Response of Lettuce to Water and Nitrogen on Sand and the Potential for Leaching of Nitrate-N

Charles A. Sanchez¹

Yuma Agricultural Center, 6425 West 8th Street, Yuma, AZ 85364

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Abstract. The low desert region of Arizona is the major area of lettuce (*Lactuca sativa* L.) production in the United States during the winter. Lettuce is commonly grown on the loam, clay loam, and clay soils of the alluvial river valleys. There is some interest in moving a portion of the vegetable production onto the sandy soils of the terraces (mesa) above the alluvial river valley to partially relieve the intensive production pressure being placed on lands in the valley. Of major concern in these sandy soils is water and N management. Studies were conducted during two seasons to evaluate the response of crisphead lettuce to sprinkler irrigation and N fertilizer and to evaluate the potential for leaching of nitrate-N on a coarse-textured soil. Lettuce yields increased in response to water and N, and were maximized by 55 cm of water and 271 kg·ha⁻¹ N in 1991–92 and 76 cm water and 270 kg·ha⁻¹ N in 1992–93. These water and N rates exceeded those typically required on finer-textured alluvial valley soils. At N and water rates required for maximum yields, 88% and 77% of the applied N was not recovered in the aboveground portions of the plant during the 1991–92 and 1992–93 seasons, respectively. Overall, data for the amount of N fertilizer not recovered, estimates of nitrate-N leaching determined during one growing season, and analysis of soil samples collected after harvest indicate the potential for large N leaching losses on this coarse-textured soil. Alternative production methods that enhance water and N use efficiencies, such as drip irrigation and/or the use of controlled-release fertilizers, should be considered on this sandy soil.

The low desert region of southwestern Arizona and southern California is the major source of cool-season vegetables during the winter months. Favorable winter temperatures in this region allow for production of a continuous supply of produce from November through April. The area of land utilized to produce winter vegetables has increased during the past 10 years. For example, in Yuma County, Ariz., alone, vegetables harvested from 13,000 ha in 1983 had a farm gate value of ≈\$63 million. By 1993, vegetables produced on 29,000 ha had a farm gate value exceeding \$200 million (Arizona Agriculture Statistics, 1995).

Lettuce occupies >70% of the land area used for vegetables in southwestern Arizona. Traditionally, most of the lettuce from this region is produced on the alluvial loam, clay loam, and clay soils of the Colorado and Gila River valleys. However, with the expansion of the vegetable industry in this region there has been less rotation to other crops, increased disease pressure, increased soil physical problems such as compaction, and intense economic competition for available land.

Accordingly, there is interest in moving some vegetable production onto the sandy

soils of the Yuma Mesa (terrace area above the alluvial valley) to partially relieve the pressure on land in the valleys. The soils of the Yuma Mesa are coarse textured (>95% sand) and considered marginal for vegetable production. Of major concern in these sandy soils are water and N management. An understanding of the interaction between irrigation and N fertilization is needed for developing management practices that optimize crop yield and quality and maximize efficiency of water and N use. The objectives of this study were to evaluate the response of iceberg lettuce to sprinkler-applied water and N fertilizer and to evaluate the potential for leaching of nitrate-N on a coarse-textured soil.

Materials and Methods

These studies were conducted on a soil mapped as a Superstition sand (Typic Calciorthid, sandy, mixed, hyperthermic 95% sand), which is typical of the coarse-textured soil on the Yuma Mesa. The experiments were irrigated using a modified self-moving lateral sprinkler irrigation system (Roth and Gardner, 1989) that applied five levels of water and five levels of N (liquid NH₄NO₃) in specified combinations. The treatments were arranged in a central composite rotatable design (Cochran and Cox, 1960), which predicts a response surface of the quadratic form. Briefly, the central composite design for this two-factor experiment called for 13 data points. These include the four points of a traditional 2 × 2 factorial, four additional points set geometrically outside the factorial square, and five

repeated measures in the center. For this experiment, a total of nine water and N combinations were defined by this statistical design, with the center treatment replicated five times to give a total of 13 plots (Table 1). Each plot was 12 m long and 4.1 m wide (four two-row flat beds on 1.02-m centers). Two blocks of the experimental design were planted to give a total of 26 plots. The lateral irrigation system contained three spray lines that ran along the 13 plots. One spray line applied water to the randomized treatments of one block and a second spray line applied water to treatments of a second block randomized differently. The third spray line was used for uniform irrigation during germination and stand establishment.

