FINAL REPORT TO
CALIFORNIA DEPARTMENT OF FOOD & AGRICULTURE

Period covered February 1, 2005 – December 31, 2008

Contractor Regents of the University of California

Address Office of the Vice Chancellor of
Research Sponsored Programs
Attn. Ahmad Hakim-Elahi
1850 Research Park Drive, Suite 300
Davis, 95618

Agreement No. CDFA #04-0747

Principal Investigator Stuart Pettygrove
Department of Land, Air & Water Resources
University of California
One Shields
Avenue Davis, CA
95616

Co-Principal Investigators Larry Schwankl
Department of Land, Air & Water Resources
University of California, Davis

Carol Frate
UC Cooperative Extension
Tulare, CA

Kent Brittan
UC Cooperative Extension
Woodland, CA

Project Title **“**Improving Water-Run Nitrogen Fertilizer Practices in Furrow- and Border Check-Irrigated Field Crops”

Statement of Objectives

1. Investigate the relationship of timing of water-run fertilizer injection during furrow and border-check irrigation events on N application uniformity and to determine the role of ammonia volatilization.
2. Develop recommendations for N fertilizer injection timing for soils with different textures or water intake rates;
3. Extend the information developed in the project through presentations at professional meetings, cooperative extension newsletter articles, and a U.C. peer- reviewed technical bulletin.

Executive Summary

We evaluated the performance of water-run fertilizer N applications during furrow and border check irrigation events in annual crop fields ranging in length from 900 to 2400 ft. This research was conducted during four summers, 2005-2008. Data were collected from 26 commercial annual crop fields in Yolo, San Joaquin, and Tulare Counties. In several fields, the normal "continuous injection" practice was compared to an alternative "delayed injection strategy", in which irrigation water is allowed to flow down the furrow before beginning injection of the N fertilizer source into the irrigation water. This is a method that has the potential to avoid overapplication of N fertilizer on the head end or upper part of fields and to improve the spatial distribution uniformity of N fertilizers and other chemicals applied in the water, so-called fertigation or chemigation.

Most of the data were collected from fertigated fields using anhydrous ammonia (AA, 82-0-0), which is the least expensive N fertilizer and is commonly used by annual crop farmers for mid-season fertigation applications. At some sites we used UAN 32 (urea ammonium nitrate solution 32-0-0), which is also often used by farmers for fertigation.

We observed significant ammonia volatilization losses at many of the sites using AA, with an average loss of N of 13% and as high as 30%. Even at the lower end of the range of losses, the volatilization loss contributed significantly to non-uniformity of N rate applied during fertigation. UAN did not lead to volatilization losses. Temperature increases of the water from the head of the furrow to the end of the field on hot days – often 10 deg F or more – likely contributed to ammonia volatilization loss during AA fertigation.

With delays in injection until irrigation water had advanced 50% or more of the distance down the furrow (i.e., the field length), fertilizer N quickly caught up to the advancing irrigation water front and in a few cases, we were able to document improvements in the spatial distribution of the N application rate.

In some situations – long fields, lengthy irrigation sets (6 hours or more) – growers should consider converting from AA to a somewhat lower rate of the more expensive UAN in combination with the delayed irrigation strategy.

Other improvements in fertigation during surface gravity irrigation events are discussed in the full report.

Introduction

Injection of N fertilizer during furrow and border check irrigation is a common practice in row crop farming in California and elsewhere in the western U.S. It often is the only practical method for applying N to surface gravity irrigated crops during mid to late season. Its main limitation is the potential for non-uniform nutrient application – due in part to non-uniformity of the depth of water applied across fields that typically are one- quarter to one-half mile long in the direction of irrigation water flow. To the extent such non-uniformity occurs, there is under- and over-fertilization in different parts of the field. In the over-fertilized parts of the field, there is an increased potential for leaching of nitrate to groundwater. Also, growers may compensate for non-uniformity by increasing N fertilizer rates to ensure that all parts of the field receive adequate N, thus increasing production costs.

Practices that can increase irrigation water distribution uniformity (and thereby the uniformity of the water-run fertilizer) are well known and include reducing field length, use of surge irrigation, and compaction of furrow bottoms, e.g., with "torpedoes" pulled through the field behind a tractor. Unfortunately, these techniques are expensive, complicated, or effective only under a limited set of conditions. Therefore, they have not been widely adopted by farmers.

A practice for improving uniformity of the fertilizer that does not depend so much on improving the irrigation water distribution uniformity is to delay the injection of fertilizer until the water has advanced some distance down the furrow. Fertilizers and other chemicals injected after water has already advanced will catch up to the advancing water relatively quickly. This can result in an improvement in fertilizer distribution uniformity by avoiding presence of applied nutrients on the upper end of the field during the time of the most rapid infiltration.

We report here the results of on-farm experiments conducted in commercial row crop fields in the Central Valley during 2005-2007 and during grower water run N fertilizer applications in corn fields during 2008. Data were collected to determine the uniformity of N applied in one-dimensional transects (field-length furrows or border checks) in the direction of water flow during water-run fertilizer application events. At several of the locations in the 2005-2007 experiments, results were compared for continuously injected N fertilizer and delayed injection. The 2008 data were collected in a follow-up study designed to further document apparent N losses that we observed during the 2005-2007 studies. These follow-up studies were conducted as part of the project reported here but after the CDFA contract expired, and they were not supported with CDFA or any other outside funding. However, the results are provided here, because they provide additional documentation that some of experimental results of data collected in the early part of the season also occur in mid- to late-season applications and under normal growing conditions.

The acreage of row crops fertigated by surface gravity irrigation methods in California and the rates of N applied by this method are not known. The main crop that is fertigated by this method is corn. In recent years, silage corn has been grown on more than 400,000 acres annually in the Central Valley of California. However, much of this acreage receives dairy lagoon water, and typically growers lower the rates of commercial fertilizer, although the degree of reduction can vary over a wide range.

