AN ABSTRACT OF THE THESIS OF

Jason K. Smesrud for the degree of Master of Science in Bioresource Engineering presented on January 5, 1998. Title: Peppermint Irrigation and Nitrogen Management for the Reduction of Nitrate Loading to Groundwater.

Redacted for privacy

Abstract approved: ____________________

John S. Selker

The agricultural production of peppermint has been shown to contribute significant quantities of nitrate-nitrogen to groundwater recharge. In an effort to provide new tools for increasing nitrogen efficiency within peppermint production, three research questions were proposed: i) How should plant tissue samples be collected to achieve the greatest precision when using the mint stem nitrate test for nitrogen management?; ii) What is the consumptive use of water by peppermint in the post-harvest period?; and iii) How does irrigation uniformity affect nitrate loading to groundwater when N is supplied through chemigation?

In the first investigation, structured field experiments were designed and conducted on commercial peppermint fields to isolate potential environmental, management, and sampling influences on stem nitrate test results. The most significant effects observed were those of the type of stem material collected (a 441% effect at $p < 0.001$) and the number of stems collected to estimate the field mean concentration. It was found that the variance of the sample population and the number of stems required for a given sampling

error could be greatly reduced by only collecting stems from within the plant canopy. Less pronounced but statistically significant differences in stem nitrate concentrations were produced by variations in solar radiation on hourly (a 17% effect at $p < 0.05$) and daily (a 29% effect at $p < 0.01$) scales. In an analysis of stem nitrate spatial variability, a purely random distribution of stem nitrate concentrations was observed on the 1-150 m scale.

For the second investigation, a field study was conducted to measure the consumptive use of peppermint in the post-harvest period and to develop crop coefficients (Kc) used to predict evapotranspiration rates. The soil water balance was measured on two fields with a neutron moisture probe over an 80 day period. Over the 49 days following harvest, a cumulative consumptive use of 96 mm was observed. Basal crop coefficients increased from near zero to approximately 0.40 within 40 days post-harvest.

The third, and final, investigation developed a simple heuristic statistical model to explore the effective adequacy of chemical application as influenced by the uniformity of irrigation. To perform this analysis, an expression was presented whereby irrigation distribution parameters for the normal, or Gaussian, model could be derived from common irrigation design terms. The results of this model indicate that the effective chemical adequacy is greatly compromised when the irrigation uniformity coefficient is low and/or the design irrigation adequacy is high.

Peppermint Irrigation and Nitrogen Management for the Reduction of Nitrate Loading to Groundwater

by

Jason K. Smesrud

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Jason K. Smesrud, Author

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DEDICATION

In loving memory of my father

Peppermint Irrigation and Nitrogen Management for the Reduction of Nitrate Loading to Groundwater

Chapter 1

General Introduction

In a 1994 sampling of 281 domestic drinking water wells in the agriculturally active portions of Lane County, Oregon, 22% of the wells sampled delivered water with nitrate-nitrogen concentrations exceeding the 10 mg/L maximum contaminant level for drinking water (Penhallegon, 1994). Other groundwater studies in the Willamette valley have also pointed to Lane County as a problem region for nitrate contamination (Petit, 1988). Following these findings, an Environmental Protection Agency funded screening study was initiated to monitor nitrate leaching under several important crops in Lane County (Shelby, 1995). In this study, the agronomic management of peppermint (*Mentha piperita var.*) was identified as one of the highest contributors of the crops investigated to the deep percolation of nitrate-nitrogen. Consequently, much attention has been given to this issue and several subsequent studies have investigated the required agronomic rates of nitrogen (N) fertilizer and irrigation within this crop (Christiansen, 1996; Mitchell and Farris, 1995; Hart, 1995; and Mitchell et al., 1994). There are several questions still to be answered however that may provide growers with water and N management information that will mitigate the present situation. The following research was conducted to answer three such questions: i) How should plant tissue samples be collected to achieve the lowest possible sampling bias when using the mint stem nitrate test for N management?;

ii) What is the consumptive use of water by peppermint in the post-harvest period?; and iii) How does irrigation uniformity affect nitrate loading to groundwater when N is supplied through chemigation? In order to conduct these investigations under realistic conditions and to heighten the awareness of the present groundwater situation within the grower community, all fieldwork was conducted on commercial peppermint fields.

Chapter 2

Field Sampling Considerations for the Stem Nitrate Test in Peppermint

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ABSTRACT

The stem nitrate test for peppermint (*Mentha piperita* var.) is a promising nitrogen management tool. When used properly, this test may aid in obtaining significant savings of fertilizer costs and in the protection of groundwater quality. There are several factors related to environmental conditions, nitrogen management, and sampling procedures that have not been evaluated and may confound interpretation of test results. The objective of this study was to measure the response of stem nitrate concentrations to factors that would be expected to influence the test and develop guidelines for the collection of stem tissue. The factors considered here were solar radiation effects on both hourly and daily scales; spatial variability; differences between alternative plant materials; and the temporal response of tissue nitrate concentrations to soluble nitrogen application. The most influential of these variables were the type of stem material (a 441% effect at $p = 3.55E-6$) and the number of stems collected to estimate the field mean concentration. It was found that the variance of the sample population and the number of stems required for a given sampling error could be greatly reduced by only collecting stems from within the plant canopy. Collecting only these stems, 30 stems were found to be adequate to estimate the field mean concentration within 10 to 15 percent of the true population mean ($p < 0.05$). Statistically significant differences in stem nitrate concentrations were produced by variations in solar radiation on both hourly ($p < 0.05$) and day length ($p < 0.01$) scales. When measuring the diurnal response, a 17 percent reduction in stem nitrate concentration was observed over a nine-hour period from 12:00 hours to 21:00 hours. On the day length scale, an 80 percent reduction in incoming solar radiation produced a 29 percent increase in stem nitrate concentrations after three days of shading. In the analysis

of stem nitrate spatial variability, no discernable range of autocorrelation was detected indicating a purely random distribution of stem nitrate concentrations on the 1-150 m scale. Given this finding and under the conditions of the analyses (late season with stem nitrate in excess of critical levels), it is not important that samples collected for this test fully cover the field being assessed, despite the intuitive appeal of full-field sampling as a standard procedure. The response of stem nitrate concentrations to soluble nitrogen application was minimal, probably due to plant nitrogen status in the test plots being well above the critical deficiency content prior to application. With the data produced from these investigations, users of the peppermint stem nitrate test are presented with a method to collect data in the field whereby nitrogen management interpretations of the test can be more consistent and reliable. In addition, these results indicate the need for researchers to fully report the method of sampling employed when presenting finding for stem tissue tests.

INTRODUCTION

The use of plant tissue nitrate concentrations as an indicator of nitrogen (N) nutrition has been established as a useful tool for decision-based N management in peppermint (Brown, 1982a). Several other crops have also found application of this test including lettuce (Pritchard et al., 1995), potatoes (Rosen et al., 1995), corn (McClenahan and Killorn, 1988), wheat (Roth et al., 1989; Knowles et al., 1991), cabbage (Gardner and Roth, 1989), and cauliflower (Gardner and Roth, 1990). Some advantages of the tissue nitrate test over other plant-response fertilization indicators are the relative ease of analysis and the greater sensitivity to N nutrition than other tissue analyses such as leaf total Kjeldahl N (Brown, 1982a) and SPAD chlorophyll readings (Mitchell et al., 1995; Westcott and Wraith, 1995). An important limitation of the plant tissue nitrate test however, is that nitrate concentrations in plant tissue are influenced by several environmental factors not related to N availability. In general, all processes affecting the absorption, translocation, and reduction rates of nitrates in the plant system influence nitrate concentrations in plant tissue. Factors shown to appreciably affect tissue nitrate concentrations include N availability, solar radiation, CO_2 concentration, salinity, water stress, and Mo and Mn deficiency (Maynard et al., 1976). Some of these factors may not be limiting in a field production setting and need not be accounted for in a plant sampling strategy. Others however, may be critical to the results obtained in the field and need to be well understood for the test to be reliable.

The effect of solar radiation on plant tissue nitrate concentrations have been well documented in other crops (Kanaan and Economakis, 1992; Scaife and Stevens, 1983; Iversen et al., 1985; Cantliffe, 1973; Minotti and Stankey, 1973). These studies demonstrate that plant tissue nitrate concentrations are inversely related to solar radiation. This response is primarily due to the inhibition of nitrate reductase activity in the absence of light which slows the rate of nitrate assimilation into amino acids thus encouraging nitrate accumulation (Hageman et al., 1961). Under field conditions, this influence is manifested over both the diurnal or hour length scale and the day length scale where depressions in solar radiation are superimposed over the diurnal cycle, as in the case of overcast periods. Investigating the diurnal fluctuations of whole-plant tissue nitrate concentrations in beets, Minotti and Stankey (1973) observed nitrate concentrations varying by more than two-fold over a twelve hour period with the high at 04:00 hours and the low at 16:00 hours. Hageman et al. (1961) obtained similar results from corn leaf tissue with nitrate concentrations varying nearly two-fold over an eight hour period with the high at 05:00 hours and the low at 13:00 hours. In the same study, the effect of sustained light reduction on nitrate reductase activity in corn leaf tissue was investigated over a two-week period. Over the course of this experiment, 90, 80, 60, and 30 percent reductions in light intensity lowered nitrate reductase activity by approximately 70, 42, 40, and 15 percent respectively.

In the Pacific Northwest, split-application of N is a common practice within peppermint production with soluble urea-ammonium nitrate being applied through the irrigation system. The total N application is often split into as many as ten applications. This type of management, where plant N status can be quickly adjusted, is ideally suited to the use of stem nitrate testing for N application scheduling. Sampling under this management regime however can be complicated by the frequent applications of N. In general, samples should reflect stable plant tissue concentrations and should not be taken when concentrations are changing rapidly. If the time between fertilization and a concentration plateau is significant however, sampling should avoid areas where stem nitrate concentrations are still recovering from a fertilization event.

Another important effect on the practical utilization of this test is the issue of spatial variability. This variability may arise due to several factors including heterogeneity in N application, soil type, plant stand density, and plant health. Irrigation practices may account for much of this variation since the N distribution is governed by the uniformity of irrigation. Huettig (1969), for example, found that the coefficients of variation (C.V.) in peppermint stem nitrate concentrations were 37.9% and 38.7% for two sites receiving broadcast N and 89% on one site receiving N through irrigation. Two main forms of fertility gradients produced under irrigation may account for this discrepancy. First, a sharp gradient is imposed during a fertigation cycle where some areas have been recently fertilized while others may not have received N for several weeks. This gradient is controlled by the time taken for irrigation equipment to cover the field. Secondly, N is applied with the same uniformity as irrigation water and is thus subject to the variability imposed by overlapping and non-uniform sprinkler patterns. Superimposed over the fertility gradient may be several other spatially variable influences on stem nitrate concentrations including water stress, soil aeration, nitrogen supply, disease, and pest damage. As these influences are not necessarily visible in the field, and sampling for each possible influence is impractical, general guidelines for a spatial sampling pattern that minimizes sampling error would be helpful to users of this test.

It is important when collecting samples in the field to have a well-defined protocol so that similar materials are collected and comparisons across time and location have some meaning. Although there is an established protocol for the plant part used in the peppermint stem nitrate test (Brown, 1982b), there are no guidelines for the type of stems to select. Once peppermint has developed a full canopy, lodging of tall stems is common. This can produce a patchwork pattern of standing and fallen stems across the field. Such variation may cause a systematic sampling bias when only one stem type is chosen given the possibility that different stem types may have very different nitrate concentrations.

The aforementioned considerations have not been addressed for peppermint tissue testing which limits the reliability of this important tool. As a result, the objectives of this study were to investigate: i) the effects of different types of plant tissue on test results; ii) the influence of solar radiation in controlling observed tissue nitrate concentrations; iii) the spatial variability of stem nitrate concentrations, which represents the cumulative effects of all influential environmental variables over the field scale; and iv) the response of stem nitrate concentrations to soluble, mid-season N application.

MATERIALS AND METHODS

Individual tissue samples consisted of the top 15 cm of stem with leaves and petioles removed, following the protocol outlined by Brown (1982b). Stems were first cut approximately 20 cm from the top, stripped of leaves and petioles, trimmed to 15 cm from the tip, and stored in paper bags until returning to the lab. The stripping of leaves and petioles and trimming of stems was completed within 15 minutes of sampling under all experiments except for the study investigating diurnal radiation effects where 40 minutes elapsed before stripping. Samples were dried within 10 hours of sampling in an oven at 70° C for 12 hours. Tissues were then ground to pass through a 20-mesh screen and transferred to envelopes which were stored in a drier at 70^{O} C until analysis. One-half hour before weighing, ground samples were placed in a desiccator. A 200 mg sample was weighed into a 60 mL plastic, wide-mouth bottle and 20 mL of 2% acetic acid added. The bottle was capped tightly and shaken on low for 45 minutes. Following shaking, the solution was filtered through Whatman #42 filter paper into a vial, capped, and refrigerated until analysis. Analysis of the extract for nitrate-N was determined with an ALPKEM RF-300 rapid flow analyzer (Clackamas, OR) which utilizes cadmium to reduce nitrate to nitrite, complexes nitrite with sulfanilamide and N-(1-Napthyl)-

ethylenediamine dihydrochloride, and measures light absorption of the solution at 540 nm.

All experiments were conducted on commercial peppermint fields. Due to the constant irrigation within peppermint, replicated experimental plots were aligned parallel to irrigation laterals so similar irrigation and N treatments could be ensured over all experimental plots. Fields were chosen based upon their homogeneity in irrigation, soils, slope, and plant stand in an attempt to minimize experimental error.