Colorado River water with an average electrical conductivity (ECw) of 1.4 dS·m⁻¹ and an average nitrate-N concentration of 0.2 mg·L⁻¹ was used for all irrigations. Uniform irrigation was applied for 16 d after planting (DAP) in 1991–92 and 38 DAP in 1992–93 to establish stands before irrigation and N treatments were imposed (Fig. 1). A longer time was required for stand establishment in 1992–93 because of the cooler temperatures associated with a later planting date. After treatments were initiated, water was generally applied twice weekly during the growing period. The amount of water applied for the 100% consumptive use (CU) level in each irrigation was estimated from Erie et al. (1981). Nitrogen applied at the 100% level each week was based on existing fertilizer recommendations for lettuce but modified with midrib nitrate-N analysis (Doerge et al., 1991) and experience gained. Other irrigation and N levels were proportional to the central treatment as specified by the central composite design.

The amount of water applied during each irrigation was calculated from the flow rate and the time required for the irrigation system to move a known distance, and controlled by the use of nozzles of various sizes. All plots

Table 1. Water and N treatments used in study.

Treatment ^a	Water ^b applied (%)	Nitrogen ^c applied (%)
1	50	100
2	65	53
3	65	147
4	100	33
5	100	100
6	100	167
7	135	53
8	135	147
9	150	100

^aWater applied at the 100% level each week after stand establishment was estimated after Erie et al. (1981). Other treatments were applied in the proportional amounts indicated.

^bNitrogen applied to the 100% level each week after stand establishment was based on existing fertilizer recommendations and modified with midrib nitrate-N analysis and experience gained. Other treatments were applied in the proportional amounts indicated.

^cThe central composite design called for treatment 5 to be replicated 5 times down the row to give a total of 13 plots per line. The whole treatment structure was blocked and re-randomized down two lines to give a total of 26 plots.

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¹E-mail: sanchez@ag.arizona.edu

received uniform irrigation until stand establishment. The total amounts of water applied for the uniform irrigations were 9.8 cm in 1991–92 and 8.7 cm in 1992–93. After plant stands were established, the volume of water applied was generally proportional to the 100% CU treatment (Fig. 1). Deviation in water received did occur when rainfall fell, such as occurred at 96 DAT in 1992–93. The total amounts of water received by the crop for the 50%, 65%, 100%, 135%, and 150% CU treatments were 30.1, 34.0, 43.2, 52.4, and 56.3 cm in 1991–92 and 34.4, 39.3, 50.6, 61.9, and 66.8 cm in 1992–93. These totals include 7.2 cm and 9.6 cm of rainfall in 1991–92 and 1992–93, respectively.

Stainless-steel orifice plates and a positive displacement injector pump were used to meter the required amount of liquid NH_4NO_3 fertilizer into the irrigation water in each plot. In 1991–92, no N was applied prior to stand establishment. Because of the longer time period required to establish stands in 1992–93, three uniform applications of N totaling 22 $\text{kg}\cdot\text{ha}^{-1}$ were applied to all plots. After stand establishment, cumulative N fertilization rates were proportional to the 100% N treatment (Fig. 1). Nitrogen applied for the 33%, 53%, 100%, 147%, and 167% N treatments totaled 84, 134, 253, 372, and 423 $\text{kg}\cdot\text{ha}^{-1}$ in 1991–92 and 103, 151, 265, 380, and 428 $\text{kg}\cdot\text{ha}^{-1}$ in 1992–93.

Phosphorus as triple superphosphate was broadcast at the rate of 224 $\text{kg}\cdot\text{ha}^{-1}$ and disked into the soil before each planting. Based on a lack of positive responses to K fertilization, the Univ. of Arizona makes no K fertilizer recommendation for desert lettuce (Kerns et al., 1999), and no K fertilizer was applied in these experiments.

Two rows of 'Vango' lettuce were planted every 1.02 m. This arrangement is typically used on raised two-row beds on 1.02-m centers, but we used a flat-bed culture to facilitate the use of the overhead sprinkler system. Planting dates were 22 Nov. 1991 and 21 Dec. 1992. Plants were thinned at the four-leaf stage to an intra-row spacing of 0.3 m to give an approximate population of 62,000 plants/ha. Harvest dates were 1 Apr. 1992 and 8 Apr. 1993. Mature lettuce was harvested from 6.2 m of two rows (one flat bed) in the center of each plot. Total aboveground weight was determined immediately and marketable weights were determined after trimming and grading.

Midribs were collected periodically over each season to assess N content and guide N fertilization practices. At maturity, whole aboveground plant subsamples were collected from each plot. Plant material was dried at 65 °C for 48 h and ground to pass a 0.417-mm (40-mesh) screen. Nitrate-N in midrib tissue was determined potentiometrically after extraction with a $\text{Al}_2(\text{SO}_4)_3$ buffer solution (Baker and Smith, 1969). Total N was determined using a micro-Kjeldahl method (Bremner and Mulvaney, 1982). Total dry-matter and N concentration values were used to calculate total N accumulation. The amount of N that was applied but not recovered was calculated by subtracting N accumulated in the aboveground

Fig. 1. Cumulative irrigation and rainfall received by (A, B), and N applied to (C, D), lettuce during 1991–92 (A, C) and 1992–93 (B, D). Uniform irrigation was applied through stand establishment. Thereafter, irrigation rates were 50%, 65%, 100%, 135%, and 150% consumptive use (CU) estimates. Uniform N totaling 22 $\text{kg}\cdot\text{ha}^{-1}$ was applied in 1992–93. All N applications in 1991–92, and N applications after stand establishment in 1992–93, were 33%, 53%, 100%, 147%, and 167% the estimated requirement.

