

Analysis and Evaluation of the Performance of Surface N-Fertigation on the Yuma Mesa¹

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Abstract

The application of N-fertilizers mixed with a surface irrigation stream (surface N-fertigation) is widely practiced in the Yuma Mesa. Guidelines for the efficient management of surface N-fertigation systems are needed. The purpose of the work reported herein is to evaluate the relative effectiveness of existing surface N-fertigation management practices in the Yuma Mesa. This has been accomplished through the following steps: (1) a complete set of performance indices that can be used to assess the relative merit of alternative management scenarios are identified and defined and Equations as well as solutions for quantifying the performance indices are proposed; (2) surface fertigation field experiments (using Br⁻ as a tracer) were performed in two irrigation basins at the Yuma Mesa research farm of the University of Arizona during the fall season of 2000; (3) the spatial distribution as well as the application efficiency and adequacy of Br⁻ applied with irrigation water was determined using the performance functions proposed herein; and (4) the results were analyzed to assess the merits and limitations of existing practices.

Introduction

In the Yuma Mesa, surface N-fertigation (the application of N-fertilizers mixed with a surface irrigation stream) is widely practiced. Flexibility, cost effectiveness, and the potential for improved seasonal fertilizer application efficiency are advantages of fertigation over traditional fertilizer application methods. However, in the absence of appropriate management practices, surface N-fertigation efficiencies and uniformities can be low compared to conventional fertilizer application methods (Gardner and Roth, 1984; Jaynes et al., 1992).

The transport and fate of nitrogen, especially nitrate, are closely related to water movement, both on the surface and through the soil profile. Consequently, in irrigated areas, inefficient irrigation practices can cause nitrate pollution of surface-water and groundwater resources (Adriano et al., 1972; Letey, et al., 1977; Letey et al., 1978; Stark et al., 1983; Sanchez et al., 1994). Existing surface irrigation management approaches are inadequate in the context N-fertigation, where a mixture of water and N-fertilizer are applied – instead of water only. Interest in studies that relate to the transport and fate of N-fertilizer applied with a surface irrigation stream is growing (Jaynes et al., 1992;

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Boldt et al., 1994; Izadi et al., 1996; Playan and Faci, 1997; Garcia-Navarro et al., 2000). However, comprehensive surface N-fertigation management procedures have yet to emerge.

The objective of the work reported herein is to evaluate the relative merit of existing surface N-fertigation management practices in the Yuma Mesa. This has been accomplished through the following steps: (1) a complete set of performance indices for an N-fertigation management system was identified and defined, (2) in the fall season of 2000, surface N-fertigation field trial was performed in two experimental basins in the research farm of the Yuma Agricultural Center of the University of Arizona (bromide ion, Br^- , was used as a tracer to simulate the movement of nitrate, NO_3^- , on the surface and through the soil profile), (3) the data collected during the field experiments were used in performance calculation and analysis. This paper presents a summary of the results and related analysis.

Definition and evaluation of fertigation performance indices

In order to evaluate the performance of a fertigation event, it is necessary to delineate the region from which crops extract water and N (i.e., the crop root zone). It is also necessary to determine the water and N input and output components (Figure 1). In addition, useful mathematical formulations of the N-fertigation performance indices are possible, only if the probable configuration of the N-fertilizer distribution in the soil profile is properly understood. Figures 2 and 3 depict an example of a possible N-fertilizer profile and N-fertilizer mass inflow into, and out flow from, a basin. Note that Figure 3c is impertinent to a basin. As can be seen from Figure 2, depending on the relationship between the net N-fertilizer requirement, N_r , the maximum N-fertilizer amount applied, N_{max} , and the minimum N-fertilizer amount applied, N_{min} ; a fertigation event can fall into one of the following three cases: *Case 1* = $N_r < N_{min}$, *Case 2* = $N_{min} < N_r < N_{max}$, and *Case 3* = $N_{max} \neq N_r$. *Case 1* represents a situation in which the basin is under-fertilized over its entire length. *Case 2* represents a partial under-fertilization and *Case 3* is a situation in which the basin is entirely over-fertilized.