Plant Material

A completely randomized design (Petersen, 1984, pp. 36-48) was used to analyze for differences in peppermint tissue nitrate between stems of different characteristics. On July 20, 1997, eight random locations were selected within a single field covering an area of approximately 4 ha. The stand at this field consisted of a partially lodged canopy with the still erect stems in the pre-flower stage. At each location, stem samples were collected within a 1.0 m radius. Ten stems were collected from three classifications of plant material stratified by inter-nodal spacing. The distance between the fifth and sixth leaf node from the tip of the stem for Class I, II, and III stems were less than 3.7 cm, 3.7 cm to 5.1 cm, and greater than 5.1 cm respectively. Class I stems were generally those stems standing exposed above the main plant canopy and were the closest to maturity of the three classes. These stems were dark purple in color and slightly woody with some stems in the pre-flower stage. Class II stems accounted for the bulk of available stem material and were those stems accounting for the majority of the closed canopy. Stems from this class were mostly green, turning to red towards the tip. Class III stems were found slightly below the main canopy and were generally fleshy and light green in color.

Diurnal Radiation Effects

The influence of diurnal variation in solar radiation on peppermint stem nitrate concentrations was tested using a completely randomized design with time as the treatments. Five 9.0 m^2 plots were selected at random along a single transect aligned parallel to the irrigation laterals. The maximum plot separation was 271 m. Thirty stems were randomly selected from each plot every three hours from 6am to 9pm within 20 minutes of the hour over a one-day period. Leaves and petioles were removed, and stems trimmed within 40 minutes of sampling. Temperature, relative humidity, and solar radiation were monitored at one location within the block with an automated micro-meteorological station.

Extended Radiation Effects

The effect of extended reductions in solar radiation on peppermint stem nitrate concentrations was tested using a randomized, complete block, split-plot design (Petersen, 1984, pp. 128-140) with radiation level as the main plot and time as the sub-plot. Four 9.0 m^2 plots were randomly located within six blocks all aligned on a transect paralleling the irrigation laterals. Three shade levels (47, 65, and 80 percent shade) were imposed by shade cloth suspended 15 to 45 cm above the crop canopy. Thirty stem samples were randomly selected from each plot once on the day prior to shading (July 14, 1997), and once daily for each of the following five days at approximately the same time of day.

Spatial Variability

The spatial variability of peppermint stem nitrate concentration over the field scale was evaluated on fields 1, 3, and 4 on July 24, 23, and 25, 1997 respectively. Fifty sampling points were located within a 2 ha area of each field using a sampling scheme designed to maximize the number of sample pairs over a wide range of separation distances. This strategy increases the accuracy of a geostatistical analysis (Clark, 1979; and Isaaks and Srivastava, 1989) which is based upon the change in sample variance as the separation distance between sampling points increases. The minimum and maximum lag distances were 1 m and 177 m respectively. Transects used in this sampling plan were aligned both parallel and perpendicular to irrigation laterals to capture the possible effects of anisotropic spatial variability. Figure 2.1 illustrates the sampling plan with the solid gridlines representing irrigation laterals and the dotted gridlines locating the sprinkler heads upon these laterals. The ten stems closest to each designated sampling point were collected for this analysis.

The data from day 0 of the shading experiment (July 14, 1997), prior to any treatment, were also analyzed for spatial variability. These data represented another method of sampling in that, 30 samples were collected over 9 m^2 plots instead of the point samples taken at the other three locations. Using the distance between plot centers, the minimum and maximum lag distances were 3 m and 335 m respectively.

The spatial variability of stem nitrate concentrations on the field scale was evaluated using both omni-directional and uni-directional semi-variograms. In the directional analyses, an angular tolerance of 15 degrees and a maximum bandwidth of 5 m was employed in two directions, 0 degrees and 90 degrees. The 0 degree analysis was aligned parallel, and the 90 degree analysis perpendicular, to irrigation laterals. The analysis of the shading plot data (Field 5) could only be performed in one direction since the plots were aligned on a linear transect paralleling irrigation laterals. The lag spacing and lag tolerances of all analyses were set to 2 m to capture the small-scale variability. The geostatistical software package, VARIOWIN 2.2 was used to construct the standardized semi-variograms (Pannatier, 1996).

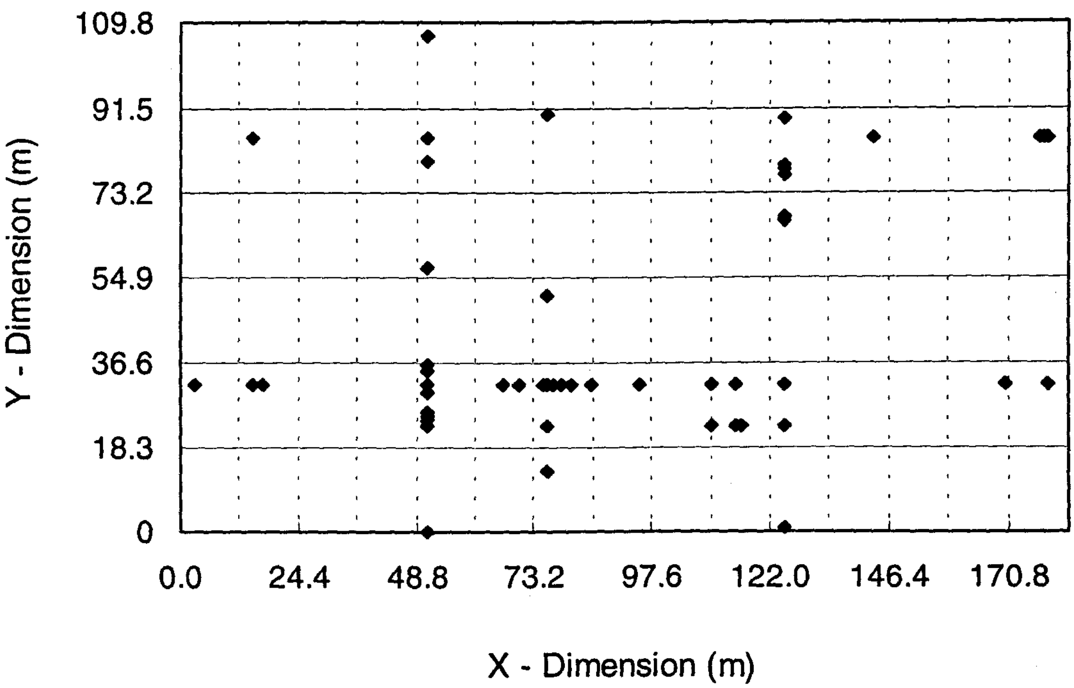

FIGURE 2.1. Location of sampling points for spatial variability analysis.

Nitrogen Fertilization Response

The recovery of peppermint stem nitrate concentrations after addition of soluble N was tested using a completely randomized design with time as the treatments. Four 9.0 m^2 plots were selected at random from blocks located on three separate fields under different management. All plots were sampled once immediately prior to N application (July 1, 1997) and then sampled once daily at the same time over the five following days. Rates of N application were determined from grower records (Table 2.1). The objective of this analysis was not to prove that significant differences exist between pre- and post-fertilizer times but rather to investigate the time taken for stem nitrate concentrations to respond to N application and reach a plateau value.

TABLE 2.1. Nitrogen application history for fields used in the N response study.

Field I.D.	N applied prior to experiment		Soluble N application on day 0 (lbs. N/acre)
	Dry (lbs. N/acre)	Liquid (lbs. N/acre)	
1	60	130	30
5	100	125	40
10	80	80	40

RESULTS AND DISCUSSION

Plant Material

The null hypothesis that the variances of stem classes were the same was rejected ($p < 0.05$) using Bartlett's test for homogeneity of variance (Bartlett, 1937) on the raw data. With a square root transformation (Little and Hills, 1978, p. 154) of the data however, the null hypothesis could be accepted. The square root transformed data were checked for normality by being plotted against the corresponding z-score and were found to be normally distributed ($r^2 = 1.00$) thus satisfying the second assumption of the analysis of variance (Devore, 1995, p. 394). The resulting completely randomized design analysis and mean separations were thus performed on the transformed data.

One of the most striking results of this study were the highly significant ($p = 3.55E-6$) differences in stem nitrate concentrations between stems of different characteristics (Table 2.2). The stem nitrate concentrations of class II and III stems were 440% and 430 % higher than those of class I stems respectively. Class II and III stems (described in methods) however were essentially identical and did not test significantly different ($p < 0.05$) using the least significant difference (LSD) (Petersen, 1994, p. 154).

Selection of different groups of stem classes clearly affected the variability within composite samples and the number of samples required to achieve a given error criteria. Analyzing different combinations of the three stem classes bulked together, class II and III stems produced a C.V. of 0.34 while a composite of class I, II, and III stems resulted in a C.V. of 0.63. Using a two-tailed t-statistic at the 95 percent confidence interval, the variance, and an allowable error of estimation (Petersen and Calvin, 1986), the required number of samples was estimated for each combination of stem classes (Figure 2.2). It was found that using equal proportions of class II and III stems as opposed to classes I, II, and III stems reduced the number of samples required to estimate the mean concentration within 15 percent of its true value ($p < 0.05$) from 99 to 28 stems. Thus, only by sampling class II and III stems exclusively will the previously recommended thirty stem composite sample (Brown, 1982b) bring the mean estimation within acceptable error

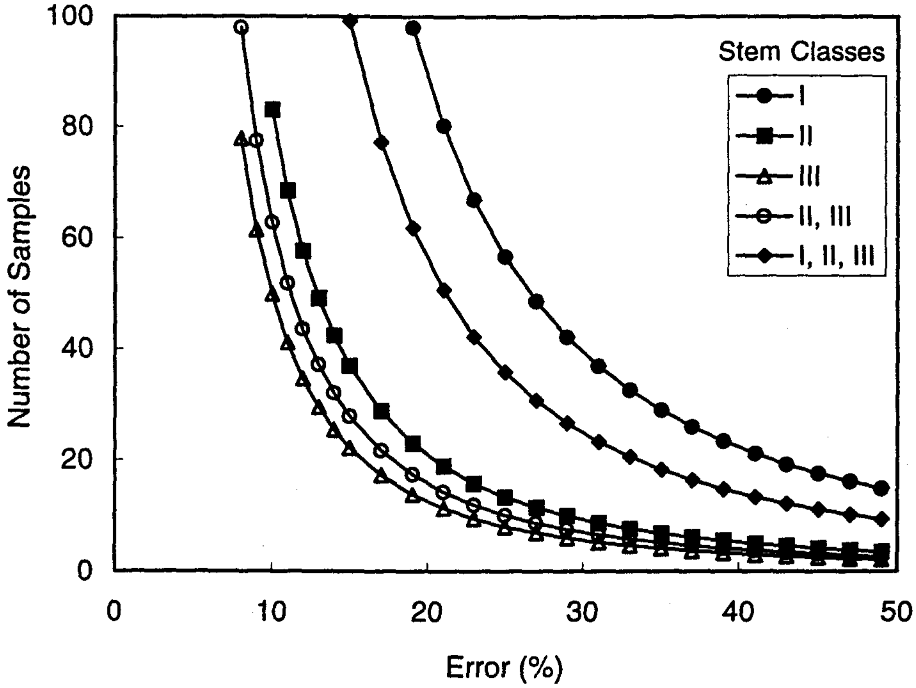

FIGURE 2.2. Number of samples required to estimate the mean within a given error ($p < 0.05$) for five combinations of stem material.

TABLE 2.2. Difference in stem nitrate-N concentrations (ppm) between three classes of plant material stratified according to inter-nodal spacing between the fifth and sixth leaf node.

	Stem Classes				
	I	II	III	II, III	I, II, III
Minimum	730	3730	3600	3600	730
Maximum	5800	13000	12000	13000	13000
Mean	2000 a	8900 b	8600 b	8735 b	6500 b
C.V.	0.80	0.39	0.30	0.34	0.63

[a] Means followed by the same letter are not significantly different at the 99 percent confidence interval.

limits. It should be noted that as the allowable error is reduced, the required number of samples increases drastically (Figure 2.2). Pursuing a sampling error below 10 to 15 percent appears impractical for routine field sampling and is not required for fertilizer management requirements.

Diurnal Radiation Effects

The influence of diurnal solar radiation patterns on peppermint stem nitrate concentration was measured on July 20, 1997 under clear skies (Figure 2.3). The variability in daily mean plot concentrations was so large that no significant differences were detectable ($p < 0.05$) from the raw data. As seen in Table 2.3, daily plot means ranged from a low of 2700 ppm to a high of 9800 ppm with an average C.V. between plots of 0.48. Within each plot however, the variability was rather low with the C.V. ranging between 0.09 and 0.20. This stability in stem nitrate concentration within plots implies that thirty stems were adequate to approximate the mean plot concentration over the 9 m^2 plot area.

Given the relatively stable concentrations within plots, all observations were normalized by dividing individual observations by the daily plot mean concentration for each respective plot (Figure 2.4). With the aid of this transformation, significant differences were detected ($p = 0.03$) between sampling times. Although the 06:00 hour and 15:00 hour samples were not significantly different from any other times, the 09:00 hour and the 12:00 hour samples were significantly different from both the 18:00 hour and 21:00 hour samples.

The observed trends in stem nitrate concentrations did not follow the expected response. Instead of an inverse relation between plant tissue nitrate and solar radiation, the peak stem nitrate concentration coincided approximately with the peak solar radiation. The maximum difference in normalized stem nitrate concentration was represented by a 17 percent decrease from the 12:00 to the 21:00 hour sampling.

When samples were collected, it was noted that the degree of wilting of stems and leaves prior to stripping of leaves and petioles changed dramatically throughout the day from virtually no wilting at 06:00 hours to a peak at the 12:00 hour sampling. It is not known to the authors if these observations provide an explanation or if there is any physical explanation for the observed response in stem nitrate concentrations.