Also, other annual crops receive N fertilizer in the furrow or border check irrigation water, including grain corn, cotton, processing tomato, small grains, and vegetable crops. Very little dairy lagoon water is applied to these crops. We speculate that in the Central Valley, at least 500,000 acres of annual crops receive an average of 50 lb N/acre applied by this method. This would constitute 1.7% of the fertilizer N reported sold in 2007 (740,000 US tons N) in the state of California, and it equals about 3.5% of the N reportedly sold as anhydrous ammonia (81-0-0) and urea ammonium nitrate solutions (mainly 32-0-0), which are the fertilizer forms most commonly used for fertigation in furrow and border check systems.

In this report, we use interchangeably the terms “water run fertilizer application” and “fertigation” to describe application of fertilizer via furrow and border check irrigation water injection.

Work Description

This research was conducted in two phases. Phase 1 in 2005-2007 consisted of fertilizer injection timing studies in 11 annual crop farm fields during regular farmer irrigation events.

In Phase 2, measurements were made in 15 fields in Tulare County during the farmers’ regular fertigation activity, rather than in researcher-initiated furrow comparisons, as was done in the Phase 1 studies. In 13 of the 15 2008 sites, the corn crop was at an advanced stage of growth (i.e., tall), which is more typical of conditions when farmers usually fertigate. The 2005-2007 studies were all carried out at an early stage of crop development or in some cases in bush bean fields, and this was done to make it possible for researchers to see the advancing water during irrigation events. The Phase 2 study was conducted under conditions of the more typical mid- to late-season fertigation.

Site Selection

Grower cooperators and fields for Phase 1 2005-2007 (Table 1) were selected based on the following factors:

- Willingness of grower to irrigate three sets in a field, one per day on three days in succession with similar set lengths, water advance rates, and soil texture
- Irrigator able to maintain relatively constant water inflow rate during experiment
- Irrigation sets of at least 4-5 hours in length
- Willingness of grower to apply water-run fertilizer N at earlier crop growth stage than normal to accommodate research needs
- Willingness of grower to delay cultivation until after experiments
- Relatively uniform soil texture and field slope

At most locations, arrangements were made with local fertilizer suppliers and the grower to provide a commercial tank of anhydrous ammonia and to adjust the tank discharge rate each day to researcher specifications. This involved some guesswork in matching fertilizer discharge rate to irrigation application time; and we usually were not able to achieve identical N application rates on different sets (days) in the same field.

Table 1. Summary of farm field sites used in 2005-2007 for water-run fertilizer N treatment comparisons. AA=Anhydrous ammonia, UAN=urea ammonium nitrate 32% N solution.

Date	Site Code	County	Crop	Soil texture (0-8 inch depth)	Length of irrigation run (ft)	Soil pH	Fertilizer
2005							
6/6-7	PA05A	Tulare	Corn	Sandy loam/loam	1100	7.5	AA
6/13-14	SA	San Joaquin	Corn	Silty clay	900	7.0	AA
6/21-23	ST05	Tulare	Corn	Sandy loam/loamy sand	1800	7.1	AA
6/29-7/1	PA05B	Tulare	Corn	Sandy loam	1200	7.5	AA
7/25-27	VE	San Joaquin	Corn	Loam/sandy loam	1300	7.5	AA
2006							
6/6-8	ST06	Tulare	Corn	Sandy loam	1300	7.6	AA
6/27-29	SO	Tulare	Corn	Loam**	2400	7.6	UAN
7/18-20	RE	Tulare	Corn	Loam	1250	7.5	AA
2007							
7/18-19	CO	San Joaquin	Beans	Clay loam	1500	7.6	UAN
7/25-26	TR	Yolo	Beans	Loam/clay loam	1300	7.5	UAN
7/31-8/2	BA	Tulare	Corn	Clay loam	1200	7.5	AA

**Border check irrigation system, no-till

For Phase 2 in 2008, farmers in Tulare Co. were selected from county UC Cooperative Extension lists and also from contacts with local fertilizer retailers. Fifteen farmers who were planning to water run anhydrous ammonia on corn or other summer fodder crops were identified. Site characteristics and conditions at the time of the monitored fertigation event are shown in Table 2.

Table 2. Summary of farm field site characteristics used for monitoring of performance of farmer water run anhydrous ammonia applications in 2008.

Site #	Crop	Approx. canopy height (ft)	Canopy Cover %	Field Length (ft)	Irrigation Type (B=border F=furrow)	Air temp (deg F)
2008-1	Sudangrass	1	25-30	878	B	82
2008-2	Milo sorghum	2.25	60	1295	F	89
2008-3	Corn	6.5	100	2175	F	91
2008-4	Corn	9	100	1295	F reduced till	62
2008-5	Corn	4.5	95-100	1270	F, siphons	67
2008-6	Corn	6.5	100	2574	F, flat	88
2008-7	Corn	7.5	95-100	352	F	82
2008-9	Corn	7.5	95-100	1283	B, no till, flat	96
2008-8	Corn	7	100	1123	F	94
2008-10	Corn	7	95-100	1300	F	70
2008-11	Corn	7	95-100	1300	F	92
2008-12	Corn	7.5	100	2525	F+B	66
2008-13	Corn	5	75	1270	F+B	65
2008-14	Corn	8	95-100	502	F+B	92
2008-15	Corn	8	95-100	2000	F+B	98

Research Procedures

Fertilizer N Sources

At one location in 2006, a border-check irrigated field was fertigated with urea- ammonium nitrate solution instead of anhydrous ammonia. The fertilizer was supplied by a commercial fertilizer retailer and pumped into a standpipe following the grower's normal practice. At two locations in 2007, we used our own custom injection system with a small tank of urea ammonium nitrate solution and a pump that distributed the fertilizer (diluted as necessary) via a manifold to each of three individual furrows. The purpose of this was to allow comparison of continuous injection and delayed injection strategies in side-by-side furrows during the same irrigation set. Procedures for injection of anhydrous ammonia fertilizer and development of injection timing schedules injection timings were discussed with the cooperating growers, crop consultants, and fertilizer suppliers.