Performance of a fertigation event can be defined as a measure of how close a surface N-fertigation event is to a reference (ideal) fertigation event. A reference (an ideal) fertigation event can be defined as one that applies the required amount of water and N-fertilizer over the crop root zone without loss. From the preceding definition of performance, a set of three indices can be identified as one that constitutes a complete set of performance indicators for a surface N-fertigation event. This set includes: nitrogen application efficiency (E_{aN}), nitrogen requirement index (I_{rN}), and nitrogen distribution uniformity (DU_N). Definitions of these indices are given subsequently. Details on the equations and associated simplifications as well as solutions are not included here, but can be obtained from Zerihun et al. (2002).

1. Nitrogen application efficiency: N application efficiency can be defined as the ratio of the mass of the effective N-fertilizer that is stored in the crop root zone to the mass of the N-fertilizer admitted into a basin. *Nitrogen requirement index (I_{rN}):* can be defined as the ratio of the mass of the effective N-fertilizer actually stored in the crop root zone to the total mass of N-fertilizer that need to be stored in order to meet the N-fertilizer crop consumptive use need. *Nitrogen application uniformity:* Distribution uniformity (DU_N) and Christiansen's uniformity coefficient (UCC_N) can be used to evaluate the uniformity of N-fertilizer application. *Nitrogen distribution uniformity (DU_N):* DU_N is defined as the ratio of the minimum N-fertilizer amount stored in a soil layer of specified depth to the average N-fertilizer amount stored in the same soil layer and over the entire length of the basin. *Christiansen's uniformity coefficient for nitrogen, UCC_N ,* is the ratio of the difference between the average amount of N-fertilizer stored in a soil layer of specified depth and the mean absolute deviation from the average amount to the average amount of N-fertilizer stored in the soil layer.

Efficiency, adequacy, and uniformity constitute a complete set of performance criteria for surface N-fertigation. However, a complete accounting of the N-fertilizer applied in a fertigation event and diagnostic information, as to how the performance of a surface N-fertigation event can be improved, are obtained only from evaluations of the components of the N-fertilizer losses. A brief discussion on the constituents of the surface N-fertigation losses is presented below.

Nitrogen loss indicators

In general, there are three indices that are of relevance in this category: nitrogen leaching loss, nitrogen runoff loss, and nitrogen surplus within the crop root zone. However, since this project deals only with basins (a system with no runoff loss), subsequent discussion will not include nitrogen runoff loss.

(1) *Nitrogen leaching loss* represents that portion of the water-applied N-fertilizer that leaves the crop root zone at its bottom boundary as a constituent of deep percolation water (Figure 2). Nitrogen leaching fraction, L_{fN} , is an index that can be used to quantify leaching losses. N-leaching fraction can be defined as the ratio of the mass of the Nitrogen leaching losses to the mass of the N-fertilizer admitted into the basin. (2) *Nitrogen surplus* represents a portion of the N-fertilizer that is stored in the crop root zone in excess of the N-fertilizer requirement. Nitrogen surplus fraction, S_{fN} , can be used as an index to quantify the N surplus in the crop root zone. Nitrogen surplus fraction is defined as the ratio of the mass of the N-fertilizer that is stored in the crop root zone in excess of the N-fertilizer requirement to the total mass admitted into the basin.

Performance and related indices described above have been used to assess the merit of fertigation management practices in the Yuma Mesa. Description of the field experiment as well as summary of performance calculations and analysis of results is presented below.

Field experiment and laboratory analysis

In the fall season of 2000, a surface fertigation experiment was performed in two irrigation basins (33.5 m H 186 m each) at the Yuma Mesa research farm of the University of Arizona. One of the basins had a level bed and the second one had a bed slope of 0.1 percent. The basins were used to irrigate lemon trees grown on Superstition sand (a soil type with more than 90 percent sand fraction). Due to uncertainties in the quantities of soil background N, bromide ion, which is known to have similar transport properties as nitrate, was used as a tracer to simulate NO_3^- in these studies. A KBr solution with an average concentration of 336.5 g/L and a total volume of 276 L was prepared, which is enough to cover the two basins at an average application rate of 5 gram of Br^- per square meter of basin area. A simple setup that uses a float valve arrangement was used to meter the KBr solution from a feed tank placed at an elevated platform into the upstream end of a lined field supply basin. The injection of the KBr solution into the irrigation stream occurred throughout the irrigation application time at a constant rate of 4.416 L/min. Each basin was irrigated with the entire field supply basin discharge of 623 L/sec. Water samples were collected at regular time intervals at selected locations along the length of each basin, including the basin inlets. Mean KBr concentrations of water samples collected at the inlets of the two basins were 0.0564 g/L and 0.0388 g/L for the level and graded basins, respectively. Two days after the experiment, soil samples were collected from thirty-nine sampling stations in each basin. Soil sampling was performed along three transects that were 14.7 m apart and that ran parallel to the full length of each basin. Thirteen sampling points, 14.2 m apart each, were located along each transect. At each sampling station, four soil samples were collected over a depth of 1.2 m at intervals of 0.3 m. Bromide was extracted from the soil samples with water, in a 1:1 solution to sample ratio. Extracts were filtered and the Br^- concentrations of the extracts and the water samples were determined colorimetrically (Zitomer and Lambert, 1963) using an autoanalyzer (Marti and Arozarena, 1981).