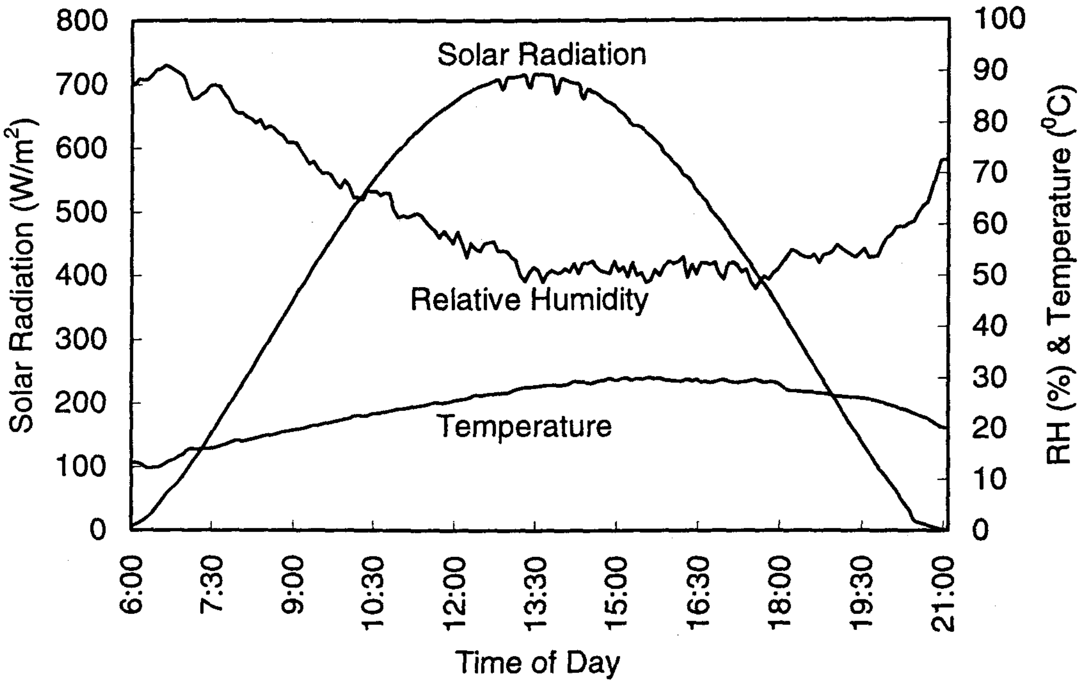

FIGURE 2.3. Meteorological variables measured during the diurnal variability study.

TABLE 2.3. Stem nitrate-N concentrations (ppm) across time of day and plot location.

	Time of Day							
Plot	6:00	9:00	12:00	15:00	18:00	21:00	Mean	C.V.
1	10000	10000	9600	8200	8200	8900	9300	0.11
2	9000	8700	10000	11000	9900	9700	9800	0.09
3	6800	6800	7100	6100	7000	6200	6700	0.06
4	5500	7800	7700	7000	6300	5900	6700	0.14
5	3500	3700	3200	3300	2000	2800	3100	0.20
6	2300	2800	3300	3000	2900	2100	2700	0.16
Mean	6200	6700	6900	6400	6000	5900		
C.V.	0.50	0.44	0.45	0.47	0.51	0.52		

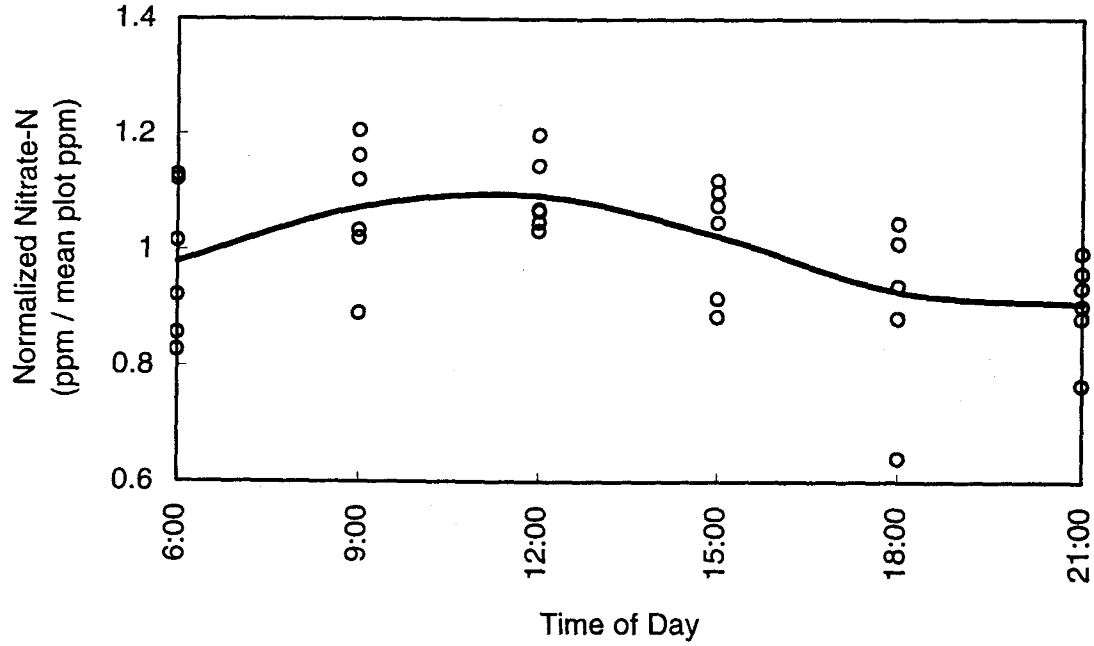

FIGURE 2.4. Diurnal variation in normalized stem nitrate-N concentrations.

Extended Radiation Effects

In this study, the shade/date interaction was not significant ($p < 0.01$) but the effects of shade treatments and time since the treatments were imposed on stem nitrate concentrations did test significant ($p < 0.01$)[1]. A linear contrasts of totals (Petersen, 1994, pp. 102-109) was used to test for differences between the four shade treatments across all dates. Using these contrasts, the 47 and 80 percent shade treatments were significantly different than the control at the 99 percent confidence interval and the 65 percent shade treatment was significantly different at the 95 percent confidence interval (Figure 2.5 A). Although the 47, 65, and 80 percent shade treatments were all significantly different from each other ($p < 0.01$), the shade responses appeared very similar. This can be seen more clearly when the data is normalized by dividing through by the respective treatments' mean concentration on day zero (Figure 2.5 B). This transformation starts all plots at the same concentration so changes in time can be more easily compared. Using these transformed data, the maximum increase in stem nitrate concentration over the control was 24 percent for the 80 percent shade treatment after five days of shading. The increase in concentration of shade treatments over the control for each data was analyzed using the least significant increase (LSI) (Petersen, 1994, p. 155) ($p < 0.01$) on the raw data. With this analysis, the 47 and 80 percent treatments began showing significant increases over the control beginning the third day of treatment and continuing throughout the fifth day (Table 2.4).

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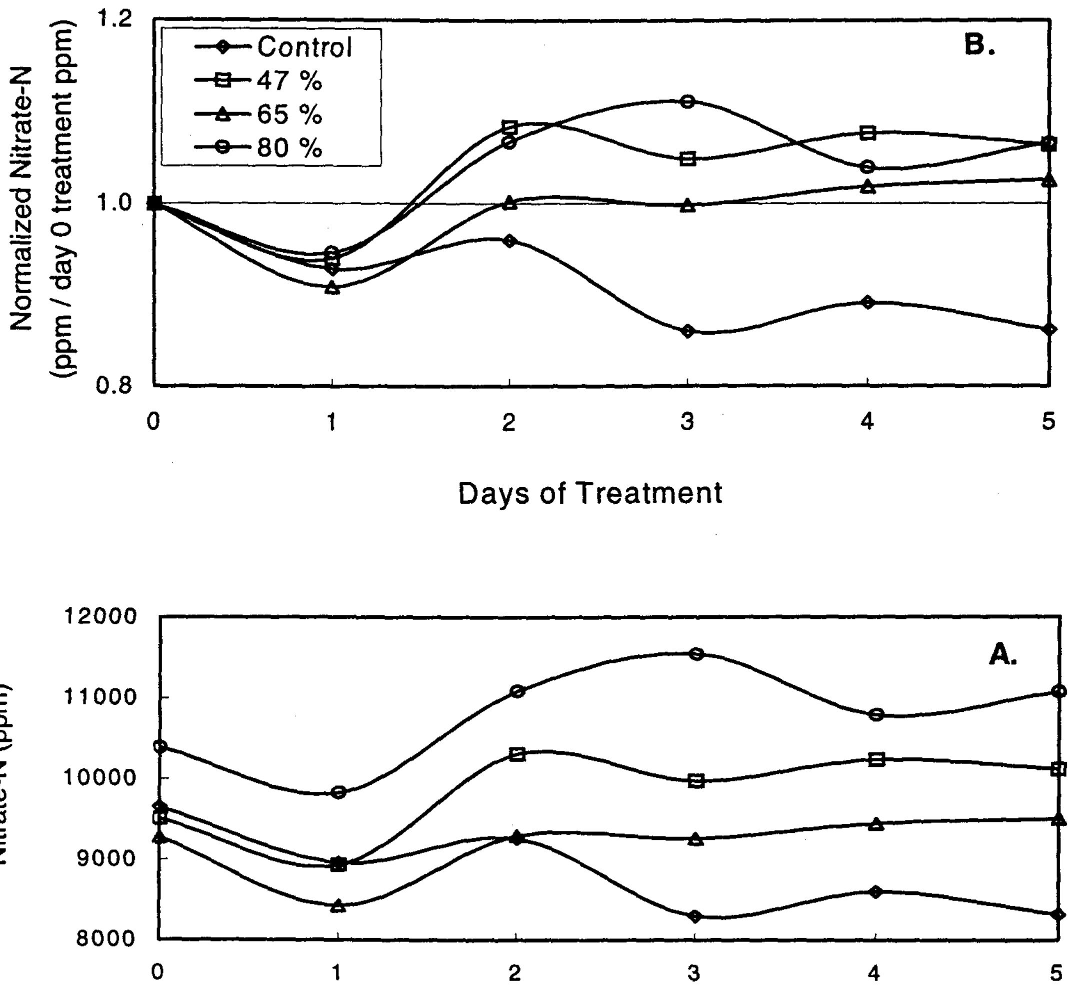
[1] Where actual p-values were not available, threshold values are reported.



FIGURES 2.5 A & 2.5 B. Response of stem nitrate-N concentrations to five days of shade treatment. A. Raw Data. B. Data normalized by the respective treatment mean on day 0.

TABLE 2.4. Effect of shading on stem nitrate-N concentrations (ppm).

	Shade			
Date	0	47	65	80
14-Jul	9600	9500	9300	10400
15-Jul	9000	8900	8400	9800
16-Jul	9300	10300	9300	11100
17-Jul	8300	10000 a	9300	11500 a
18-Jul	8600	10200 a	9400	10800 a
19-Jul	8300	10100 a	9500	11100 a

[a] LSI at the 95 percent confidence interval = 1602
[b]Means followed by a letter are significantly different from the control at the 95 percent confidence level.

Spatial Variability

The standardized semi-variograms suggest that the nugget effect (Isaaks and Srivastava, 1989, p. 143) dominated on all fields (Figure 2.6). No discernable range could be extracted from any of the plots and the directional analyses did not display any more structure than the omni-directional analyses. Fields 1, 3, and 5 were very similar with a nearly constant semi-variance over all lag distances. Field 4 did show an increase in the semi-variance with lag distance for the omni-directional and 0 degree analyses. The two sill values at standardized semi-variance values of approximately 1.0 and 1.5 however are more indicative of a bimodal distribution than of an increasing semi-variance within the range of auto-correlation. It was noted while sampling this field that a significant area within the stand was infected with *Verticillium dahliae* which may explain the bimodal distribution.

The nugget effect is indicative of sampling error or high short-range variability. As discussed in the plant material results, stems of different characteristics can maintain very different nitrate concentrations. As there was no effort to collect a certain class of stem material, the possibility remains that short-range variability produced by sampling different stem material may have obscured a range of autocorrelation. The lack of spatial structure from the shade plot data on day 0 (Field 5) however, provides confidence that the sampling error was not great enough to produce this effect. Each composite sample in this experiment consisted of thirty stems collected over a 9 m^2 plot which considerably reduced the field scale variability as compared to Fields 1, 3, and 4 that were sampled using ten stem, point estimates (Table 2.5). As evidenced by the diurnal radiation response data, thirty stems collected over a 9 m^2 plot was sufficient to provide an accurate estimate of the plot mean. If a true spatial structure were present, regardless of the variability between stem classes, it should have been evident in the spatial analysis of Field 5 (Figure 2.6).

TABLE 2.5. Stem nitrate-N concentrations (ppm) from fields included in the spatial variability analysis.