Fig. 2. Effect of water and N on marketable yield (A, B), and N accumulation of aboveground tissue (C, D), of lettuce during the 1991–92 (A, C) and 1992–93 (B, D) growing seasons.

tissue from the total N applied.

Estimates of nitrate-N leaching were determined following each irrigation or rainfall event after the first N fertilization in the 1992–93 growing season. Ceramic suction cups were installed at the 50-cm soil depth on the assumption that nitrate-N that moved to or below this depth would not be available for uptake by lettuce. Soil solution samples were obtained by applying and maintaining a suction of ≈ 0.05 MPa for 24 h. The leaching fraction (LF) was estimated using neutron probe soil moisture measurements as follows:

$$LF = IW + SMD,$$

where IW is the amount of water received as irrigation or rainfall and SMD is soil moisture deficit. The SMD was calculated by subtracting the soil moisture content immediately before irrigation (SM_{ix}) from the soil moisture content at field capacity (SM_{FC}). The SM_{FC} was estimated by repeated measurements of soil moisture with a neutron probe 5 h after irrigation. Nitrate-N concentrations in the soil solution samples were analyzed using the automated hydrazine method (Eaton et al., 1989). Nitrate-N leaching loads were calculated for each time interval by multiplying the leaching fraction by nitrate-N concentrations of samples collected at the 50-cm soil depth. Total nitrate-N leaching was calculated as the sum of all leaching events.

Soil samples were also collected from each plot in 1992–93 to a depth of 90 cm (individual samples representing 0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm) to determine residual soil nitrate-N in the soil. Five cores were collected from each plot, air-dried, and composited. Soil nitrate was determined by steam distillation after extraction with 2 M KCl (Keeney and Nelson, 1982).

Crop production functions were fitted to quadratic equations using SAS-REG and SAS-RSREG (SAS Institute, 1989). Marketable yield, N recovered and not recovered in the aboveground tissue, and N leached below the rooting zone were regressed on total water received (irrigation plus rainfall) and N fertilizer applied.

Results and Discussion

Marketable lettuce yields were increased by both water and N in both growing seasons (Fig. 2). Yields were maximized by 55 cm water and 271 kg·ha⁻¹ N in 1991–92 (41.7 Mg·ha⁻¹) and 76 cm water and 270 kg·ha⁻¹ N in 1992–93 (38.9 Mg·ha⁻¹) (Table 2). These yields were a little lower than those typically obtained on the fine-textured alluvial valley soils under favorable conditions.

The amount of water predicted for maximum yield was at the upper end of the treatment range in 1991–92 and slightly exceeded the treatment range in 1992–93. In both experiments, the amounts required exceeded the 22 cm estimate of Erie et al. (1981). Lower irrigation efficiencies on this sandy soil probably indicated that water storage was limited and much of the water infiltrated below the rooting zone. Leaching fractions were espe-

Table 2. Equation constants for yield response of lettuce, N recovered by lettuce, N applied but not recovered, and N leached below lettuce root zone.

Year	Equation constants ²						Required for maximum yield	
	b ₀	b ₁	b ₂	b ₃	b ₄	b ₅	Water (cm)	N (kg·ha ⁻¹)
<i>Marketable yield</i>								
1991–92	−85.0	2.43	0.433	−0.0155	−0.00050	−0.00273	0.55	55
1992–93	−119.7	2.41	0.504	−0.0120	−0.00063	−0.00221	0.62	76
<i>N recovered by plant</i>								
1991–92	−104.9	3.35	0.442	−0.0246	−0.00036	−0.00443	0.57	---
1992–93	−134.1	2.54	0.755	−0.0089	−0.00093	−0.00403	0.47	---
<i>N applied not recovered</i>								
1991–92	104.9	−3.35	0.558	0.0246	0.00036	0.00443	0.99	---
1992–93	134.1	−2.54	0.245	0.0089	0.00093	0.00403	0.98	---
<i>N leached</i>								
1992–93	130.5	−5.44	−0.412	0.0720	0.00041	0.00481	0.79	---

²All equations follow the form $y = b_0 + b_1W + b_2N + b_3W^2 + b_4N^2 + b_5WN$, where b_0 through b_5 are constants and W = water and N = nitrogen.