Sample fertigation performance calculation using field data

The total mass of Br^- applied in a one-meter wide strip of each basin was obtained by numerically integrating the mass flow rate of Br^- into the basin over time (Tables 1 and 2). The same procedure was used to calculate the mass of Br^- that entered the soil in one-meter wide strips that ran along the full length of the three transects in each basin (Tables 1 and 2). An effective rooting depth of 0.9 m was used in the calculation of the quantities of effective N-fertilizer. The basin-wide average application efficiency of Br^- was 82.2 percent and 80.5 percent for the level basin and graded basin, respectively. Using a typical N-fertilizer application rate for the low desert area (about 5 g/m²) as the target application rate for Br^- , the basin-wide requirement index was calculated as 0.69 for the level basin and 0.39 for the graded basin. Obviously, the high basin-wide application efficiencies were achieved at the expense of

the N requirement index. The data in Tables 1 and 2 indicate that the main cause for low I_{RN} is that a substantial part of the N-fertilizer (about 16.5% for the level basin and 52% for the graded basin) did not reach the basin entrance – it either remained in the feed tank or in the field supply canal, of course a portion of this discrepancy can also be attributed to measurement and sampling errors. The fact that a significant amount of N-fertilizer remained in the field conveyance system indicates that estimates of gross N-fertilizer requirement need to take into account conveyance losses explicitly, if adequate fertilization is to be achieved. It can also be observed from Tables 1 and 2 that there exist significant variation in performance, between transects, within a basin. Although ascertaining the exact causes for these differences require further studies, likely causes are micro-topographic variations, soil spatial variability, and presence of preferential flow paths. Finally, with the exception of transect 2 of the level basin, in which a surplus Br^- of 3.8 percent was observed, the amount of Br^- that was retained in the crop root zone fell short of the requirement along the other transects of both basins (Table 1, Figures 4a-4f).

Within a basin, the uniformity of Br^- application varied depending on the uniformity index used and the layer of the soil profile (that is the sampled depth versus the effective rooting depth) for which uniformity was calculated (Tables 1 and 2). In general, Br^- distribution uniformity was consistently lower than the corresponding uniformity coefficient values (Tables 1 and 2). The significant differences in the mean basin-wide DU_{NR} and DU_{NS} values for the level basin (Table 1) indicated that the mean basin-wide bromide application uniformities for the crop root zone could be significantly different from the mean basin-wide bromide application uniformities for the entire sampled depth. The coefficient of variation, for DU_N and UCC_N , was calculated for both basins and summarized in Table 3. The maximum and mean coefficient of variation values for DU_N were 0.245 and 0.197, respectively (Table 3). On the other hand, the maximum and average coefficient of variation values for UCC_N were 0.11 and 0.072, respectively (Table 3). These suggest that, for the two basins considered in the current study, DU_N is prone to a wider variation compared to UCC_N . However, this does not necessarily imply that DU_N is always more sensitive than UCC_N . It can easily be shown that two entirely different N profiles in two different fields, with the same mean and minimum N, can have the same DU_N values but widely differing UCC_N values.

In general, the relative magnitude of UCC_N and DU_N indicates whether the bulk of the field observed variability is distributed along the entire channel reach or represented by isolated spikes/troughs at one or a couple of points along the channel. For instance, in the case of transects 1 and 3 of the level basin (Figures 4a and 4c) the bulk of the field observed variability was distributed over the entire length of each transect. As a result the differences between the average (N_{av}) and the minimum (N_{min}) values of the two transects were close to the mean deviations from their N_{av} values, hence the ratios of DU_N to UCC_N for both transects were close to one (Table 3). On the other hand, in the graded basin, where localized extremes dominated the observed variability (Figures 4d-4f), the ratios of DU_N to UCC_N were low (Table 3), indicating the presence of major spikes/troughs in the corresponding N-fertilizer profiles somewhere along the transects.