	Field Number			
	1	3	4	5
Minimum	1800	1900	2700	6600
Maximum	12000	13000	13000	13000
Mean	6700	6800	7500	9700
C.V.	0.41	0.44	0.37	0.19

The data taken for these analyses were collected over somewhat limited conditions and thus the application is constrained to the same degree. The time frame considered was relatively narrow with samples collected between July 14 and 25. At this point in the season, dry matter accumulation and N uptake rates have passed their peak rates and are on the decline (Hart, 1995). Field averaged stem nitrate concentrations were also much

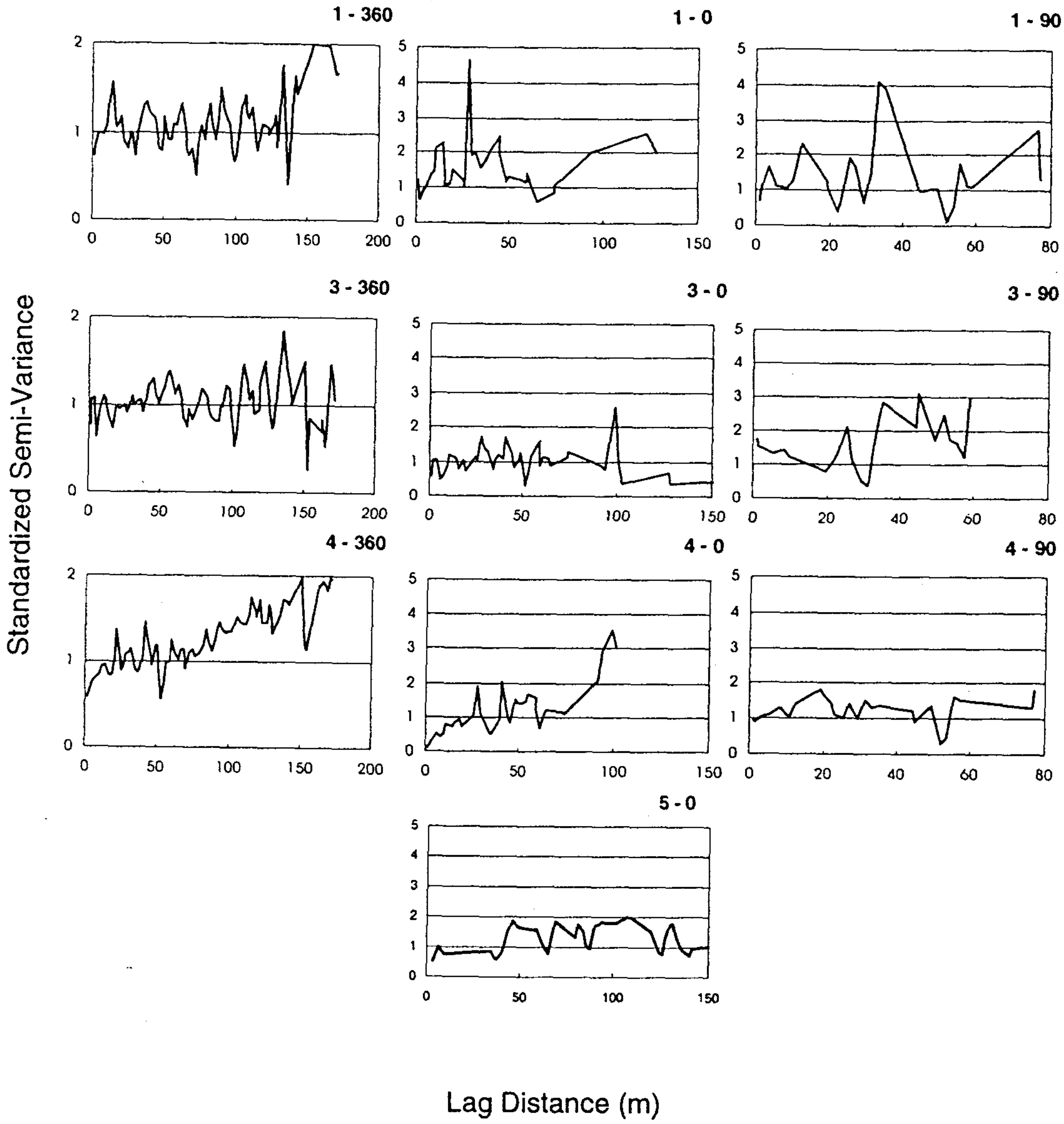


FIGURE 2.6. Standardized semi-variograms for fields 1, 3, 4, and 5 (shade plots) using omni-directional pairs (360), pairs aligned along the x-axis (0), and pairs aligned along the y-axis (90). On Field 5, the only pairs available were aligned along a single transect.

higher than the critical deficiency content (CDC) (Marschner, 1995, p. 465) on fields 1, 3, 4, and 5 at 6690, 6810, 7480, and 9702 ppm respectively. Brown (1982a) estimated the CDC for peppermint stem nitrate to be approximately 2600 ppm at July 14 and 1850 ppm at July 24 corresponding to the dates for field 5 and fields 1, 3, and 4 respectively.

Nitrogen Fertilization Response

The response of stem nitrate concentrations to soluble N applications was relatively weak. In fields 1 and 5, stem nitrate concentrations were lower over the five days following N application than they had been prior to fertilization (Figure 2.7). Field 10, which had the lowest pre-fertilization stem nitrate levels, did however show a slight increase in stem nitrate concentration. The pre-fertilization stem nitrate concentration on this field (Field No. 10) was 6002 ppm as opposed to the 9483 ppm of Field No. 1 and the 11283 ppm of Field No. 5. Brown (1982a) estimated the CDC for peppermint stem nitrate to be approximately 4400 ppm at July 1 when these experimental plots were fertilized. In other studies investigating mid-season petiole nitrate in potatoes (Rosen et al., 1995) and stem nitrate in peppermint (Mitchell et al., 1995), mid-season N applications rarely increased tissue nitrate levels when pre-fertilization concentrations were above the CDC. This may well be the cause of the limited N responses observed here.

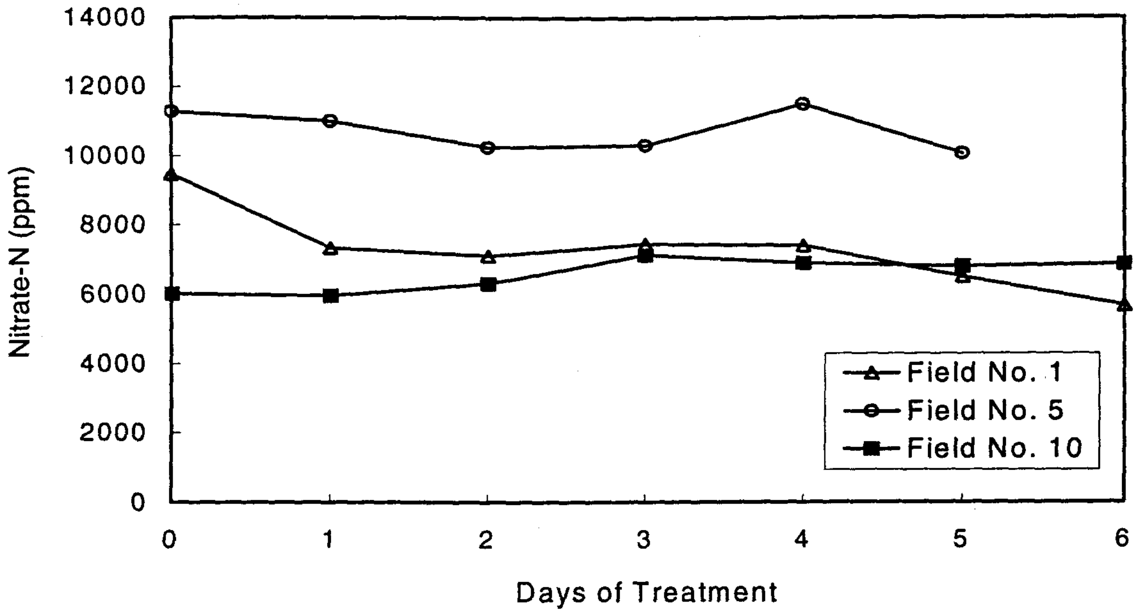


FIGURE 2.7. Response of stem nitrate-N to liquid N application over three fields.

CONCLUSIONS

As a result of the wide variation in stem nitrate concentrations between stems of different characteristics, the protocol for peppermint stem sample collection should be redefined to account for this factor. In particular, stems standing erect above the canopy should be avoided and sampling concentrated on stems within the canopy. Since there was no significant difference ($p < 0.05$) between stems of different inter-nodal spacing within the canopy, no particular attention need be given to selecting a certain stem type here. When this strategy is adhered to, a sample size of thirty stems should be adequate to estimate the mean within 10 to 15 percent of its true value ($p < 0.05$) over a relatively homogeneous stand of peppermint. Where soils or the overall stand change dramatically, it is wise to stratify the sampling with thirty stems being collected independently from each region.

Variations in solar radiation on both hourly and day length scales produced significant, but not dramatic, differences in stem nitrate concentrations. When measuring the diurnal response, a 17 percent reduction in stem nitrate concentration was observed over a nine-hour period from 12:00 hours to 21:00 hours. On the day length scale, the influence of an 80 percent reduction in incoming solar radiation produced a 29 percent increase in stem nitrate concentrations after three days of shading. Although these two influences are relatively small in comparison to the stem material selected, they suggest that consistency in these factors should be pursued, and reporting test conditions with respect to these factors will be important in the comparison of studies of stem concentration. When possible, samples from any given field should be taken at approximately the same time for each sampling event. With regard to shading by cloud cover, these effects may be impossible to avoid but should be recorded. When interpreting test results where sampling has been affected by prolonged shading, the potential increase in stem nitrate concentrations should be considered.

In the analysis of stem nitrate spatial variability, no discernable range of autocorrelation was detected indicating a random distribution of stem nitrate concentrations on the field scale. This suggests that it is not important that samples collected for this test fully cover the field being assessed, despite the intuitive appeal to do so. The sampling for these analyses was limited to the late season (July 14 to 25, 1997) with all fields exhibiting stem N concentrations well in excess of the CDC, thus applications of these conclusions should not be extended to significantly different conditions.

It appears from data presented here and from previous research that the stem nitrate response to soluble N application is minimal when initial nitrate concentrations are above the CDC. Since our data did not investigate the response in the deficient range, it is still unknown exactly how stem nitrate concentrations respond to soluble N applications under these conditions.

This effort was intended to be a screening study, with the main focus being to determine which factors influencing peppermint stem nitrate concentrations must be considered in a sampling strategy. Several influences were identified and their associated effects quantified. Most importantly, these results indicate the need for researchers to fully report the method of sampling employed when presenting finding for stem tissue tests.

Some factors influencing stem nitrate concentrations will need further investigation before firm conclusions can be made. This research should include: i) an investigation of stem nitrate response to soluble N applications under N deficient conditions; ii) an analysis of spatial variability in stem nitrate throughout the growing season and especially under N deficient conditions; and iii) a validation of the actual CDC throughout the growing season.

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Chapter 3

Post-Harvest Water Requirements of Peppermint (*Mentha piperita var.*)

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ABSTRACT

Peppermint (*Mentha piperita var.*) is a perennial field crop that is commonly irrigated following harvest to promote fall re-growth. A field study was conducted to measure the consumptive use of peppermint in the post-harvest period and to develop crop coefficients used to predict evapotranspiration rates. The soil water balance was measured on two fields with a neutron probe during an 80 day period from July 29, 1997 to October 17, 1997. Over the 49 days following harvest, a total consumptive use of 96 mm was measured. Basal crop coefficients increased from approximately zero to 0.40 within 40 days following harvest.

INTRODUCTION

Peppermint (*Mentha piperita var.*) is a high value, irrigated field crop grown for its leaves and oil with approximately 150,000 acres of production nationwide. As a perennial crop, peppermint can be grown for several years within one rotation. Harvest generally occurs in late July to early August in the Pacific Northwest (PNW) and is timed according to the 50% bloom stage for oil production (Jackson and Hee, 1972). Following harvest, propane flaming is commonly used to burn the remaining crop matter (i.e. stems, rhizomes, and uncollected leaves) for control of *Verticillium dahliae*, a fungal disease infecting the crop (Crowe, 1995). In the period between harvest and winter dormancy (August through mid-October), the PNW climate is warm and dry, making post-harvest irrigation of peppermint critical. Although several estimates exist for the consumptive use (CU) of water by peppermint during the pre-harvest period (Mitchell, 1997; AgriMet, 1994; and Cuenca, 1992), none of these account for CU during the post-harvest period.

Mitchell (1994) investigated the effects of post-harvest water management on peppermint oil yield in the growing season following irrigation treatments. Thirty and seventeen percent reductions in yield were observed with the no irrigation and monthly irrigation treatments respectively when compared to weekly irrigation. While reinforcing the need for post-harvest irrigation, the study did not investigate the level of crop water demand during this period.

Without published estimates of the CU, post-harvest irrigation scheduling for peppermint is restricted to a trial and error approach for the grower. Many growers continue irrigation at the same rate as pre-harvest levels for several weeks following harvest. It is clear that in going from a full transpiring canopy to a relatively bare soil surface, water requirements will decrease, which should be reflected by a reduction in applied irrigation. The costs of over irrigation go beyond the direct costs of water and power and can include increased crop disease problems and the loss of critical plant nutrients from the root zone into underlying aquifers susceptible to contamination. With the intent of providing a firm basis for scheduling the irrigation of peppermint following harvest, the objectives of this research were to: i) measure the CU of peppermint in the re-growth period following harvest; and ii) develop crop coefficients for the CU of post-harvest peppermint.

METHODS AND MATERIALS

This experiment was conducted on two commercial peppermint fields located in Lane County, OR. Site 1 soils were coarse loamy, mixed, mesic fluventic Haploxerolls. '*Black Mitcham*' peppermint was planted to this field in 1990 and was irrigated using hand set sprinkler irrigation. Site 2 soils were fine, mixed, mesic Pachic Ultic Argixerolls. On this field, '*Murray Mitcham*' peppermint was planted in 1995 and was irrigated with side roll sprinkler irrigation. Soil water content measurements at both locations began prior to harvest on July 29, 1997 and were continued through October 17, 1997. Within one day prior to cutting, the first post-harvest soil water content measurements were taken and the crop hand cut in 2.0 m radius circles around each tube. The cutting date was August 7, 1997 (DOY 219) on site 1 and August 4, 1997 (DOY 216) on site 2

Soil water content was monitored with a Campbell Pacific Nuclear 503DR (Martinez, CA) neutron probe at six locations over each field. Aluminum access tubes (5.08 cm i.d.) were installed to a depth of 140 cm and were aligned in transects parallel to irrigation laterals to ensure uniform irrigation treatments over all tubes. Separate calibration equations were developed for each site using paired volumetric soil water content observations and neutron count ratios. Prior to measurements at each location, a series of 32, 8 s counts were taken on a standard absorber to obtain the standard neutron count used in the count ratio. Two 64 s counts were then taken at ten depths (5, 15, 25, 35, 45, 55, 65, 85, 105, 125 cm). Immediately following these readings, two soil cores 10 cm in length and 3 cm in diameter were obtained within 50 cm of access tube for each reading depth from 25 to 125 cm. Gravimetric soil water content of the soil was determined by drying at 105^0 C for 24 hr and volumetric water content calculated using an average wet bulk density from each distinct soil horizon at each access tube. Wet bulk density estimations were obtained from an intact core, 3 cm in length and 5.38 cm in diameter, collected within 50 cm of each tube. For routine soil water content measurements, two 32 s counts were taken at each depth following the work of Williams and Sinclair (1981), which suggested that counting times longer than 30 s are unlikely to increase accuracy significantly. Soil water content measurements were taken on all six access tubes at least once during each irrigation interval at each site to allow for the observation of possible water drainage below the effective rooting depth.

