Evaluation of Sprinkler Fertigation of Vegetables

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Report submitted to the Arizona Specialty Crops Council
August, 2014

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Chapter 1. Project Summary

1.1 Project background and summary of results

Vegetable production in the Lower Colorado River Region (LCRR) is a multi-billion dollar business. The soils used for vegetable production range from loamy sand to silty clay with production generally skewed toward the heavier textured soils. Furrow irrigation was used as the primary irrigation method for row crops, including vegetables, in the LCRR. Recently there has been an expansion in season-long use of sprinkler systems for vegetable production, with the aim of increasing irrigation efficiency. The application of water soluble nitrogen fertilizers, such as nitrates, mixed with irrigation (fertigation) is widely practiced in the LRRC in the context of sprinkler irrigation of vegetable crops. Nitrogen fertilizer recommendations for leafy cool season vegetables range from 150 to 250 kg N/ha depending on crop, soil, and weather conditions. For leafy vegetables produced under season-long sprinkler systems 60 to 80% of the N is applied in season through the irrigation system. The sources of N fertilizer in season-long sprinkler systems are typically UAN32 and AN20.

Compared to conventional fertilizer application methods, fertigation presents a number of potential advantages. It allows a more precise matching of crop available soil nitrogen content with crop nitrogen needs (Muirhead et al., 1984, Burt et al., 1998). In addition, reduced soil compaction, crop damage, and energy and labor costs are also cited as some of the benefits of fertigation (Burt et al., 1998; Fares and Abbas, 2009).

The performance of a field-scale fertigation event can be evaluated in terms of fertigation uniformity, efficiency, and adequacy (Zerihun et al., 2003). A complete evaluation of field-scale nitrogen fertigation performance over a fertigation event, cycle, or a season requires quantification of the various nitrogen input and output fluxes and change in storage, as affected by solute transport processes as well as a host of coupled physical and biochemical mechanisms in the effective crop root depth (e.g., Burt et al., 1998). The scale of field work required as well as the equipment and data processing and analyses needs of such a study constitute a major challenge that cannot be undertaken as part of the current study. Therefore, the goal here is limited to conducting field-scale nitrogen fertigation uniformity evaluations under solid-set sprinkler systems.

In the context of solid-set sprinkler systems, the practical significance of uniformity as a performance criterion stems from the fact that high uniformity is a requirement for the attainment of adequate and efficient fertigation (Zerihun and Sanchez, 2014; Burt et al., 1998). Moreover, uniformity indices are generally considered as indirect indicators of the potential for soil water/nutrient deficit, deep percolation, nutrient leaching, and groundwater pollution from fertigation.

Considering that fertigation is a process that applies irrigation water and soluble fertilizer to croplands, it is evident that fertigation uniformity evaluation requires the use of a composite index consisting of irrigation and fertilizer application uniformity indicators. Observing that fertilizer application uniformity levels cannot be automatically deduced from irrigation uniformity, in this study irrigation and fertilizer application uniformity indices are treated as two distinct, nonetheless, related and equally important aspects of field-scale sprinkler fertigation uniformity.

Results of previous irrigation uniformity evaluations in the Yuma Valley Irrigation Districts of the LCRR (Zerihun et al., 2011; Zerihun and Sanchez, 2012) suggest that typical field-wide irrigation application uniformities in the area could be high. Average Christiansen's uniformity coefficient (*UCC*) and low-quarter distribution uniformity (DU_{lq}) of about 0.85 and 0.75, respectively, can be achieved, provided the systems are operated under ambient weather conditions conducive for attaining high uniformity. The results of these studies have also shown that, even when field-scale irrigation uniformities are high, significant variations in test-plot scale uniformity levels exist within a field. This highlights the significance, as related to field-scale irrigation performance, of proper setting and routine maintenance and replacement of system components or lack thereof. These results also underline the need for field-wide irrigation uniformity evaluations to be conducted based on more than one plot-scale tests, suitably distributed through the irrigated field.

Modeling studies and measured field-scale hydraulic data (Zerihun et al., 2011; Zerihun and Sanchez, 2012) show that typical sprinkler systems in the Yuma Valley Irrigation Districts are designed for high irrigation uniformity. In addition, results of the modeling studies showed that the hydraulic design of sprinkler systems in the area is robust: i.e., system hydraulics exhibit low sensitivity to appreciable changes in pipe hydraulic resistance and field slopes. The implication is that field-scale irrigation uniformity should be virtually insensitive to variations in these factors within reasonable ranges, provided the system is well maintained and operated in accordance with the operational and environmental requirements considered conducive for the attainment of high irrigation uniformity.

Considering that nitrogen fertigation is widely and routinely practiced in sold-set sprinkler systems in the Yuma Valley Irrigation Districts, the need for field studies aimed at evaluating the ranges of variations and typical averages of field-scale application uniformity of nitrogen fertilizers in the area is evident. Hence, the study reported here can be viewed as an initial step toward such a goal.

The study proposes a methodology, consisting of field and analytical procedures, for field-scale fertigation uniformity evaluation of solid set sprinkler systems. It defines fertilizer application rate as the most appropriate variable in terms of which field-scale fertilizer application uniformity can be expressed. It also presents the equations for the uniformity indices, cast in their general form, and describes their mathematical properties along with the practical fertigation management implications of those properties.

The results of a fertigation study by Zerihun and Sanchez (2014) shows the spatial variability of nitrogen application rate is a function of the interactive effects of the spatial trends in the irrigation and concentration data sets. Practically significant additional results of this study are summarized in this report. In addition, their application in the analyses of the relationships between the uniformities and the spatial variability patterns of measured irrigation depth, nitrogen concentration, and the resultant application rate data sets are highlighted.

As part of the current study, two sets of field-scale fertigation uniformity evaluations were conducted in growers' fields in the Yuma Valley Irrigation Districts. The first set of field evaluations consists of four field tests performed in different growers' fields in the winter of 2013. These uniformity evaluations took place in fields cropped with vegetables and under season-long sprinkler irrigation. Nitrogen fertilizer was applied in the form of ammonium nitrate and urea solution. A second set of field evaluations, consisting of four fertigation tests, were conducted in the winter of 2014 in a grower's field cropped with spinach. The fertilizer used in these evaluations is ammonium nitrate.

The results of these studies largely confirm the observations of past studies that typical sprinkler system configurations in the Yuma area are such that high irrigation uniformity can be achieved, provided the systems are operated under conducive ambient weather conditions. On the other hand, the computed field-wide nitrogen application rate uniformity levels for these fields are low. The field-scale average fertilizer application rate UCC, vary in the range 0.556 to 0.796, and DU_{lq} vary between a minimum of 0.465 and a maximum of 0.689. The overall field-scale average application rate UCC and DU_{lq}, calculated as the arithmetic mean of all the data sets, are 0.7 and 0.575, respectively. Computed field-wide nitrogen application rates vary between a minimum of 0.5g/m^2 and a maximum of 2.8g/m^2, with an overall average of 1.8g/m^2. Considering an approximate required nitrogen application rate of 2.5g/m^2 per fertigation event, these application rates are considered low. However, crop available soil background nitrogen content is likely to be sufficiently high to mitigate the effects, of the apparent nitrogen deficit, on crop yield. Considering the limited scope of the study presented here, the results cannot be automatically generalized for sprinkler fertigation systems over the entire Yuma Valley Irrigation Districts. Nonetheless, the consistency of the results across different fields suggest that they may not be untypical either.

Additionally, in 2014 four test-plot scale fertigation field evaluations were performed in the Maricopa Agricultural Center of the University of Arizona. The main goal of these evaluations was to assess the effect of fertilizer application configurations (the timing and duration of fertilizer application compared to that of irrigation) on the spatial distribution of concentration. Results of the test-plot scale field evaluations show that fertigation uniformity levels for all the test-plots are high, with UCC and DU_{lq} values that are either sufficiently close to, or exceeding, 0.85 and 0.75, respectively. Outcomes of this study also suggest that in a sprinkler system in which the effect of solute transport processes on the spatial distribution of concentration is limited, fertilizer can be applied with high uniformity irrespective of the fertilizer application configuration, provided the solute concentration at the system inlet is kept fairly constant for the duration of fertilizer application and that the uniformity of the underlying irrigation event is high.

The study highlighted that fertilizer application rate uniformity is a function of factors and processes affecting the spatial distribution of irrigation and concentration over an irrigated field. The variables on which irrigation uniformity depends are reasonably well established and are to a significant degree controllable (e.g., Christiansen, 1942; Livingston et al., 1985; Fischer and Wallender, 1988; Keller and Bliesner, 1990; Nderitu and Hills, 1993; Martin et al., 2007; Zerihun et al, 2012). On the other hand, the same cannot be said about the variables and mechanisms affecting the field-scale spatial distribution of, sprinkler applied, nitrogen concentration. However, based on the general theory of solute transport in hydraulic networks (e.g., Tzatchkov et al., 2002; Taylor, 1954) a concise description of the factors and mechanisms affecting the uniformity of the spatial distribution of solute concentration in field-scale sprinkler systems is presented and pertinent future research need in the area is highlighted.

Overall the results of the study underline the fact that in sprinkler systems that are routinely used for fertigation purposes (such as those in the Yuma Valley Irrigation Districts of the LCRR), the design and management of the irrigation system cannot be decoupled from that of the fertilizer application subsystem. A detailed list of specific recommendations along with insights gained and lessons learned in the course of this study are outlined in sections 3.4 and 5 of the report.

The report consists of six chapters. Chapter 1 presents project summary. Chapter 2 lists the activities performed as part of the study reported here and presents a detailed description of the field uniformity evaluation methodology, uniformity equations and their properties along with field evaluation results. Chapter 3 presents goals and outcomes of the study, including specific recommendations for future studies. Chapter 4 identifies beneficiaries of the project. Chapter 5 presents a list of insights gained and lessons learned in the course of this study.

1.2 Project objectives

The specific objectives of the study reported here are: (1) To develop a field and data processing methodology for field-scale fertigation uniformity evaluations in fields under season-long (solid-set) sprinkler irrigation in the Lower Colorado River Region (LCRR), (2) To conduct limited fertigation uniformity evaluations in growers' fields in the Yuma Valley Irrigation Districts of the LCRR, and (3) To develop recommendations for further studies.

Chapter 2. Project approach

This section of the report lists the activities conducted as part of the current study. The tasks accomplished include nitrogen fertigation evaluation of vegetable cropped fields under season-long sprinkler irrigation in the Yuma Valley Irrigation Districts of the LCRR; laboratory analysis of irrigation water samples to determine the concentration of applied nitrogen fertilizer; processing and analysis of field and laboratory data; and writing and submission of final report. A description of the field and laboratory methods along with the analytical tools and techniques used in the study is also provided here. The section concludes with a presentation and discussion of results obtained.

2.1 Activities

2.1.1 Field evaluations

Field-scale evaluations: Two sets of field-scale fertigation uniformity evaluations were conducted as part of the current study. During the winter season of 2013 four nitrogen fertigation field evaluations, each in a different grower's field, were conducted in the Yuma Valley Irrigation Districts. A second set, consisting of four fertigation tests, were conducted in the winter of 2014 in a grower's field, cropped with spinach and, under season-long sprinkler irrigation. Nitrogen fertilizer was applied in the form of either UAN32 or AN20 at rates typically used by growers, which range from 5 to 15 gallons of fertilizer material depending on projected nitrogen requirement of the crop.

The field-scale spatial distribution of irrigation and fertilizer application rates are functions of the interactive effects of a complex set of factors, which include: sprinkler system hydraulics, as encapsulated by sprinkler pressure heads/discharge variations, ambient weather condition (particularly wind velocity), sprinkler system operational practices (including maintenance and setting of system components), the fertilizer application configurations at the system inlet, and solute mixing due to transport processes during solute conveyance from point of injection to sprinkler nozzles.

Typically, the spatial distribution of irrigation water and fertilizer applied through fertigation exhibits significant variability over an irrigated field. Hence, a realistic characterization of field-scale fertigation uniformity requires sampling the fertigation variability at more than one point in the field. The basic field-scale sprinkler fertigation uniformity sampling unit is a test-plot. During each of the field-scale fertigation uniformity evaluations, conducted as part of the current study, three test-plots were installed over the irrigated field (section 2.4.1). The test-plots were arranged along the field diagonal from the system inlet, each representing approximately equal fractions of the total area of the irrigated field (section 2.3). The test-plots, each measuring 9.14m×10.67m (30.0ft×35.0ft), were set in between two adjacent laterals and were subdivided into grid squares of 1.524m×1.524m (5.0ft×5.0ft). In each grid square a rain gage is installed. Irrigation precipitation depths, collected in the rain gages, were recorded immediately following a fertigation event and are used subsequently to compute test-plot scale and field-scale uniformity. Water samples were collected in appropriately labeled vials from each of the rain gages, which were then sealed and frozen within two hours following sampling, in order to preserve the integrity of sample constituents (i.e., mineral nitrogen forms) until laboratory analysis. Measured nitrogen concentration and corresponding depths will be used to determine nitrogen application uniformity.

Test-plot scale evaluations: In the winter of 2014, four test-plot scale uniformity evaluations were performed in the research farm of the Maricopa Agricultural Center (MAC) of the University of Arizona (UA). In these field evaluations, the bromide ion was applied (in the form of potassium bromide solution) in four different fertilizer application configurations (section 2.4.1). Bromide is used here as a tracer to simulate the spatial distribution of nitrate-nitrogen and the target bromide application rate was the typical nitrogen application rate in the area, $5 g/m^2$. The goal of this field evaluation was to assess the effect of different bromide application configurations on the spatial distribution of bromide. The size of the test-plots used in this study vary from 9.14m×9.14m (30.0ft×30.0ft) to 9.14m×10.21m (30.0ft×33.5ft).

2.1.2. Laboratory analysis

Ammonium- and nitrate-nitrogen and bromide contents of irrigation water were determined colorimetrically using an Astoria 2 with methods specified by the manufacturer. The methods for nitrate- and ammonium-nitrogen concentration determination are based on those reported by (Mulvaey 1996). Bromide concentration as was measured based the method developed by Zitomer and Lambert (1963). Urea-nitrogen was determined with a micro-plate method as described by Greenan et al. (1995).

2.1.3. Data processing and analysis

Fertigation is a process that applies both irrigation water and soluble fertilizers to crops. During fertigation, solute concentration may vary spatially through a sprinkler hydraulic network and temporally during the course of a fertigation event. Hence, fertilizer application uniformity cannot be automatically deduced from irrigation uniformity. The implication is that fertigation uniformity is a composite parameter consisting of irrigation and fertilizer application uniformity indicators. Accordingly, throughout this manuscript irrigation and fertilizer application uniformity indices are treated as two distinct, nonetheless, related and equally important aspects of field-scale sprinkler fertigation uniformity.

Irrigation depths collected in the rain gages within a test-plot are used to compute test-plot scale average, maximum, and minimum depths along with irrigation uniformity indices. The indices used, in the current study, to evaluate test-plot scale irrigation uniformity consists of the Christiansen's uniformity coefficient and the low-quarter distribution uniformity (Keller and Bliesner, 1990; Martin et al., 2007) and are described in Section 2.3.3. Computed test-plot scale depths and uniformity indices are scaled-up to field level through averaging (Zerihun et al., 2011).

The spatial distribution uniformity of nitrogen fertilizer applied through fertigation is defined here in terms of the nitrogen application rate (section 2.3.2). However, the mass of nitrogen in the irrigation water cannot be measured directly, hence nitrogen application rate is determined here as a function of the measurable quantities of irrigation depth and concentration. The computation of nitrogen application rates and uniformity is based on total elemental nitrogen. Considering that the nitrogen fertilizers applied in these studies consist of ammonium nitrate and urea, total nitrogen is given as the sum total of nitrate-, ammonium-, and urea-nitrogen. The concentration of nitrogen in the irrigation water, collected in each of the rain gages in a test-plot, is determined through laboratory analysis of water samples (section 2.1.2). The nitrogen fertilizer application rate in a grid square is then computed as the product of the precipitation depth in the rain gage and the nitrogen concentration in the rain gage water (section 2.3.3). Grid square nitrogen fertilizer application rates are used to compute test-plot scale maximum, minimum, and average nitrogen application rates along with the uniformity indices. Test-plot scale fertilizer application rate uniformity is evaluated in terms of the Chrstiansen's uniformity coefficient and the low-quarter distribution uniformity. Following the same approach as that used to compute irrigation uniformity, test-plot scale fertilizer application rate uniformity indices are then scaled-up to field-level through averaging.

2.1.4. Report writing

The last phase of the sprinkler fertigation project presented here consists of the writing and submission of the report. A summary of the contents of this report is provided in section 1.1.

2.2 Review

2.2.1. Introduction

The application of nitrogen fertilizers through fertigation presents a number of potential advantages compared to conventional methods. Fertigation allows a more precise matching of crop available soil nitrogen content with crop nitrogen needs (Muirhead et al., 1984, Burt et al., 1998), leading to increased plant nitrogen uptake and yield. Fertigation can also minimize nitrogen loss through gaseous emissions and leaching, resulting in increased opportunity for crop nitrogen recovery and diminished adverse environmental effects (Hanson, et al., 2014). Reduced soil compaction, crop damage, and energy and labor costs are some of the additional benefits of fertigation compared to conventional methods (Burt et al., 1998; Fares and Abbas, 2009). However, in any given application the realization of these potential advantages is predicated on the assumptions that: the scheduling of nitrogen fertigation and estimation of required application rates of nitrogen fertilizer matches well with crop needs. Furthermore, irrigation needs to be efficient, uniform, and adequate and the fertilizer application configuration should favor the deposition of applied nitrogen in the region of the soil profile from which maximum nitrogen recovery by plants takes place.

2.2.2. The scheduling and estimation of required application rates of nitrogen fertilizers

In principle, the practice of fertigation involves applying seasonal nitrogen fertilizer crop consumptive use needs in smaller doses spread over multiple fertigation cycles spanning the irrigation season. Hence, accurate estimation of crop nitrogen fertilizer requirements associated with a set number of fertigation cycles, during the growing season of a crop, and synchronizing its application schedule with the irrigation schedule is key to achieving efficient fertigation.

A description of crop nitrogen fertilizer requirement proposed by Zerihun et al. (2003) for applications in surface irrigation methods can be used for sprinkler fertigation as well. Accordingly, crop nitrogen fertilizer requirement, in the context of a fertigation event (a fertigation cycle), can be defined as the quantity of nitrogen fertilizer that needs to be stored in the effective crop rooting depth to raise the existing soil mineral nitrogen content to a level that is within an agronomic optimum. An agronomic optimum is defined here as the soil mineral nitrogen content of the effective crop root depth that is required to ensure the minimum amount of plant nitrogen uptake, associated with maximum crop yield, for the duration of a fertigation cycle.

Evidently, the description of crop nitrogen fertilizer requirement given above reflects the net effect of the interaction between plant nitrogen uptake as well as solute transport processes and a host of soil physical and biochemical processes that adds mineral nitrogen to, or removes mineral nitrogen from, the plant available soil nitrogen pool of the effective crop rooting depth. Assuming the availability water and other essential plant nutrients do not impose a limiting condition, crop nitrogen fertilizer requirement can vary as a function of optimal crop nitrogen uptake for the fertigation cycle considered, nitrogen fertilizer sources used, soil type and its organic matter content, soil mineral nitrogen content, and ambient environmental factors (soil moisture content, pH of soil solution, and temperature).

For a given crop, soil, and environmental conditions crop nitrogen fertilizer requirements can be obtained from local agronomic recommendations. From the stand point of fertigation system operation, the objective of sprinkler nitrogen fertigation is to deliver a prescribed quantity of nitrogen fertilizer (nitrogen fertilizer requirement) to a site within the soil profile where it can be used by the crop with minimum loss in the delivery process. In principle, nitrogen fertilizer losses in a sprinkler fertigation event consists of ammonia volatilization during conveyance and from droplets during their passage between the sprinkler nozzles and the irrigated field surface, if ammonia producing nitrogen fertilizer is used. Considering the significance, to ammonia volatilization, of the exposure of irrigation water to a moving air current (wind) for appreciable time (e.g., Dunmead et al., 1982), it is likely that in a field-scale sprinkler system nitrogen loss through volatilization, during conveyance, could be considered minimal. This, however, needs to be verified through future field studies. Additional pathways for nitrogen fertilizer losses are associated with spray wind drift and leaching losses, the latter mainly in the form of nitrate and to some extent urea, if applicable. Typically, sprinkler systems are operated at irrigation application rates (irrigation depth per unit time) that do not exceed the steady state soil intake rate, in which case the nitrogen fertilizer losses through surface runoff can be considered negligible.

The preceding highlights that estimation of gross nitrogen fertilizer application rate associated with a fertigation cycle should take into account both conveyance and leaching losses. Given the gross nitrogen fertilizer application rate for a fertigation cycle, the fertigation schedule needs to be synchronized with the irrigation schedule in such a way that crop water and nitrogen nutrient stress is avoided or minimized, at least during the most critical crop growth stages.

2.2.3. Effect of irrigation performance on fertigation

Irrigation performance consists of uniformity, application efficiency, and adequacy indices. The practical significance of uniformity as an irrigation performance index stems from the fact that high irrigation uniformity is a requisite condition for achieving an efficient and at the same adequate sprinkler irrigation. As would be discussed subsequently efficient and adequate irrigation has favorable influences on various soil processes related to the transport and fate of nitrogen fertilizers.

Following infiltration of irrigation applied water and nitrogen fertilizer into the soil, soil water content at the time of fertigation and subsequently (which depends on the irrigation depths) is a key factor in the solute transport as well as other soil physical and biochemical processes that affect nitrogen fertilizer availability to crops, losses in the form of gaseous emissions, and leaching below the crop root zone. Inefficient irrigations, especially those with significant deep percolation, can lead to leaching of nitrates and urea below the crop root zone. It can also create anoxic conditions, favorable for denitrification, in the soil profile. On the other hand, efficient irrigation may minimize denitrification by maintaining well aerated soil profile. In addition, when environmental factors and availability of essential plant nutrients are not limiting, adequate and efficient irrigation may lead to vigorous crop growth, optimal plant nitrogen uptake, and hence optimal yield. The preceding highlights the fact that fertilizer application uniformity, efficiency, and adequacy in a fertigation cycle or over a season is closely related to the underlying irrigation performance (irrigation uniformity, efficiency, and adequacy).