As can be seen in Figures 4a-4f, the areas circumscribed by the N-profile for the sampled depth (solid line) and the N-profile for the crop root depth (dashed line) represent the amounts of Br^- leached below the crop root zone and recovered in the soil samples. Obviously, along some transects the total amount of Br^- leached below the crop root zone exceeded the amount of leached Br^- recovered through soil sampling (Table 1 and 2). Along the length of run of each of the three transects of the level basin, the distribution of the leached Br^- was rather uniform (Figures 4a-4c). In contrast, the bulk of the graded basin leaching occurred towards the downstream end of the basin (Figures 4d- 4f). This is associated with the excess deep percolation that occurs toward the lower reaches of graded basins that are irrigated with large flow rates (Sanchez and Zerihun, 2000).

Finally, although there were variations from transect to transect, basin-wide mass balance shows that the soil sampling was able to recover nearly all of the Br^- that was applied to the level basin and about 96 percent of the Br^- that entered the graded basin.

Summary and Conclusions

A complete set of field-event scale surface N-fertigation performance indices are identified and defined. A summary of sample performance calculations are presented for a fertigation experiment performed on irrigation basins at the Yuma Mesa Experimental Farm of the University of Arizona. Within the confines of a field-event scale, the

performance indices can be used to assess the relative merit of alternative design and management options and as diagnostic tools to evaluate existing fertigation system operation scenarios. However, in any setting, high levels of surface N-fertigation performance can be achieved only through a combination of technically sound system design and management approaches and appropriate fertilizer application modes. Future research need to explore these aspects of N-fertigation.

Experimental results indicate that current N-fertigation practices may result in high basin-wide application efficiencies (82% and 80%, for the level and graded basins, respectively). However, high application efficiencies were achieved at the expense of the N requirement index (0.69 and 0.39 for the level and graded basins, respectively). The main cause for the low I_{RN} values is that a substantial part of the N-fertilizer (about 16.5% for the level basin and 52% for the graded basin) did not reach the basin entrance – it either remained in the feed tank or in the field supply canal. Of course, a portion of this discrepancy can also be attributed to measurement and sampling errors. The fact that a significant amount of N-fertilizer remained in the field conveyance system indicates that estimates of gross N-fertilizer requirement need to take into account conveyance losses explicitly, if adequate fertilization is to be achieved. Results also indicate that there exist significant variation in performance, between transects, within a basin. Although ascertaining the exact causes for these differences require further studies, likely causes are micro-topographic variations, soil spatial variability, and presence of preferential flow paths.

References

- Adriano, D.C., Takatori, F.H., Pratt, P.F., and Lorenzo, O.A. 1972. Soil nitrogen in selected row-crop sites in southern California. *J. Environ. Quality*, 1:279-283.
- Boldt, A.L., Watts, D.G., Eisenhauer, D.E., and Schepers, J.S. 1994. Simulation of water applied nitrogen distribution under surge irrigation. *Transactions of the ASAE*, 37(4):1157-1165.
- Garcia-Navarro, P., Playan, E., and Zapata, N. 2000. Solute transport modeling in overland flow applied to fertigation. *J. Irrig. and Drain. Engrg., ASCE*, 126(1):33-40.
- Gardner, B.R. and Roth, R.L. 1984. Applying nitrogen in irrigation waters. In Nitrogen in crop production, Ed., Hauck, R.D., pp. 493-505, *American Society of Agronomy, Crop Science Society of America, Soil Science Society of America*, Madison, Wisconsin.
- Izadi, B., King, B., Westermann, D., and McCann, I. 1996. Modeling transport of bromide in furrow-irrigated field. *J. Irrig. and Drain. Eng., ASCE*, 122(2):90-96.
- Jaynes, D.B., Rice, R.C., and Hunsaker, D.J. 1992. Solute transport during chemigation of level basin. *Transactions of the ASAE*, 35(6):1809-1815.
- Letey, J., Blair, J.W., Devitt, D., Lund, L.J., and Nash, P. 1977. Nitrate-nitrogen effluent from agriculture tile drains in California. *Hilgardia*, 45:289-319.
- Letey, J., Blair, J.W., Stolzy, L.H., and Ayers, R.S. 1978. Effect of water management on nitrate leaching. Ed., Pratt, P.F., pp. 15-18, *Proc. National conference on Management of N in irrigated agriculture*, Sacramento, CA.
- Marti, V. C. and Arozarena, C. E. 1981. Automated determination of bromide in water. Proceedings No. 734, Pittsburgh Conference.
- Playan, E. and Faci, J.M. 1997. Border fertigation: field experiments and a simple model. *Irrig. Sci.*, 17:163-171.
- Sanchez, C.A., Roth, R.L., and Gardner, B.R. 1994. Irrigation and nitrogen management for sprinkler irrigated cabbage on sand. *J. Am. Soc. Hort. Sci.*, 119:427-433.