N Fertilizer Injection Timing – Experimental Treatments

At each site in Phase 1 at sites using anhydrous ammonia, we attempted to carry out one treatment each day with measurements taken on one or two adjacent furrows. Wheel and non-wheel furrows do not flow at the same rate, and we attempted to choose furrows with similar advance rates each day – usually the non-wheel row. Advance rate was measured using flumes placed in each of three furrows, and after water had advanced a short distance, we selected one of the furrows for data collection and water sampling. Treatments carried out on three days in sequence were (1) continuous fertilizer injection, i.e, inject N for the entire set, (2) delay injection until water reached approximately halfway down the length of the field, and (3) delay until water reached 75-80% of the length of the field. At most sites, the target N application rate was 40 to 60 lb N/acre. Target rates often were not achieved because of irrigation set time uncertainty and in some cases due to apparent lack of precision in fertilizer injection controllers.

Field Measurements, Sample Collection and Analysis

At each field, surface soil samples were collected at 9-12 locations in the field to determine the variability in soil texture (particle size by pipette method), pH, electrical conductivity, and sodium (SAR). During fertigation events, the following measurements were made:

(1) Water flow rate into individual furrows using standard RBC flumes and converting flume readings into flow rates in gallons/minute using the flume manufacturer's chart.
(2) Irrigation water advance times at markers placed at 100 ft intervals down the furrow to the end of the field;
(3) NH_4-N concentration in the irrigation water at the head of the furrow and at intervals along the length of the furrow approximately every 20-60 minutes during the irrigation set.
(4) At sites using anhydrous ammonia, water pH measurements were made.
(5) At some sites, furrow water temperature, air temperature, and wind speed at the furrow water surface were measured.

Furrow water and irrigation source water samples were collected into plastic bottles containing 1-2 milliliters of a strong acid in order to prevent loss of NH_3 to the air. Samples were stored in the field in an ice chest, then transferred to laboratory refrigerators (4 deg C) until analysis for N, usually less than one week after collection. Samples for pH measurement were collected without any preservative, and pH was measured on site with a temperature compensating portable pH meter and reference electrode.

NH_4 concentrations were measured in the laboratory on samples collected during anhydrous ammonia fertigation using a solid-state ion specific electrode. Total Kjeldahl N and nitrate were measured in the samples from urea-ammonium nitrate fertilized sites by the UC ANR Analytical Laboratory. Quality control was provided by use of analysis of replicates and diluted samples.

We also were able to determine when injected fertilizer N (at the anhydrous ammonia sites) had reached field inlet points and irrigation advance fronts in the field by monitoring water pH. Typically, as the fertilizer N began to reach a point in a ditch, furrow or valve, water pH would increase from 7-7.5 to 8-9, then within minutes, would increase to 9.5-10, as full N concentration was reached. This was useful for determining how quickly ammonia was reaching the advancing water in furrows with the delayed injection treatment. We also used lime-sulfur fertilizer as a visible tracer at a few of the sites. This has a milky appearance when injected into irrigation water (Schwankl, 2003).

Estimating N Application Rate Over the Length of Field

For each data set (at most sites, there were three sets of individual furrow data), we attempted to use advance times and furrow inflow rates to estimate an infiltration function. The infiltration function was then used to estimate the depth of water applied at several points along the length of the furrow. We then multiplied those water depths by the time-weighted sample N concentrations and the appropriate conversion factor to obtain total N application quantities (expressed as lb N/acre) over the whole fertigation episode.

In some of the data sets, the advance data were not well behaved, and we could not estimate an infiltration function. This occurred in some irrigation sets as a result of (1) large fluctuations in furrow inflow rates due to changing water levels in head ditches or stand pipes or pump malfunction, (2) variable slope in fields caused the advance to stall or speed up as it flowed down furrows, (3) fluctuation in advance due to variability in soil infiltration capacity across the field.

Where we could not estimate an infiltration function, we were still able to examine the change in N concentration and the rate at which fertilizer N would "catch up" with the advancing water front in the delayed injection treatment; however, we could not compare spatial distribution uniformity in the total N applied for the different injection timing treatments.

Research Results

Impact of anhydrous ammonia (AA) on irrigation water pH.

As expected, the injection of anhydrous ammonia (AA) into irrigation water greatly increased the water pH. At all sites, irrigation water (from wells and surface supplies) had a pH before fertilizer injection of 6.9-7.8. AA injection by bubbling it into irrigation water in ditches or standpipes resulted in pH values of 9.0 to 10.5 (Table 3). Ammonia volatilization is highly sensitive to pH (Jayaweera and Mikkelsen, 1990), because at high pH values, more of the ammonia is present as dissolved NH_3 gas, rather than as the non- volatile NH_4^+ ion. At each site, the observed pH varied with NH_4 concentration (data not shown), but combining data from different sites did not indicate a consistent relationship of the pH (or the pH increase) with NH_4 concentration.

Table 3. Anhydrous ammonia increases pH of irrigation water.

Site	pH of irrig water	pH of water + anhydrous ammonia	NH_4 concentration, mg N/L after AA injection
2008-1	7.3	9.9	27
2008-4	7.8	10.0	105
2008-5	7.4	10.0	133
2008-6	7.1	9.0	5
2008-9	7.3	10.1	31
2008-12	7.3	9.2	24
2008-13	7.8	10.2	125

Increase in temperature of irrigation water down furrow.

Water temperature is another factor that controls the rate of ammonia volatilization (Jayaweera and Mikkelsen, 1990). On warm days, cool irrigation water was significantly heated as it flows down the furrow as shown in Table 4 and Figs. 1 and 4. Water in furrows at the tail end of fields was >10 deg F warmer than at the head of the field in seven of the 2008 sites, including five sites with 95-100% canopy cover. This temperature gradient likely contributes to loss of volatile ammonia after irrigation water enters fields during fertigation with anhydrous ammonia.

Table 4. Summary results from 2008 fertigation measurements. In sites # 3 and 6, apparently NH_3 had either not reached the end of the field or had already been turned off, as indicated by low N concentrations and pH values.