2.2.4. Effect of fertilizer application configuration

The timing and duration fertilizer application, as related to the duration of irrigation, affect the subsurface distribution of nonsorbing nitrogen species, such as nitrate and to a lesser degree urea. This in turn has a significant effect on the potential availability to crops and susceptibility to leaching below the root zone of these fertilizers. However, the goal in the current study is limited to assessing the effect of solute application configurations at the sprinkler inlet (section 2.4.1) on the spatial distribution of the bromide ion.

2.3. Development of methodology

In this section field and analytical methods are proposed for the evaluation of field-wide irrigation and fertilizer application uniformity. The field and computational procedure for test-plot scale irrigation uniformity evaluation is reasonably well developed (Keller and Bliesner, 1990; Martin et al., 2007; Zerihun et al., 2011). However, the same cannot be said about fertilizer application uniformity through sprinkler fertigation. The basic field unit for solid set sprinkler irrigation uniformity evaluation is a test-plot. Zerihun et al. (2011) proposed a procedure in which multiple test-plots suitably distributed over the irrigated field can be used to sample the effects, on irrigation uniformity, of factors related to system hydraulics as well as system component maintenance and settings. In the study reported here this approach is adopted, with appropriate modifications, for use in field-scale irrigation and fertilizer application uniformity evaluation.

2.3.1. Field evaluation of irrigation application uniformity

Factors affecting uniformity, their field-wide variability, and the need for sampling: The basic field unit for solid set sprinkler irrigation system uniformity evaluation is a test-plot. Typically, a uniformity evaluation test-plot consists of a rectangular area circumscribed by four adjacent sprinklers, with dimensions equal to the sprinkler spacing along laterals and the lateral spacing. A test-plot is further discretized into grid squares of a suitably selected dimension. During irrigation uniformity evaluation rain gages are placed at about the center of each grid square and the irrigation system is operated for a duration equal to the regular irrigation application time practiced by growers. Immediately following irrigation, the depth collected in each rain gage is recorded. Assuming depths collected in each rain gage within a test-plot represent the average precipitation rate over the corresponding grid square area, they can then be used to compute test-plot scale irrigation uniformity with a suitable set of uniformity indices (Section 2.3.3).

Test-plot scale irrigation uniformity data may not be representative of the field-scale spatial distribution of irrigation depths (e.g., Zerihun et al., 2011; Zerihun and Sanchez; 2012). Factors that affect the spatial distribution of irrigation at a field-scale include sprinkler pressure head (discharge) variation due to energy loss and field slopes as well as variation in sprinkler hydraulic characteristics due to nonuniform wear and tear and/or inadvertent mixing of different sprinklers. In addition, the proper setting and maintenance of system components or lack thereof (including vertical setting of sprinkler riser pipes, routine maintenance such as regular cleaning of sprinkler nozzles, and detection and maintenance of leakage) are important determinants of precipitation patterns about sprinklers. Although the microclimate (especially wind velocity) in close vicinity of the sprinkler field can have a significant effect on sprinkler irrigation uniformity, it can be assumed that its effect is uniform over the field.

The preceding discussion suggests that in order to take into account the effects of the factors listed above on field-scale irrigation depth and uniformity, test-plot scale evaluations may need to be conducted at more than one locations in the field. In principle the most accurate field evaluation may require conducting distribution uniformity tests over the entire irrigated field, nonetheless, such an approach is impractical if the grid squares are to be of sufficiently high spatial resolution. An approximation of the field-scale irrigation uniformity can be obtained, with reduced cost and effort, based on a small number of plot-scale evaluations distributed through the field. In which case, each of the uniformity evaluation test-plots would be used as field-wide sampling points of the spatial variability in the applied irrigation depths. The question then is how to determine the number and location of the uniformity evaluation test-plots over the irrigated field.

The relative significance of most of the factors that affect irrigation uniformity and their spatial distribution over the irrigated field is generally not predictable priori to field evaluations. On the other hand, the effect of system hydraulics on irrigation uniformity in a field-scale solid set sprinkler system is predictable, provided certain basic assumptions as regards system hydraulic, geometric, and topographic characteristics are met. This suggests that the known pattern in sprinkler pressure head (discharge) distribution, as affected by system hydraulics, can be used to advantage to develop a preliminary layout of the distribution of test-plots in the irrigated field. Although such a layout is specifically designed to capture the effects of system hydraulics on uniformity, it may also account for some of the effects of the other inherently probabilistic factors.

In the winter of 2011, a field study was conducted in a grower’s farm in the Yuma Valley Irrigation Districts, with support from the Arizona Specialty Crops Council, to evaluate the practical utility of this observation in designing the layout of test-plots over an irrigated field for field-scale irrigation uniformity evaluation. A detailed discussion of the methodology and results is presented by Zerihun et al., (2011), however, subsequent section presents a concise discussion of the results.

A layout of uniformity evaluation test-plots based on consideration of system hydraulic effects: Considering a well maintained and properly set system installed on a nearly level field surface with spatially invariant laterals/mainline diameters and sprinkler characteristics (common in the Yuma Valley Irrigation Districts), the field-wide spatial distribution of sprinkler pressure head (and hence discharge) can be shown to be a decreasing nonlinear convex function of distance from the system inlet. This suggests that in order to sample the effects of sprinkler pressure head variability on field-scale irrigation uniformity effectively, the spatial distribution of the test-plots may need to be skewed towards the inlet of the sprinkler system, where much of the variability is concentrated. Accordingly, in the study referenced above, the irrigated field was subdivided into nine field blocks of varying sizes, with the smaller field blocks set close to the system inlet and the larger field blocks at the distal end of the field (Figure 1a). A uniformity evaluation test-plot is placed close to the center of each field block. The assumption here is that each field block is sufficiently small for pressure head variability to be negligible within the block, hence the associated test-plot scale uniformity can be considered representative of the field block. Test-plot scale uniformity can be quantified in terms of standard indices (section 2.3.3). The test-plot scale uniformity indices and the minimum, maximum, and average depths can then be scaled-up to field-level through averaging. During the field tests irrigation uniformity data was collected in the test-plots. In addition, hydraulic data consisting of measured pressure heads along laterals adjacent to the test-plots were obtained.

Irrigation depth data collected within the same field during three comparable irrigation events (considering hydraulic and ambient weather condition) showed significant variations in test-plot scale *UCC (*ranging between 0.77 and 0.87) and DU_{lq} (varying between 0.69 and 0.82) can exist in a well maintained and operated sprinkler system (Zerihun et al., 2011). Subsequent field uniformity evaluations conducted by the authors in the Yuma Valley Irrigation Districts, including those conducted as part of the current study, showed that even larger irrigation uniformity variations exist within a field. On the other hand, hydraulic measurements and simulation studies showed that the effect of system hydraulics on the observed variability of test-plot scale uniformity is negligible, mainly due to the relatively large pipe diameters and nearly level land slopes common in the area. Hence, some combination of such factors as variations in sprinkler characteristics due to nonuniform wear and tear, inadvertent mixing of sprinklers with different hydraulic characteristics, and issues related to routine sprinkler system component maintenance and settings could be the main contributory factors to the observed in-field variability of irrigation uniformity. Considering that the effect of wind is supposed to be uniform over an irrigated field, it cannot explain the observed variability in test-plot scale uniformities within a field.

The inferences that stem from the preceding discussion is that a realistic evaluation of field-scale sprinkler irrigation system uniformity should preferably be based on more than one test-plot scale measurements, each used as a sampling spot of the spatial variability of irrigation in the field. However, the actual number, and placement within the field, of each uniformity evaluation plot need to be left to the discretion of the irrigator conducting the evaluation. Any information on maintenance issues or the spatial distribution of sprinklers with differing hydraulic characteristics can be used to advantage in determining the placement of the test-plots in the field. Considering a scenario consisting of carefully laid out test-plots, the larger the number of the test-plots in the field, the more accurate the field-scale uniformity estimates should be. On the other hand, the time and effort needed to perform such field tests increases with the number of test-plots in a field. Hence, in subsequent field studies, conducted by the authors between 2012-2014, typically three uniformity evaluation test-plots were used in an irrigated field. The test-plots were spatially distributed along the main diagonal of the field from the system inlet and were spaced in such a way that each represents field blocks of equal size.

2.3.2 Field evaluation of fertilizer application uniformity

Irrigation uniformity evaluation test-plots can be used as the basic field (sampling) units for evaluating the spatial uniformity of any farm input applied with irrigation, including nitrogen fertilizer. Hence, in the study presented here the irrigation evaluation test-plots are treated as the basic field sampling units for the evaluation of field-scale fertigation (irrigation and fertilizer application) uniformity.

Typically, agricultural inputs for crop production, including irrigation and fertilizers, are expressed in terms of application rates: volume of water or mass of fertilizer per unit area of cropped land. Hence, sprinkler irrigation uniformity is often expressed as a function of irrigation depths, although it should not necessarily be expressed as such. Similarly nitrogen fertilizer application uniformity, with sprinklers, can be defined in terms of the spatial distribution of the fertilizer mass per unit area of field (e.g., gram per square meter). Observing that the mass of solutes in irrigation water cannot be measured directly, nitrogen application rates are computed on the basis of the measureable quantities of concentration and irrigation depth.

As pointed out in a preceding section, precipitation depths collected in the rain gages are considered as representative averages of the irrigation depths in the respective grid squares. Furthermore, the average nitrogen application rate for a grid square can be computed as a function of depth collected in the rain gage and nitrogen concentration in the rain gage water. Given the nitrogen application rates associated with each grid square in a test-plot, the spatial distribution uniformity of applied nitrogen for the test-plot can then be computed with suitable equations (section 2.3.3). Note that nitrogen concentration and application rate can conveniently expressed in terms of elemental nitrogen, especially when different sources of nitrogen are used.

Test-plot scale fertilizer application uniformity may not be representative of field-scale uniformity. The spatial distribution of nitrogen application rate is a function of factors that affect irrigation uniformity and the time and spatial evolution of fertilizer concentration through the sprinkler hydraulic network. A description of the factors that affect irrigation uniformity is presented in a preceding section. In principle, the time and spatial variation of nitrogen fertilizer concentration within a field-scale sprinkler pipe network can be a function of the fertilizer application configuration at the system inlet, solute transport processes consisting of advection and hydrodynamic dispersion, and wind effects on dilution patterns.

The preceding highlights the need to use more than one test-plot to effectively sample the spatial variability of fertilizer application rates at a field-scale and to derive a realistic estimate of the field-scale fertigation uniformity. As would be shown subsequently (section 2.3.3), test-plot scale fertilizer application rates and corresponding uniformity indices are computed as a function of measured water depths and concentrations. Following the approach described above, the test-plot scale maximum, minimum, and average application rates and uniformity indices are then scaled up to field level through averaging.

2.3.3. Fertigation (irrigation and fertilizer application) uniformity equations and their properties

Test-plot scale uniformity

Uniformity is a measure of the variability inherent in a data set. Often variability in a data is expressed with reference to the average. In this study two standard indices that are designed to measure different aspects of data variability, with respect to the mean value, are used to quantify fertigation uniformity: Christiansen's uniformity coefficient, *UCC [-]*, and the low-quarter distribution uniformity, DU_{lq} *[-]*. Although these indices are customarily used to evaluate irrigation uniformity (Martin et al., 2007; Burt et al., 1997; Keller and Bliesner, 1990), there is no limitation as regards their application to quantifying the spatial variability of any agricultural input applied with irrigation water.

For generality of notion, here a uniformity evaluation test-plot is simply considered as a well defined area in a sprinkler irrigated field, which in turn is subdivided into smaller elemental areas of arbitrary shape and size, each of which are associated with a rain gage. Furthermore, it is assumed that the ratio of the catchment area of the rain gage to the corresponding elemental area should be sufficiently large for the measured application rate to be considered a representative average of the associated elemental area. In what follows forms of the *UCC* and DU_{lq} equations applicable to the conditions described above are presented. The equations will then be reduced to their commonly used forms.

Christiansen's uniformity coefficient

The equation for test-plot scale Christiansen's uniformity coefficient, *UCC [-]*, of a farm input applied with irrigation water can be given as:

$$UCC = 1.0 - \frac{\dfrac{\sum_{k=1}^{K} a_k \left| x_k - x_{av} \right|}{\sum_{k=1}^{K} a_k}}{x_{av}} \tag{1}$$

where k = rain gage, K = the total number of rain gages in a test-plot, x_k = application rate of a farm input (irrigation or fertilizer) computed based on measurements in the *kth* rain gage (*[L] or [M/L^2]*), a_k = size of the *kth* elemental area in a test-plot (L^2), and x_{av} = the weighted average application rate for the test-plot (*[L] or [M/L^2]*):

$$x_{av} = \frac{\sum_{k=1}^{K} a_k x_k}{\sum_{k=1}^{K} a_k} \qquad (2)$$

Note that in order to maintain consistency with the definition used for fertilizer application rate, in this paper the phrase irrigation application rate is used in reference to the volume of irrigation per unit field area (irrigation depth), instead of irrigation depth per unit time (the definition customarily used in the irrigation literature).

Low-quarter distribution uniformity

The equation for a test-plot scale low-quarter distribution uniformity, DU_{lq} *[-]*, of a farm input applied with irrigation water is given as:

$$DU_{lq} = \frac{x_{lq}}{x_{av}} \qquad (3)$$

where x_{lq} = the weighted average of the application rates in a quarter of the test-plot area with the lowest application rates (*[L] or [M/L^2]*):

$$x_{lq} = \frac{\sum_{i=1}^{I} a_i x_i}{\sum_{i}^{I} a_i} \qquad (4)$$

In Eq. 4, *i* = index of the application rates in a quarter of the test-plot area with the lowest rates and *I* = a numerical value equal to the total number of measured application rates in a quarter of the test-plot area with the lowest rates.

As can be noted from Eq. 3, distribution uniformity is a measure of the significance of localized extreme negative deviations from the average application rate. Different forms of distribution uniformity (e.g., distribution uniformity based on the minimum or lower-half of the application rate data) are in common use, each assigning different levels of stringency as regards the definition of what constitutes extreme negative deviation from the average. However, the low-quarter distribution uniformity, DU_{lq}, is used here, because it has been widely applied in irrigation uniformity evaluations. The Christiansen's coefficient of uniformity, *UCC*, on the other hand, can be viewed as an index designed to measure the spatially distributed test-plot scale variability from the average.

Simplified forms of uniformity equations

Equations 1 and 3 represent more general forms of the *UCC* and DU_{lq} indices applicable to conditions in which the elemental areas constituting a test-plot can be of variable size and in principle they can also be of arbitrary shape. In practice, fertigation uniformity evaluation test-plots are rectangular and the elemental areas within the test-plots are of the same shape and dimension (typically squares because of simplicity and symmetry). In which case the equation for *UCC* reduces to the form:

$$UCC = 1.0 - \frac{\dfrac{\sum_{k=1}^{K} \left| x_k - \bar{x} \right|}{K}}{\bar{x}} \qquad (5)$$

and the equation for DU_{lq} is given as:

$$DU_{lq} = \frac{\bar{x}_{lq}}{\bar{x}} \qquad (6)$$

where $\bar{x}$ = the arithmetic average of application rates over the test-plot (*[L] or [M/L^2]*) and $\bar{x}_{lq}$ = the arithmetic mean of the lowest quarter of the application rates within the test-plot (*[L] or [M/L^2]*).

When Eqs.1 and 3 or 5 and 6 are used to quantify fertilizer application rate uniformity, the variable x_k, which represents fertilizer application rate is computed as the product of fertilizer concentration, c_k *[M/L^3]*, and irrigation depth, d_k *[L]*:

$$x_k = c_k d_k \qquad (7)$$

Properties of the fertigation uniformity equations

Equations 5 and 6 are the most commonly used forms of the uniformity indices, hence subsequent discussion will be based on these equations. The following is a list of the properties of equations 5-7 and their practical computational implications.

(1) Considering a test-plot scale irrigation depth or fertilizer application rate data, its *UCC* and DU_{lq} indices remain unaffected if each element of the data set is multiplied by a constant.

The implication is that the volume of precipitation collected in rain gages, instead of depth, can be used directly to compute irrigation uniformity. Note that this is especially convenient if rain gages graduated in volumetric units are used in fertigation uniformity evaluation. Likewise, the mass of fertilizer in the rain gages, instead of fertilizer application rates, can be used to calculate application rate uniformity, if the spatial distribution of fertilizer is expressed as such.

(2) If the fertilizer concentration over a test-plot is constant, the fertilizer application rate uniformity will be equal to irrigation uniformity. Observe that this is a corollary to the property stated above.

In such a scenario, the problem of fertigation uniformity evaluation reduces to that of irrigation uniformity evaluation. In practice this may occur in a sprinkler system in which the effect of solute transport processes on the spatial distribution of fertilizer concentration is limited and the fertilizer concentration at the system inlet is fairly constant throughout the duration of irrigation.

(3) Test-plot scale UCC and DU_{lq} are independent of the spatial distribution of the application rate data points within a test-plot.

This implies that two test-plots with different spatial distributions of application rate data can have the same UCC and DU_{lq}, provided the data sets can be shown to be equivalent after having been sorted separately in ascending/descending order. In other words, the uniformity indices associated with a given irrigation depth or fertilizer application rate data set remain unchanged under any possible spatial permutation of the data. Although the computation of irrigation uniformity or fertilizer application rate uniformity is independent of the spatial distribution of the data points, it should be noted that the computation of fertilizer application rates from depth and concentration data sets, Eq. 7, requires a proper accounting of the spatial distribution of the data points within the test-plot.

(4) Test-plot scale fertilizer application rate uniformity is an aggregate index of the interactive effects of the local spatial trends in the irrigation depth and fertilizer concentration data sets;

This property of the uniformity indices is less intuitive than those described above, but it is also key to understanding and defining the factors that affect fertilizer application uniformity. Considering that fertilizer application rate is a multiplicative function of irrigation depth and fertilizer concentration, Eq. 7, it can be reasoned that the spatial trends and scale of variability inherent in the irrigation depth data as related to those of the concentration data should be the main determinants of the uniformity of the resultant application rate data. A detailed analyses of the interactive effects, of the spatial trends in the depth and concentration data sets, on the variability (uniformity) of the resultant fertilizer application rate data was performed by Zerihun et al. (2014). The results of this study validates the preceding characterization of the application rate uniformity index. A summary of the significant results is presented in the next section.

2.3.4. The relationship between irrigation, concentration, and application rate data sets

A combination of intuitive mathematical reasoning and simplified hypothetical examples were used by Zerihun et al. (2014) to show that the spatial variability (hence uniformity) of the fertilizer application rate is a function of the interactive effects, of the local spatial trends and scale of variability, of the depth and concentration data sets. Important inferences stemming from these analyses are summarized here so that they can serve as the basis for subsequent discussion (section 2.4.4).

(1) In parts of a test-plot where the local spatial trends in the irrigation depth data have the same monotonicity as that of the concentration data, the local spatial variability of

the resultant application rate data tends to be larger than the variability inherent in both the depth and concentration data sets.

(2) In any given section of a test-plot the relative contributions, of the depth and concentration data sets, to the local variability of the resultant application rate data are proportional to the scale of variability inherent in the depth and concentration data sets.

(3) In parts of a test-plot where the spatial trends in the depth and concentration data sets have opposite monotonicity, the local spatial variability of the resultant application rate data tends to be smaller than that of the depth and/or concentration data set(s).

Note that if the local spatial variability inherent in the depth and concentration data sets are of appreciably different scale, then the variability of the resultant application rate data tends to fall somewhere in between those of the depth and concentration data sets. On the other hand, the local spatial variability in the application rate data set could be less than those inherent in both the depth and concentration data sets, provided the variability in these data sets are of comparable scale.

Note that the term monotonicity is used here, in relation to the spatial trends of depth and concentration data sets, to refer to the mathematical property of the data sets as increasing or decreasing functions of distance. If, for instance, both data sets are locally increasing or locally decreasing functions of distance in some part of the test-plot, then they are described as having same monotonicity there. On the other hand, if in some part of the test-plot the depth data is a locally increasing function of distance whereas the concentration data is a decreasing function of distance or vice-versa, then the functions are considered to be of opposite monotonicity in that part of the test-plot. Note that monotonic properties of depth and concentration data sets are alternatively referred to as spatial overlap patterns between depth and concentration data. Furthermore, the term local function behavior should imply that a function exhibits a given mathematical property of interest (e.g., monotonicity) in a subset of its domain (which is the test-plot in the current application). Likewise, global function behavior implies that a property of interest spans the entire test-plot.

The results summarized above with respect to the relationships between the spatial variability of application rate, irrigation depth, and concentration data sets were obtained based on analyses of simplified hypothetical examples consisting of data sets with uniform, or locally variable yet repetitive, spatial patterns. Nonetheless, it has revealed some interesting and practically significant qualitative interrelationships between application rate uniformity and those of depth and concentration uniformity, a summary of which is presented subsequently:

(1) Irrigation or fertilizer concentration uniformity alone may not always be adequate to characterize fertilizer application rate uniformity,
(2) A combination of low irrigation and low concentration uniformity may not necessarily lead to low application rate uniformity,

(3) A combination of low irrigation uniformity and high concentration uniformity and vice-versa will likely lead to low application rate uniformity,
(4) A combination of marginally high irrigation and concentration uniformity levels, or marginally high irrigation and high concentration uniformity indices or vice-versa, may not necessarily lead to acceptably high fertilizer application rate uniformity, and
(5) The sufficiency condition for attaining acceptably high fertilizer application rate uniformity, as defined by a preset uniformity threshold, consists of a fertigation scenario with sufficiently high irrigation depth and fertilizer concentration uniformity.

A fertigation scenario meeting the sufficiency condition has significant practical advantages over any other: it ensures acceptably high irrigation and fertilizer application rate uniformity and it facilitates the attainment of efficient and adequate fertigation. The fact that a fertigation scenario meeting the sufficiency condition maximizes both irrigation and fertilizer application uniformity levels is self-evident. However, its features relating to the attainment of high efficiency and adequacy may require further discussion.