Sanchez, C.A. and Zerihun, D. 2000. Guidelines for improved irrigation practices for citrus grown on the sandy soils of the Yuma Mesa irrigation district. *Final report submitted to the U.S. Bureau of Reclamation, Yuma Area Office.*

Stark, J.C., Jarrell, W.M., and Lety, J. 1983. Evaluation of irrigation-nitrogen management practices for celery using continuous-variable irrigation. *Soil Sci. Soc. Am. J.*, 47:95-98.

Zerihun, D., Sanchez, C.A., and Farrell-Poe, K.L., F.J. Adamsen and D.J. Hunsaker. 2002. Performance indices for surface N-Fertigation. *J. Irrig. and Drain. Engrg., ASCE*, (accepted).

Zitomer, F. and Lambert, J. L. 1963. Spectrometric determination of bromide ion in water. *Anal. Chem.* 35(11): 1731-1734.

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Table 2. Summary of sample fertigation performance calculations, graded basin

Table 3. Coefficient of variation for DU_N and UCC_N

Table 1. Summary of sample fertigation performance calculations, level basin

Dist. ¹ (m)	Br _r ² (g/m)	Transect 1		Transect 2		Transect 3		Mass inflow of Br ⁻	
		Br ⁻ infiltrated (g/m)	Br ⁻ in root zone (g/m)	Br ⁻ infiltrated (g/m)	Br ⁻ in root zone (g/m)	Br ⁻ infiltrated (g/m)	Br ⁻ in root zone (g/m)	Time (min)	Mass flow rate (g/m/min) ³
0.0	5	3.100	2.948	4.207	3.186	2.549	2.403	0	40.9
7.2	5	3.100	2.948	4.207	3.186	2.549	2.403	1.9	41.7
21.5	5	3.877	3.024	3.764	2.938	3.251	3.251	6.4	42.3
35.8	5	3.737	3.197	4.201	3.235	2.452	2.041	12.7	42.5
50.1	5	3.348	3.181	3.326	2.943	4.757	3.807	18.4	42.6
64.4	5	4.876	4.066	4.250	3.208	3.119	2.786		
78.8	5	5.441	4.833	4.844	3.947	5.022	3.953		
93.1	5	3.691	3.283	5.486	4.423	0.659	0.551		
107.4	5	4.374	3.353	5.492	4.325	4.757	3.785		
121.7	5	5.438	4.266	8.154	7.047	5.951	4.817		
136.0	5	4.450	3.672	4.077	3.737	5.432	4.347		
150.4	5	5.449	4.423	4.212	3.829	3.734	3.453		
164.7	5	4.652	4.053	4.388	3.443	3.937	2.965		
179.0	5	3.440	3.245	2.241	2.095	2.225	2.028		
186.0	5	3.440	3.245	2.241	2.095	2.225	2.028		
MBr⁴ (g/m)	930.0	800.1	680.3	839.4	692.1	699.4	575.2		777.5
Performance									Mean basin-wide performance
E_{aN} (%)			87.5		85.3		74.0		82.3
I_{rN} (-)			0.73		0.71		0.62		0.69
DU_{NS}⁵ (-)		0.73		0.50		0.59			0.61
DU_{NR}⁶ (-)			0.81		0.56		0.66		0.68
UCC_{NS}⁷ (-)		0.83		0.79		0.67			0.76
UCC_{NR}⁸ (-)			0.86		0.78		0.71		0.78
Losses									Mean basin-wide losses
R_{rN} (%)			0.0		0.0		0.0		0.0
L_{rN} (%)			15.1		18.9		16.0		16.7
S_{rN} (%)			0.0		3.8		0.0		1.3
									Mean basin-wide PRS
PRS⁹ (%)		102.6		108.0		90.0			100.2
									Mean basin-wide mass balance error
Mass bal. error (%)			-2.6		-8.0		10.0		-0.2