Site #	Head end water temperature, Deg F	Tail end water temp	Change in Water temp (head minus tail)	Head end Avg pH	Tail end Avg pH	pH change (head minus tail)	NH4 concentration at head, mg N/L	NH4 at tail, as % of head end
2008-1	80	96	17	9.9	9.6	0.38	21	75
2008-2	79	93	14	10.2	9.3	0.90	27	52
2008-3	75	89	15	10.2	7.2	3.00	102	1
2008-4	72	65	-6	10.0	9.1	0.90	105	49
2008-5	68	67	0	10.0	9.8	0.20	133	70
2008-6	74	79	5	9.0	7.6	1.35	5	23
2008-7	70	74	4	9.9	9.5	0.40	30	104
2008-8	84	85	1	9.9	9.4	0.45	25	129
2008-9	69	82	12	10.2	9.3	0.90	31	79
2008-10	63	67	4	9.7	9.2	0.55	43	73
2008-11	64	88	24	9.4	9.1	0.30	48	72
2008-12	68	65	-3	9.2	9.1	0.05	24	105
2008-13	72	67	-6	10.2	9.7	0.50	125	64
2008-14	64	76	12	10.0	9.6	0.35	43	90
2008-15	64	80	17	9.7	9.1	0.60	43	45

Mean NH4 tail value -- sites 3 and 4 excluded; sites 7, 8, and 12 set to100%	**Avg**	**0.50**	**74**

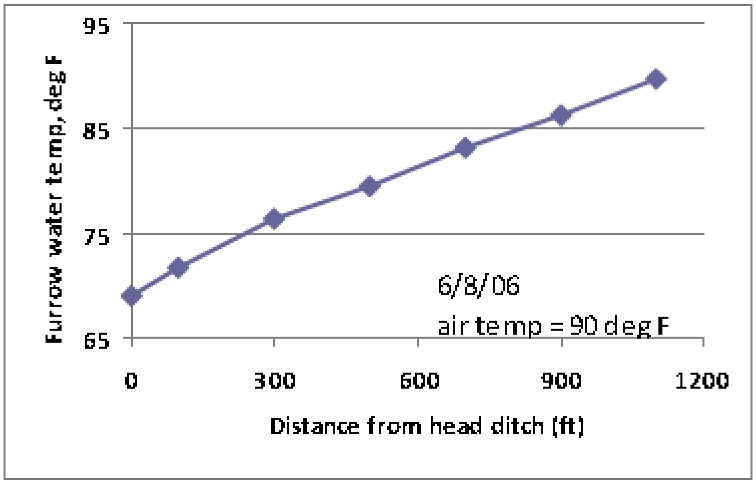

Fig. 1. Increase in furrow water temperature at increasing distance from head of field.

Ammonia volatilization loss during anhydrous ammonia fertigations

We did not attempt to directly measure ammonia volatilization loss from water during our research activities. However, the combined evidence – drops in NH4 concentration down the furrow and the pH data – indicate with certainty that ammonia is being volatilized. We observed this during the majority of anhydrous ammonia fertigation events monitored in this project. Fig. 2 summarizes data from 19 sites combined from Phase 1 and Phase 2 of the project. Three of the 19 sites showed no apparent volatilization. The lowest losses (using tail end/head end NH4 concentrations as the indicator) occurred at inflow NH4 concentrations of <40 ppm N; but there was not a consistent relationship, and high losses occurred at both high and low inflow NH4 concentrations (Fig. 2)

Additional evidence for ammonia volatilization is seen in the consistent drop in concentrations along the length of the furrow during anhydrous ammonia fertigation (see upper curves in Figures 3, 4, and 5), and the lack of such a decrease in fertigation using non-volatile urea ammonium nitrate as the fertilizer source (Fig. 6).

Delayed injection strategy to improve nutrient distribution uniformity during fertigations.

The results of our research shows very clearly that when injection of fertilizer is delayed until irrigation water has advanced down the furrows 30-70% of the total field length, the injected material very quickly catches up to the advancing water front. This is seen both with anhydrous ammonia and UAN fertigation. Examples are shown in Figs. 3, 4, and 6.

We usually were not able to calculate the distribution down the furrow (or border check) of N application rates following fertigation. This was due to the above-mentioned variability of water inflow rates and advance rates down furrows. A further problem was the inconsistent performance of the irrigation system from one set to the next. An example of this problem is shown in Table

5. The 3-4 irrigations made on the same day in the same part of a field with relatively uniform soil resulted in a wide range of set times (length of time required to irrigate one set of furrows), water depths applied and water distribution uniformities. With each set being used for a single irrigation injection treatment, it was difficult to compare injection strategies under similar irrigations.

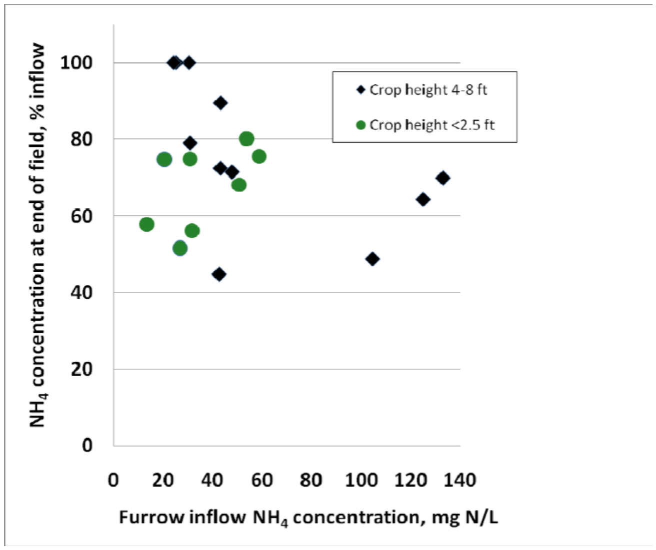

Fig. 2. Ammonium N concentration in irrigation water at upper and lower end of field during water-run anhydrous ammonia application at 19 on- farm locations during 2005-2008. Y axis values are water NH_4 concentrations at the bottom end of fields expressed as a percentage of the top end (inflow) concentration.