It can be readily reasoned that under a fertigation scenario with a poor fertilizer application rate uniformity, it is not feasible to attain adequate and at the same time efficient application of fertilizer. Under such a fertigation scenario one can either maximize application efficiency at the expense of adequacy (and accept some levels of apparent crop nutrient stress along with the consequent adverse effects on crop yield) or one may opt to meet crop nutrient needs fully and then accept inefficient application of fertilizer. Evidently, fertilizer application uniformity is computed based on collected depths and fertilizer concentration in rain gages (note that assuming runoff is negligible, this is considered a good approximation of conditions at the irrigated field surface). On the other hand, application efficiency takes into account irrigation water and fertilizer losses associated with conveyance and environmental effects, in addition to deep percolation losses. However, the fact that system maintenance and environmental requirements (such as wind velocity) for attaining high uniformity and application efficiency are the same, further supports the notion that high fetigation uniformity facilitates the attainment of high application efficiency. The preceding shows that, with sprinkler irrigation, high fertilizer application rate uniformity is a necessary condition for adequate and efficient field-scale application of fertilizer.

2.3.5. Sampling and laboratory analysis

In each irrigation uniformity test-plot, once irrigation depths are recorded, water samples were collected with appropriately labeled vials from each of the rain gages. One vial is needed per rain gage. In order to maintain the integrity of the chemical constituents of the sample, the vials were then immediately sealed and were frozen within 2h of sampling. Water samples were then analyzed as described in section 2.1.2.

2.4 Results and discussion

2.4.1 Introduction

Field-scale fertigation evaluations: The objective of the fertigation evaluations is to establish a baseline data on field-wide averages and ranges of variations of nitrogen application rates and uniformity indices in the Yuma Valley Irrigation Districts of the LCRR. Accordingly, two sets of field-scale fertigation evaluations were conducted in growers' fields in the winter seasons of 2013 and 2014. Four uniformity evaluations (labeled as data sets I, II, III, and IV) were conducted in different growers' fields in 2013. Four additional fertigation field tests (V, VI, VII, and VIII) were conducted in a grower's farm in 2014. For the evaluations of 2014, the field was subdivided into three sections and data sets VI and VII were collected in two different subdivisions of the field, but data sets V and VIII were obtained from the same sections of the field.

In subsequent discussion references to nitrogen concentration and application rate should imply total elemental nitrogen concentration or application rate, instead of nitrogen fertilizer material as a whole. The type of nitrogen fertilizers used in these field evaluations are a mix of ammonium nitrate and urea solution or only ammonium nitrate solution. Hence, total nitrogen is expressed as the sum total of nitrate-, ammonium-, and urea-nitrogen where ammonium nitrate and urea were applied or it is expressed as the sum of nitrate- and ammonium-nitrogen, if only ammonium nitrate solution is used.

In order to sample field wide variability of uniformity as influenced by hydraulics and system component maintenance and settings, three test-plots were installed in each of the irrigated fields. The test-plots were arranged approximately diagonally from the system inlet and each test-plot represents nearly equal fractions of the total area of the irrigated field. A test-plot covers a rectangular area of 9.14m× 10.67m (30.0ft×35.0ft), which is discretized into 42 grid squares, measuring 1.524m×1.524m (5ft×5ft), Figure 1b. A rain gage is placed in each of the grid squares. Measured precipitation depths and concentrations were used to compute plot scale fertilizer application rate uniformity estimates. The test-plot scale fertilizer application rate uniformity estimates were then scaled-up to field level through averaging. The details of the procedure and equations used are described in section 2.3.

Test-plot scale fertigation evaluations: In the winter of 2014, four test-plot scale fertigation uniformity evaluations were conducted in the research farm of the Maricopa Agricultural Center of the University of Arizona. The test-plots used in this study vary in size from 9.14m×9.14m (30.0ft×30.0ft) to 9.14m×10.21m (30.0ft×33.5ft). In these studies the bromide ion was applied, in the form of potassium bromide solution, in four different fertilizer injection configurations. Considering a 3.0h test irrigation duration, the four different fertigation application configurations are: (1) The duration of fertilizer application lasts over the entire test irrigation event, (2) Fertilizer is applied only during the first hour of irrigation, (3) Fertilizer is applied only during the middle hour, and (4) Fertilizer is applied during the last hour of irrigation. The goal here is to assess the effect of inlet boundary condition on the spatial variability (uniformity) of fertilizer application rate.

Materials, weather data, and uniformity thresholds: The rain gages used in these field evaluations were obtained from the Irrigation Training & Research Center of the California Polytechnic State University, San Luis Obispo, CA. They have a catchment area of 104.84cm^2 and are graduated in 5.0mL increments up to 100.0mL volume. For measurements ranging between 100.0mL and 200.0mL they are graduated in 25.0mL increments. The maximum measurable depth with these rain gages is about 19.1mm with an estimated precision ranging between 0.1mm and 0.5mm (computed based on assumed volumetric reading errors ranging between ±1.0mL to ±5.0mL).

The average wind velocities for the 2013 data sets were obtained from the Yuma Valley AZMET (http://ag.arizona.edu/azmet/azdata.htm) station and hence represent average values for the area during the uniformity evaluations: i.e., they are not average wind velocities measured in the immediate ambience of the irrigated fields. On the other hand, wind velocities for the 2014 data sets were averages computed based on measurements, during the fertigation event, with a micrometeorological station setup near the test fields or test-plots.

The uniformity of sprinkler irrigation and factors affecting it have been studied relatively more extensively (e.g., Christiansen, 1942; Fischer and Wallender, 1988; Nderitu and Hills, 1993; Zerihun et al., 2011). Hence, recommended ranges of acceptable irrigation uniformity levels for use in system design and management applications exist (e.g., Keller et al., 1980; Keller and Bliesner, 1990). However, to the best of authors' knowledge such metrics, have not yet been established, for fertilizer application rate uniformity evaluations. Based on literature data and authors' experience with field evaluation of sprinkler irrigation uniformity, tentative fertilizer application uniformity acceptability thresholds are set here. Accordingly, a fertigation event with irrigation and fertilizer application rate UCC and DU_{lq} equaling or exceeding 0.75 and 0.7, respectively, is considered to have an acceptably high level of fertigation uniformity. These values closely parallel the acceptability thresholds, for irrigation uniformity of field crops, suggested by Keller and Bliesner (1990). Note that the intent here is to use these uniformity thresholds only for characterizing the relative merit of computed fertigation uniformity indices in this report.

2.4.2 Field-scale uniformity evaluations

Data set I: The first fertigation evaluation was conducted on February 23, 2013 in a grower's field with an irrigated area of 192.0m×393.2m (630.0ft×1290.0ft, Table 1). Irrigation duration was 3.0h and a solution of ammonium nitrate and urea was applied throughout the test irrigation. The average wind speed in the Yuma Valley during the irrigation is about 1.2 m/s. A summary of the total nitrogen application rate over each of the test plots in the field is presented in Table 1.

Computed test-plot scale average application rates vary from 1.1g/m^2 to 1.5g/m^2. Christiansen's uniformity coefficient for the upstream, middle, and downstream test-plots are 0.755, 0.655, and 0.665, respectively. Nitrogen application rate DU_{lq} is 0.607 for the upstream end test-plot, 0.416 for the middle test-plot, and 0.459 for the downstream end test-plot. The field-scale nitrogen application rates vary in the range 0.3g/m^2 and 2.7g/m^2, with an average rate of 1.3g/m^2. The field-wide average UCC and DU_{lq} are 0.692 and 0.494, respectively; which suggests a poor fertilizer application rate uniformity.

A summary of the test-plot scale and field scale maximum, minimum, and average depths, nitrogen concentrations, and application rates along with related UCC and DU_{lq} values are summarized in Table 2. The field-wide irrigation uniformity (UCC of 0.864 and DU_{lq} of 0.784) is high. On the other hand, with a UCC of 0.726 and a DU_{lq} of 0.552, the field-scale uniformity of nitrogen concentration is low.

Data set II: The second fertigation field evaluation event was conducted on February 28 of 2013 in a section of a grower's farm measuring 128.0m (420.0ft) along the mainline and 393.2m (1290.0ft) along the laterals (Table 3). The average wind speed in the Yuma Valley area during the fertigation evaluation is 4.5m/s. The duration of irrigation was 3.0h and a solution of ammonium nitrate and urea was applied throughout the irrigation. A summary of the total nitrogen application rate over each of the test-plots in the field is presented in Table 3.

Test-plot scale average nitrogen application rates vary between 0.4g/m^2 and 0.7g/m^2. Computed UCC for total nitrogen fertilizer application rate in the upstream end, middle, and downstream end test-plots are 0.666, 0.607, and 0.613, respectively. Test-plot application rate DU_{lq} varies from 0.475 to 0.498. The field-scale nitrogen application rate vary between 0.1g/m^2 and 1.5g/m^2, the average application rate being 0.5g/m^2.The field-scale average nitrogen application rate UCC and DU_{lq} are 0.629 and 0.489, respectively, suggesting a poor uniformity.

The field-scale irrigation uniformity (UCC = 0.846 and DU_{lq} = 0.761) is high. The relatively high wind speed in the Yuma Valley during the irrigation evaluation suggests a more pronounced adverse effect on irrigation uniformity. However, the measured uniformity levels (Tables 3) indicate that wind speed in the immediate ambience of the irrigated field might not be as high. On the other hand, the field-scale uniformity of nitrogen concentration is low: UCC of 0.705 and DU_{lq} of 0.545.

Data set III: This field evaluation was performed on March 1 of 2013 in a part of a grower's field covering an area of 96.0m×374.9m (315.0ft×1230.0ft, Table 4). The duration of irrigation was 3.0h and 24min and ammonium nitrate was applied during the entire irrigation. The average wind speed in the Yuma Valley during the fertigation evaluation was about 3.3m/s. A summary of the total nitrogen application rates over each of the test-plots in the field is presented in Table 4.

Average test-plot scale nitrogen application rates vary within a narrow interval of 1.9g/m^2 to 2.2g/m^2. Total nitrogen application rate UCC values are 0.648, 0.614, and 0.680 for the upstream end, middle, and downstream end test-plots, respectively (Table 3). The corresponding DU_{lq} vary between 0.487 for the upstream end test-plot and 0.509 for the middle test-plot. The field-scale nitrogen application rates vary over a wide range of 0.3g/m^2 to 5.7g/m^2. The computed field-scale fertilizer application rate UCC of 0.647 and DU_{lq} of 0.499 fall well short of a uniformity level that can be considered satisfactory.

The field-scale nitrogen concentration UCC of 0.795 can be considered high, however, the corresponding DU_{lq} of 0.636 indicates significant localized negative deviations from the average (Table 2). Hence, the overall concentration uniformity can be considered low. With a *UCC* of 0.7 and a DU_{lq} of 0.571, the field-scale irrigation uniformity as well is low. Average wind speed in the Yuma Valley, during the irrigation evaluation, is appreciably higher than what is considered conducive for higher uniformities (Table 4). However, it is likely that higher wind speeds may not be the only contributing factor to the low irrigation uniformity. For instance the relatively lower irrigation *UCC* and DU_{lq} computed for the middle test-plot, compared to the rest of the test-plots in the field (Table 2), points to a localized routine maintenance issue and/or improper setting of sprinkler components as the possible causes.

Data set IV: The fourth fertigation uniformity evaluation was conducted on March 2, 2013 in a section of a grower's farm measuring 74.7m (245.0ft) along the mainline and 182.9m (600.0ft) along the laterals (Table 5). The average wind speed in the Yuma Valley area during the field evaluation was 2.2m/s. The irrigation application time was 3.0h and a solution of ammonium nitrate and urea was applied for the entire duration of the test irrigation. A summary of the test-plot scale total nitrogen application rates is presented in Table 5.

The average test-plot scale application rate vary in the range between 2.5g/m^2 and 3.2g/m^2. Test-plot scale *UCC* values, for total nitrogen fertilizer application rate, are 0.759, 0.770, and 0.774 for the upstream end, middle, and downstream end test-plots, respectively (Table 5). Test-plot scale DU_{lq} vary in the range 0.625 to 0.666. The field-scale average application rate is 2.8g/m^2. While the computed field-scale application rate *UCC* value of 0.767 is acceptably high, the field-scale DU_{lq} value of 0.648 is considered low. Hence, the overall field-scale application rate uniformity can be described as low.

As can be noted from Table 2, the field-scale uniformity of nitrogen concentration (*UCC* of 0.881 and *DUlq* of 0.809) is high. Although the field-wide irrigation *UCC* of 0.748 can be considered marginally acceptable, the very low irrigation DU_{lq} of 0.582 implies that overall irrigation uniformity can be described as low. The average wind speed in the Yuma Valley during the irrigation evaluation (Table 5) does not suggest that the velocity of wind has appreciable adverse effect on irrigation uniformity. In addition, irrigation uniformity as measured by DU_{lq} is very low for all the test-plots, which is not the case for the corresponding *UCC* values. Hence, this points to a need for evaluating current irrigation practices as related to system component settings, routine and long term maintenance of system components, and the hydraulics of the sprinkler system in order to determine the factors contributing to the low field-scale and test-plot scale irrigation uniformities.

Data set V: This field evaluation was conducted on March 4 of 2014 in a grower's farm measuring 64.0m×365.8m (210.0ft×1200.0ft) in the Yuma Valley Irrigation Districts (Table 6). The duration of the test irrigation was 3.0h and a solution of ammonium nitrate was applied for the entire irrigation. A summary of the total nitrogen application rates for each of the test-plot in the field is presented in Table 6.

The average test-plot scale nitrogen application rate vary within a relatively narrow range of 1.3g/m^2 to 1.6g/m^2. Computed test-plot scale *UCC*, for total nitrogen application rates, are 0.768 for the downstream end test-plot, 0.717 for the middle test-plot, and 0.788 for the upstream end test-plot. Test-plot scale DU_{lq} ranges between 0.574

and 0.740. The minimum field-scale nitrogen application rate is 0.7g/m^2 and the maximum is 3.0g/m^2 and the average rate is 1.4g/m^2. Field-scale nitrogen fertilizer application rate *UCC* is 0.758 and DU_{lq} is 0.676. Although the field-wide *UCC* suggests an acceptably high application rate uniformity, the modest DU_{lq} suggests that the application rate data contains appreciable levels of localized negative deviations from the average rate. Overall, the resultant field-scale application rate uniformity can be described as low.

A summary of the test-plot scale and field scale maximum, minimum, and average depths, nitrogen concentrations, and application rates along with related *UCC* and DU_{lq} values are summarized in Table 7. The field-scale irrigation uniformity is quite high (*UCC* of 0.922 and DU_{lq} 0.889). Although the field-wide uniformity of nitrogen concentration (*UCC* of 0.754 and DU_{lq} of 0.7) is much lower than that of irrigation uniformity, it is marginally acceptable.

Data set VI: This field evaluation was conducted on February 28 of 2014 in a section of a grower’s farm measuring 64.0m×420.6m (210.0ft×1380.0ft) in the Yuma Valley irrigation Districts (Table 8). The duration of the test irrigation was 3.0h and a solution of ammonium nitrate was applied during the first hour of the test irrigation. The average wind speed during the irrigation was 2.9m/s. A summary of the computed nitrogen application rate data is presented in Table 8.

Test-plot scale average nitrogen application rate vary in the range of 1.5g/m^2 and 2.0g/m^2. The test-plot *UCC* range from 0.721 to 0.808. Computed DU_{lq} is lowest, 0.611, for the downstream end test-plot and is highest, 0.675, for the middle test-plot. Field-scale nitrogen application rate vary between 0.7g/m^2 and 3.7g/m^2 and the field-wide average rate is 1.8g/m^2. Field-scale application rate *UCC* is 0.750 and DU_{lq} is 0.636, suggesting a low overall application rate uniformity.

With a field-scale *UCC* of 0.789 and DU_{lq} of 0.687 (Table 7), irrigation uniformity can be described as marginally low. During the later part of the field evaluation wind was stronger than would be considered conducive for high irrigation uniformity. It may, therefore, have some effect on the observed level of irrigation uniformity. On the other hand, the field-scale uniformity of nitrogen concentration (*UCC* of 0.874 and DU_{lq} of 0.794) is high.

Data set VII: This field evaluation was conducted on February 27, 2014 in a section of a grower’s farm measuring 64.0m (210.0ft) along the mainline and 420.6m (1380.0ft) along the laterals (Table 9). The average wind speed in the Yuma Valley area during the field evaluation was 0.6m/s. The duration of irrigation was 3.0h and a solution of ammonium nitrate was applied during the second hour of the test irrigation. Table 9 summarizes the nitrogen application rate data computed based on measured irrigation depths and concentrations.

The average test-plot scale application rate vary in the range between 2.5g/m^2 and 2.9g/m^2. Test-plot scale *UCC* values, for total nitrogen fertilizer application rate, are 0.826, 0.790, and 0.772 for the upstream end, middle, and downstream end test-plots, respectively. Test-plot scale DU_{lq} vary in the range 0.665 to 0.716. The field-scale average application rate is 2.7g/m^2. While the computed field-scale application rate UCC of 0.796 can be considered acceptably high, the field-scale DU_{lq} value, of 0.689 is modest. Hence, overall field-wide application rate uniformity can be described as marginally low.

The field-wide uniformity of nitrogen concentration (UCC of 0.833 and DU_{lq} of 0.724) and irrigation (UCC of 0.876 and DU_{lq} of 0.796) are both high (Table 7). Note that the low wind speed (average wind speed of 0.6m/s) during the test irrigation should be considered as a factor in the observed high irrigation uniformity.

Data set VIII: This fertigation evaluation was conducted on Februray 28 of 2014 in a grower's farm measuring 64.0m×365.8m (210.0ft×1200.0ft) in the Yuma Valley Irrigation Districts (Table 10). The duration of the test irrigation was 3.0h and a solution of ammonium nitrate was applied during the last hour of the test irrigation. The average wind speed during the irrigation, 6.5m/s, was significantly larger than what is considered suitable for achieving high irrigation uniformity. A summary of the computed nitrogen application rates is presented in Table 10.

The average test-plot scale nitrogen fertilizer application rate vary in the range of 1.5g/m^2 and 2.3g/m^2. The test-plot UCC values, for total nitrogen application rates, vary between 0.495 and 0.641. Computed DU_{lq} is lowest (0.410) for the downstream end test-plot and is highest (0.569) for the upstream end test-plot. Field-scale nitrogen application rate vary over a wide range of 0.4g/m^2 and 5.2g/m^2 with a field-wide average rate of 1.9g/m^2. Field-scale application rate UCC is 0.556 and DU_{lq} is 0.465, suggesting a poor field-wide nitrogen application ate uniformity.

Field-wide irrigation UCC of 0.660 and DU_{lq} of 0.548 suggest poor field-scale uniformity (Table 7). Considering that this evaluation was conducted on the same subdivision of the field as that of data set V and that the two evaluations were conducted only a few days apart, the sharp decrease in irrigation uniformity level during the current test compared to that of data set V is likely related to the strong wind during the current test. On the other hand, the effect of wind on the distribution uniformity of concentration (UCC of 0.745 and DU_{lq} of 0.617) does not appear to be as significant.

2.4.3 Field-scale uniformity evaluations, discussion

Summary: This section presents a summary of the ranges of variations and field-scale averages of the measured nitrogen application rates, along with the computed uniformity indices, of the data sets presented above. It also discusses the practical design and management implications of these results.

The field-scale minimum, maximum, and average nitrogen application rates for all the eight data sets presented above are summarized in Table 11. The measured minimum field-scale nitrogen application rates vary between 0.1g/m^2 for data set II to 1.2 g/m^2 for data sets IV and VII. The field-scale maximum application rates range between 1.5g/m^2

for data set II and 5.7 g/m^2 for data set III. The average field-wide application rates vary from 0.5g/m^2 for data set II to 2.8 g/m^2 for data set IV. The overall average field-scale application rate, computed as the arithmetic mean of all the data sets (Table 11), is 1.8g/m^2.

Considering an approximate required nitrogen application rate (per fertigation event) of about 2.5g/m^2, it then follows that the average field-scale application rates in all but two of the test fields (data sets IV and data set VII) were well below the requirement. In these fields, the difference between the required and the field-wide average nitrogen application rates vary from a minimum of 20% to a maximum of 80% of the required rate (Table 11). Appreciable under-fertilization can be noted even in those fields with an average application rate slightly greater than the requirement (Tables 5 and 9). The low application rate and the poor uniformity, particularly the very low DU_{lq}, imply severe under-fertilization in most of the test fields. While some part of this apparent deficit could possibly be explained by sampling error, it is significantly large to be entirely attributed to that. Considering the significant level of apparent fertilizer deficit, there are no indications whatsoever that crop yield was adversely affected. Perhaps the background crop available soil nitrogen content is sufficiently high to mitigate the effects of under-fertigation.

The field-scale average nitrogen application rate uniformity indices along with test-plot scale minimum and maximum values, for all the eight data sets presented above, are summarized in Table 12. The minimum test-plot scale application rate *UCC* vary over a wide range between 0.495 (data set VIII) and 0.772 (data set VII). The maximum test-plot scale *UCC* ranges from 0.641 (data set VIII) to 0.826 (data set VII). The field-scale average *UCC* vary in the range 0.556 (data set VIII) to 0.796 (data set VII). The average field-scale *UCC* (computed as the arithmetic mean of the field-scale *UCC*'s of all the data set) is 0.7. This is significantly lower than the threshold for acceptably high *UCC* (0.75≤). As can be noted from Table 12, only four of the eight data sets (data set IV, V, VI, and VII) have field-wide *UCC* values that can be considered acceptable. Remarkably, however, three of these data sets have *UCC* values that can only be considered marginally so. On the other hand, one-half of the field data sets have *UCC* values well below the threshold, ranging between 0.556 and 0.692. Evidently, the field-wide uniformity of nitrogen application rate is typically low.

As can be noted from Table 12, the minimum test-plot scale nitrogen application rate DU_{lq} vary over a wide range, between 0.410 (data set VIII) and 0.665 (data set VII). The maximum test-plot scale DU_{lq} also spans a wide interval ranging from 0.569 (data set VIII) to 0.740 (data set V). The field-wide average DU_{lq} vary from a minimum of 0.465 (data set VIII) to 0.689 (data set VII). The average field-scale nitrogen application rate DU_{lq}, computed by taking the arithmetic mean of the DU_{lq}'s of all the data sets, is 0.575; well below the threshold for acceptably high DU_{lq} (0.7≤). It can also be noted from Table 10, that half of the data sets have very low field-scale average DU_{lq}'s (<0.5) and that none of the field-wide DU_{lq}'s exceed 0.7. The implication is that nitrogen application rates in all of the test fields show significant localized negative deviations from the field-wide averages.