¹Note that soil samples were not collected from the upstream and downstream ends of the basin, instead Br⁻ amounts calculated for the nearest sampling stations were used in the calculation of performance, ²Intended average application rate of Br⁻, ³Mass flow rate of Br⁻ into the basin in grams per minute per meter width of basin, ⁴Mass of Br⁻ applied and retained in the sampled soil depth in grams per meter width of basin, ⁵Nitrogen distribution uniformity - sampled depth, ⁶Nitrogen distribution uniformity – effective rooting depth, ⁷Christiansen’s uniformity coefficient for nitrogen - sampled depth, ⁸Christiansen’s uniformity coefficient for nitrogen – effective rooting depth, and ⁹Percent recovered by sampling.

Table 2. Summary of sample fertigation performance calculations, graded basin

Dist. ¹ (m)	Br _r ² (g/m)	Transect 1		Transect 2		Transect 3		Mass inflow of Br ⁻	
		Br ⁻ infiltrated (g/m)	Br ⁻ in root zone (g/m)	Br ⁻ infiltrate d (g/m)	Br ⁻ in root zone (g/m)	Br ⁻ infiltrated (g/m)	Br ⁻ in root zone (g/m)	Time (min)	Mass flow rate (g/m/min) ³
0.0	5	1.188	1.037	0.826	0.486	0.875	0.794	0	41.08
7.2	5	1.188	1.037	0.826	0.486	0.875	0.794	1.6	41.08
21.5	5	2.284	2.084	1.220	1.139	1.139	1.096	5.5	34.26
35.8	5	1.528	1.426	2.192	2.106	1.150	1.064	10.5	19.89
50.1	5	1.264	1.177	1.334	1.220	1.528	1.431	15.4	20.29
64.4	5	1.442	1.312	1.150	1.015	1.717	1.577		
78.8	5	1.787	1.636	1.496	1.409	1.620	1.501		
93.1	5	2.562	2.268	2.093	1.933	6.369	2.738		
107.4	5	4.973	4.687	2.554	2.430	2.538	2.138		
121.7	5	4.992	4.766	2.473	2.295	2.738	2.111		
136.0	5	2.354	2.176	2.414	1.739	2.473	2.203		
150.4	5	2.333	2.198	4.755	1.976	2.198	2.057		
164.7	5	2.970	2.646	2.381	1.852	2.738	2.306		
179.0	5	2.533	2.354	3.132	2.819	2.579	2.349		
186.0	5	2.533	2.354	3.132	2.819	2.579	2.349		
MBr⁴ (g/m)	930.0	460.9	425.9	400.8	320.6	424.4	334.2		447.2
Performance									Mean basin-wide performance
E_{aN} (%)			95.2		71.7		74.7		80.5
I_{Rn} (-)			0.46		0.34		0.36		0.39
DU_{NS}⁵ (-)		0.48		0.38		0.38			0.41
DU_{NR}⁶ (-)			0.45		0.28		0.44		0.39
UCC_{NS}⁷ (-)		0.66		0.63		0.61			0.63
UCC_{NR}⁸ (-)			0.65		0.65		0.70		0.67
Losses									Mean basin-wide losses
R_{fN} (%)			0.0		0.0		0.0		0.0
L_{fN} (%)		7.8		17.9		20.2			15.3
S_{fN} (%)			0.0		0.0		0.0		0.0
									Mean basin-wide PRS
PRS⁹ (%)		103.1		89.6		94.9			95.9
									Mean basin-wide mass balance error
Mass bal. error (%)		-3.1		10.4		5.1			4.1

¹ Note that soil samples were not collected from the upstream and downstream ends of the basin, instead Br⁻ amounts estimated for the nearby sampling stations were used in the calculation of performance, ² Intended average application rate of Br⁻, ³ Mass flow rate of Br⁻ into the basin in grams per minute per meter width of basin, ⁴ Mass of Br⁻ applied and retained in the sampled soil depth in grams per meter width of basin, ⁵ Nitrogen distribution uniformity - sampled depth, ⁶ Nitrogen distribution uniformity - effective rooting depth, ⁷ Christiansen's uniformity coefficient for nitrogen - sampled depth, ⁸ Christiansen's uniformity coefficient for nitrogen - effective rooting depth, and ⁹ Percent recovered by sampling.