Calibration equations were developed for both sites using the unbiased statistical treatment of Haverkamp et al. (1984) with volumetric soil water content regressed against neutron probe count ratios. This approach was taken to minimize the calibration error, which was shown to be the most significant error component in soil water content estimation using the neutron method when adequate replication was provided (Williams and Sinclair, 1981). On site 1, a wide range of soil water content (approximately 0.20 to 0.55 volumetric) was available for use in calibration and good correlation ($r^2 = 0.92$) was obtained. The soil remained very moist on site 2 however, and only a narrow range of soil water content (approximately 0.50 to 0.55 volumetric) was available for calibration, resulting in a lower correlation coefficient ($r^2 = 0.65$). The resulting calibration equations were used to estimate the volumetric soil water content from neutron probe count ratios taken between 15 and 125 cm. When neutron counts are taken at depths shallower than 15 cm, neutron escapement out of the soil column artificially lowers the estimation of soil water content (Grant, 1975) and correction equations must be employed. Using the equations developed by Parkes and Siam (1979), a correction factor for neutron escapement was iteratively applied to count ratios from the 5 cm depth. Due to the error encountered with surface (0 cm depth) measurements, soil water content at the soil surface was estimated by linear interpolation back to 0 cm from the 5 and 15 cm depth readings.

Two methods were investigated for the determination of the lower depth limit of plant-water extraction. Soil water retention was first measured (Klute, 1986) on intact cores taken from each horizon at each access tube. These data were then fit to the van Genuchten (1980) soil water retention model with the Mualem (1976) constraint using the RETC code (van Genuchten et al., 1991). Inverting the van Genuchten model with the measured retention characteristics, total soil water pressure potential profiles were constructed from soil water content measurements for each sampling event. From these data, the zero-flux plane (ZFP) was investigated, which is the depth where all soil water movement above is upward as plant extraction and surface evaporation and all movement below is downward as drainage (Kirsch, 1993; and Arya et al., 1975; and Richards et al., 1956). The ZFP is typically located at the position where $dH/dz = 0$ with the total potential, H, approaching more negative values both above and below, where z is the soil depth. Although theoretically attractive, this method was not practical for the strongly stratified alluvial soils used in this study. As can be seen in Figure 3.1 (tube 12, site 1), three depths could have been chosen as the ZFP using these criteria. This is partially due to the use of three sets of soil water retention parameters, which creates artificial gradients in H between depths where different sets of parameters were used. Due to these difficulties, the ZFP was chosen to be the depth at which soil water content varied the

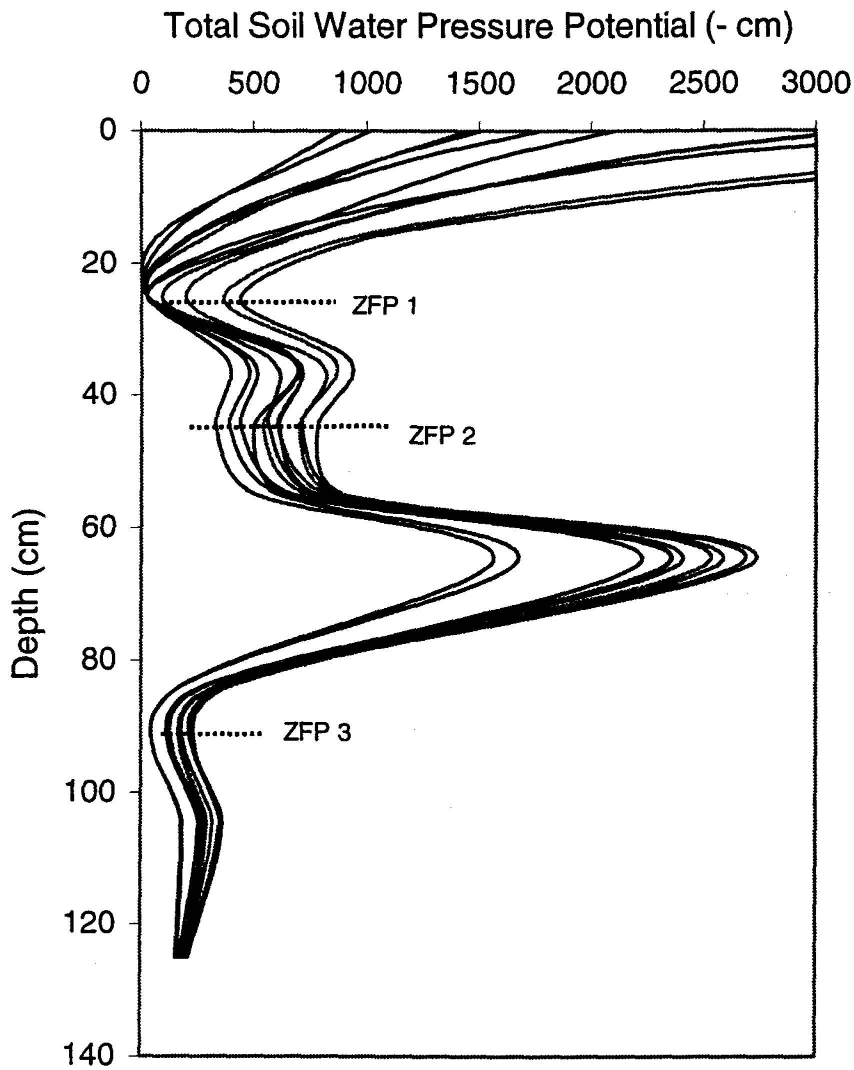
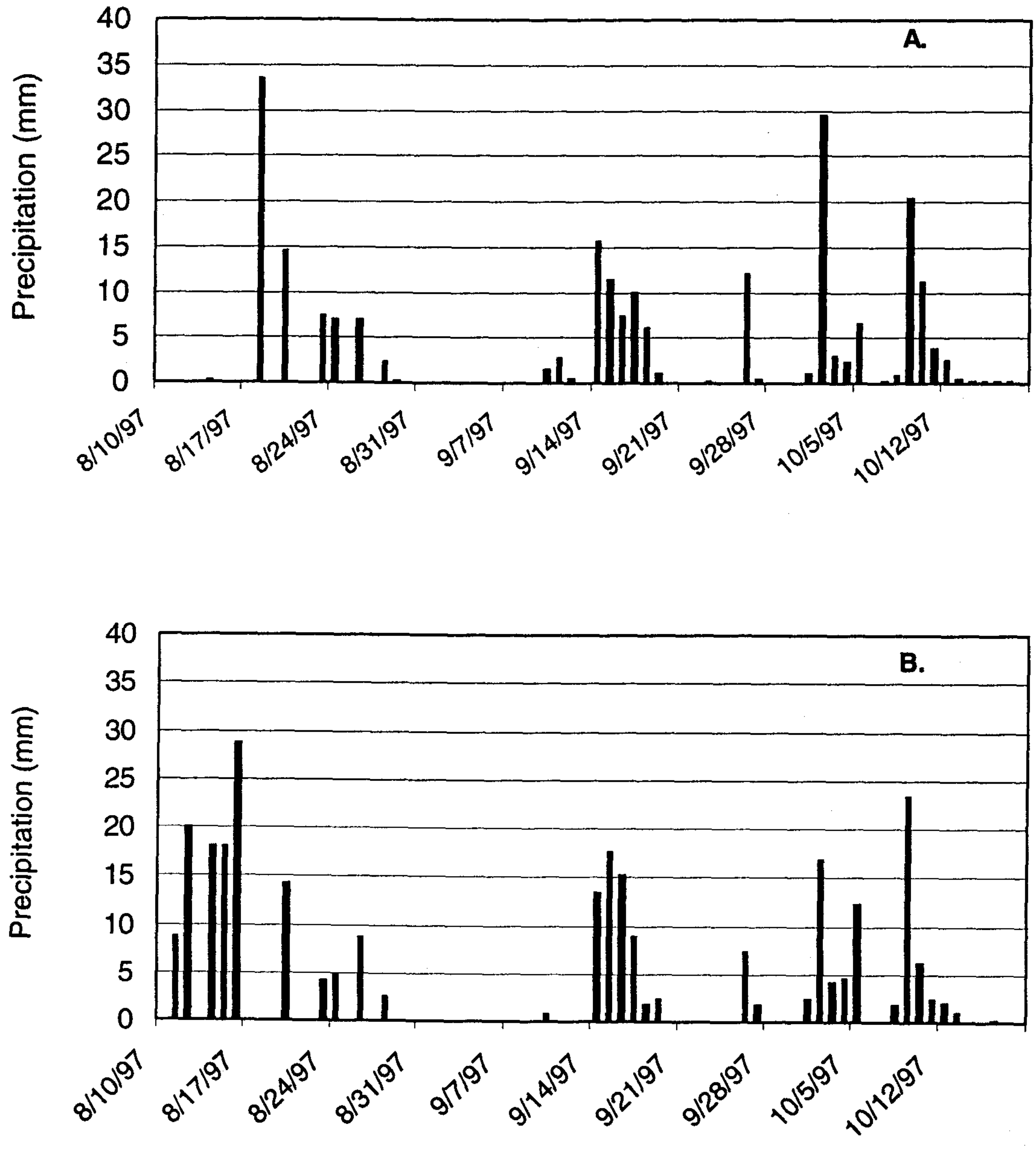


FIGURE 3.1. Total soil water pressure potential profiles and potential zero flux planes (ZFP) from Tube 12 on Site 1.

least over the period between DOY 210 and 266. The maximum variation in volumetric soil water content at any given ZFP across all twelve tubes was 0.03. Given this relatively static water content, the flux of water past the ZFP would have been essentially constant both entering into and leaving the specified depth interval, which is unlikely. Furthermore, on the last two sampling dates, which occurred after significant precipitation events (Figure 3.2), the water content at the ZFP increased dramatically (Figure 3.3) indicating drainage and hence the ability to detect drainage. Data taken on



FIGURES 3.2 A. and 3.2 B. Precipitation and irrigation recorded by tipping bucket rain gauges on site 1 (A) and site 2 (B).

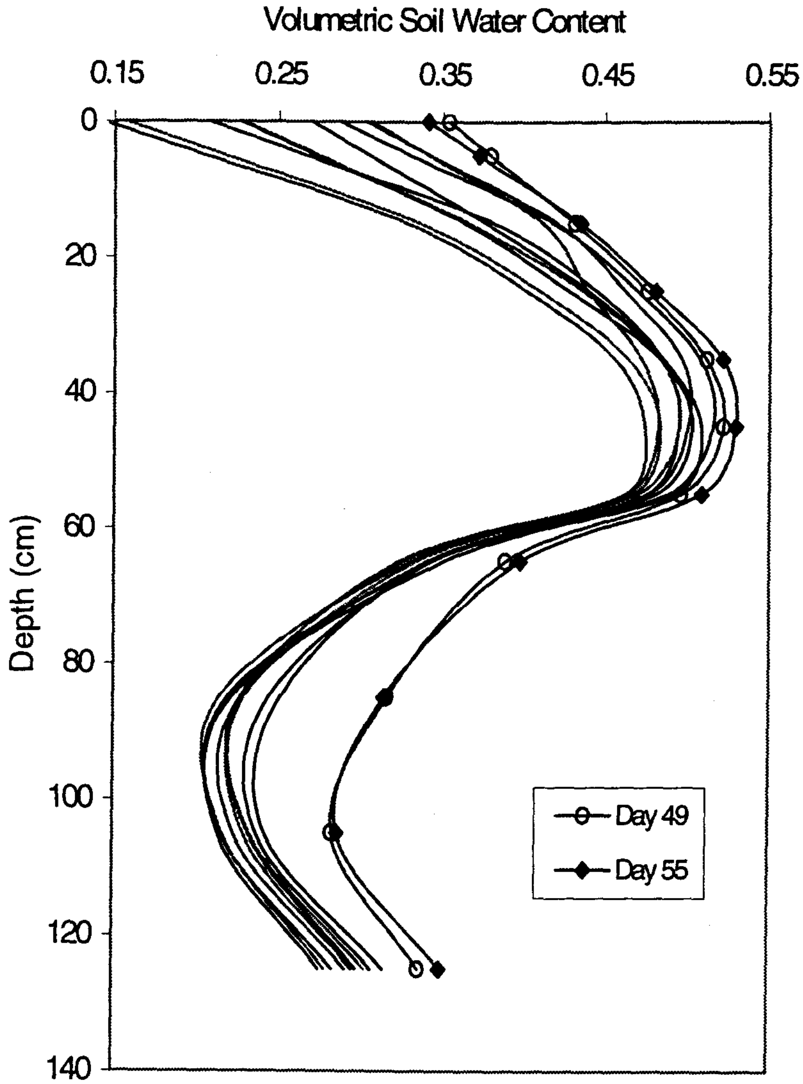


FIGURE 3.3. Volumetric soil water content profiles indicating drainage on days 49 and 55 from Tube 12 on Site 1.

DOY 286 and 290 from site A and DOY 280 and 290 from site B were excluded from the data set due to this drainage.

Setting the ZFP as the bottom of the plant extraction reservoir, a simple water balance was employed as follows

$$ET = \frac{1}{dt}(P - \Delta S) \qquad (1)$$

$$\Delta S = \int_{ZFP}^{0} (\theta_t - \theta_{t+1}) dz \qquad (2)$$

where *ET* is the rate of evapotranspiration or consumptive use, *dt* is the time interval between measurements, *P* is precipitation, ΔS is the change in soil water storage in units of depth, θ represents volumetric soil water content, and *dz* is the depth interval over which the integration is performed. The soil water content above the ZFP was determined by fitting a cubic spline to the soil water content profile and integrating between successive samplings using *Simpson's* rule (Press et al., 1992) as suggested by Haverkamp et al. (1984) to minimize the estimation error. Precipitation and irrigation were measured between neutron probe readings with 10 cm diameter rain gauges inserted into each of the access tubes. One continuously recording, tipping bucket rain gauge was also used at each site to monitor the timing of irrigation and precipitation events.