Fig. 3. Effect of water and N on N that was applied but not recovered in the aboveground tissue of lettuce plants during 1991–92 and 1992–93 growing seasons.

cially high during the early growth period when crop consumptive use was minimal, and during heavy rainfall events when the amount of water received could not be controlled. For example, at 96 DAP in 1992–93, a rainfall occurred shortly after an irrigation event, and at the higher irrigation regimes (≥ 100 CU) most of the water received (or nearly an equivalent amount previously stored in the root zone) percolated below the root zone.

The amounts of N predicted for maximum yield were near the center of the treatment range in both experiments. This is generally consistent with the average, seasonal, midrib nitrate-N values; these exceeded the critical concentration of $8000 \text{ mg} \cdot \text{kg}^{-1}$ at N rates equal to or greater than those used in our central treatments, but were below the critical concentration at lower N rates (data not shown). Nevertheless, the amounts of N predicted for maximum yield exceeded lettuce N fertilizer rates typically required on the finer-textured soils of the alluvial valleys (Doerge et al., 1991; Gardner and Pew, 1972, 1974). Rates for maximum lettuce yield seldom exceed $200 \text{ kg} \cdot \text{ha}^{-1}$ on alluvial valley soils. Lower N efficiencies on this sand were probably associated with leaching by irrigation or rain water that infiltrated below the root zone. Data for the amount of N recovered in the aboveground tissue (Fig. 2), and the amount of N that was applied but not recovered in such tissue (Fig. 3), show the potential for large leaching losses on this coarse-textured soil. At water and N rates for maximum yield, N recovered in the aboveground tissue averaged $32 \text{ kg} \cdot \text{ha}^{-1}$ in 1991–92 and $61 \text{ kg} \cdot \text{ha}^{-1}$ in 1992–93. These recoveries are lower than those we typically observe on fine-textured valley soils. At the N and water rates required for maximum yield, 88% and 77% of applied N was not recovered in the aboveground tissue during the 1991–92 and 1992–93 seasons, respectively.

Actual estimates of nitrate-N leaching in 1992–93 indicated increasing losses to irrigation and N (Fig. 4). The estimated amount of N leached was $150 \text{ kg} \cdot \text{ha}^{-1}$ at water and N rates required for maximum yield. Thus, $>55\%$ of the N applied leached below the rooting zone during the growing season. These data are further corroborated by analysis of soil samples collected after harvest. Note that residual $\text{NO}_3\text{-N}$ generally decreased in the upper soil profile but increased in the lower profile with increased irrigation rate (Fig. 5).

Furthermore, $\text{NO}_3\text{-N}$ in the lower soil profile also generally increased with N fertilization. Although I cannot adequately explain the low surface nitrate-N levels at the $428 \text{ kg} \cdot \text{ha}^{-1}$ N rate in 1992–93, one possibility is a high late-season uptake of N in this treatment.

Overall, results from this study indicate that lettuce can be produced on the coarse-textured soils of the Yuma Mesa but with greater inputs of water and N than are typically required on the finer-textured soils of the alluvial valley. In previous experiments with broccoli (*Brassica oleracea* L. Italica Group) and cauliflower (*Brassica oleracea* L. Botrytis Group), we found that economic optimal yields were $>99\%$ of maximum yields over a wide

1992-1993

Fig. 4. Effects of water and N on nitrate-N leached below the rooting zone of lettuce during the 1992–93 growing season.

Fig. 5. Effects of three irrigation regimes with N application constant (A), and three fertilization rates with water received constant (B), on residual nitrate-N in the soil profile after lettuce harvest.

range of prices for water and N and of crop values (Sanchez et al., 1996). Lettuce crop value and cultural practices are similar to those for broccoli and cauliflower, and production on sand is probably economically feasible. However, results from these studies show a potential for large amounts of nitrate-N leaching on the coarse-textured soil of the Yuma Mesa using the production system evaluated. A recent groundwater quality survey in the Yuma area showed that, while most wells sampled in the Colorado and Gila River Valleys had very low nitrate-N concentrations, some wells on the adjacent Yuma Mesa were close to or exceeded the Environmental Protection Agency (EPA) standard of $10 \text{ mg} \cdot \text{L}^{-1}$ (U.S. Bureau of Reclamation, 1991). Currently, the Yuma Mesa soils are primarily used for the production of alfalfa (*Medicago sativa* L.) and citrus. Vegetables would probably

displace alfalfa, which currently receives very minimal amounts of N fertilizer, relying largely on biological N fixation. The possibility that expansion of the vegetable industry onto the sandy mesa soils would increase the nitrate-N content of groundwater should be considered. Perhaps alternative production methods that enhance water and N use efficiencies, such as drip irrigation (Thompson and Doerge, 1996), should be considered. Another viable option for improved N management on sands might be controlled-release N fertilizers, provided N release rates closely correspond to crop demand.

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