Table 12 show that data sets VII and VIII have the highest and lowest field-scale application rate uniformity, respectively. These tests were conducted in two different sections of the same sprinkler system. Hence, they are of comparable hydraulic, topographic, and geometric configurations and are under the same maintenance and operational practices. However, the two fertigation evaluations were conducted under significantly different ambient wind speeds of 0.6m/s (data set VII) and 6.5m/s (data set VIII), which appears to be the main difference between these fertigation events. This, evidently, underscores the significance of the effect of wind on fertigation uniformity.

The practical significance of high fertilizer application rate uniformity stems from the fact that it is a necessary condition for adequate and efficient field-scale application of fertilizer with sprinkler irrigation. The poor field-wide fertilizer application rate uniformity of most of the data sets, presented above, therefore, suggests that with the current fertigation practices it is hardly possible to attain adequate and at the same time efficient application of nitrogen fertilizer in these farms. In other words, given the current levels of fertilizer application rate uniformity, one can either maximize application efficiency at the expense of adequacy (and accept some levels of apparent crop nutrient stress along with the consequent adverse effects on crop yield) or one may opt to meet crop nitrogen needs fully and then accept inefficient application of nitrogen fertilizer. Considering the limited scope of the study, generalization of the results to sprinkler fertigation practices over the entire Yuma Valley Irrigation Districts may not be automatic. Nonetheless, the consistency of the results across different fields suggests that they may not be untypical of fertigation practices in the area.

As summarized in Figure 2, results of a study by Zerihun and Sanchez (2014) shows that nitrogen application rate uniformity is a function of the interactive effects of the spatial trends and scale of variability inherent in the irrigation and concentration data sets. Significant outcomes of this study are summarized in section 2.3.4 and their application in analyzing the relationships between measured depth and concentration data sets and the resultant application rate data is presented in section 2.4.4. Before that, however, a concise description of the physical factors and mechanisms affecting irrigation depth and fertilizer concentration uniformity (which in turn influence application rate uniformity) is presented.

Physical factors and processes affecting fertigation uniformity: The main sources of spatial variability in sprinkler irrigation and the required design and management interventions to enhance irrigation uniformity are reasonably well established (Zerihun and Sanchez, 2012; Burt et al., 1997; Nderitu and Hills, 1993; Fischer and Wallender, 1988; Livingston et al., 1985). Figure 3 summarizes the interplay of factors considered to be the main determinants of irrigation uniformity and other performance indices in any given sprinkler irrigation event. These factors consist of system hydraulic, geometric, and topographic characteristics; maintenance and setting of system components; ambient weather conditions; and soil-crop and operational practices.

Sprinkler system hydraulic, geometric, and topographic factors are mainly set at the system design stage such that the field-scale spatial variation of sprinkler pressure head/discharge is limited to within a preset range about the design pressure head. In addition, system design should aim at ensuring that the sprinkler application rate does not exceed soil intake rate. These factors along with the state of maintenance of system components and the proper installation/setting of these components or lack thereof determine the actual field-scale spatial distribution of sprinkler pressure head/discharge (Figure 3). The field-wide spatial distribution of irrigation depths and hence uniformity follow directly from the interactive effects of the spatial distribution of sprinkler pressure heads, sprinkler design factors, and the prevailing ambient weather condition (most significantly wind velocities). Finally, the combined effect of irrigation management decisions (mainly related to the duration of irrigation), pertinent soil-crop properties, and the spatial distribution of irrigation determine the resultant irrigation application efficiency and adequacy.

It follows from the preceding discussion that a properly designed and well maintained sprinkler system can attain high application uniformity, if operated under conducive ambient weather conditions (i.e., low wind speed and cool and not so dry weather). Considering that the application rate of field sprinkler systems are generally considered steady, given a highly uniform irrigation and pertinent soil-crop parameters, the goal of attaining adequate and sufficiently efficient irrigation is reduced to the task of determining the duration of irrigation.

In sharp contrast to the more extensive studies conducted in relation to irrigation uniformity, to the best of authors' knowledge there is no published study that defines the factors and processes affecting the spatial distribution of fertilizer concentration and examine their interrelationship. However, based on the general theory of solute transport in hydraulic networks (e.g., Tzatchkov et al., 2002; Taylor, 1954) and authors' field and modeling experience with surface fertigation methods, a tentative outline of factors and mechanisms that may likely account for much of the field-scale spatial variability of sprinkler applied nitrogen concentration is proposed. These include inlet (upstream) boundary condition, solute mixing due to the physical mechanism of advection-dispersion in the conveyance network, and ambient weather condition (Figure 4).

The inlet (upstream) boundary condition establishes the time variation of concentration at the upstream physical boundary of the sprinkler system and as such it should have a significant effect on the evolution of solute concentration with time and distance through much of the sprinkler pipe network. The solute transport mechanism of advection-dispersion acts on the incoming solute flux and modify its concentration, to a varying degree, during its passage through the conveyance network. Evaporation from droplets, modifies concentration and, is primarily a function of temperature and humidity as well as droplet size. To the extent that the effect of evaporation on concentration vary with droplet size, it is conceivable that evaporation (hence the temperature and humidity in the immediate ambience of the irrigated field) can have a subtle but likely a very limited effect on the spatial distribution of concentration. The effect of wind on concentration distribution may mainly come in the form of differential dilution and could conceivably be significant if nitrogen concentration is variable.

Evidently, the discussion in the preceding paragraphs regarding the factors and mechanisms affecting the field-scale variability of nitrogen concentration is intended here to be merely a hypothesis and as such it can only be considered as a basis for a more detailed further study.

2.4.4 Analyses of field-scale uniformity evaluation results

In this section the effects of the spatial overlap patterns and scale of variability of the measured depth and concentration data sets on the spatial variability of the resultant application rate data will be examined. The discussion will largely be based on dimensionless surfaces depicting the spatial variability of irrigation depth, nitrogen concentration, and application rates for a selected test-plot from each of the data sets. Moreover, the corresponding test-plot scale uniformity of these data sets (Tables 2 and 7) will also be used in the analyses. Here the goal is to highlight the potential sources of the observed low nitrogen application rate uniformities of the data sets presented in the preceding section.

Data set I: In order to relate the uniformity of nitrogen application rate with those of irrigation depth and nitrogen concentration, here we consider the downstream end test-plot of data set I. As can be noted from Table 2, the irrigation uniformity of the downstream end test-plot (UCC = 0.864 and DU_{lq} = 0.803) is high, but the concentration uniformity (UCC = 0.7 and DU_{lq} = 0.507) is low. The resultant application rate uniformity of (UCC = 0.665 and DU_{lq} = 0.459) is as well low. Note that a combination of high irrigation and low concentration uniformity has resulted in a low application rate uniformity, which is consistent with the inferences (pertaining to uniformity relationships) summarized in section 2.3.4.

Figures 5a-5c depict dimensionless surfaces representing the spatial variability patterns of the measured irrigation depths and nitrogen concentrations and the resultant application rates for the downstream end test-plot of data set I. The aim here is to examine the interactive effects of the spatial trends (in the irrigation and concentration data sets) on the uniformity of the resultant nitrogen application rate data. In order to remove scale effects and allow direct visual comparison between the irrigation depth, nitrogen concentration, and application rate data sets, the surfaces are expressed in dimensionless form. Each data set was normalized by dividing the data points with the respective maximum values. With this transformation all the data sets vary in the range 0.0 to 1.0.

Figure 5a shows that the irrigation data exhibits some variability in a direction normal to the mainline at points that are close to the left-hand side lateral. On the other hand, the concentration data shows similar spatial variability attributes near the right-hand side lateral (Figure 5b). However, the dominant trend in the spatial variation of irrigation and concentration is that both data sets peak at points near the left-hand side lateral and then fall with distance in a direction parallel to the mainline, reaching their lowest points in close vicinity of the right-hand side lateral (Figures 5a and 5b). The implication is that the broader spatial trends in both data sets have the same monotonicity. As can be noted from the general inferences summarized in section 2.3.4, such an overlap pattern should result in an application rate data with a uniformity index lower than those of the depth and concentration data sets. Evidently, this explains the observation that the computed uniformity of the resultant application rate data is less than those of the depth and concentration data sets (Table 2).

Furthermore, it can be noted that the nitrogen application rate surface more closely tracks the concentration data set compared to that of the irrigation data (Figure 5a-5c). Consistent with the inferences presented in section 2.3.4, the concentration data (with a much larger variability compared to that of the irrigation data) appears to have a dominant effect on the scale and pattern of variability of the resultant application rate data set.

Although for the irrigation and concentration data sets considered here global spatial trends are clearly discernible, it should be noted that such is not often the case. Note that for practical reasons the preceding discussion is limited to a single test-plot. Nonetheless, it highlights the practical significance of the interactive effects of the spatial trends and scale of variability, in the irrigation and concentration data sets, on the variability of the application rate data set.

Data set II: For purpose of analysis the middle test-plot of data sets II (Table 2) is considered here. The test-plot scale irrigation uniformity (*UCC* of 0.818 and DU_{lq} of 0.716) can be considered acceptably high, but the corresponding nitrogen concentration uniformity (*UCC* of 0.714 and DU_{lq} of 0.518) is low. The resultant application rate uniformity of *UCC* = 0.607 and DU_{lq} = 0.498 is as well low. Evidently, this combination concentration, irrigation, and application rate uniformity is consistent with the inferences summarized in section 2.3.4.

Dimensionless surfaces depicting the spatial variability patterns of depth, concentration, and application rate over the middle test-plot of data set II are presented in Figures 5d-5f.

As can be noted from Figures 5d and 5e, both irrigation depth and nitrogen concentration surfaces peaked at the upper right hand corner of the test-plot and then exhibit a rapid decrease in the immediate vicinity of the peak, which is then followed (mostly) by a gradual decrease with distance towards the opposite edges of the test-plot. Hence, the predominant trends in both data sets have the same monotonicity. According to the inferences stated in section 2.3.4, these spatial patterns suggest that the test-plot scale application rate uniformity should be less than the uniformity of the corresponding irrigation and concentration data sets. Note that the computed test-plot scale uniformity of the resultant application rate data set is in agreement with this observation (Table 2).

The surface for the resultant nitrogen application rate data more closely tracks the concentration distribution than the irrigation distribution (Figure 5d-5f), which is related to the much wider variability inherent in the centration data compared to that of the irrigation data.

Data set III: In order to relate test-plot scale nitrogen application rate uniformity with the corresponding irrigation and concentration uniformity, consider the middle test-plot of data set III (Table 2). The test-plot scale irrigation uniformity of *UCC* = 0.645 and DU_{lq} = 0.488 is low. Although the concentration *UCC* of 0.773 can be considered acceptably high, a DU_{lq} of 0.611 is considered low. Hence, overall the test-plot scale concentration uniformity can be described as low. The resultant application rate uniformity (*UCC* = 0.614 and DU_{lq} = 0.509) is as well low. As can be noted from the inferences summarized in section 2.3.4, the combination of low irrigation and concentration uniformity in itself does not necessarily imply low nitrogen application rate uniformity. However, the spatial overlap patterns and scale of variability of the irrigation depth and nitrogen concentration data sets can be examined to highlight the source of the resultant poor nitrogen application rate uniformity.

Dimensionless surfaces depicting the spatial trends in irrigation depth, concentration, and resultant application rate for the middle test-plot of data set III are presented in Figures 6a-6c.

As can be noted form Figure 6a, the irrigation surface peaks at the upper right-hand corner of the test-plot and then decreases rapidly with distance toward the opposite edges of the test-plot. The depth data is dominated by a global spatial trend with much of its variability limited to the upper right hand corner to the test-plot. . On the other hand, the nitrogen concentration surface attains its peak close to the left-hand side lateral and exhibits rapid decrease to relatively lower levels near the vicinity of the peak. For the most part, however, the concentration surface is dominated by local trends and varies within a relatively narrow range, which explains the high test-plot scale *UCC* of *0.773*.

Some local overlap patterns, between the irrigation and concentration data sets (Figures 6a and 6b), can be discerned which may have contributed to a limited extent to the low application rate uniformity (Table 2). Nonetheless, much of the variability in the resultant fertilizer application rate data can be mainly attributed to the dominant effect of the irrigation data set, which shows a much wider range of variability compared to the nitrogen concentration data set (Figures 6a-6c).

Data set IV: For the purpose of relating nitrogen application rate uniformity to the uniformity of the corresponding irrigation and concentration data sets, here we consider the upstream end test-plot of data set IV (Table 2). The test-plot scale irrigation uniformity (*UCC* of 0.744 and DU_{lq} of 0.583) can be considered low. On the other hand, the corresponding concentration uniformity of *UCC* = 0.872 and DU_{lq} = 0.796 is high. Overall, the uniformity of the resultant application rate data set (*UCC* of 0.759 and DU_{lq} of 0.666) can be considered low, which is consistent with the characterization of the qualitative relationship between depth, concentration, and application rate uniformity (section 2.3.4).

Dimensionless surfaces depicting the spatial distribution of depth, concentration, and application rate for the upstream end test-plot of data set IV are presented in Figures 6d-6f.

For the most part, the spatial distributions of irrigation depth and nitrogen concentration are such that areas of the test-plot with the shallowest application depths have also received some of the highest nitrogen concentration levels (Figures 6d and 6e). In addition, at points in close vicinity of the right-hand side lateral moderately high irrigation depths are overlapped with low concentrations. Overall these areas of the test-plot are characterized by overlap patterns consisting of opposite trends between the irrigation and concentration data sets. The inferences deduced in a section 2.3.4 suggest that the net effect of these overlap patterns should lead to reduced variability in the resultant application rate surface in this part of the test-plot. On the other hand, the depth and concentration overlap pattern near the upper right-hand corner of the test-plot should result in increased local variability of the resultant application rate data. However, the range of spatial variability and the test-plot scale uniformity of the resultant application rate surface fall in between those of the irrigation depth and nitrogen concentration surfaces. This suggests that spatial overlap patterns that have the effect of reducing variability in the application rate data (which covers a large fraction of the test-plot area) also have a more dominant effect on the test-plot scale uniformity compared to the overlap patterns that have the opposite effect on the application rate data.

Overall the spatial pattern and scale of variability of the nitrogen application rate data more closely track the irrigation depth data than that of the nitrogen concentration data set (Figures 6d-6f). This suggests that the much larger variability inherent in the depth data, compared to that of the concentration data set, has a dominant effect on the resultant application rate data, which is consistent with the inferences presented in section 2.3.4.

Data set V: In order to highlight the relationship between test-plot scale application rate, concentration, and irrigation uniformity, here the middle test-plot of data set V is considered (Table 7). The irrigation uniformity ($UCC = 0.897$ and $DU_{lq} = 0.855$) is quite high, but the concentration uniformity ($UCC = 0.733$ and $DU_{lq} = 0.643$) can be described as low. The fact that the resultant test-plot scale application rate uniformity ($UCC = 0.717$ and $DU_{lq} = 0.574$) is low is consistent with the broad relationship between the uniformity indices summarized in section 2.3.4.

Dimensionless surfaces depicting the spatial variations in irrigation depth, nitrogen concentration, and application rate for the middle test-plot of data set V are presented in Figures 7a-7c.

Figure 7a depicts an irrigation data with clearly discernible global spatial trend for the most part. Figure 7b, on the other hand, shows a concentration data set dominated by highly variable local spatial trends. It can be noted that the depth and concentration surfaces have same local spatial patterns (monotonicity) in a number of spots in the test-plot: upper right-hand corner, upper left-hand corner, lower left-hand corner, middle segments of the edges of the test-plot that are opposite to the upper right-hand corner. In addition, in an area of the test-plot that has received the shallowest depth, the spatial patterns of depth and concentration are the same. Evidently, these overlap patterns led to increased local variability of the resultant application rate data set compared to that of the corresponding depth and concentration data sets (Figures 7a-7c). Note that, to a significant extent, this explains the observed relatively low application rate uniformity as well (Table 7).

As can be noted from Figures 7a-7c, the scale and pattern of variability of the resultant application rate data set more closely track those of the concentration data set. Observe that this is related to the dominant effect of the concentration data set, which has a much wider range of variation compared to that of the irrigation data set.

Data set VI: For the purpose of analysis we consider here the downstream end test-plot of data set VI (Table 7). With a UCC of 0.783 and a DU_{lq} of 0.616, the overall test-plot scale irrigation uniformity can be described as low. On the other hand, the uniformity of the concentration data ($UCC = 0.860$ and $DU_{lq} = 0.792$) is high. The resultant test-plot scale application rate uniformity (*UCC* of 0.721 and a DU_{lq} of 0.611) is low. The combination of test-plot scale irrigation, concentration, and application rate uniformity is broadly consistent with the discussion in section 2.3.4.

Dimensionless surfaces depicting the spatial trends in depth, concentration, and application rate for the downstream end test-plot of data set VI are presented in Figures 7d-7f.

It can be noted that the irrigation data peaks at the upper right-hand corner of the test-plot and then shows a rapid decrease in close vicinity of the peak (Figure 7d). In the same area of the test-plot the concentration data set shows vary limited variability. As would be expected (section 2.3.4), the scale and pattern of variability of the resultant application rate data set in that part of the test-plot is dominated by the variability in the irrigation data set (Figure 7d). In addition, along the opposite edge of the test-plot (considering a direction parallel to the mainline), it can be noted that there is a segment of the test-plot where depth and concentration have same spatial trends and another segment where they have opposite spatial trends (Figures 7d and 7e). Note that in both these segments of the test-plot, the scale and pattern of variability of the resultant application rate surface (Figure 7f) is consistent with the inferences stated in section 2.3.4.

The significant localized variability of the application rate data, which is mainly attributable to the spatial variability in the irrigation data, is likely the main contributing factor to the observed low application rate uniformity.

Data set VII: In order to highlight the relationship between test-plot scale uniformity of application rate, depth, and concentration, we consider here the upstream end test-plot of data set VII (Table 7). The test-plot scale irrigation uniformity of $UCC = 0.870$ and $DU_{lq} = 0.794$ is high. The nitrogen concentration *UCC* of 0.806 can be considered acceptably high, but the corresponding DU_{lq} of 0.69 is marginally low. Hence, overall the concentration uniformity can be described as marginally low. The resultant application rate uniformity of $UCC = 0.826$ and DU_{lq} of *0.716* can be described as marginally high. Note that the computed uniformity indices for application rate, depth, and concentration data sets do not neatly fit in the relationships summarized in Section 2.3.4. However, considering that: *(i)* the uniformity relationships are qualitative, *(ii)* the nitrogen concentration uniformity is only marginally low (a percentage point below the threshold), and *(iii)* the application rate uniformity is only marginally high (a percentage point above the threshold), it can be observed that the uniformity relationships, summarized in section 2.3.4, are essentially valid here as well.

Dimensionless surfaces depicting spatial trends in irrigation depth, concentration, and application rate for the upstream end test-plot of data set VII are presented in Figures 8a-8c.

The surfaces in the middle section of the test-plot (considering the direction parallel to the laterals) are characterized by a relatively heavier irrigation and low nitrogen concentration, with discernibly opposite spatial trends (monotonicity), Figures 8a and 8b. Evidently, this combination of spatial patterns and scale of variability, between the irrigation and concentration data sets, led to a reduction in the local variability of the resultant application rate data compared to that of the concentration data set (Figure 8c). Note that this observation is consistent with pertinent inferences summarized in section 2.3.4.

Furthermore, in an area of the test-plot adjacent to the left-hand side lateral, irrigation depth tends to increase as one moves away from the lateral. Whereas concentration shows very limited localized variation within the same section of the test-plot. Note that the pattern and scale of variability in the resultant application rate data in that part of the test-plot closely tracks the irrigation data set than the more uniform nitrogen concentration data set, which is in agreement with the relevant deductions summarized in section 2.3.4.

In a part of the test-plot that is close to the lower right-hand corner, irrigation depth and concentration data sets have same spatial trends (Figures 8a and 8b), which led to a significant localized drop in the application rate surface (Figure 8c). Evidently, this is the reason for the relatively wider range of variation of the resultant application rate data set compared to that of the irrigation and concentration data sets. Interestingly the application rate DU_{lq} is slightly greater than that of the concentration data set (Table 7). The likely reason is that the very low spot in the nitrogen application rate surface is limited to a small fraction of the test-plot area (compared to that of the concentration surface), hence its effect is not sufficient to lower the test-plot scale DU_{lq} below that computed for the concentration data set.

Data set VIII: In order to relate test-plot scale application rate uniformity with the uniformity of irrigation and concentration, we consider here the upstream end test-plot of data set VIII. The test-plot scale irrigation uniformity ($UCC = 0.632$ and $DU_{lq} = 0.497$) is low. On the other hand, the nitrogen concentration uniformity of ($UCC = 0.787$ and $DU_{lq} = 0.704$) is marginally acceptable. With a $UCC = 0.641$ and $DU_{lq} = 0.569$, the resultant application rate uniformity is poor. Note that the combination of irrigation, concentration, and application rate uniformity is consistent with pertinent inferences presented in section 2.3.4.

Dimensionless surfaces of depth, concentration, and application rate for the upstream end test-plot of data set VIII are depicted in Figures 8d-8f.

The spatial variation of both the irrigation and concentration data sets are dominated by local trends. The irrigation surface peaks at the upper right-hand corner and decrease rapidly with distance toward the opposite edges of the test plot (Figure 8d). In the same part of the test–plot the nitrogen concentration surface is mainly dominated by local spatial patterns, nonetheless, its range of variability compared to the depth data is very small (Figure 8e). As would be expected, the scale and pattern of variability of the resultant application rate surface, in this part of the test-plot, is largely dominated by the variability in the irrigation data (Figures 8d-8f).

In an area of the test-plot close to the lower right-hand corner, the irrigation depth and concentration surfaces have the same spatial trends and comparable scale of variability (Figures 8d and 8e). Consistent with the inferences stated in section 2.3.4, the resultant application rate surface has the same spatial trend as the depth and concentration data sets but with a larger scale of variability (Figure 8f).

Furthermore, in the upper left-hand corner of the test-plot the irrigation and concentration surfaces have opposite monotonicity (Figures 8d and 8e). In addition, the irrigation data shows appreciably larger scale of variability compared to that of the nitrogen concentration data set. Observe that the scale of variability of the resultant application rate surface, in this part of the test-plot, falls somewhere in between the depth and concentration surfaces, but more closely approximates the irrigation surface compared to that of the concentration surface. Note that this observation regarding the scale and pattern of variability of the resultant application rate surface is consistent with relevant inferences stated in section 2.3.4.