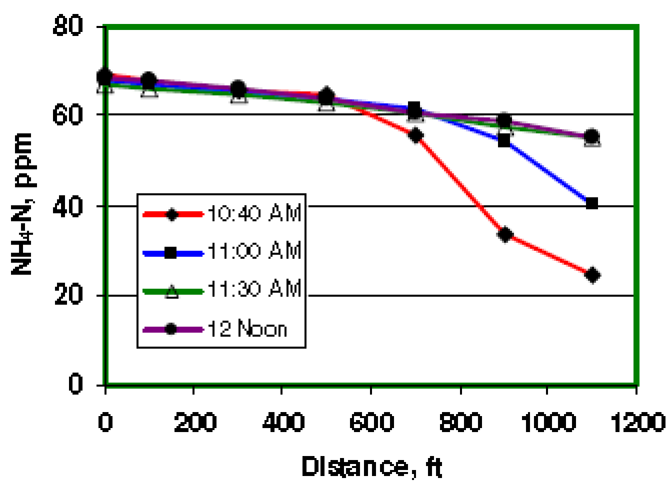

Fig. 3. NH_4 concentration in delayed injection treatment with anhydrous ammonia shows that N rapidly reaches advance front when injection is begun after water has advanced 50% of distance across field.. (Site RE in Table 1). Persistent decline in NH_4 concentration over length of furrow is due to NH_3 volatilization loss.

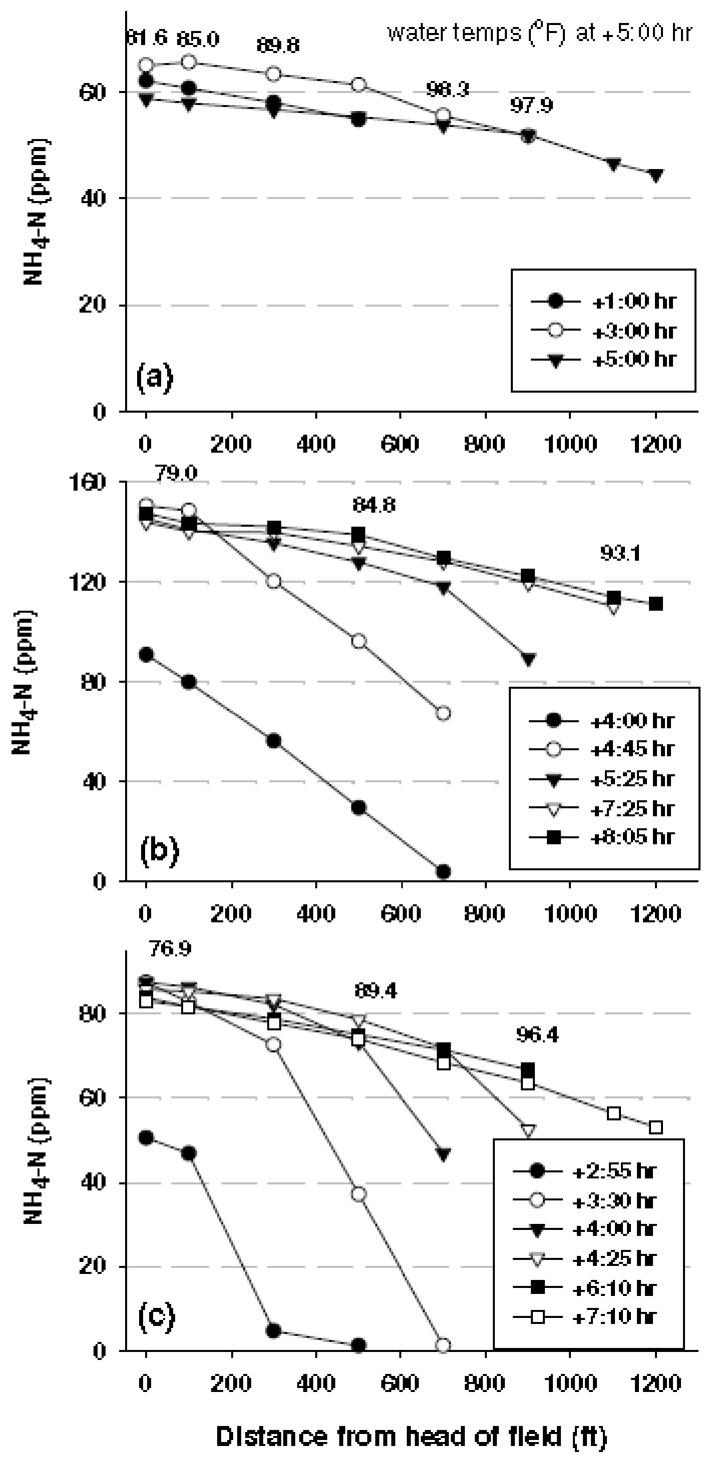

Fig. 4. Ammonium N concentrations in furrow water during anhydrous ammonia fertigations on three successive days. (a) continuous injection, (b) and (c) delayed until water advanced to 720-750 ft from head of furrow. Hours shown in legend indicate time elapsed since start of irrigation. (Site BA, Table 1