Table 3. Coefficient of variation for DU_N and UCC_N

Level basin							
Transect	UCC_{NS} (-)	Basin-wide mean (-)	Coefficient of variation (-)	UCC_{NR} (-)	Basin-wide mean (-)	Coefficient of variation (-)	DU_{NS}/UCC_{NS} ¹ (-)
1	0.83	0.76	0.109	0.86	0.78	0.096	0.88
2	0.79			0.78			0.63
3	0.67			0.71			0.88
Transect	DU_{NS} (-)	Basin-wide mean (-)	Coefficient of variation (-)	DU_{NR} (-)	Basin-wide mean (-)	Coefficient of variation (-)	DU_{NR}/UCC_{NR} (-)
1	0.73	0.61	0.191	0.81	0.68	0.213	0.94
2	0.50			0.56			0.72
3	0.59			0.66			0.93
Graded basin							
Transect	UCC_{NS} (-)	Basin-wide mean (-)	Coefficient of variation (-)	UCC_{NR} (-)	Basin-wide mean (-)	Coefficient of variation (-)	DU_{NS}/UCC_{NS} (-)
1	0.66	0.63	0.039	0.65	0.67	0.043	0.73
2	0.63			0.65			0.60
3	0.61			0.7			0.62
Transect	DU_{NS} (-)	Basin-wide mean (-)	Coefficient of variation (-)	DU_{NR} (-)	Basin-wide mean (-)	Coefficient of variation (-)	DU_{NR}/UCC_{NR} (-)
1	0.48	0.41	0.14	0.45	0.39	0.245	0.69
2	0.38			0.28			0.43
3	0.38			0.44			0.63

¹ Ratio of distribution uniformity to Christiansen's coefficient of uniformity.