2.4.5. Test-plot scale uniformity evaluations

In 2014, four test-plot scale field evaluations were conducted in the Maricopa Agricultural Center (MAC) of the University of Arizona. In these evaluations the bromide ion, applied in the form of potassium bromide solution, was used as a tracer to simulate the spatial distribution of a nonsorbing nitrogen fertilizer species, such as nitrate-nitrogen. The main objective is to assess the effect of inlet boundary conditions (fertilizer application configurations) on fertilizer application rate uniformity. Each fertigation test lasted for three hours and four bromide application configurations, with the same format as those described in section 2.4.1, were used in these evaluations.

Figure 9 shows the layout of the test-plots used in these field evaluations and components of the sprinkler fertigation system. Four test-plots (labeled here as test-plots I, II, III, and IV) were installed within a small field sprinkler system comprised of a main and laterals. Two of the test plots (I and II) have 42 rain gages and the other two (III and IV) have 36 rain gages. The water supply system consists of an underground farm water distribution network operating under gravity. A centrifugal pump installed at the edge of the irrigated field provides the required sprinkler system dynamic head (Figure 9). The fertilizer injection apparatus consists of a feed tank (containing a well-mixed potassium bromide solution) and a diaphragm pump. The diaphragm pump injects the potassium bromide solution at a pre-calibrated rate at the inlet of the sprinkler system.

Four fertigation evaluations were conducted, each in a different test-plot and with a different fertilizer application configuration, labeled here as data set IX, X, XI, and XII. Data set IX, X, XI, and XII were collected in test-plots I, II, III, and IV, respectively (Figure 9). Furthermore, data sets IX, X, XI, and XII were collected when the sprinkler system was operated under fertilizer application configurations 1, 2, 3, and 4, respectively (section 2.4.1). During any given field evaluation all the sprinkler riser pipes in the field, except a block of twenty (4×5) about the test-plot (rectangular area in Figure 9), are capped and sealed. The goal was to limit the number of sprinklers, operating at a time, to the bare minimum required to ensure a completely over-lapped test-plot. The resultant system can then be considered sufficiently small for the effect of solute transport processes, on concentration uniformity, to be considered negligible.

Data set IX: The first test-plot scale uniformity evaluation was conducted on March 28, 2014 in the research farm of MAC in a test-plot measuring 10.2m×9.1m (33.5ft×30.0ft). Irrigation duration was 3.0h and a solution of potassium bromide was applied throughout the test irrigation. The objective in this evaluation was to apply a constant bromide concentration throughout the test duration (fertilizer injection configuration I). However, because of fertilizer injection system malfunction bromide was not applied for approximately 30.0min right in the middle of the test irrigation (Figure 10). The bromide injection configuration can then be considered as having two consecutive finite pulses with an approximate 30min off-cycle. The overall average bromide injection rate computed based on measurements at the system inlet is 67.8mg/L.The average wind speed in the immediate ambience of the test-plot is 1.3m/s. A summary of the bromide application rates over the test-plot (Test-plot I) is shown in Table 13.

The computed test-plot scale bromide application rates vary from 0.7g/m^2 to 1.3g/m^2 and the average is 0.9g/m^2 (Table 14). The test-plot scale bromide application rate *UCC* and DU_{lq} are 0.895 and 0.853, respectively. Note that the very high test-plot scale bromide application rate uniformity is derived from an even higher irrigation uniformity (*UCC* = 0.903 and DU_{lq} = 0.867) and concentration uniformity (*UCC* = 0.954 and DU_{lq} = 0.932). This is consistent with the discussion in section 2.3.4 as regards the relationship between solute application rate uniformity, on one hand, and irrigation and concentration uniformity on the other.

The test-plot scale average concentration of 88.3mg/L, Table 14, is close to the average of the peak concentration levels of the two bromide pulses, approximately equal to 97.6mg/L and 100.9mg/L (Figure 12). Considering a condition in which all things remain unchanged, this observation suggests that if in fact bromide was applied at a fairly constant rate over the entire irrigation duration (no discontinuity), the average test-plot scale concentration would likely be appreciably closer to the average concentration at the sprinkler system inlet. The practical significance of this is that considering a fertigation event in which transport effects on concentration variation are limited, the concentration at the sprinkler nozzles (and hence the average field-scale concentration) can potentially be controlled by applying fertilizer solution at a near-constant (preset) rate throughout the irrigation duration. In which case, high fertigation uniformity can be achieved, if only the design, management, maintenance, and operational requirements for high irrigation uniformity are met.

Data set X: The second test-plot scale evaluation was conducted on March 31, 2014 at MAC in a test-plot spanning an area of 10.2m×9.1m (33.5ft×30.0ft). Irrigation duration was 3.0h and a solution of potassium bromide was applied during the first hour of the test irrigation event (Figure 10). The average wind speed in area of the test-plot is 2.9m/s. A summary of the total bromide application rates over the test-plot (Test-plot II) is shown in Table 13.

The computed bromide application rates over the test-plot vary in the range 0.7g/m^2 to 1.6g/m^2 and the average is 1.2g/m^2 (Table 14). The test-plot scale Br application rate *UCC* and DU_{lq} are 0.852 and 0.771, respectively, which suggests a very high bromide application rate uniformity. Considering the very high test-plot scale irrigation uniformity (*UCC* = 0.853 and DU_{lq} = 0.792) and concentration uniformity (*UCC* = 0.932 and DU_{lq} = 0.88), here as well the relationship between high application rate uniformity and very high irrigation and concentration uniformity is evident.

The average bromide concentration at the sprinkler system inlet, of about 190.0mg/L (Figure 10), is significantly larger than the test-plot scale average concentration of 119.3mg/L (Table 14). The dilution of the bromide solution by the bromide free water applied during the last two hours of the fertigation may, to some extent, account for the lower concentrations in the test-plot samples.

Data set XI: The third test-plot scale uniformity evaluation was conducted on March 3, 2014 at MAC in a test-plot spanning an area of 9.1m×9.1m (30.0ft×30.0ft). Irrigation duration was 3.0h and a solution of potassium bromide was applied during the middle hour of the test irrigation (Figure 10). The average wind speed in the immediate ambience of the test-plot is 1.7m/s. A summary of the bromide application rates over the test-plot (Test-plot III) is shown in Table 13.

The computed bromide application rates over the test-plot vary in the range 0.8g/m^2 to 2.4g/m^2 and the average is 1.3g/m^2 (Table 14). The test-plot scale bromide application rate UCC and DU_{lq} are 0.830 and 0.771, respectively, which suggests a very high uniformity. Both the test-plot scale irrigation uniformity (UCC = 0.899 and DU_{lq} = 0.822) and concentration uniformity (of UCC = 0.885 and DU_{lq} = 0.840) are very high. Note that the high bromide application rate uniformity is a consequence of the very high irrigation and concentration uniformities.

The significant difference between the average bromide concentration at the sprinkler system inlet (of about 271.0mg/L, Figure 10) and the test-plot scale average bromide concentration of 111.6mg/L (Table 14) is, to a certain degree, related to the dilution during the remaining two-thirds of the test irrigation event.

Data set XII: The last test-plot scale uniformity evaluation was conducted on March 4, 2014 at the MAC in a test-plot spanning an area of 9.1m×9.1m (30.0ft×30.0ft). Irrigation duration was 3.0h and a solution of potassium bromide was applied during the last one-third of the irrigation application time (Figure 10). The average wind speed in the area of the test-plot is 1.2m/s. A summary of the bromide application rates over the test-plot (Test-plot IV) is shown in Table 13.

The computed bromide application rates over the test-plot vary in the range 1.2g/m^2 to 2.0g/m^2 and the average is 1.6g/m^2 (Table 14). The test-plot scale bromide application rate UCC and DU_{lq} are 0.890 and 0.824, respectively, suggesting a very high application rate uniformity. Comparing the application rate uniformity for data set XI with those of data sets IX and X, one may note here the favorable effect of low wind speed on application rate uniformity. Both the test-plot scale irrigation uniformity (UCC = 0.894 and DU_{lq} = 0.855) and concentration uniformity (of UCC = 0.913 and DU_{lq} = 0.861) are very high. Once again, it can be noted that the high bromide application rate uniformity is related to the very high irrigation and concentration uniformities.

To some extent as a result of dilution, here as well, the bromide concentration at the sprinkler inlet (about 348.0mg/L, Figure 10) is significantly larger than the test-plot scale average bromide concentration (145.8mg/L, Table 14).

2.4.6. Test-plot scale uniformity evaluations, a summary

A summary of some observations derived from the test-plot scale field evaluations is presented here. Note that these observations are of preliminary nature and need to be verified by more comprehensive field evaluations.

(i) In a sprinkler system in which the effects of solute transport processes on concentration variation are limited, fertilizer can be applied with high application rate uniformity irrespective of the solute application configurations at the system inlet; provided the concentration at the system inlet is kept fairly constant for the duration of fertilizer application and that the uniformity of the underlying irrigation event is high.

(ii) Considering a scenario in which fertilizer is applied in the form of a finite pulse, during a fraction of the irrigation time, to a system in which the effects of solute transport processes on concentration are limited; the resultant application rate uniformity is mainly a function of the wind velocity pattern during fertilizer application. However, concentration (as well as irrigation) uniformity would be affected by wind velocity patterns over the duration of irrigation.

(iii) In a sprinkler system in which the effects of solute transport processes on concentration variation are limited, the concentration variation at the sprinkler nozzles (and hence over the field) can potentially be controlled by applying fertilizer solution at a near-constant (preset) rate throughout the irrigation duration. In which case, high fertigation uniformity can be achieved, if only the design, management, maintenance, and operational requirements for high irrigation uniformity are met.

Chapter 3. Goals and outcomes achieved

As listed in section 1.2, the specific goals of the study reported here are: (1) To develop a field and data processing methodology for field-scale fertigation uniformity evaluations in vegetable cropped fields under season-long sprinkler use in the LCRR, (2) To conduct limited fertigation uniformity evaluations in growers' fields in the Yuma Valley Irrigation Districts of the LCRR, and (3) To develop recommendations for further studies. The following is a concise description of the activities and outcomes achieved as related to each of these objectives.

3.1. Development of methodology for field-scale fertigation uniformity evaluations

A methodology for field-scale fertigation uniformity evaluation is proposed in section 2.3. In what follows a brief outline of pertinent activities is presented.

(i) *Variability of field-scale irrigation and nitrogen application rates and the need for sampling*: The study highlighted the fact that field-scale spatial distribution of irrigation and fertilizer application rates can be highly variable. A methodology for sampling the field-scale spatial variability of sprinkler applied irrigation depths and nitrogen application rates is proposed. Test-plots are defined here as the basic field-scale sprinkler fertigation uniformity sampling units. The number of test-plots in an evaluation field may need to be set based on considerations of cost, time, and effort

needed to conduct the field evaluation, on one hand, and the required level of accuracy on the other. The spatial arrangement of the test-plots in a field can take into account the effect of factors that cause systematic variability over the field (such as system hydraulics). Other factors whose spatial variability is less predictable and have random effects on the distribution of irrigation and fertilizer, can be used to design the spatial arrangement of the test-plots within a field only if specific data as regards their location in the field is known a priori.

Each test-plot should be placed inside a subdivision of the field within which the spatial variability of irrigation and fertilizer application rate can be considered practically negligible. In which case, the test-plot scale average irrigation depth, average nitrogen application rate, and uniformity indices can be assumed representative of the corresponding field subdivision. The area of the field subdivisions can be of the same size or can be variable. For a general application, a set of equally spaced three test-plots arranged along the field diagonal, from the system inlet, can be considered satisfactory. Note that in all of the field evaluations conducted as part of the current study this latter approach was used.

(ii) *Fertigation field evaluations*: Fertigation field evaluations should be conducted under suitable ambient weather conditions for a preset duration. Irrigation depths collected in the rain gages, in each of the test-plots, need to be recorded immediately following the end of a fertigation event. Subsequently, water samples are to be taken from each of the rain gages with appropriately labeled vials. The samples should then be sealed and frozen (within 2h of sampling), in order to preserve the integrity of the dissolved constituents (mineral nitrogen forms) untill laboratory analysis. The above constitute the basic data sets collected in a fertigation evaluation event. However, depending on the objective of the evaluation a more extensive set of data types (including discharge and solute concentration in the sprinkler network as well as solute concentration in the soil profile) can be measured at selected points distributed throughout the field.

(iii) *Laboratory analysis of water samples*: Water samples are to be analyzed in a a laboratory to determine the concentration of mineral nitrogen forms (nitrate-, ammonium-, and urea-nitrogen) and bromide as described in section 2.1.2.

(iv) *Data processing*: Measured irrigation depths and nitrogen concentrations are used to compute total nitrogen application rates in each of the test-plots. Based on these data sets the test-plot scale minimum, maximum, and average irrigation depths, nitrogen concentrations, and application rates are determined. Test–plot scale uniformity indices (defined in terms of Christiansen's uniformity coefficient and low-quarter distribution uniformity) can then be calculated with appropriate equations given in section 2.3.3. The test-plot scale averages and uniformity indices can be scaled up to field level through averaging.

(v) *Analyses of fertigation uniformity equations and data sets*: As part of the methodological development fertigation uniformity equations and the relationships between pertinent data sets were analyzed: (a) important properties of the uniformity equations were identified and their practical implications discussed, (b) based on results of a study by the authors (Zerihun and Sanchez, 2014) and measured field data sets, the field-wide uniformity of nitrogen application rates was shown to be a function of the spatial trends and scale of variability inherent in the irrigation and

concentration data sets, (c) based on results of the study referenced above and measured field data sets some important qualitative relationships that exist between the uniformity of irrigation, concentration, and application rate data sets have been highlighted.

3.2. Field uniformity evaluations

3.2.1 Field-scale fertigation evaluations

Field-scale fertigation uniformity evaluations were conducted in growers' fields in the Yuma Valley Irrigation Districts. The goal of the evaluations is to establish a baseline data on the ranges of variations of field-wide nitrogen application rate uniformity indices and approximate application rates. A detailed description of the measured data sets and analysis of results is presented in section 2.4.2. The following presents a concise list of activities and significant outcomes achieved.

(i) During the winter season of 2013 four nitrogen fertigation field evaluations, each in a different grower's field, were conducted in the Yuma Valley Irrigation Districts. A solution of ammonium nitrate and urea was applied in each of these field tests.

(ii) A second set of field evaluations, consisting of four fertigation tests, were conducted in the winter of 2014 in a grower's field cropped with vegetables and under season long sprinkler irrigation. The fertilizer used in these evaluations is ammonium nitrate.

(iii) Typical nitrogen application rate for the test fields is low. Six of the eight fertigation evaluation fields considered in the current study have average field-wide nitrogen application rates ranging between $0.5 g/m^2$ and $2.0 g/m^2$, which is well below the approximate required application rate of $2.5 g/m^2$.

(iv) Typical nitrogen application rate uniformity for the test fields is poor. Only 50% of the test fields have a marginally acceptable field-scale *UCC*, with the remaining half having only a *UCC* value well below the acceptable threshold of 0.75. Moreover, a minimum DU_{lq} of 0.465 and an overall mean DU_{lq} 0.575, suggest that severe localized under-fertilization may have occurred in many of the test fields.

(v) The measured test-plot scale nitrogen application rates and the computed uniformity indices along with their ranges of variations and field-scale averages are presented in section 2.4.2. Summaries of the significant results of the field evaluations are presented in sections 2.4.3 and 5.

3.2.2. Test-plot scale fertigation evaluations

Four test-plot scale fertigation evaluations were conducted in 2014 at the Maricopa Agricultural Center. The goal is to obtain some insight on the relationship between inlet boundary condition and the spatial distribution of nitrogen fertilizer constituents in the field.

(i) In the winter of 2014, four test-plot scale uniformity evaluations were conducted. In these evaluations the bromide ion was applied (in the form of potassium bromide solution) in four different fertilizer application configurations (section 2.4.1).

(ii) The measured test-plot scale bromide application rates, the computed uniformity indices, and their ranges of variations are presented in section 2.4.5. Summary of the results are also presented in section 5.

3.3. Recommendations

(i) Considering the limited scope of the current study, generalization of the results to sprinkler fertigation practices over the entire Yuma Valley Irrigation Districts may not be automatic. Hence, additional field-scale fertigation uniformity evaluations may need to be conducted to better establish the range of variability as well as typical nitrogen application rate uniformity levels in the area.

(ii) An important factor that affects the uniformity of applied nitrogen is the spatial variability of nitrogen concentration. Based on the general theory of solute transport processes in hydraulic networks and authors' experience with surface fertigation systems in the Yuma Valley Irrigation Districts, a set of factors and mechanisms affecting the spatial variability of concentrations have been identified. However, thorough and comprehensive field and modeling studies may be needed in order to establish conclusively pertinent factors and mechanisms as well as their relative significance and interactions.

(iii) The practical significance of the fertigation uniformity indices stems from the fact that attaining high uniformity is a requirement for achieving an efficient and at the same time adequate fertigation. Nonetheless, high efficiency and adequacy do not automatically follow high uniformity. Hence, future studies aimed at a more comprehensive evaluation of fertigation performance (including the quantification of fertigation adequacy and efficiency) in the Yuma Valley Irrigation Districts may be needed.

(iv) Consideration of optimal application of fertilizers through fertigation needs to be an integral part of the design and management process of sprinkler systems that are routinely used for fertigation purposes.

(v) The development of a coupled field-scale sprinkler system hydraulic and solute transport model that can be used as a flexible and cost-effective tool for fertigation performance evaluation and system design and management is an important challenge.

Chapter 4. Project beneficiaries

Project beneficiaries include growers in the Lower Colorado River Region that use solid-set sprinkler systems to apply water and fertilizer to vegetable crops.

Chapter 5. Lessons learned

(i) Equations of irrigation uniformity indices are typically expressed as a function of irrigation depth. This study shows that the equivalent variable, to depth, in nitrogen fertigation uniformity evaluation is the nitrogen application rate.

(ii) Typical field-scale nitrogen application rates for the fields considered in this study are lower than an assumed target nitrogen application rate of 2.5g/m^2 per application.

(iii) Typical field-scale nitrogen application rate uniformity levels for the fields considered here can be described as low (with UCC and DU_{lq} values well below 0.75 and 0.7, respectively).

(iv) The low field-scale fertilizer application rate uniformities in the test fields suggest that given the current fertigation practices it may as well be hardly possible to have efficient and at the same time adequate nitrogen fertilizer application through fertigation.

(v) The standard irrigation uniformity equations are recast in a form applicable to the evaluation of fertilizer application uniformity. In addition, important properties of these equations were identified and related practical fertigation management implications are discussed.

(vi) The results of a fertigation study by the current authors (Zerihun et al., 2014) and application of those results to field measured data show that nitrogen application rate uniformity is a function of the spatial trends and scale of variability inherent in the irrigation depth and nitrogen concentration data sets.

(vii) The results of a fertigation study by the current authors (Zerihun et al., 2014) and those of the test-plot scale uniformity evaluations conducted as part of the current study show that the sufficiency condition for high nitrogen application rate uniformity consists of a fertigation scenario with very high irrigation and nitrogen concentration uniformities.

(viii) Considering a sprinkler system in which the effects of solute transport processes on concentration variation are limited, the concentration variation at the sprinkler nozzles (and hence over the field) can potentially be controlled by applying fertilizer solution at a near-constant (preset) rate throughout the irrigation duration. In which case, high fertigation uniformity can be achieved, if only the design, management, maintenance, and operational requirements for high irrigation uniformity are met.

(ix) The close interrelationship between the factors and processes affecting fertilizer application rate and irrigation uniformity underscores the fact that in sprinkler systems that are routinely used for fertigation purposes, the design and management of the irrigation system cannot be decoupled from that of the fertilizer application subsystem.