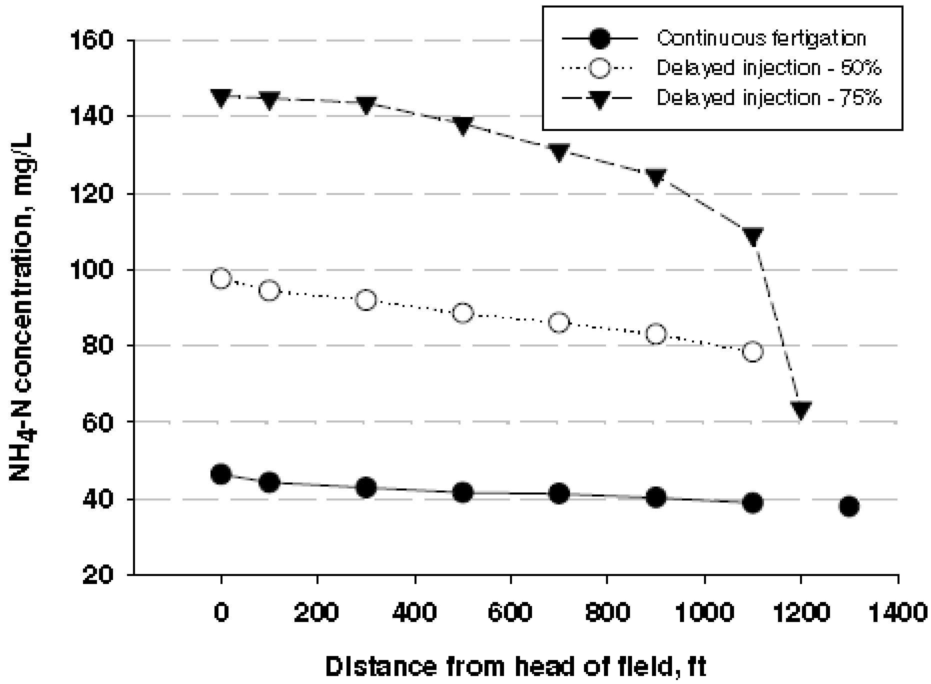

Fig. 5. Ammonium concentration in furrow irrigation water for three anhydrous ammonia N timing strategies. Data from site ST06 (see table 1) on three different irrigation sets on consecutive days.

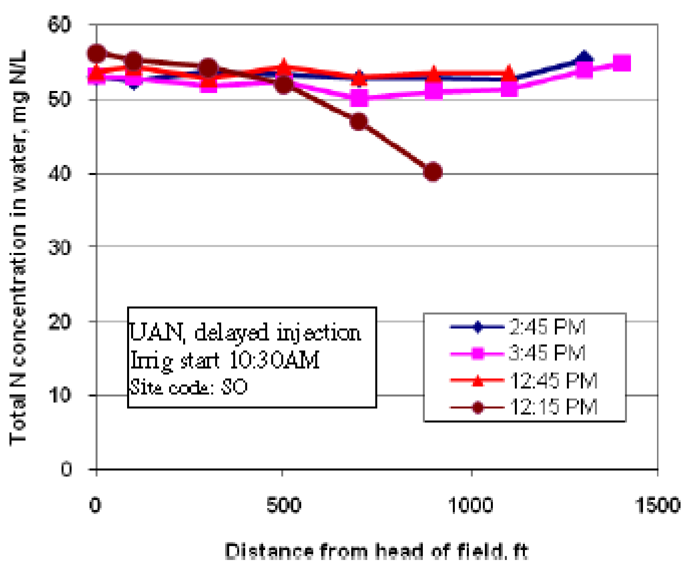

Fig. 6. Total N concentration in furrow water during fertigation with non-volatile N fertilizer material.

Table 5. Example of calculated average depth of water applied and distribution uniformity (DU=lowest quarter as percent of mean depth). Each row of data is an estimate based on single furrow measurements. See Table 1 for site descriptions.

Date	Set Time (hrs)	Applied Water (in)	DU (%)
Site ST-06			
6/6/06	5	5.1	85
6/6/06	6	6.2	90
6/6/06	7	7.2	92
6/7/06	5	5.1	71
6/7/06	6	6.2	79
6/7/06	7	7.2	83
6/7/06	8	8.2	86
6/8/06	5	4.8	54
6/8/06	6	5.8	68
6/8/06	7	6.7	75
6/8/06	8	7.7	79
Site RE			
7/19/06	9	10.4	55
7/19/06	10	11.6	63
7/19/06	11	12.8	73
7/19/06	12	13.9	72

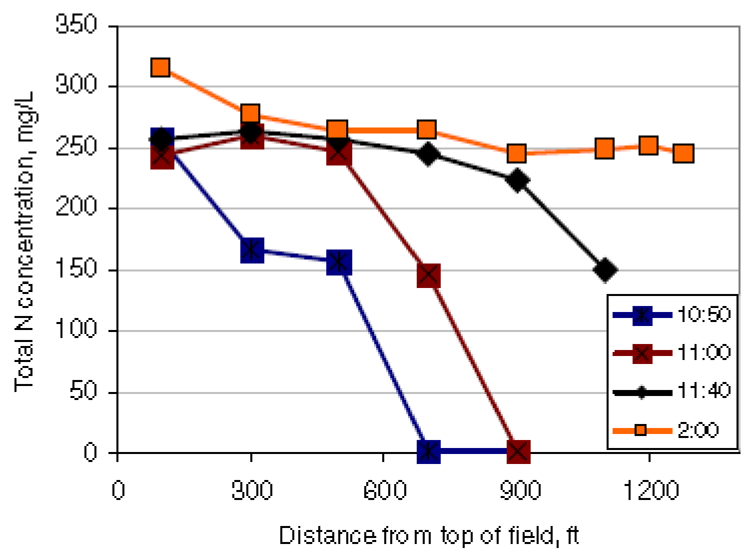

Fig. 7. Total N concentration in delayed injection treatment with UAN fertilizer shows that N rapidly reaches advancing irrigation water front. Increased concentration at top of field at 2 pm is due to drop in inflow rate. (Site TR in Table 1)