Reference evapotranspiration (ET_r) values used were obtained from the automated U.S. Bureau of Reclamations' AgriMet weather station in Corvallis, OR located 20 to 30 km from the study sites. This ET_r is calculated using the 1982 *Kimberly-Penman* method (Wright, 1982 and Dockter, 1994). Crop coefficients (K_c) were calculated as follows

$$K_c = \frac{ET}{ET_r} \qquad (3)$$

with the measured ET and estimated ET_R values being averaged over the measurement interval. These crop coefficients represent water use under the specific conditions of surface soil water content present during measurement. In order to generalize the measured data to other soil water content conditions, a basal crop coefficient is required, which represents crop water use when the soil water content is sufficient to sustain maximum transpiration but the soil surface is dry enough so that evaporation is minimal. Wright (1981) proposed an expression for the measured crop coefficient, K_c, as a function of the basal crop coefficient, K_{cb}, when the soil surface is wet where

$$K_c = K_{cb} + (1 - K_{cb})[1 - \left(\frac{t}{t_d}\right)^{1/2}](f_w) \qquad (4)$$

where $t < t_p$

and where t is the number of days since a significant irrigation or precipitation event, t_d is the approximate number of days taken for the soil surface to dry, and f_w is the relative proportion of the soil surface wetted by irrigation or precipitation. In this analysis, Kcb was derived using the *Newton-Raphson* method (Press et al., 1992) on daily time steps and was averaged over the measurement interval. With both sites being relatively uniformly irrigated, f_w was taken as 1.0. The estimated times required for the soil surface to dry were taken as 4 days for the silt loam soils of site 1 and as 6 days for the silty clay loam soils of site 2. Significant irrigation or precipitation was evaluated based upon a minimum depth requirement of 1.0 mm over a one day period. Although another correction can be applied for limiting soil water conditions, the soil water content remained fairly high over the measurement period and was not assumed to limit plant transpiration.

RESULTS AND DISCUSSION

Over the 49-day period following harvest, the cumulative CU estimated for peppermint on site 1was 96 mm with the cumulative reference CU being 240 mm (Figure 3.4). ET rate estimates from site 2 exceeded the ET_p during certain periods of the observation period (Table 3.1). These high estimates occurred only over measurement intervals where significant precipitation or irrigation was recorded. Due to the extremely low intake rates of this soil and observation of runoff during irrigation, it is believed that the elevated estimates were caused by surface runoff, which was neglected in the water

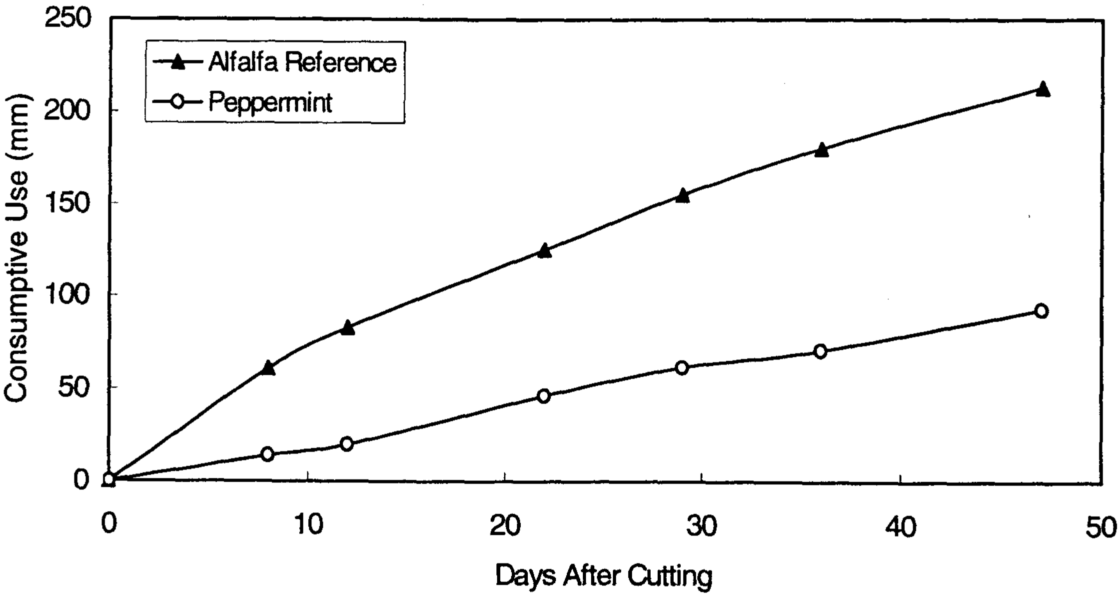


FIGURE 3.4. Cumulative consumptive use by the alfalfa reference as estimated by AgriMet (USBR) and post-harvest peppermint on site 1.

TABLE 3.1. Water balance summary.

Site	DOY	DAH	Precipitation/ Irrigation (mm)	ET (mm/d)	CV	ET_r (mm/d)	K_c	K_{cb}
1	222	3	0.3	1.76	0.44	7.64	0.23	0.16
	229	10	33.5	1.43	0.43	5.49	0.26	0.13
	236	17	38.1	2.66	0.16	4.25	0.63	0.37
	244.5	25.5	0.0	2.18	0.22	4.29	0.51	0.50
	251.5	32.5	4.8	1.32	0.21	3.58	0.37	0.26
	260.5	41.5	52.1	2.00	0.40	2.97	0.67	0.46
2	218	2	0.0	1.41	0.29	7.44	0.19	0.06
	223	7	37.0	5.23	0.13	8.13	0.64	*
	226	10	28.7	9.81	0.13	6.43	1.52	*
	228.5	12.5	36.1	11.59	0.17	5.33	2.17	*
	235.5	19.5	28.7	3.02	0.09	4.25	0.71	*
	244.5	28.5	0.0	1.74	0.16	4.29	0.41	0.22
	251.5	35.5	0.8	0.94	0.20	3.58	0.26	0.26
	260.5	44.5	59.2	4.27	0.05	2.97	1.44	*

DOY - day of year in the middle of the measurement interval
DAH - days after harvest
CV - coefficient of variation between ET estimates obtained from the six access tubes on each site
* - crop coefficient estimates followed by an asterisk were discarded due to uncertainty from potential runoff

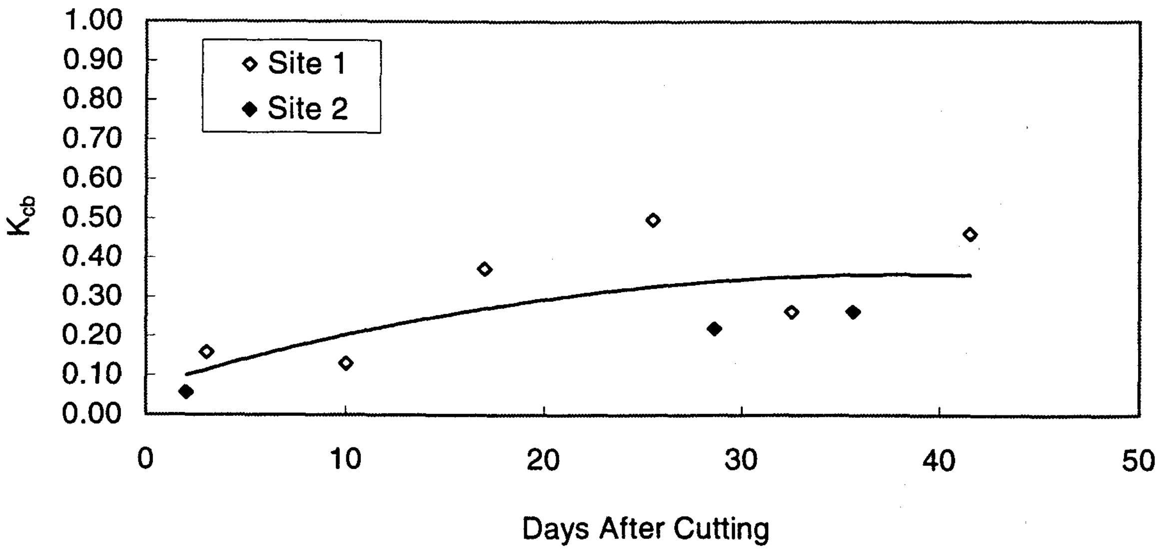


FIGURE 3.5. Crop coefficient (K_{cb}) estimates for post-harvest peppermint.

balance procedure, and therefore were not included in the analysis. Over intervals where little to no rain was observed (DAH 7, 35.5, and 44.5 in Table 3.1), ET estimates fell into similar ranges as those observed on site 1 and were not subject to uncertainty due to potential runoff.

The combined K_{cb} estimates from site 1 and from site 2, where no significant precipitation was recorded, show an increase in K_{cb} from near zero to a maximum of approximately 0.40 over the first 40 days following harvest (Figure 3.5). A second order quadratic model was fit to the data using a least squares techniques resulting in the following equation

$$K_{cb} = -0.0002t^2 + 0.0152t + 0.0702 \quad (5)$$

where t is the number of days elapsed since cutting. It is important to note that it is not recommended that the above equation be used to predict K_{cb} beyond 38 days post-harvest since estimates will decline from the maximum value of 0.36.

Given the finding presented here, growers are presented with crop water use estimates that may allow significant reductions in post-harvest irrigation levels. When these crop coefficients are used for irrigation scheduling, instead of full irrigation at pre-harvest levels (0.90 ET_r), an estimated 175 mm of water over the 60 day period following harvest can be saved and the nutrient loss associated with excess irrigation can be avoided. Although the proposed crop coefficient estimates represent a limited data set, the results appear reasonable. More precise estimates could be obtained through experiments on more fields and over many growing seasons. However, such experiments are unlikely to occur due to the cost relative to the narrow audience for these data.

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Chapter 4

Influences of Irrigation Uniformity on the Effective Adequacy of Chemigation

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ABSTRACT

All irrigation systems apply water non-uniformly, often causing losses of water and soluble nutrients. In this analysis, the effective adequacy of chemical application as influenced by the uniformity of irrigation is investigated with a simple heuristic statistical model. An expression is also presented whereby irrigation distribution parameters, based on a Gaussian model, can be derived from common irrigation design terms. The results of this model indicate that the effective chemical adequacy is greatly compromised when the irrigation uniformity coefficient is low and/or the design irrigation adequacy is high.

INTRODUCTION

Chemigation is a common method used for the application of agricultural chemicals. This practice is characterized by chemical injection into the irrigation system during operation, which distributes both water and chemical over the irrigated surface. It is a relatively inexpensive and effective means of applying chemicals, especially where aerial application is the only alternative. However, there are several risks associated with this practice that must be recognized. Without proper anti-siphon equipment, chemicals can be drawn back into the water supply upon pump shutdown. There is also the risk of non-target application through system leakage, surface water interception, or wind-drift. Beyond these obvious hazards is the issue of application non-uniformity, a problem that cannot be solved but can only be abated.

The uniformity of chemical application using chemigation generally follows that of the irrigation uniformity, which varies widely in agricultural sprinkler systems. Since totally uniform irrigation is unattainable, water is applied in excess in some areas of fields and in deficit in others. To minimize the area receiving deficit irrigation, the common field practice is to apply excess water over the majority of the irrigated area. The over-irrigated area is described by the irrigation adequacy, or the fractional area over which irrigation equals or exceeds the net irrigation requirement. Recommended levels of adequacy are 90, 75, and 50 percent for specialty or high value, field, and orchard crops respectively (Cuenca, 1989). These target adequacy levels represent a balance between the costs of irrigation and the increased revenue from crop yield for an incremental increase in irrigation. Figure 4.1 illustrates the combined adequacy/uniformity relation for water application with an adequacy level of 90 percent and a Hawaiian Sugar Planter's Uniformity Coefficient (UC_H) of 80 percent. In this figure, i_n is the net irrigation depth requirement, i_m is the mean applied irrigation depth (set to a value of 1.0), and i is the irrigation depth applied at some probability level, $F(i)$, scaled by i_m.

Chemical injection rates are commonly calculated using aerial averaged irrigation rates (Trimmer et al., 1992; SCS Staff, 1983). This approach gives rise to a design chemical adequacy level of 50 percent where the mass of chemical is applied in excess over half of the area and is applied in deficit over the remaining half. Figure 4.2 displays this relation for the same level of uniformity as in Figure 4.1 where C_n is the net chemical mass application requirement, C_m is the mean chemical mass application (set to a value of 1.0), and C is the chemical mass application applied at some probability level, $F(C)$, scaled by C_m. Since one design adequacy level may be used for the chemical and another for water, three cases arise:

Case I: Water is applied in deficit and the chemical is applied in deficit.

Case II: Water is applied in excess and the chemical is applied in deficit.

Case III: Water is applied in excess and the chemical is applied in excess.

The fractional irrigated areas subject to each of these cases are defined as (Figure 4.3):

Area I: $1 - \alpha$

Area II: $\alpha - 0.50$

Area III: 0.50

where α is the irrigation adequacy. A case where the chemical is applied in excess with the irrigation being applied in deficit can only occur when the chemical adequacy is greater than the irrigation adequacy, which is not a standard practice.