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Tables

Table 1. Computed total nitrogen application rates and uniformity indices for data set I

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to mainline							Rain gage index parallel to mainline							Rain gage index parallel to mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index parallel to laterals		1	2.4	0.8	1.0	1.5	2.1	1.8	1.1	1.8	0.3	1.5	1.7	-	-	0.7	1.3	1.2	1.0	-	1.8	-	1.7
		2	1.1	1.3	0.9	1.5	1.9	1.9	0.5	1.3	1.1	0.3	-	-	1.4	0.8	1.0	0.9	1.2	1.7	1.7	-	1.7
		3	1.0	1.3	1.9	1.2	1.6	1.8	-	2.0	0.5	0.8	1.7	-	0.9	0.4	0.6	1.0	1.2	1.8	2.2	2.0	2.2
		4	1.3	1.3	1.0	1.5	1.7	1.7	1.2	1.2	1.1	1.1	1.2	-	0.6	0.8	0.3	1.0	1.7	1.5	2.3	-	2.7
		5	0.8	1.8	1.5	2.3	1.7	1.5	1.5	1.7	1.4	1.4	1.1	-	0.5	0.3	0.3	0.7	1.8	1.3	2.1	2.3	1.8
		6	0.7	1.3	1.5	2.2	1.8	1.5	1.0	0.0	0.9	1.2	1.5	1.5	1.0	1.1	0.7	0.6	1.4	1.5	2.0	2.2	1.7
		Unit																					
Average wind speed during fertigation test		*m/s*	1.2																				
Duration of test irrigation event/fertigation event		*h*	3.0/3.0																				
Dimension	Test-plot	*ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*ft*	210.0×430.0							210.0×430.0							210.0×430.0						
Test-plot Scale	Average rate	g/m^2	1.4							1.1							1.5						
	UCC	-	0.755							0.655							0.665						
	DU$_{lq}$	-	0.607							0.416							0.459						
Field scale	Minimum rate	g/m^2	0.3																				
	Maximum rate	g/m^2	2.7																				
	Average rate	g/m^2	1.3																				
	UCC	-	0.692																				
	DU$_{lq}$	-	0.494																				

Based on irrigation depth and nitrogen concentration measured on 02/23/2013, Yuma Valley Irrigation Districts

Table 2. A summary of the average, maximum, and minimum water depths, total nitrogen concentrations, and application rates along with uniformity indices at test-plot and field scales: data sets I, II, III, and IV

		Data set I									Data set II								
		Test-plot scale data									Test-plot scale data								
		Upstream end test-plot			Middle test-plot			Downstream end test-plot			Upstream end test-plot			Middle test-plot			Downstream end test-plot		
		Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate
		mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2
Test-plot Scale	Average	13.1	110.3	1.4	12.4	94.0	1.1	13.3	104.7	1.5	14.8	43.5	0.700	14.3	35	0.5	14.0	24.8	0.4
	UCC (-)	0.883	0.799	0.755	0.847	0.679	0.655	0.864	0.700	0.665	0.869	0.757	0.666	0.818	0.714	0.607	0.851	0.645	0.613
	DUlq (-)	0.820	0.656	0.607	0.731	0.492	0.416	0.803	0.507	0.459	0.791	0.587	0.475	0.716	0.598	0.498	0.777	0.450	0.493
Field-scale		Field-scale data									Field-scale data								
		Depth			Conc			Applic. rate			Depth			Conc			Applic. rate		
		mm			mg/L			g/m^2			Mm			mg/L			g/m^2		
	Average	12.9			102.9			1.3			14.4			34.4			0.5		
	Minimum	7.6			22.1			0.3			7.2			1.6			0.1		
	Maximum	19.1			220.3			2.7			19.1			80.3			1.5		
	UCC (-)	0.864			0.726			0.692			0.846			0.705			0.629		
	DUlq (-)	0.784			0.552			0.494			0.761			0.545			0.489		
Test-plot Scale																			
		Data set III									Data set IV								
		Test-plot scale data									Test-plot scale data								
		Upstream end test-plot			Middle test-plot			Downstream end test-plot			Upstream end test-plot			Middle test-plot			Downstream end test-plot		
		Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate
		mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2
	Average	6.6	299.1	2.0	7.0	280.2	1.9	8.5	250.9	2.2	12.6	204.1	2.5	14.3	223.4	3.2	12.6	231.6	2.8
	UCC (-)	0.728	0.808	0.648	0.645	0.773	0.614	0.728	0.805	0.680	0.744	0.872	0.759	0.776	0.898	0.770	0.724	0.874	0.774
	DUlq (-)	0.605	0.626	0.487	0.488	0.611	0.509	0.619	0.670	0.500	0.583	0.796	0.666	0.614	0.844	0.625	0.549	0.787	0.654
Field-scale		Field-scale data									Field-scale data								
		Depth			Conc			Applic. Rate			Depth			Conc			Applic. rate		
		mm			mg/L			g/m^2			Mm			mg/L			g/m^2		
	Average	7.4			276.7			2.0			13.2			219.7			2.8		
	Minimum	1.9			68.2			0.3			4.8			144.8			1.2		
	Maximum	19.1			426.4			5.7			19.1			305.9			5.3		
	UCC (-)	0.700			0.795			0.647			0.748			0.881			0.767		
	DUlq (-)	0.571			0.636			0.499			0.582			0.809			0.648		

Table 3 Computed total nitrogen application rates and uniformity indices for data set II

			Test-plot 1							Test-plot 2							Test-plot 3						
			Rain gage index parallel to mainline							Rain gage index parallel to mainline							Rain gage index parallel to mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index parallel to laterals		1	1.1	-	0.7	0.8	0.6	0.4	0.2	0.3	0.3	0.6	0.4	0.4	0.6	0.2	0.6	0.4	0.1	0.2	0.2	-	0.4
		2	1.2	1.1	0.9	0.4	0.6	0.3	0.3	0.3	0.5	0.6	0.2	0.2	0.3	0.4	0.6	0.6	0.2	0.2	0.1	0.4	-
		3	0.7	1.1	0.9	0.4	0.6	0.6	-	0.4	0.4	0.3	0.4	0.4	0.6	-	0.4	0.4	0.3	0.2	0.5	0.6	0.3
		4	0.7	0.4	0.6	0.6	0.7	-	0.7	0.3	0.3	0.6	0.5	0.7	1.1	-	0.3	0.2	0.3	0.2	0.7	0.5	-
		5	0.7	0.5	0.3	0.6	0.8	1	1.1	0.8	0.2	0.4	0.5	-	1.5	0.5	0.2	0.4	0.2	0.4	0.4	0.5	0.8
		6	-	1.1	0.5	0.6	0.3	0.6	0.2	-	0.9	0.5	0.5	1	-	0.9	-	0.4	0.2	0.3	0.5	0.3	0.2
		Unit																					
Average wind speed during fertigation test		*m/s*	4.5																				
Duration of test irrigation event/fertigation event		*h*	3.0/3.0																				
Dimension	Test-plot	*ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*ft*	140.0×430.0							140.0×430.0							140.0×430.0						
Test-plot Scale	Average rate	*g/m^2*	0.7							0.5							0.4						
	UCC	-	0.666							0.607							0.613						
	DU$_{lq}$	-	0.475							0.498							0.493						
Field scale	Minimum rate	*g/m^2*	0.1																				
	Maximum rate	*g/m^2*	1.5																				
	Average rate	*g/m^2*	0.5																				
	UCC	-	0.629																				
	DU$_{lq}$	-	0.489																				

Based on irrigation depth and nitrogen concentration measured on 02/28/2013in the Yuma Valley Irrigation Districts

Table 4. Computed total nitrogen application rates and uniformity indices for data set III

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to mainline							Rain gage index parallel to mainline							Rain gage index parallel to mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index parallel to laterals		1	2.0	3.3	3.3	2.9	2.4	2.6	1.2	5.7	3.0	2.8	1.8	1.9	1.4	1.9	4.9	5.4	2.8	2.7	2.8	1.9	3.6
		2	1.2	2.7	3.2	2.1	0.7	0.9	1.3	4.2	2.9	2.3	1.5	0.9	1.5	0.7	2.8	2.2	2.4	2.1	1.3	2.2	-
		3	1.7	2.7	1.8	1.9	1.3	-	1.1	2.5	2.4	2.3	1.2	1.1	0.8	0.9	0.9	2.8	1.9	1.9	1.2	1.4	1.6
		4	1.6	2.3	2.4	1.7	1.6	1.6	1.0	1.9	2.3	1.5	1.1	-	1.2	1.0	1.5	2.0	2.0	1.3	1.2	0.3	0.7
		5	2.8	2.4	-	1.1	0.4	1.6	1.8	2.4	1.8	1.2	1.2	1.5	1.1	1.5	2.2	2.2	2.7	2.0	1.0	1.8	2.0
		6	5.5	3.1	-	2.4	1.6	-	2.0	3.6	2.2	2.5	1.9	1.1	3.1	-	3.7	3.3	2.0	1.9	2.2	1.7	2.1
		Unit																					
Average wind speed during fertigation test		*m/s*	3.3																				
Duration of test irrigation event/fertigation event		*h*	3.4/3.4																				
Dimension	Test-plot	*ft*	30.0×35.0							30.0×30.0							30.0×35.0						
	Farm block	*ft*	105.0×410.0							105.0×410.0							105.0×410.0						
Test-plot scale	Average rate	g/m^2	2.0							1.9							2.2						
	UCC	-	0.648							0.614							0.680						
	DU_{lq}	-	0.487							0.509							0.500						
Field scale	Minimum rate	g/m^2	0.3																				
	Maximum rate	g/m^2	5.7																				
	Average rate	g/m^2	2.0																				
	UCC	-	0.647																				
	DU_{lq}	-	0.499																				

Based on irrigation depth and nitrogen concentration measured on 03/01/2013 in the Yuma valley Irrigation Districts

Table 5. Computed total nitrogen application rates and uniformity indices for data set IV

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to mainline							Rain gage index parallel to mainline							Rain gage index parallel to mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index parallel to laterals		1	3.2	-	2.4	2.1	1.6	2.6	3.3	3.2	2.8	3.3	1.8	1.8	2	2.5	4.2	3.4	2.1	1.8	2.3	2.1	3.3
		2	2.8	3.7	2	1.7	1.2	1.2	2.7	3.6	4.1	2.8	1.7	1.6	2	1.9	2.7	3	2	1.5	1.4	1.3	2
		3	2.2	2.4	2.4	1.7	2	1.9	3.1	2.7	3.5	2.8	2.7	2.3	3.2	2.7	2.7	2.4	2.4	2.3	2	2.3	2.5
		4	1.7	2	2.2	2.9	3.1	3.8	3.8	2.6	3.3	4.1	3.8	3.5	4.2	3.8	2.5	3.6	4.5	3.5	4.1	3.2	2.2
		5	1.8	2.1	3	2.3	3.9	4	-	3.3	3.8	3.9	4.1	4.2	5.3	-	2.9	3.2	4.2	3.4	3.3	3.1	2.7
		6	2.6	3.1	2.2	1.9	2.1	2.7	2.9	2.2	3.5	3.9	3.5	4.2	4.1	3.6	3.9	3.8	2.7	3.3	2.6	2.9	2.8
		Unit																					
Average wind speed during fertigation test		*m/s*	2.2																				
Duration of test irrigation event/fertigation event		*h*	3.0/3.0																				
Dimension	Test-plot	*ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*ft*	81.7×200.0							81.7×200.0							81.7×200.0						
Test-plot scale	Average rate	g/m^2	2.5							3.2							2.8						
	UCC	-	0.759							0.770							0.774						
	DU$_{lq}$	-	0.666							0.625							0.654						
Field scale	Minimum rate	g/m^2	1.2																				
	Maximum rate	g/m^2	5.3																				
	Average rate	g/m^2	2.8																				
	UCC	-	0.767																				
	DU$_{lq}$	-	0.648																				

Based on irrigation depth and nitrogen concentration measured on 03/02/2013 in the Yuma Valley Irrigation Districts

Table 6. Computed total nitrogen application rates and uniformity indices for data set V

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to mainline							Rain gage index parallel to mainline							Rain gage index parallel to mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index parallel to laterals		1	1.2	2.4	2.2	1.6	1.1	1.1	1.6	0.9	1.2	2.1	2.3	1.9	1.1	0.9	1.0	1.1	1.4	1.2	1.1	1.4	1.2
		2	1.1	1.3	0.8	1.6	1.9	1.3	1.2	0.7	1.3	1.3	2.6	1.5	1.3	1.0	1.3	1.0	1.3	1.2	1.5	1.4	1.2
		3	1.4	0.9	1.4	1.3	1.3	0.9	1.0	2.0	1.3	0.9	2.3	1.7	1.4	1.3	2.2	2.3	1.1	1.5	2.0	1.3	1.0
		4	1.3	1.1	1.2	1.5	1.4	1.3	1.0	3.0	1.1	1.0	0.8	1.7	2.2	2.5	2.0	2.1	1.1	2.1	1.1	1.2	1.1
		5	1.0	2.0	1.2	1.4	1.4	1.0	1.0	2.0	1.9	1.7	0.9	1.4	1.7	2.0	1.9	0.0	1.8	1.0	1.2	1.6	1.2
		6	0.9	1.0	2.3	0.9	1.3	1.5	1.0	1.9	2.0	2.1	1.6	1.5	1.7	2.4	1.2	1.0	1.0	1.1	1.0	1.4	2.3
		Unit																					
Average wind speed during fertigation test		*m/s*																					
Duration of test irrigation event/fertigation event		*h*	3.0/3.0																				
Dimension	Test-plot	*Ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*Ft*	70.0×400.0							70.0×400.0							70.0×400.0						
Test-plot scale	Average rate	g/m^2	1.3							1.6							1.4						
	UCC	-	0.788							0.717							0.768						
	DU$_{lq}$	-	0.714							0.574							0.740						
Field scale	Minimum rate	g/m^2	0.7																				
	Maximum rate	g/m^2	3.0																				
	Average rate	g/m^2	1.4																				
	UCC	-	0.758																				
	DU$_{lq}$	-	0.676																				

Based on irrigation depth and nitrogen concentration measured on 03/04/2014 in the Yuma Valley Irrigation Districts

Table 7. A summary of the average, maximum, and minimum water depths, total nitrogen concentrations, and application rates along with uniformity indices at test-plot and field scales: data sets V, VI, VII, and VIII

		Data set V									Data set VI								
		Test-plot scale data									Test-plot scale data								
		Upstream end test-plot			Middle test-plot			Downstream end test-plot			Upstream end test-plot			Middle test-plot			Downstream end test-plot		
		Depth	Conc	Applic. Rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate
		mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2
Test-plot Scale	Average	9.1	144.3	1.3	9.7	168.4	1.6	9.2	154.5	1.4	9.8	206.9	2.0	9.8	182.0	1.8	7.6	200.3	1.5
	UCC (-)	0.948	0.795	0.788	0.897	0.733	0.717	0.920	0.734	0.768	0.757	0.896	0.721	0.826	0.867	0.808	0.783	0.860	0.721
	DUlq (-)	0.921	0.727	0.714	0.855	0.643	0.574	0.891	0.731	0.740	0.690	0.837	0.622	0.756	0.753	0.675	0.616	0.792	0.611
Field-scale		Field-scale data									Field-scale data								
		Depth			Conc			Applic. rate			Depth			Conc			Applic. rate		
		mm			mg/L			g/m^2			mm			mg/L			g/m^2		
	Average	9.3			155.7			1.4			9.1			196.4			1.8		
	Minimum	7.6			84.9			0.7			3.5			102.6			0.7		
	Maximum	12.4			276.3			3.0			16.7			321.4			3.7		
	UCC (-)	0.922			0.754			0.758			0.789			0.874			0.750		
	DUlq (-)	0.889			0.700			0.676			0.687			0.794			0.636		
Test-plot Scale																			
		Data set VII									Data set VIII								
		Test-plot scale data									Test-plot scale data								
		Upstream end test-plot			Middle test-plot			Downstream end test-plot			Upstream end test-plot			Middle test-plot			Downstream end test-plot		
		Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate	Depth	Conc	Applic. rate
		mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2	mm	mg/L	g/m^2
	Average	11.1	230.8	2.5	12.1	241.5	2.9	11.3	218.5	2.5	9.8	211.3	2.0	10.9	208.0	2.3	9.0	159.5	1.5
	UCC (-)	0.870	0.806	0.826	0.877	0.872	0.790	0.881	0.821	0.772	0.632	0.787	0.641	0.652	0.743	0.533	0.697	0.705	0.495
	DUlq (-)	0.794	0.690	0.716	0.793	0.755	0.665	0.802	0.726	0.685	0.497	0.704	0.569	0.532	0.596	0.415	0.613	0.552	0.410
Field-scale		Field-scale data									Field-scale data								
		Depth			Conc			Applic. rate			Depth			Conc			Applic. rate		
		mm			mg/L			g/m^2			mm			mg/L			g/m^2		
	Average	11.5			230.2			2.7			9.9			192.9			1.9		
	Minimum	7.6			113.0			1.2			3.8			56.5			0.4		
	Maximum	167.			291.4			4.5			19.1			358.1			5.2		
	UCC (-)	0.876			0.833			0.796			0.660			0.745			0.556		
	DUlq (-)	0.796			0.724			0.689			0.548			0.617			0.465		

Table 8. Computed total nitrogen application rates and uniformity indices for data set VI

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to the mainline							Rain gage index parallel to the mainline							Rain gage index parallel to the mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index, parallel to laterals		1	1.3	1.4	0.9	1.4	1.5	2.4	3.4	1.1	2.3	1.9	1.8	2.5	2.9	1.6	1.1	1.0	1.5	2.0	3.1	1.7	2.1
		2	2.6	1.8	1.3	1.2	1.6	1.8	2.0	1.9	2.0	1.5	1.8	-	2.0	2.7	1.6	1.6	-	1.6	1.4	1.2	1.4
		3	3.1	1.6	1.7	1.5	1.7	1.6	1.4	2.1	2.2	1.6	1.6	1.7	1.1	0.8	1.6	1.7	1.4	1.4	1.1	1.2	-
		4	3.3	3.4	2.1	2.0	2.4	1.8	0.9	2.0	1.9	1.5	1.9	2.1	1.2	1.0	1.4	1.2	1.3	1.1	2.0	1.2	-
		5	3.4	2.6	1.4	2.0	2.5	2.2	2.3	1.3	1.6	1.4	1.8	1.9	1.9	1.7	1.1	0.8	0.7	1.6	2.5	3.0	-
		6	2.4	2.0	1.6	1.7	2.6	3.7	2.3	1.2	1.7	1.8	1.6	2.1	3.0	1.8	1.4	0.8	0.7	1.3	2.4	2.3	-
		Unit																					
Average wind speed		*m/s*	2.9																				
Duration of test irrigation/fertigation event		*h*	3.0/1.0																				
Dimension	Test-plot	*ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*ft*	70.0×460.0							70.0×460.0							70.0×460.0						
Test-plot scale	Average rate	g/m^2	2.0							1.8							1.5						
	UCC	-	0.721							0.808							0.721						
	DU_{lq}	-	0.622							0.675							0.611						
Field scale	Minimum rate	g/m^2	0.7																				
	Maximum rate	g/m^2	3.7																				
	Average rate	g/m^2	1.8																				
	UCC	-	0.750																				
	DU_{lq}	-	0.636																				

Based on irrigation depth and nitrogen concentration measured on 02/28/2014 in the Yuma Valley Irrigation Districts

Table 9. Computed total nitrogen application rates and uniformity indices for data set VII

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to the mainline							Rain gage index parallel to the mainline							Rain gage index parallel to the mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index, parallel to laterals		1	2.5	3.7	3.6	2.5	2.3	3.2	2.4	2.1	3.1	2.4	3.9	3.7	2.0	1.8	3.1	2.6	2.2	2.8	2.6	3.3	2.6
		2	3.1	2.9	3.2	2.9	2.3	3.3	2.4	2.1	2.9	3.6	4.2	3.8	2.6	1.8	1.4	1.9	1.9	1.6	1.9	3.4	1.3
		3	2.4	2.2	2.1	1.8	1.9	2.6	2.4	3.0	2.1	3.7	4.1	3.6	2.7	1.5	4.1	2.0	1.6	2.0	1.9	3.2	2.1
		4	1.6	3.2	3.2	1.9	2.6	2.5	2.3	3.2	2.2	4.0	3.8	2.8	3.1	1.8	4.5	3.1	2.3	2.2	2.8	1.7	2.3
		5	1.2	2.9	3.1	1.8	1.8	2.5	2.0	2.6	2.2	3.7	4.0	2.4	2.9	2.6	2.9	2.1	2.9	2.3	3.0	2.7	2.5
		6	2.7	2.6	2.9	3.0	2.0	2.5	2.1	2.6	3.4	2.8	3.1	3.1	3.2	3.6	1.8	2.4	2.2	2.0	3.1	2.1	3.8
		Unit																					
Average wind speed		*m/s*	0.6																				
Duration of test irrigation/fertigation event		*h*	3.0/1.0																				
Dimension	Test-plot	*ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*ft*	70.0×460.0							70.0×460.0							70.0×460.0						
Test-plot scale	Average rate	*g/m^2*	2.5							2.9							2.5						
	UCC	-	0.826							0.790							0.772						
	DU$_{lq}$	-	0.716							0.665							0.685						
Field scale	Minimum rate	*g/m^2*	1.2																				
	Maximum rate	*g/m^2*	4.5																				
	Average rate	*g/m^2*	2.7																				
	UCC	-	0.796																				
	DU$_{lq}$	-	0.689																				

Based on irrigation depth and nitrogen concentration measured on 02/27/2014 in the Yuma Valley Irrigation Districts

Table 10. Computed total nitrogen application rates and uniformity indices for data set VIII

			Upstream end test-plot							Middle test-plot							Downstream end test-plot						
			Rain gage index parallel to the mainline							Rain gage index parallel to the mainline							Rain gage index parallel to the mainline						
			1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
			Application rate (g/m^2)							Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index, parallel to laterals		1	3.0	2.7	1.2	1.0	1.9	2.5	1.8	2.2	2.7	1.3	0.7	0.8	1.0	1.4	4.3	1.4	0.6	1.3	1.3	1.1	1.9
		2	3.1	3.1	1.2	1.3	1.2	2.3	2.1	4.4	2.0	1.0	1.1	1.1	0.9	0.9	3.9	2.4	0.4	1.0	1.0	1.0	0.5
		3	2.5	1.4	1.4	1.2	1.7	3.1	1.4	5.0	-	1.4	1.6	1.6	1.8	1.8	2.1	1.4	0.7	0.7	0.9	1.1	0.7
		4	1.5	1.4	0.9	1.2	2.3	2.0	2.3	3.9	1.4	1.9	1.6	1.8	4.7	4.7	5.2	1.2	1.1	0.8	1.4	-	2.4
		5	1.3	1.7	1.1	1.2	1.5	3.8	3.8	2.5	2.0	1.9	3.1	4.2	4.5	3.1	3.0	1.1	0.4	1.3	1.6	2.0	2.4
		6	2.8	3.8	2.0	1.3	1.6	1.0	3.1	4.8	3.5	1.7	0.8	2.6	2.8	2.7	1.4	0.8	1.0	0.7	0.7	1.2	2.6
		Unit																					
Average wind speed		*m/s*	6.5																				
Duration of test irrigation/fertigation event		*h*	3.0/1.0																				
Dimension	Test-plot	*Ft*	30.0×35.0							30.0×35.0							30.0×35.0						
	Farm block	*Ft*	70.0×400.0							70.0×400.0							70.0×400.0						
Test-plot scale	Average rate	g/m^2	2.0							2.3							1.5						
	UCC	-	0.641							0.533							0.495						
	DU_{lq}	-	0.569							0.415							0.410						
Field scale	Minimum rate	g/m^2	0.4																				
	Maximum rate	g/m^2	5.2																				
	Average rate	g/m^2	1.9																				
	UCC	-	0.556																				
	DU_{lq}	-	0.465																				

Based on irrigation depth and nitrogen concentration measured on 02/28/2014 in the Yuma Valley Irrigation Districts

Table 11. A summary of field-scale nitrogen application rates: data sets I to VIII

<table>
<tr><td rowspan="2" colspan="1"></td><td colspan="4">Application rate (g/m^2)</td></tr>
<tr><td colspan="2">Minimum</td><td>Maximum</td><td>Average</td></tr>
<tr><td>Data set I</td><td colspan="2">0.3</td><td>2.7</td><td>1.3</td></tr>
<tr><td>Data set II</td><td colspan="2">0.1</td><td>1.5</td><td>0.5</td></tr>
<tr><td>Data set III</td><td colspan="2">0.3</td><td>5.7</td><td>2.0</td></tr>
<tr><td>Data set IV</td><td colspan="2">1.2</td><td>5.3</td><td>2.8</td></tr>
<tr><td>Data set V</td><td colspan="2">0.7</td><td>3.0</td><td>1.4</td></tr>
<tr><td>Data set VI</td><td colspan="2">0.7</td><td>3.7</td><td>1.8</td></tr>
<tr><td>Data set VII</td><td colspan="2">1.2</td><td>4.5</td><td>2.7</td></tr>
<tr><td>Data set VIII</td><td colspan="2">0.4</td><td>5.2</td><td>1.9</td></tr>
<tr><td colspan="5">Summary of average field-scale application rates (g/m^2)</td></tr>
<tr><td colspan="2">Minimum</td><td colspan="2">Maximum</td><td>Overall average</td></tr>
<tr><td colspan="2">0.5</td><td colspan="2">2.8</td><td>1.8</td></tr>
</table>