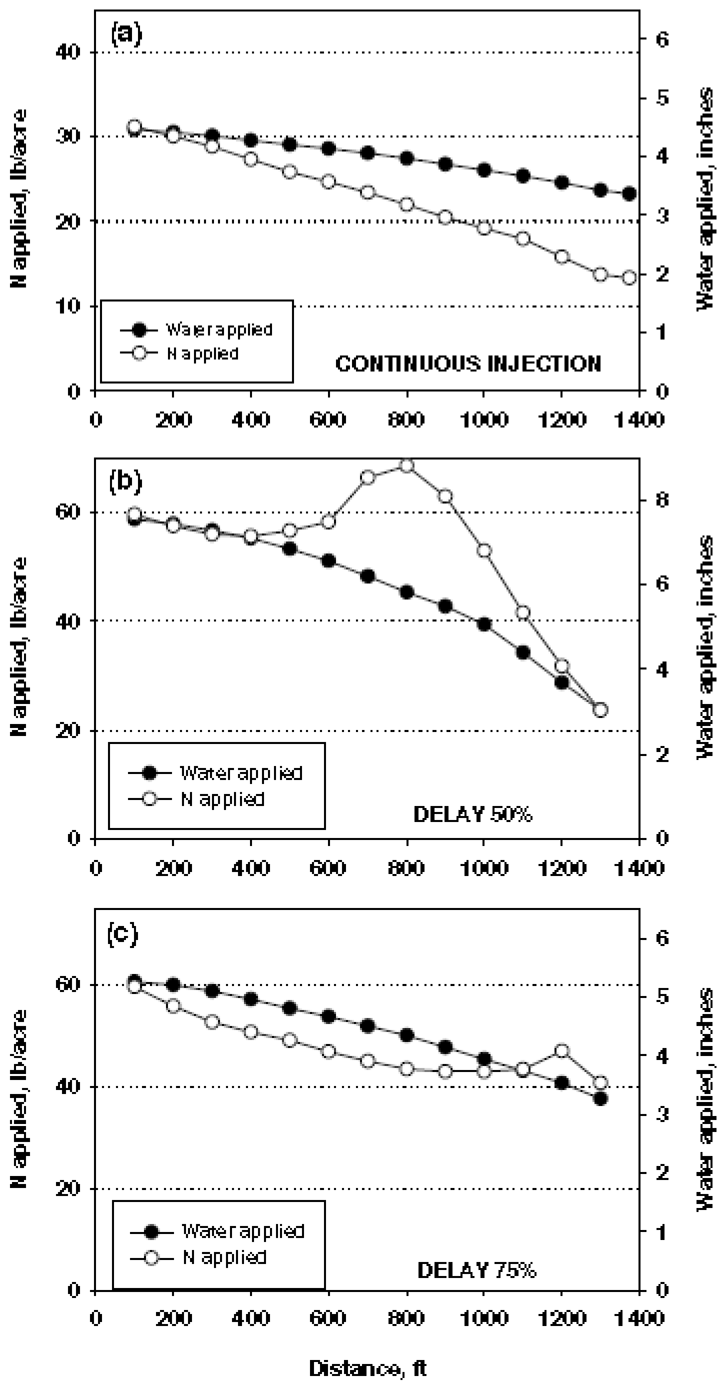

Fig. 8. Irrigation and N application spatial distribution measured down length of single furrow in sandy loam soil for (a) continuous fertilizer injection, (b) delayed injection until water advanced 50% of field length, and (c) delayed until water advanced 75% of field length. X axis values are distance down furrow.

A comparison of N and water distribution resulting from different injection timing is shown in Fig. 8. The data in this figure provides evidence for the potential for greater uniformity with delayed injection. Both of the delayed injection strategies provided greater uniformity than the continuous injection in the upper half of the field. Also with continuous injection, the tail end of the field received less than half of that applied to head end of the field. With the 50% delay treatment, the upper half of the field was more uniformly fertilized, but the lower end was not as uniform as with continuous injection.

One consideration is that with delayed injection, a higher concentration of N must be used to achieve the target N rate, and this may lead to somewhat higher ammonia volatilization loss, which itself contributes to spatial non-uniformity.

Conclusions and Recommendations

The following conclusions and recommendations are drawn from our experimental results, from consideration of the technical literature on this topic, and from our observations of grower and irrigator practice at our on-farm research sites in the Central Valley.

1. Delaying injection of water-run fertilizers until irrigation water is advanced 30- 50% of the distance across the field may provide more uniform spatial distribution of the fertilizer nitrogen compared to continuously injected fertilizer, especially under the following conditions:
    a. Long fields (one-quarter mile or longer)
    b. Soil with rapid infiltration capacity due, for example, to coarse texture
    c. Slow advance of water across field resulting from shallow field slope, low water inflow rate, and high soil infiltration capacity

2. In nearly every fertigation event where anhydrous ammonia was used, we observed declining concentrations of NH_4 in irrigation water with increasing distance from the field inlet point. At the tail end (bottom) of fields, we observed NH_4 concentrations from 10 to 50% lower than at the irrigation water inlet point. In a follow-up study in 2008 with more mature crop canopies, we observed a similar range of concentration decreases. The average decrease for all project data (19 fertigation events) was 26%, which is approximately equivalent to a loss of 13% of the total quantity of fertilizer N applied during the single fertigation event. The magnitude of apparent loss as a percentage of the applied N was not related to the target application rate or N concentration at the field inlet point.

3. Loss of volatile NH_3 during fertigation with anhydrous ammonia can exacerbate poor N distribution uniformity and thus increases the justification for using more expensive non-volatile N sources such as urea ammonium nitrate solutions. In addition to the contributing factors listed in recommendation #1, three additional factors can increase NH_3 volatilization and therefore increase the justification for use of non-volatile N fertilizer sources:
    a. High temperatures (>90° F) during fertigation events

b. Soil pH values above 8.0

c. High wind speed (>10-15 mph) or combinations of wind, small crop canopy and bed/furrow geometry that results in exposure of the surface of irrigation water to the high winds

4. In highly permeable soils, the mobility of urea and nitrate (which constitutes 75% of the total N in most urea-ammonium nitrate fertilizer solutions) can result in high N leaching losses at the upper (head) end of fields during fertigation events, particularly where irrigation water distribution uniformity is poor. In contrast, significant leaching of anhydrous ammonia N during fertigation is rarely a problem. For this reason, a delayed injection strategy should be considered when urea-ammonium nitrate is used in fertigation of highly permeable soils.