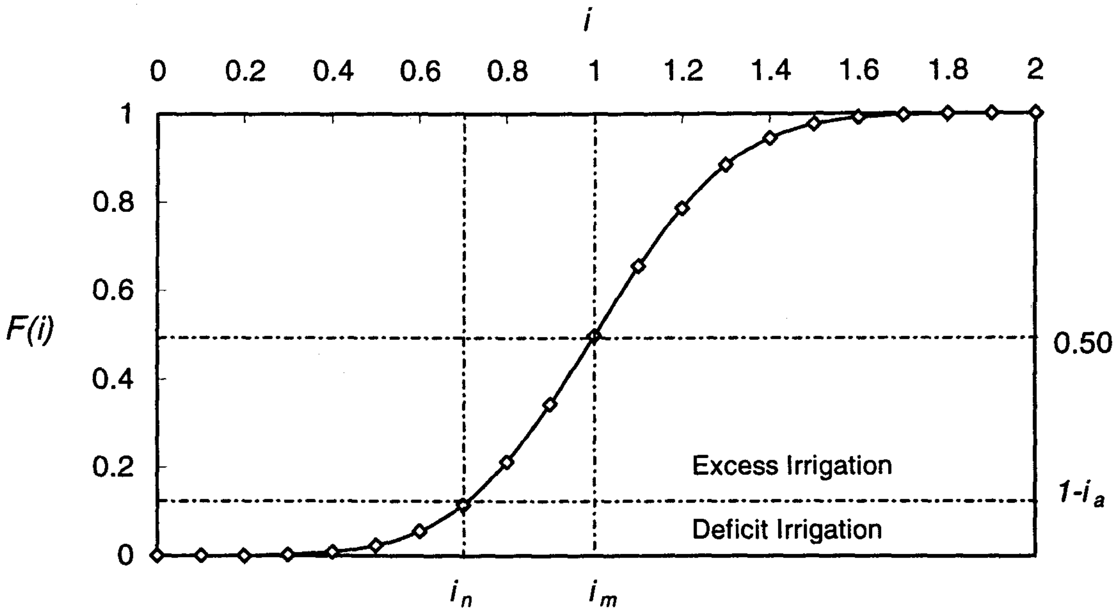


FIGURE 4.1. A normal applied water distribution, where $UC_H = 0.80$ and $\alpha = 0.90$. *F(i)* is the probability of receiving some irrigation depth, *i*.

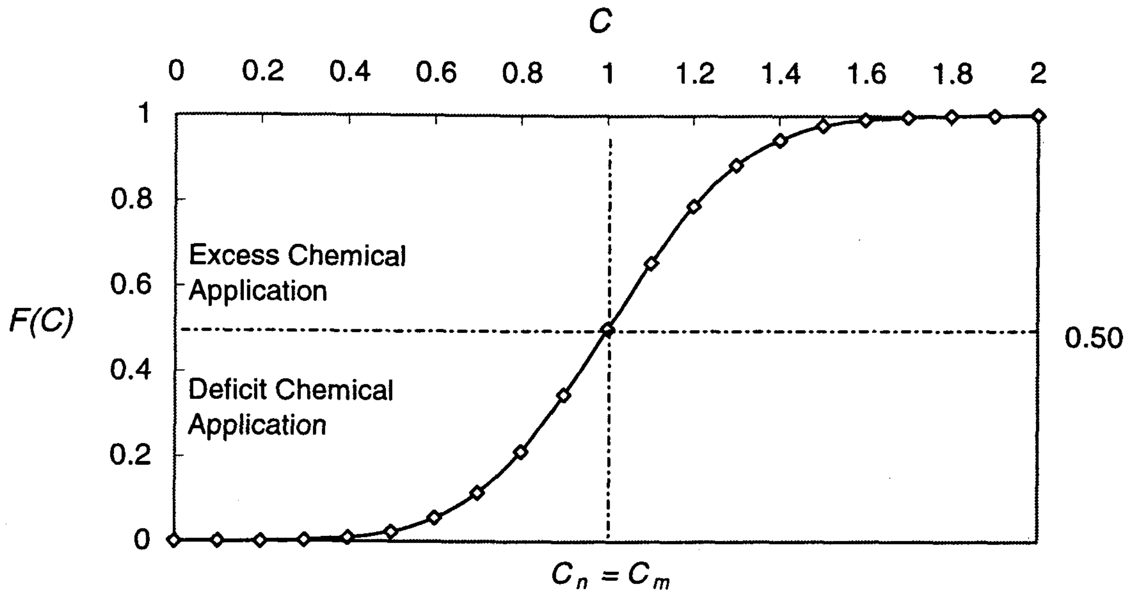


FIGURE 4.2. A normal distribution of applied chemical where the design chemical adequacy is 0.50, with $UC_H = 0.80$. The standard deviation of scaled irrigation and chemical applications are assumed to be identical. *F(C)* is the probability of receiving some chemical application, *C*.

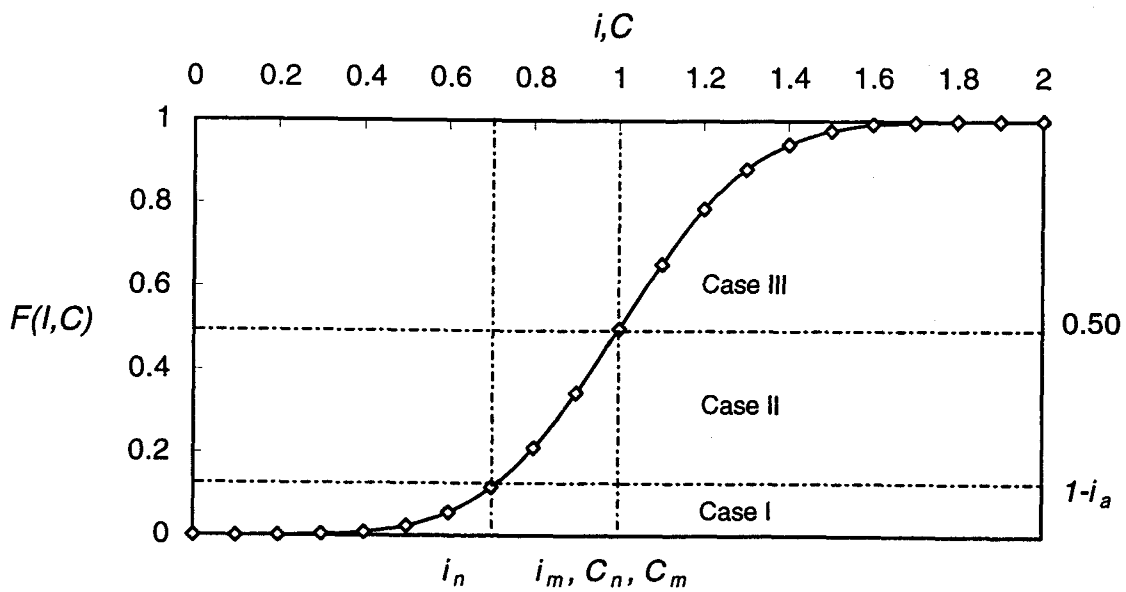


FIGURE 4.3. Three scenarios resulting from the application of some chemical at a design adequacy of 0.50 and of water at a design adequacy of 0.90, where $UC_H = 0.80$.

The assessment of chemical application within area III does not account for solute transport processes, which may significantly lower the effective chemical adequacy, or that fraction of the irrigated area retaining the chemical mass requirement in the target soil depth (e.g. root zone). Wherever irrigation is applied in excess, the water needs of the plants are met regardless of the amount of water lost to deep percolation. However, water lost to deep percolation can transport the applied chemical out of the target soil depth, reducing the effective chemical application. Although the mass of chemical supplied to Area III may be more than adequate, the amount residing in the root zone following the accompanying excess irrigation may be limited by deep percolation losses when the solute is soluble and non-sorbing. The possibility follows that the effective chemical adequacy is lower than the design chemical adequacy and deficit chemical application occurs over the majority of the target area with potentially significant losses to deep percolation and eventually to groundwater.

There are three primary ways to mitigate the problem of deficit chemical application: i) increase irrigation uniformity; ii) decrease irrigation adequacy; and/or iii) increase the chemical injection rate. Probably the most common solution in practice is to increase the rate of chemical injection to compensate for those regions receiving deficit application. This is often perceived as the least costly of the three options since increasing irrigation uniformity requires changes in irrigation management or hardware and since decreasing irrigation adequacy may result in a yield decline. The following analysis focuses on the effects of all three above strategies on water and solute percolation losses.

METHODS

Before the stochastic distribution of applied water or chemical can be investigated, a distribution type must be chosen to describe the relative aerial magnitudes of irrigation and chemical application under various conditions. The normal, or Gaussian, distribution is most widely used to characterize an applied water distribution (AWD) obtained with sprinkler irrigation. Several other distribution types have been investigated however, including the log normal, uniform, beta, gamma, and specialized power distributions (Heermann et al., 1992; Warrick et al., 1989; Warrick, 1983; and Elliott et al., 1980). Elliott et al. (1980) fit the linear, normal, and beta statistical models to 2,450 overlapped sprinkler patterns and found the beta distribution to better estimate the AWD than the normal distribution when applied over a wide range of uniformity coefficients. In the same study however, the normal model, upon which most available irrigation uniformity data is based, was shown to fit sprinkler data well for uniformity coefficients above 0.65. In other studies (Heermann et al., 1992; Warrick, 1983), the normal distribution was recommended when the coefficient of variation (CV) of irrigation depths was greater than 0.50 ($UC_H[0.60] = CV[0.50]$), corresponding closely to the findings of Elliott et al. (1980). As this level of uniformity is well below acceptable operational values, the normal distribution seems an appropriate choice for most practical applications.

When employing the normal model to characterize an AWD, the mean and standard deviation of applied water depths are required. In a typical modeling or irrigation design scenario however, the mean and standard deviation of the AWD are often unknown unless the irrigation adequacy is taken as 50 percent. When the irrigation adequacy is 50 percent, the mean and net irrigation requirement depths coincide. Under this condition, the standard deviation if of the AWD can be determined given a value for the commonly used Christiansen's (UC_C) or Hawaiian Sugar Planter's (UC_H) uniformity coefficients. Hart (1961) showed that when the distribution of irrigation depths is normal, UC_C is equivalent to UC_H, where

$$UC_H = 1 - 0.798 \frac{s_i}{i_m} \tag{1}$$

and where s_i is the standard deviation of applied irrigation depths. When the irrigation adequacy is anything but 50 percent, the irrigation adequacy, uniformity coefficient, and the net required depth of irrigation are all required to estimate the mean depth of irrigation. The following discussion outlines a methodology for deriving the mean and standard deviation of the AWD from these parameters.

The curve representing the AWD in Figures 4.1 through 4.3 represents the cumulative probability density function (cdf) for the normal model. Since this model cannot be solved analytically for the random variable in terms of its probability of occurrence, we employ the approximation of Ramberg and Schmeiser (1972) for the random standard normal number, n_j where

$$n_j = \frac{F(n_j)^{0.135} - [1 - F(n_j)]^{0.135}}{0.1975} \tag{2}$$

$$n_j = \frac{i_j - i_m}{s_i} \tag{3}$$

given that $F(n_j)$ is the probability of occurrence n_j, and i_j is the random number corresponding to $F(n_j)$. This solution is convenient in that it supplies a second equation for the two unknowns, i_m and s_i from Equation (1) and involves a probability term that can be used to incorporate the concept of irrigation adequacy.

Equation (1) can be solved for the standard deviation as a function of UC_H and i_m where

$$s_i = \frac{(1-UC_H)}{0.798} i_m \tag{4}$$

$$= bi_m$$

$$b = \frac{(1-UC_H)}{0.798} \tag{5}$$

and where the constant, b is introduced for convenience.

The irrigation adequacy is then defined as that fraction of the irrigated area receiving irrigation equal to or greater than the net irrigation requirement or

$$F(i_n) = 1-\alpha \tag{6}$$

where $F(i_n)$ is the probability of receiving deficit irrigation.

Substituting (4) into (3) for s_i and (6) into (2) for $F(n_j)$ gives us

$$\frac{i_n - i_m}{bi_m} = \frac{(1-\alpha)^{0.135} - \alpha^{0.135}}{0.1975} \tag{7}$$

or expressed in terms of the mean depth of irrigation

$$i_m = \left(\frac{i_n}{b}\right)\left[\left(\frac{(1-\alpha)^{0.135} - \alpha^{0.135}}{0.1975}\right) + \frac{1}{b}\right]^{-1} \tag{8}$$

We now have the two equations, (1) and (8), and the two unknowns, i_m and s_i, that allow us to characterize the normal distribution of irrigation depths when given values of UC_H, α, and i_n. By assuming that the injected chemical mixes completely and uniformly with the irrigation water, we can use this same expression to characterize the applied chemical distribution.

In order to assess the effective adequacy of chemigation, the transport of water and solute through the soil profile must be addressed. In this simple analysis, we will assume plug flow movement of both water and solute with a solute that is completely soluble and non-sorbing. To satisfy these assumptions, any irrigation in excess of the net irrigation requirement is calculated as a loss to deep percolation and transports some mass of chemical out of the target soil depth. The mass of solute lost to deep percolation $C_{dp}(x,y)$, at location (x,y), following the initial soil water redistribution was expressed as follows

$$C_{dp}(x,y) = \left(\frac{C_{x,y}}{i_{x,y} + \theta_i \cdot D_r} \right) (i_{x,y} - i_n) \qquad (9)$$

for $i_{x,y} > i_n$

$$C_{dp}(x,y) = 0$$

for $i_{x,y} < i_n$

given that $i_{x,y}$ is the depth of irrigation applied at location, (x,y), D_r is the target depth of soil, and θ_i is the volumetric soil water content prior to irrigation.

The major assumptions in using a plug flow model are that the effects of mechanical dispersion and molecular diffusion on solute transport are minimal and that there is no preferential flow of the soil solution. Simplifying solute transport phenomena to exclusively plug flow movement can result in the underestimation of solute loading to groundwater by five times in cracking clay soils (Bronswijk et al., 1995) and by two orders of magnitude when fingered preferential flow is substantial (Selker et al., 1996).

Therefore, the modeling approach employed here provides a very conservative estimate of water and solute loss to deep percolation. This particular model is also limited to the evaluation of deep percolation following the initial soil water redistribution, without consideration of losses due to subsequent irrigation events. To evaluate the long term effects of non-uniform water and chemical application on the soil water and solute balance, a much more complicated model would be required.