Table 12. A summary of nitrogen application rate uniformity indices: data sets I to VIII

Data ID	Type of uniformity index	Irrigation uniformity		
		Test-plot scale		Field-scale average
		Minimum	Maximum	
Data set I	UCC	0.655	0.755	0.692
	DU_{lq}	0.416	0.607	0.494
Data set II	UCC	0.607	0.666	0.629
	DU_{lq}	0.475	0.498	0.489
Data set III	UCC	0.614	0.680	0.647
	DU_{lq}	0.487	0.509	0.499
Data set IV	UCC	0.759	0.774	0.767
	DU_{lq}	0.625	0.666	0.648
Data set V	UCC	0.717	0.788	0.758
	DU_{lq}	0.574	0.740	0.676
Data set VI	UCC	0.721	0.808	0.750
	DU_{lq}	0.611	0.675	0.636
Data set VII	UCC	0.772	0.826	0.796
	DU_{lq}	0.665	0.716	0.689
Data set VIII	UCC	0.495	0.641	0.556
	DU_{lq}	0.410	0.569	0.465

Uniformity indices	Field-scale average UCC and DU_{lq} summary		
	Minimum	Maximum	Overall average
UCC	0.556	0.796	0.700
DU_{lq}	0.465	0.689	0.575

Table 13. Computed test-plot scale bromide application rates: data sets IX, X, XI, and XII

		Data set IX							Data set X						
		Rain gage index parallel to the mainline							Rain gage index parallel to the mainline						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
		Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index, parallel to laterals	1	1.3	1.1	0.9	0.9	1.0	0.8	1.0	1.4	1.6	1.5	1.1	1.0	1.2	1.5
	2	1.0	1.0	1.0	1.0	0.9	0.8	0.8	1.3	1.5	1.2	1.0	1.0	1.0	1.2
	3	1.0	0.9	1.0	1.0	1.0	0.8	0.8	1.5	1.4	1.2	1.1	1.0	1.0	1.1
	4	1.0	0.9	1.0	1.0	0.9	0.8	0.8	1.5	1.6	1.1	1.2	1.1	0.9	1.3
	5	0.9	1.1	0.9	0.8	0.9	0.9	0.8	1.4	1.3	1.3	1.2	1.1	1.1	1.2
	6	1.1	0.9	0.7	0.8	0.8	0.7	1.0	1.5	1.5	1.3	1.1	0.7	0.7	1.4

		Data set XI							Data set XII						
		Rain gage index parallel to the mainline							Rain gage index parallel to the mainline						
		1	2	3	4	5	6	-	1	2	3	4	5	6	-
		Application rate (g/m^2)							Application rate (g/m^2)						
Rain gage index, parallel to laterals	1	1.2	1.4	1.6	1.3	1.7	1.3	-	1.6	1.8	2.0	2.0	1.8	1.6	-
	2	1.4	1.5	1.6	1.5	1.2	1.5	-	1.6	1.8	1.9	1.7	1.7	1.3	-
	3	1.1	1.2	1.3	1.2	1.2	1.1	-	1.5	1.8	1.5	1.6	1.5	1.4	-
	4	0.9	1.2	1.4	1.2	1.1	1.1	-	1.3	1.4	1.8	1.7	1.6	1.3	-
	5	0.8	1.0	2.4	1.5	1.3	1.0	-	1.3	1.6	1.5	1.8	1.2	1.2	-
	6	1.2	1.3	1.9	1.7	1.6	1.1	-	1.6	1.3	1.6	1.4	1.5	1.6	-

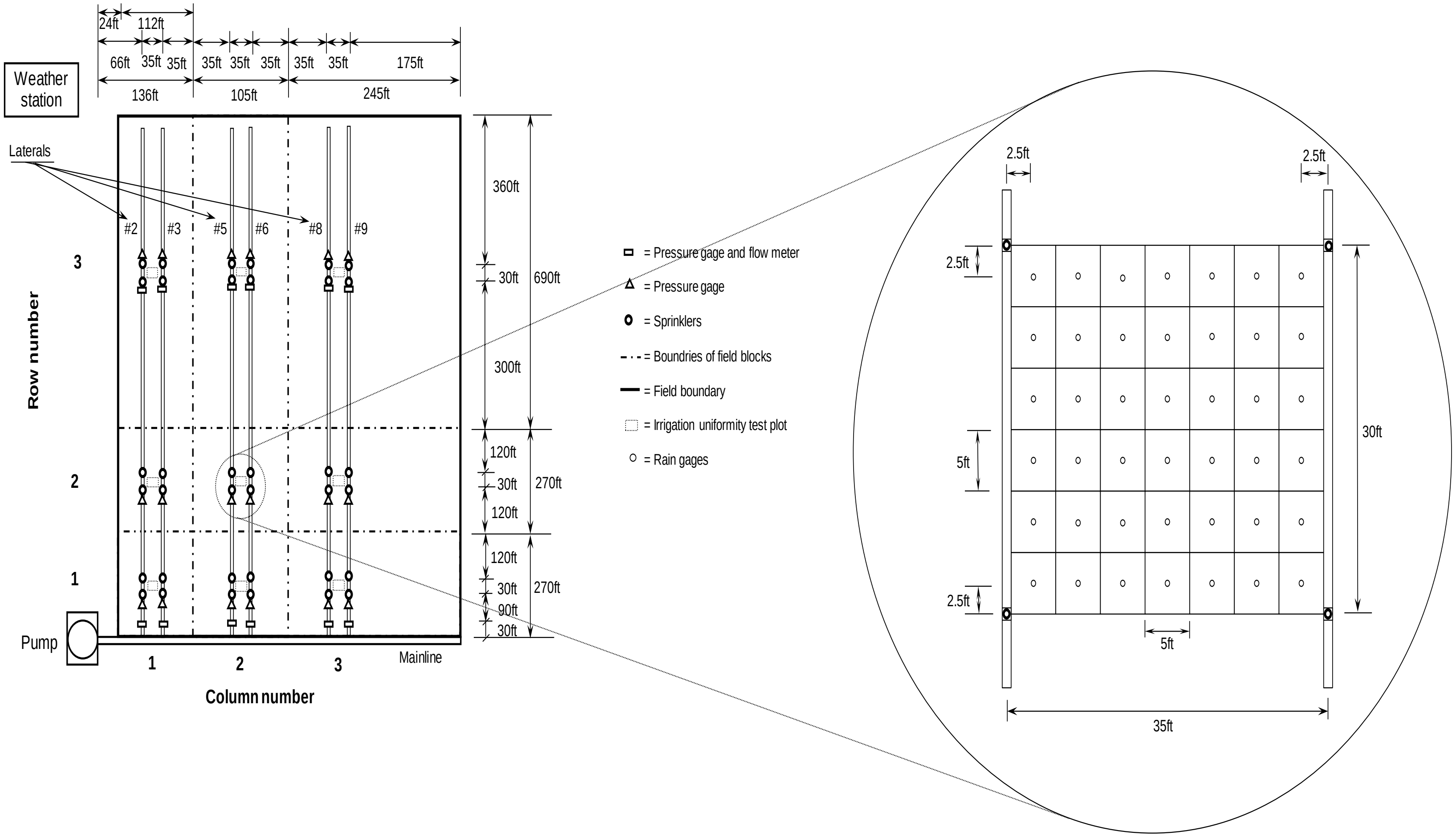
Based on irrigation depth and bromide concentration measured on 03/28/2014, 03/31/2014, 04/03/2014, and 04/04/2014 in the Maricopa Agricultural Center of the University of Arizona. Note that data sets IX, X, XI, and XII were collected in test-plots I, II, III, and IV (Figure 9), respectively.

Table 14. A summary of the test-plot scale average, maximum, and minimum water depths, bromide concentrations, and application rates along with uniformity indices: data sets IX, X, XI, and XII

		Data set IX			Data set X		
		Test-plot scale data			Test-plot scale data		
		Depth	Conc	Applic. rate	Depth	Conc	Applic. rate
		mm	mg/L	g/m^2	mm	mg/L	g/m^2
Test-plot Scale	Average	10.3	88.3	0.9	10.2	119.3	1.2
	Minimum	8.1	78.8	0.7	7.6	72.8	0.7
	Maximum	14.3	100.3	1.3	14.3	140.3	1.6
	UCC (-)	0.903	0.954	0.895	0.853	0.932	0.852
	DU_{lq} (-)	0.867	0.932	0.853	0.792	0.880	0.771
		Data set XI			Data set XII		
		Test-plot scale data			Test-plot scale data		
		Depth	Conc	Applic. rate	Depth	Conc	Applic. rate
		Mm	mg/L	g/m^2	mm	mg/L	g/m^2
Test-plot Scale	Average	12	111.6	1.3	12.6	125.1	1.6
	Minimum	8.1	80.8	0.8	9.5	98.3	1.2
	Maximum	14.3	208.8	2.4	14.3	145.8	2.0
	UCC (-)	0.899	0.885	0.830	0.894	0.913	0.890
	DU_{lq} (-)	0.822	0.840	0.771	0.855	0.861	0.824

Data sets IX, X, XI, and XII were collected in test-plots I, II, III, and IV, respectively

Figures



(a)

(b)

Figure 1. Field-scale irrigation uniformity evaluation (Zerihun et al., 2011): (a) Spatial distribution of uniformity evaluation plots and associated field blocks and (b) Layout of an irrigation uniformity evaluation plot

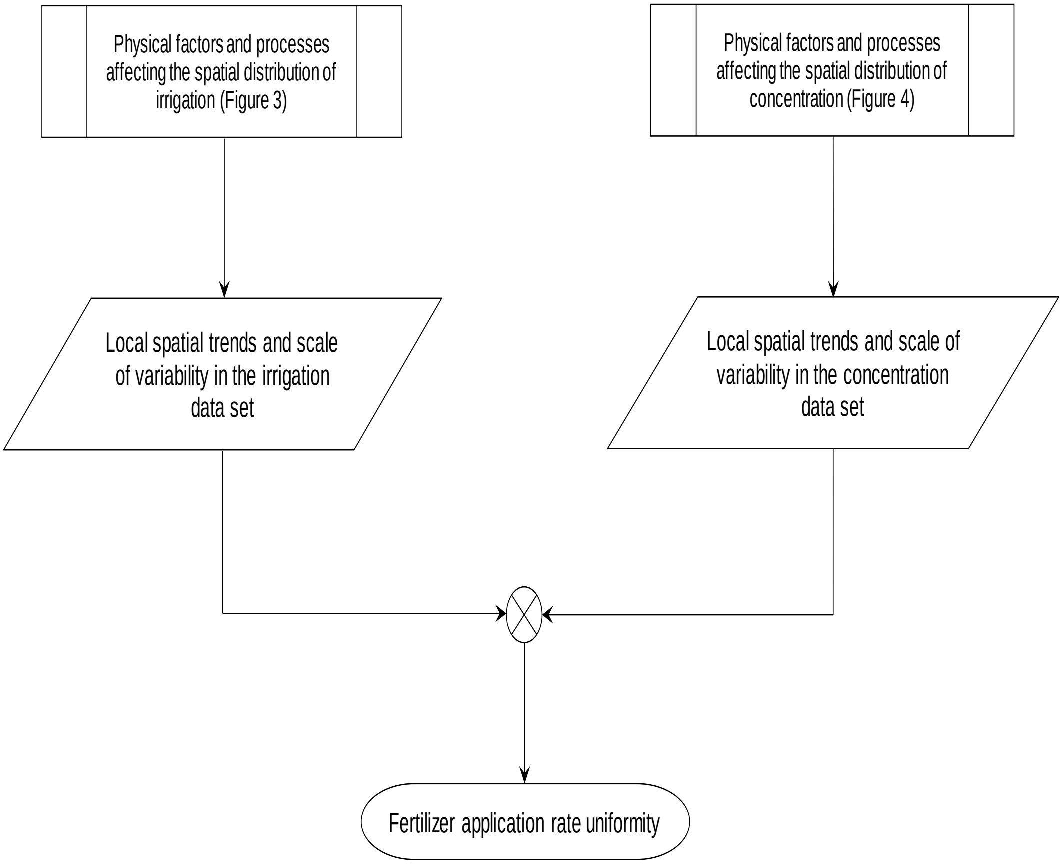


Figure 2. Flow diagram depicting the dependence of fertilizer application rate uniformity on the spatial variability of irrigation and concentration data sets

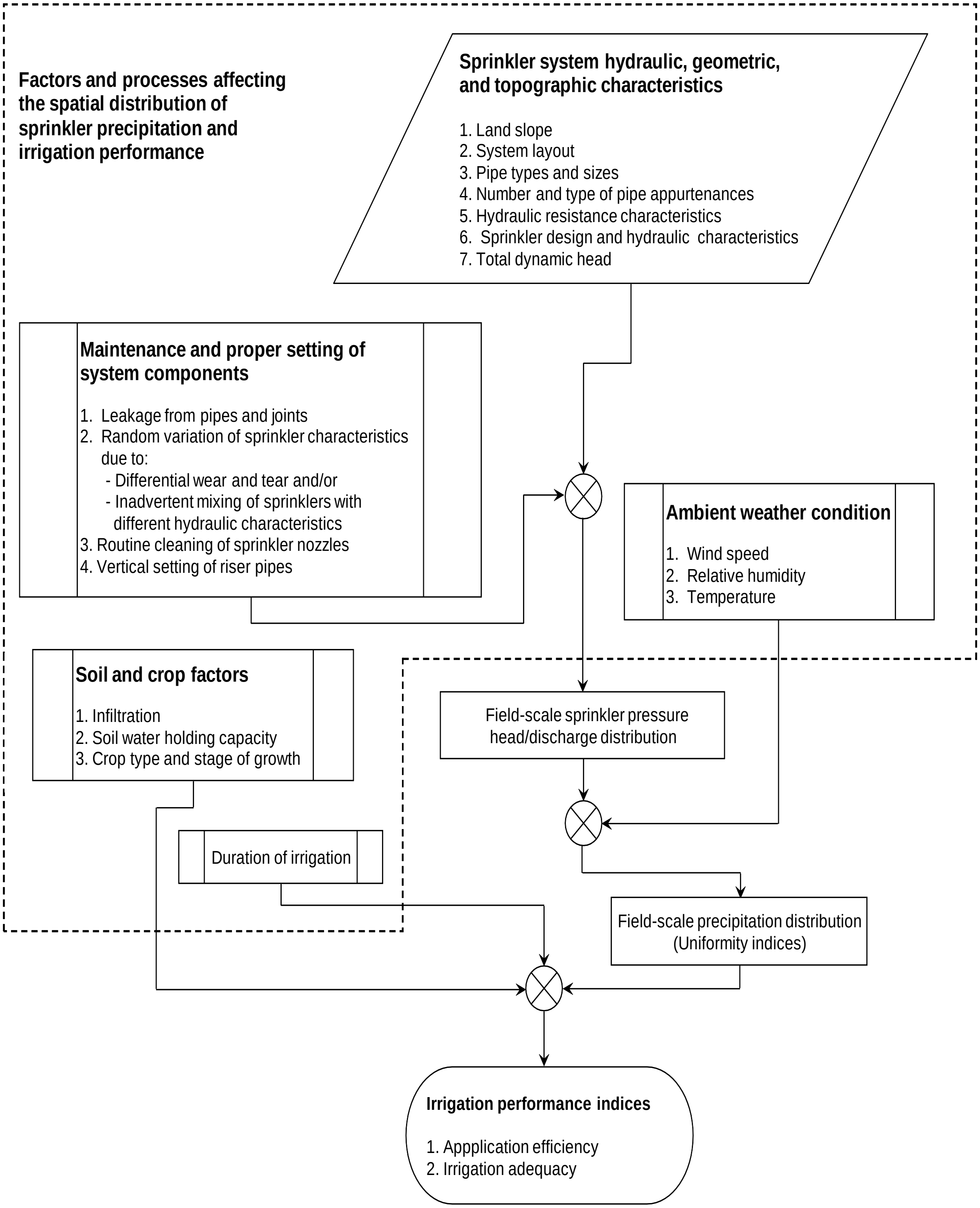


Figure 3. Flow diagram depicting the interplay of factors and processes affecting the field-scale spatial distribution of sprinkler precipitation and irrigation performance

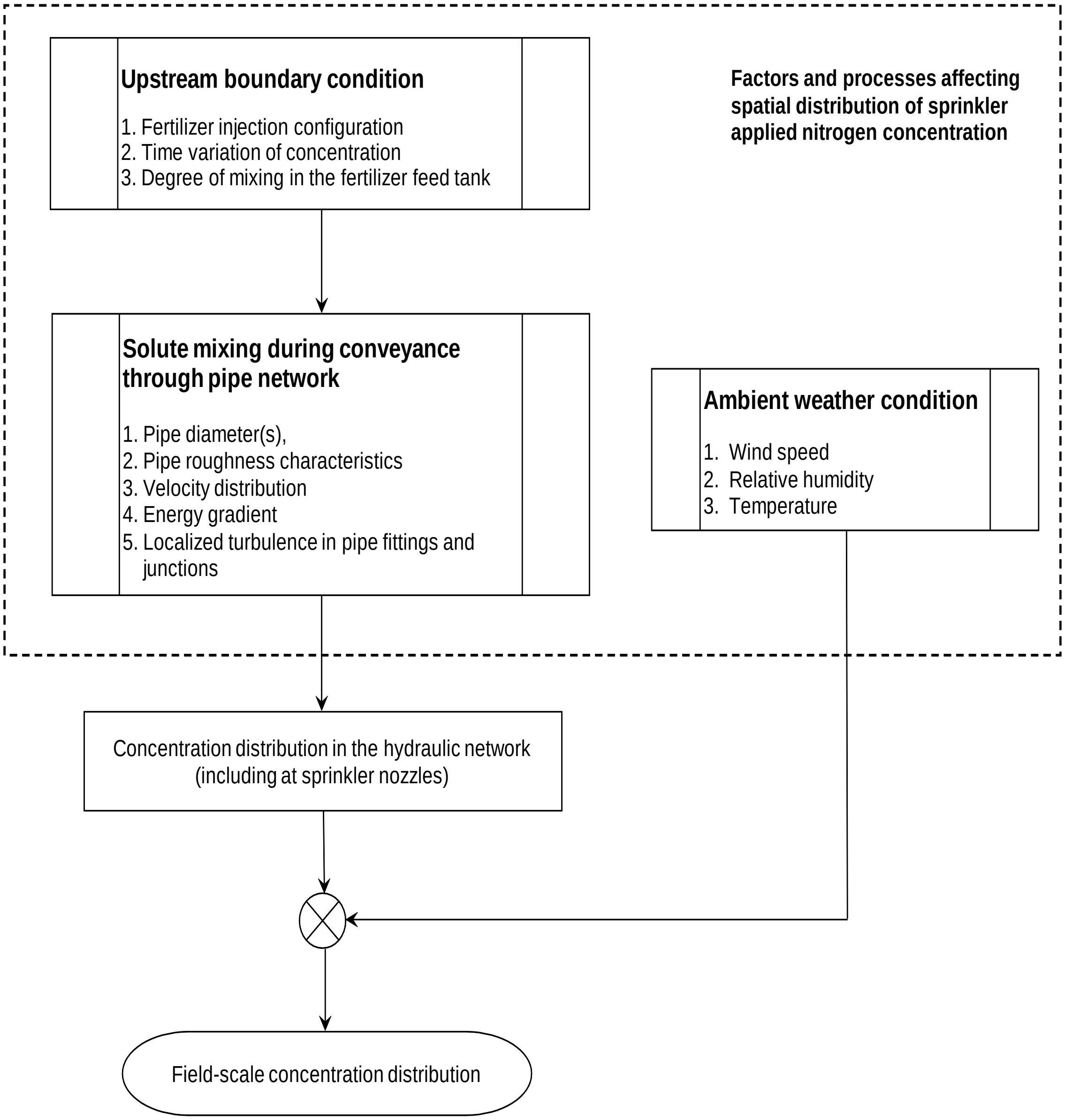
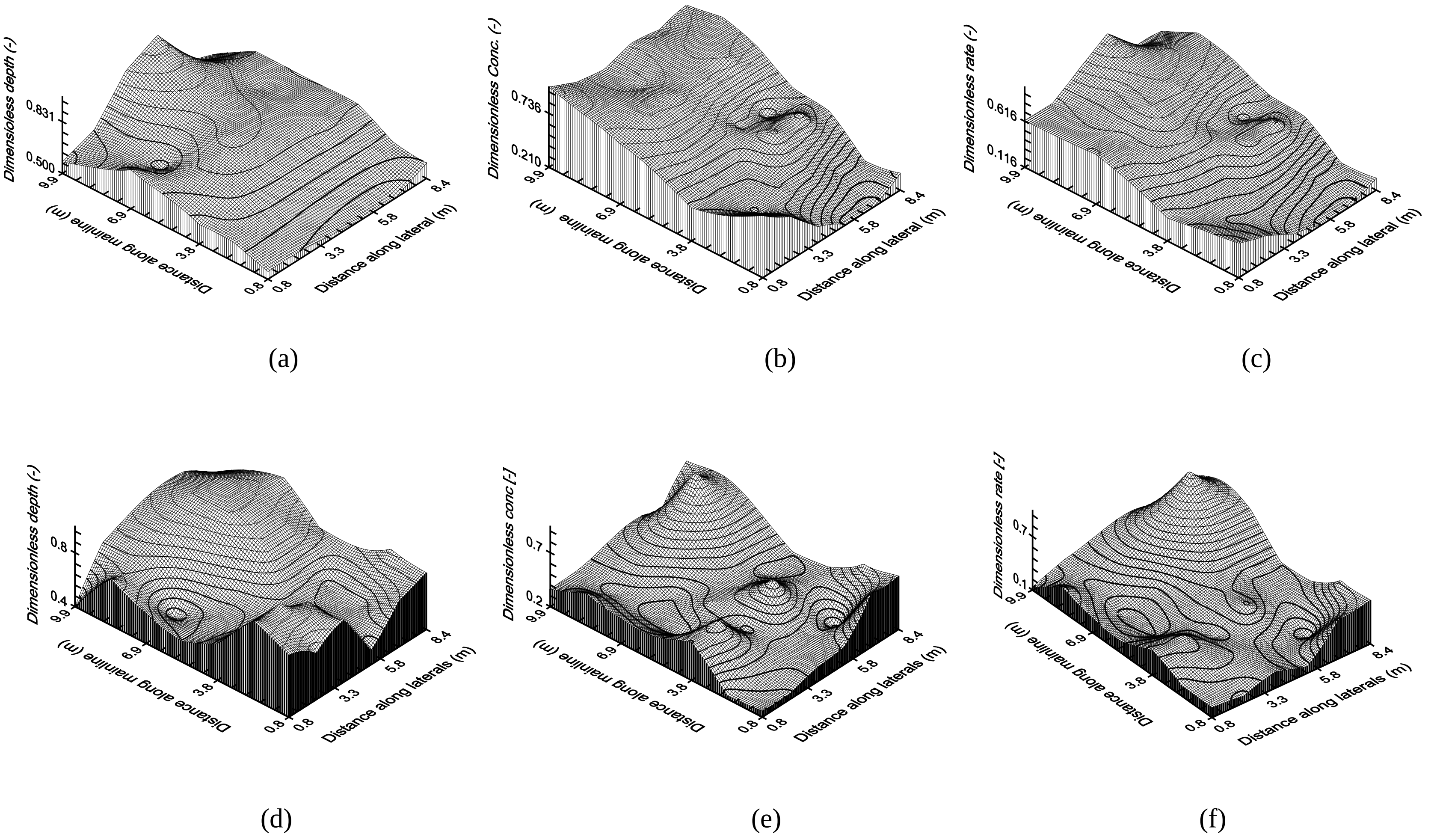