5. Where soil water intake rate varies greatly among furrows, e.g., wheel vs. non- wheel rows, irrigators sometimes adjust siphon pipes or gate openings for the purpose of equalizing water advance rates. While this improves the uniformity of the advance rate among furrows, it does not improve uniformity in the depth of water applied; and it can make the fertigation N application rate even more non- uniform. A delayed injection strategy alone will not address this particular cause of non-uniform N rates.

6. Regardless of fertigation injection timing (continuous or delayed), attention to fertilizer tank output settings is needed. In some situations, fertilizer tank settings should be adjusted from one set to the next based on the observed irrigation system performance, which can deviate from the anticipated behavior depending on soil conditions, land slope, temperature, etc. Using a constant fertilizer tank output setting based on an assumed typical irrigation rate, such as “1 acre per hour”, may lead to substantial deviation from the target N application rate.

7. Where anhydrous ammonia is used for fertigation, the delayed injection approach and adjustment of tank settings during or between irrigation sets in a field may be impractical. It will not always be possible for fertilizer supply company employees to provide this more frequent on-site service, and for farm personnel to make the necessary adjustments requires formal training and certification in the handling of this extremely hazardous material.

8. When fertigating with anhydrous ammonia, an inexpensive pocket pH combination electrode is very useful for checking for presence of NH_4 in irrigation water. We observed that water pH always increased from 7-8 to 9-10 when anhydrous ammonia had been injected, making it easy to determine if the ammonia had arrived at a given location in the head ditch, valve, or field. Also, during fertigation with anhydrous ammonia, the observed differences in pH between the inlet point at the top end of the field and the bottom of the field (e.g.,
10.0 at the top vs. 9.5 at the bottom) corresponded to differences in the NH_4 concentration as measured later in the laboratory.

Project Outreach Activities

Audience totals were approximately 500 growers, crop consultants and ag chem suppliers in the following presentations.

1. November 30, 2005 Project summary in 2005 Thirteenth Annual CDFA FREP Conference Proceedings. Salinas, CA "Improving water-run nitrogen fertilizer practices in furrow and border check-irrigated crops". (Distributed to approximately 100 in attendance)
2. February 7-8, 2006. Oral presentation at California Plant & Soil Conference, Visalia CA. "Distribution of water-run nitrogen fertilizer in furrow-irrigated row crops". (80 attending)
3. April 4, 2006. Oral presentation to project cooperating growers. Tulare, CA.
4. November 29, 2006. Oral presentation at Fourteenth Annual CDFA FREP/Western Plant Health Association nutrient management seminar, Monterey CA; also summary in conference proceedings. "Improving water-run nitrogen fertilizer practices in furrow and border check-irrigated crops". (approx 100 attending)
5. November 27-28, 2007. Project summary in Fifteenth Annual 2007 CDFA FREP Conference Proceedings. Tulare, CA. "Improving water-run nitrogen fertilizer practices in furrow and border check-irrigated crops". (Distributed to approximately 100 in attendance)
6. February 27, 2008. Oral presentation at UC Cooperative Extension Northern San Joaquin Valley grower meeting, Wesley CA. "Maximizing fertilizer N use efficiency in row crops" (approx. 80 in attendance)
7. June 2, 2009. Oral presentation at Green Acres-Blue Skies II: Ag & Air Quality— Working Towards Common Solutions conference, Davis CA. "Ammonia loss during fertigation". (approx. 60 in attendance).

Publications

1. Pettygrove, S, L.J. Schwankl, C.A Frate, K.L. Brittan, and M. Canevari. 2006.
Distribution of water-run nitrogen fertilizer in furrow-irrigated row crops. pp. 97- 103 *In* Proceedings, California Plant and Soil Conference. (Visalia, CA. Feb. 7-8, 2006). California Chapter American Society of Agronomy. http://calasa.ucdavis.edu/.

2. A peer-reviewed UC bulletin is in preparation.

Technical literature on fertigation in surface gravity irrigation systems

Burt, C., K. O'Connor, T. Ruehr. 1998. Fertigation. Irrigation Training & Research Center. California Polytechnic State University, San Luis Obispo, CA.

Chapman, H.D. 1956. The application of fertilizers in irrigation water. Better Crops with Plant Food. 40:6-10, 43-47.

Denmead, O.T., J.R. Freney, and J.R. Simpson. 1982. Dynamics of ammonia volatilization during furrow irrigation of maize. Soil Sci. Soc.Am. J. 46(1):149-155.

Fishbach, P.E. 1971. Applying fertilizer in the irrigation water. Pub. E.C. 71-792.

University of Nebraska, Lincoln, NE. Jayaweera, G.R. and D.S. Mikkelsen. 1990.

Ammonia volatilization from flooded soil systems. A computer model: I. Theoretical aspects. Soil Sci. Soc. Am. J. 54:1447-1455.

Leavitt, H. 1957. The application of liquid gaseous fertilizer. p. 85-95. *In* Natl. Joint Comm. of Fert. Appl. Proc. Natl.
Plant Food Inst., Washington, D.C. (as cited in Gardner, B.R. and R.L. Roth. 1984. Applying nitrogen in irrigation waters. p.493-506. *In* R.D. Hauck (ed.) Nitrogen in crop production. Am. Soc. of Agron., Madison, WI.)

Schwankl, L.J. 2003. Improving Water and Nutrient Management Practices on Dairies in the Southern San Joaquin Valley. August, 2003. Final Report to Prosser Trust. (Report available from author)

Strelkoff, T.S., A.J. Clemmens, H. Perea-Estrada. 2006. Calculation of non-reactive chemical distribution in surface fertigation. Agric. Water Management 86:93-101.

Warnock, R.E. 1966. Ammonia application in irrigation water. p.115-124. *In* M.H. McVickar, W.P. Martin, I.E. Miles, and H.H. Tucker. Agricultural anhydrous ammonia: Technology and use. Agric. Ammonia Institute, Memphis, TN; Am. Soc. of Agron., Madison, WI.

ACKNOWLEDGEMENTS. The authors of this report are grateful for the diligence and technical skill of UC Davis Staff Research Associate J.Y. Deng in support of this project.