Figure 1. Crop Root Zone

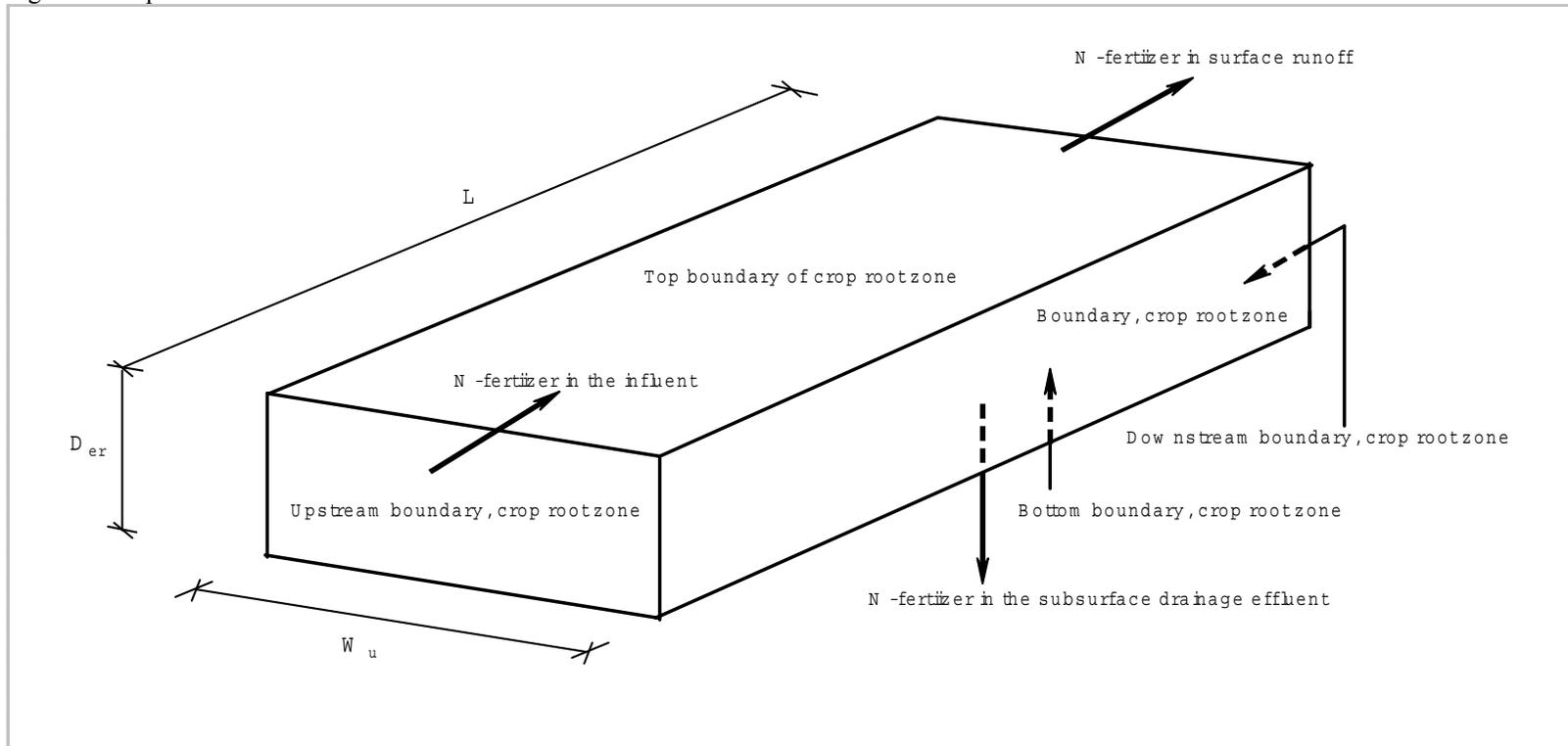
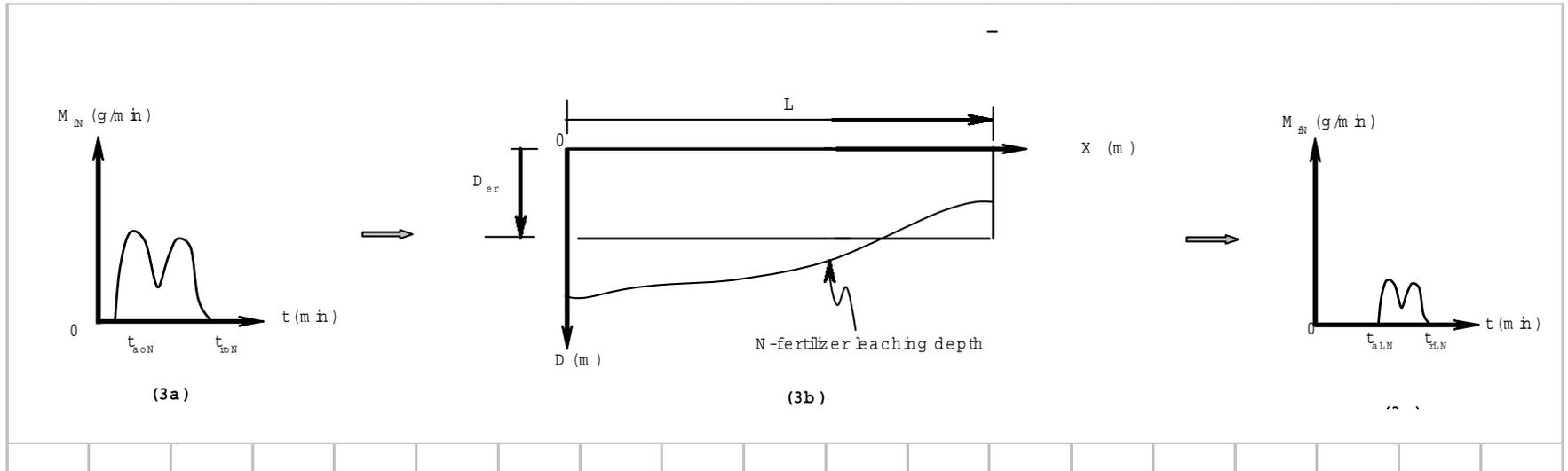


Figure 3a. Mass flow rate of N as a function of time at the inlet end, Figure 3b. N-fertilizer destination diagram, and Figure 3c. Mass flow rate of N as a function of time at the outlet end.



MfN = mass flow rate of N-fertilizer, t = time, Der = effective rooting depth, D = depth

Br_r = target Br- application rate, Br_{sd} = bromide profile for sampled depth, Br_{cr} = Br- profile for crop root zone, Br_{avsd} = Br- average for sampled depth, and Br_{avcr} = Br- average for crop root zone

Figure 4a. Br- profile along transect 1 (level basin), Figure 4b. Br- profile along transect 2 (level basin), Figure 4c. Br- profile along transect 3 (level basin), Figure 4d. Br- profile along transect 1 (graded basin), Figure 4e. Br- profile along transect 2 (graded basin), and Figure 4f. Br- profile along transect 3 (graded basin)