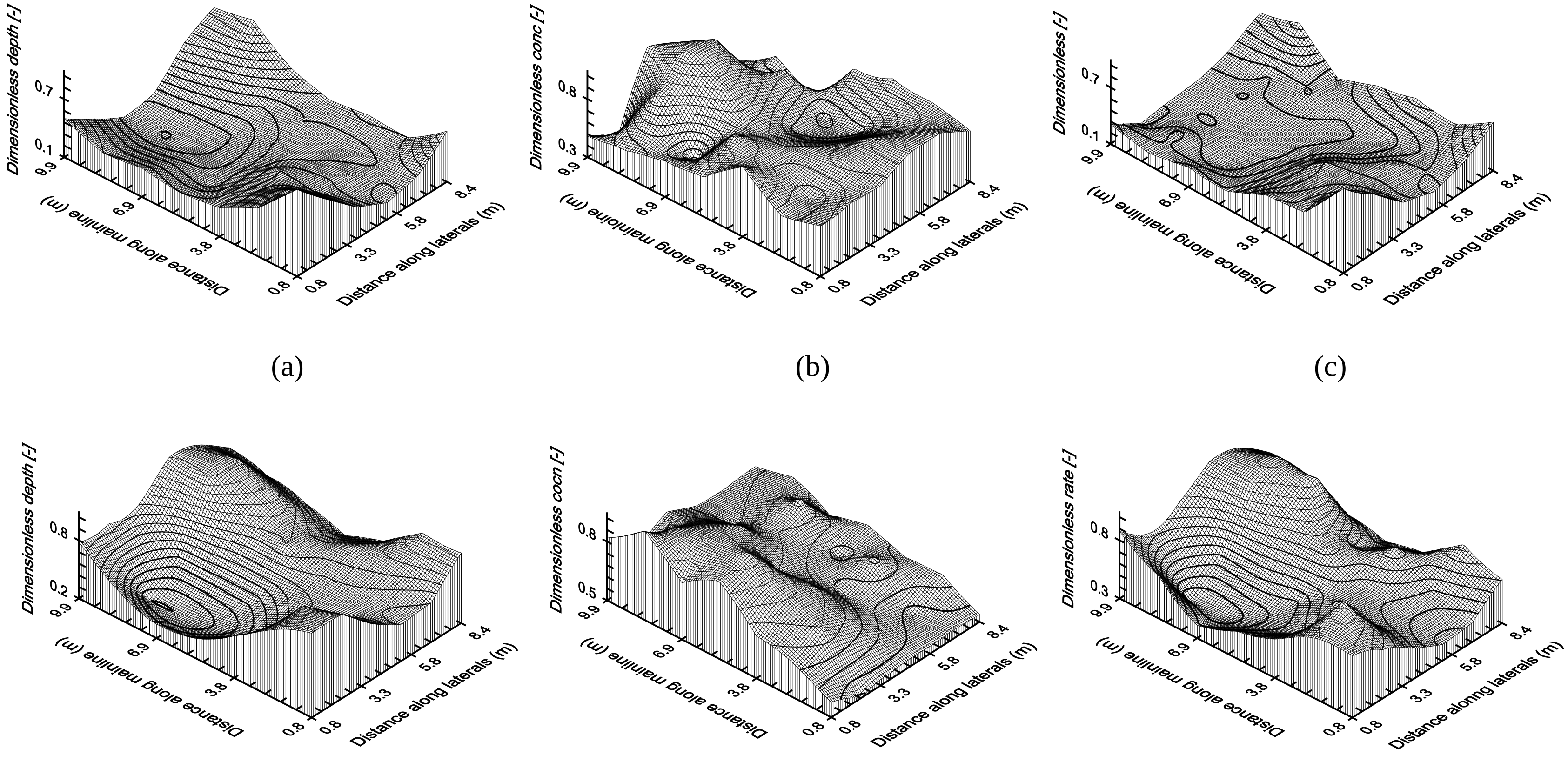
Figure 4. Flow diagram depicting factors and mechanisms affecting the field-wide spatial distribution of the concentration of sprinkler applied nitrogen fertilizer



(a) (b) (c)

(d) (e) (f)

Figure 5. Dimensionless spatial distribution of (a) Irrigation depth (data set I, downstream end test-plot), (b) Nitrogen concentration (data set I, downstream end test-plot), (c) Nitrogen application rate (data set I, downstream end test-plot), (d) Irrigation depth (data set II, middle test-plot), (e) Nitrogen concentration (data set II, middle test-plot), and (f) Nitrogen application rate (data set II, middle test-plot)



(a)

(b)

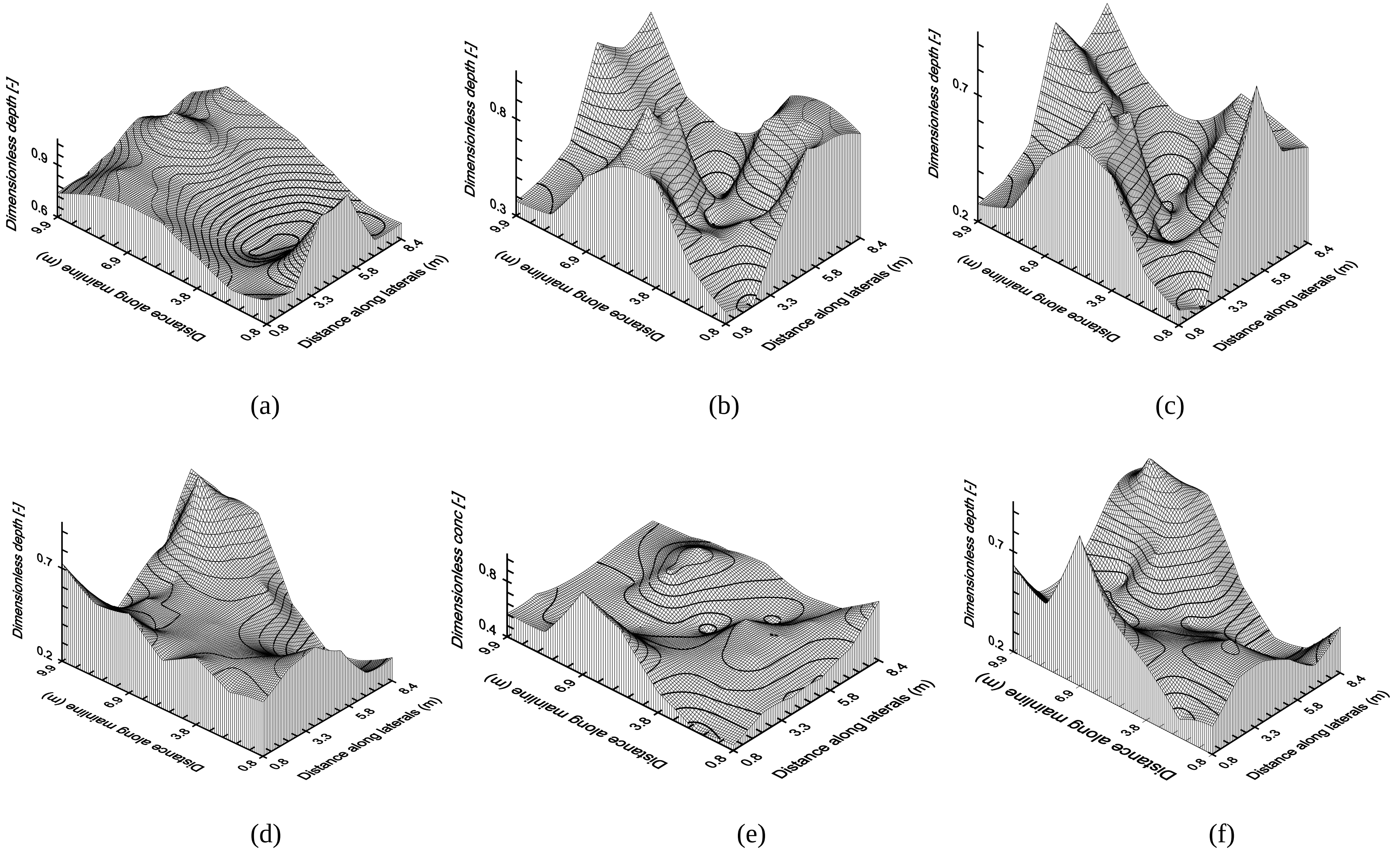
(c)

(d)

(e)

(f)

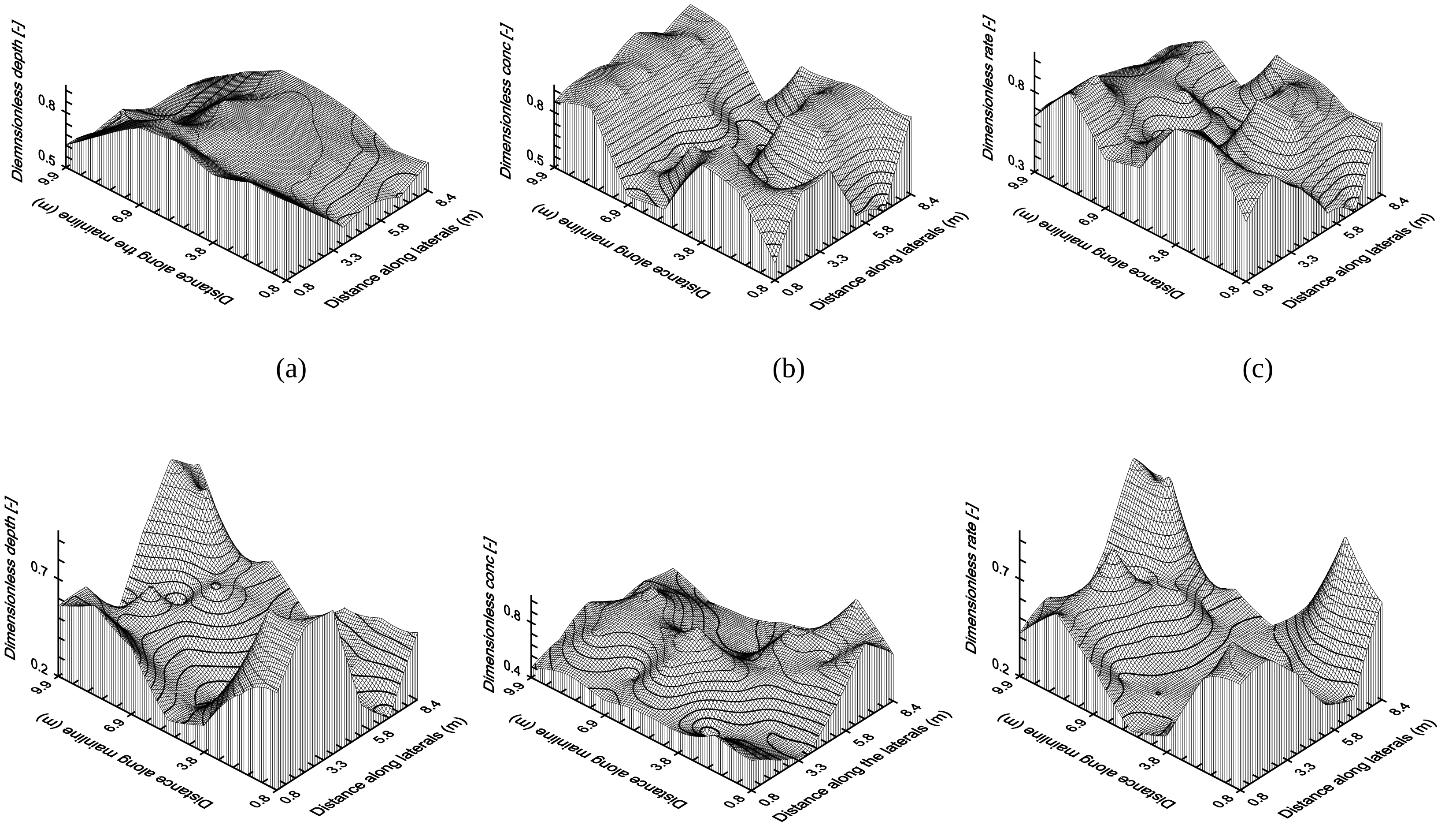
Figure 6. Dimensionless spatial distribution of (a) Irrigation depth (data set III, middle test-plot), (b) Nitrogen concentration (data set III, middle test-plot), (c) Nitrogen application rate (data set III, middle test-plot), (d) Irrigation depth (data set IV, upstream end test-plot), (e) Nitrogen concentration (data set IV, upstream end test-plot), and (f) Nitrogen application rate (data set IV, Upstream end test-plot)



(a) (b) (c)

(d) (e) (f)

Figure 7. Dimensionless spatial distribution of (a) Irrigation depth (data set V, middle test-plot), (b) Nitrogen concentration (data set V, middle test-plot), (c) Nitrogen application rate (data set V, middle test-plot), (d) Irrigation depth (data set VI, downstream end test-plot), (e) Nitrogen concentration (data set VI, downstream end test-plot), and (f) Nitrogen application rate (data set VI, downstream end test-plot)



(a) (b) (c)

(d) (e) (f)

Figure 8. Dimensionless spatial distribution of (a) Irrigation depth (data set VII, upstream end test-plot), (b) Nitrogen concentration (data set VII, upstream end test-plot), (c) Nitrogen application rate (data set VII, upstream end test-plot), (d) Irrigation depth (data set VIII, upstream end test-plot), (e) Nitrogen concentration (data set VIII, upstream end test-plot), and (f) Nitrogen application rate (data set VIII, upstream end test-plot)

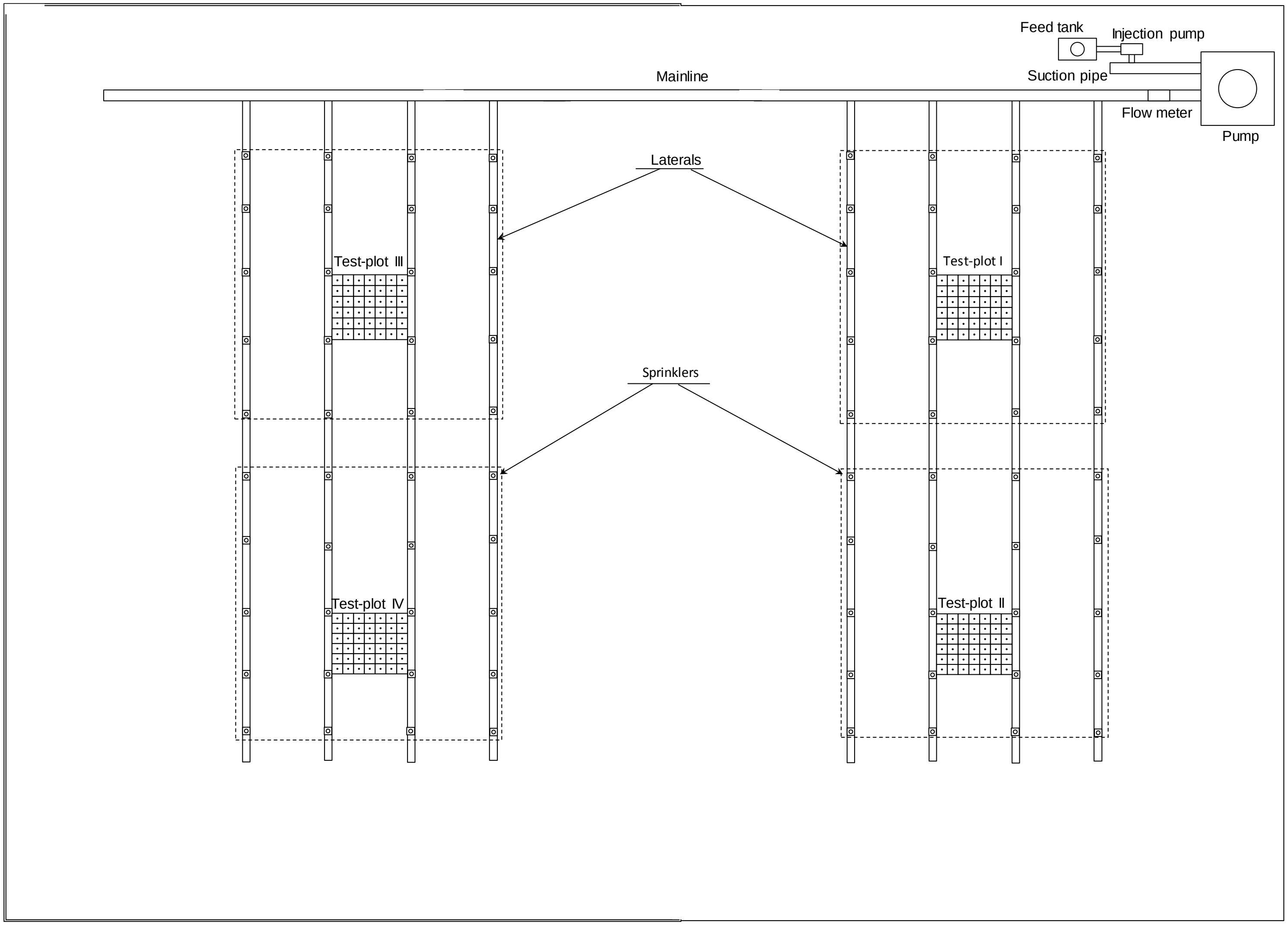


Figure 9. Layout of test-plots for the Bromide tracer study, Maricopa Agricultural Center (Note that fertilizer application configurations 1, 2, 3, and 4 were implemented in test-plot I, II, III, and IV, respectively)

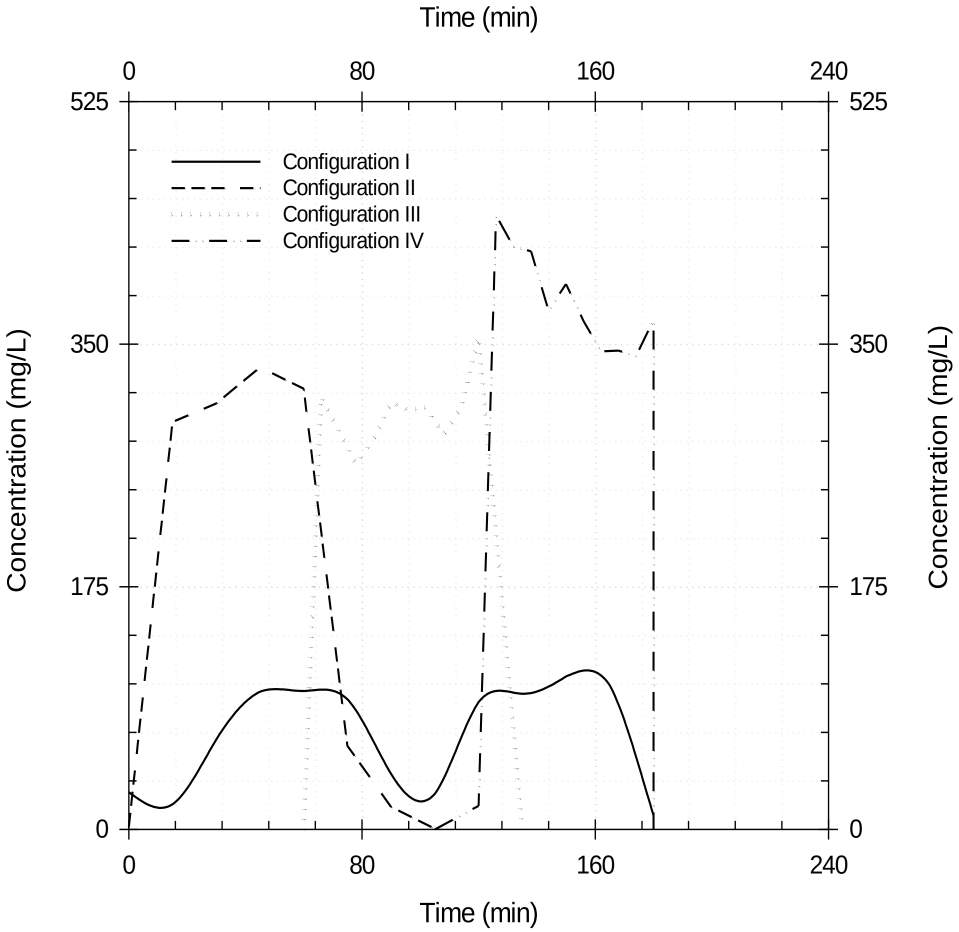


Figure 10. Measured bromide breakthrough curves at the sprinkler system inlet corresponding to the four solute application configurations