriner, DS , and JW Johnston. 1985. *Acid Deposition: Effects on Agricultural Crops.* Final Report, No. PR 1908-2, Electric Power Research Institute. Oak Ridge National Laboratory, Oak Ridge, TN.

Stein, A, and N van Breeman. 1993. Time series analysis of changes in the soil solution: Evidence for approach to nitrogen saturation in Dutch soil. *Agric. Ecosys. Environ.* 47:147-158.

Tisdale, SL, and WL Nelson. 1975. *Soil Fertility and Fertilizers.* pp 317.

Voldner, EC, LA Barrie, and A Sirios. 1986. A literature review of dry deposition of oxides sulphur and nitrogen with emphasis on long-range transport modelling in North America. *Atmos. Environ.* 20: 2101-2123.

Western Fertilizer Handbook. 1985. Interstate Printers and Publishers, Danville, IL.