RESULTS AND DISCUSSION

The first two items addressed are the effects of variable irrigation uniformity and adequacy on gross applications of irrigation and chemical. In these analyses, the target irrigation and chemical applications, corresponding to the net irrigation requirement and the mean chemical application (design chemical adequacy = 0.50) respectively, were each set to a value of 1.0. Figures 4.4.A and 4.4.B and Table 4.1 display the distributions of water and chemical application for a range of uniformity coefficients and for two levels of irrigation adequacy. It is observed from these data that as the uniformity coefficient increases, the water required to achieve a given irrigation adequacy level decreases. As seen in Table 4.1, increasing the irrigation uniformity coefficient from 0.65 to 0.90, when the irrigation adequacy is 0.90, results in a 48 percent reduction in applied water. Since we are assuming that the chemical injection rate is based upon the mean irrigation depth, the mean chemical application is not effected by changes in

TABLE 4.1. Distributions of applied irrigation and chemical.

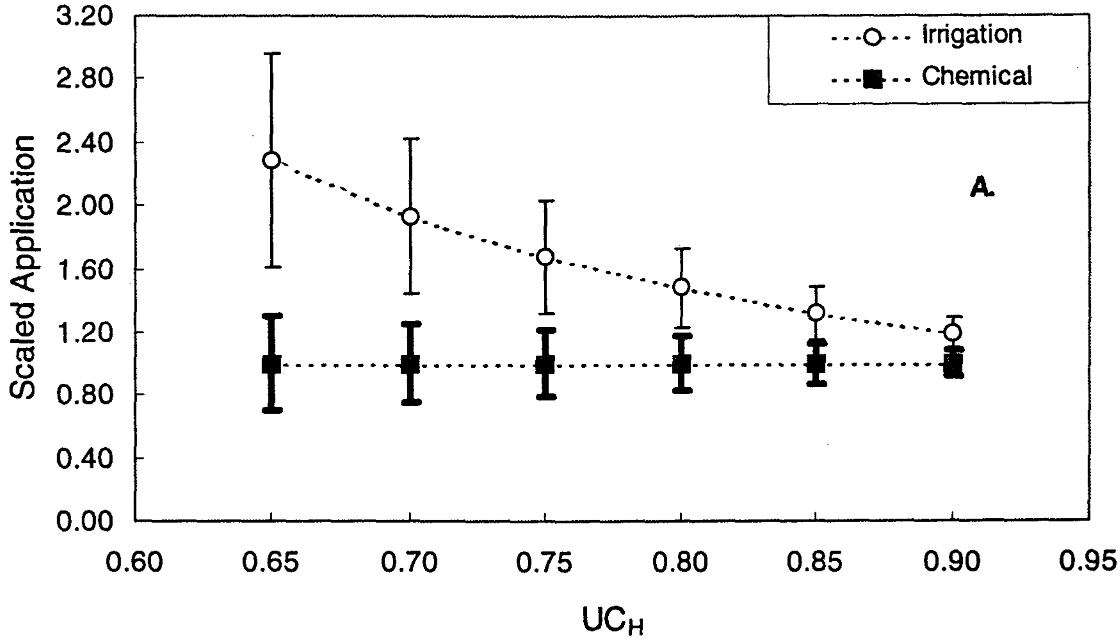
90 percent irrigation adequacy

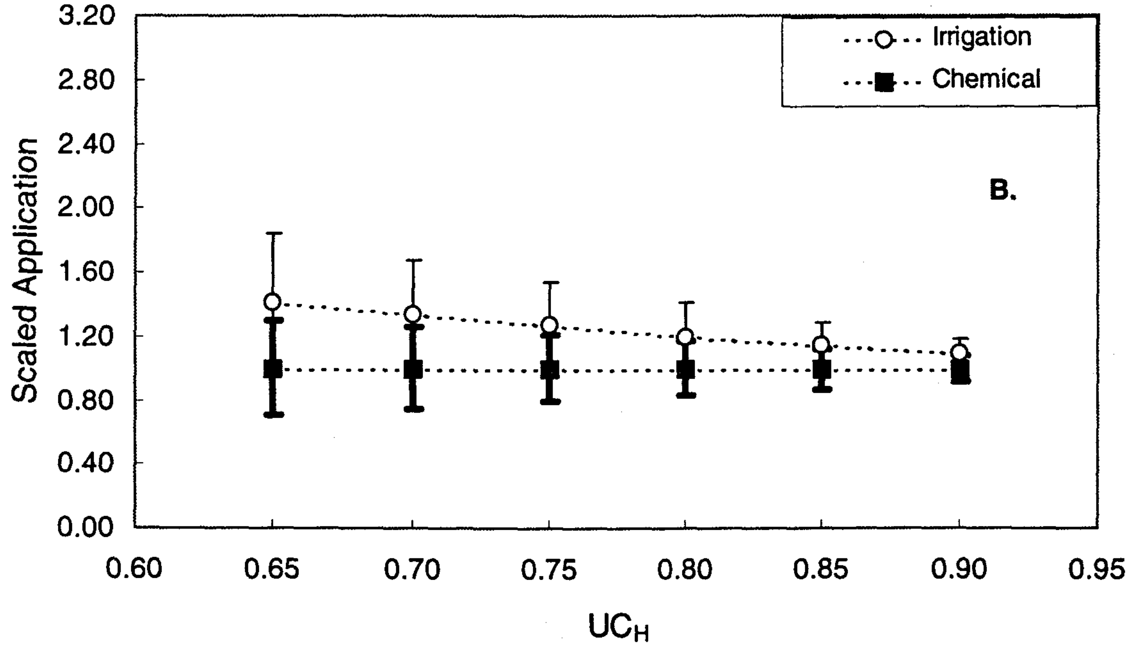
UC_H	*Irrigation* Net Application	Mean Application	Upper Quartile	Lower Quartile	*Chemigation* Mean Application	Upper Quartile	Lower Quartile
0.65	1.00	2.28	2.96	1.61	1.00	1.30	0.70
0.70	1.00	1.93	2.42	1.44	1.00	1.25	0.75
0.75	1.00	1.67	2.02	1.32	1.00	1.21	0.79
0.80	1.00	1.47	1.72	1.22	1.00	1.17	0.83
0.85	1.00	1.32	1.48	1.15	1.00	1.13	0.87
0.90	1.00	1.19	1.29	1.09	1.00	1.08	0.92

75 percent irrigation adequacy

UC_H	*Irrigation* Net Application	Mean Application	Upper Quartile	Lower Quartile	*Chemigation* Mean Application	Upper Quartile	Lower Quartile
0.65	1.00	1.42	1.84	1.00	1.00	1.30	0.70
0.70	1.00	1.34	1.68	1.00	1.00	1.25	0.75
0.75	1.00	1.27	1.53	1.00	1.00	1.21	0.79
0.80	1.00	1.20	1.41	1.00	1.00	1.17	0.83
0.85	1.00	1.14	1.29	1.00	1.00	1.13	0.87
0.90	1.00	1.09	1.18	1.00	1.00	1.08	0.92

irrigation uniformity. However, the distribution of applied chemical is strongly influenced by irrigation uniformity as indicated by the narrowing range of chemical application in Figures 4.4.A and 4.4.B as the uniformity coefficient is increased. The data in Table 4.1 indicate that when increasing the irrigation uniformity coefficient from 0.65 to 0.90, a 17 percent reduction in applied chemical is observed in the upper quartile with a 31 percent increase in applied chemical in the lower quartile. Comparing two levels of irrigation adequacy reveals that a lower adequacy allows smaller irrigation applications to achieve the target irrigation. By decreasing the irrigation adequacy from 90 percent to 75 percent, irrigation applications are decreased by 38 percent when the uniformity coefficient is 0.65 and are decreased by 8 percent when the uniformity coefficient is 0.90 (Table 4.1).

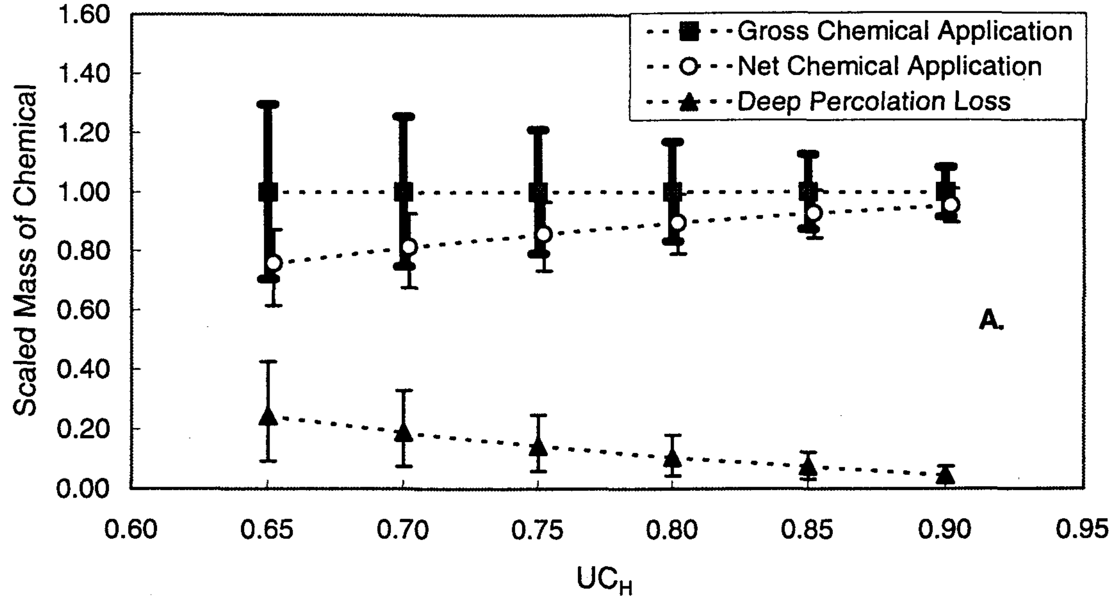


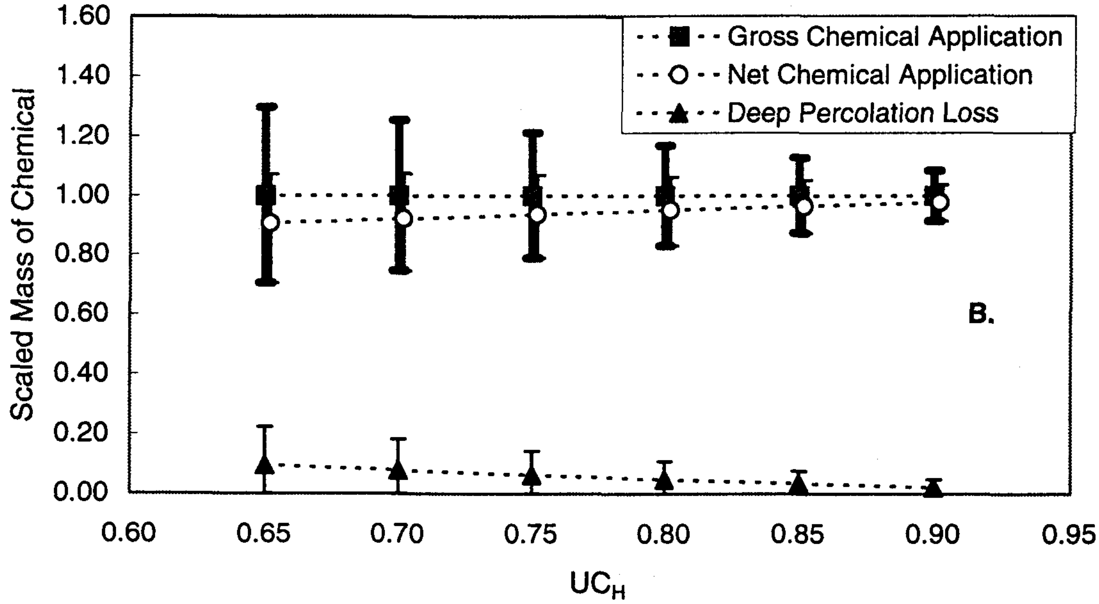


FIGURES 4.4 A & 4.4 B. Scaled applications of water and chemical as a function of UC_H at irrigation adequacy levels of 0.90 (A) and 0.75 (B). Error bars represent the upper and lower quartiles.

Although increasing the irrigation adequacy does not affect the distribution of applied chemical, it does influence the effective chemical adequacy through its control of deep percolation losses of water and chemical. In Figures 4.5.A and 4.5.B and Table 2, the results of the solute balance display this effect. The net chemical applications in the figures are defined as the gross chemical applications minus deep percolation losses of chemical. Parameter values used in these analyses were 0.25 for θ_t and 12 for the dimensionless D_r value. These values simulate a net irrigation of 50 mm over a 60 cm rooting depth that has an initial soil water content of 25 percent by volume. Under all of the scenarios considered, the net chemical application was decreased due to deep percolation losses. With 90 percent irrigation adequacy, the mean deep percolation loss of chemical was 24 percent of the targeted chemical application when the irrigation uniformity was 0.65. For this level of irrigation adequacy, over 75 percent of the irrigated area received deficit chemical application for all levels of irrigation uniformity below 0.80. The effect of decreasing the irrigation adequacy to 75 percent on chemical deep percolation was dramatic with a reduction in the mean chemical deep percolation loss of approximately 60 percent.

Increasing the design chemical adequacy can be used to counter the potentially significant reductions in the effective chemical adequacy under non-uniform irrigation. To evaluate this option, we can use the data from Figures 4.4.A and 4.4.B and Table 4.1 that display the chemical application distribution at 50 percent adequacy and irrigation distributions at 75 and 90 percent adequacy. Since water and chemical application follow the same distribution at equal levels of uniformity and adequacy, the irrigation distributions at 75 percent and 90 percent irrigation adequacy can be used to evaluate the





FIGURES 4.5 A & 4.5 B. Scaled results of the solute balance as a function of UC_H at irrigation adequacy levels of 0.90 (A) and 0.75 (B). Error bars represent the upper and lower quartiles.

TABLE 4.2. Solute balance results.

90 percent irrigation adequacy

UC_H	*Gross Chemical Application* mean application	upper quartile	lower quartile	*Net Chemical Application* mean application	upper quartile	lower quartile	*Deep Percolation Loss* mean loss	upper quartile	lower quartile
0.65	1.00	1.30	0.70	0.76	0.87	0.61	0.24	0.43	0.09
0.70	1.00	1.25	0.75	0.81	0.93	0.67	0.19	0.33	0.07
0.75	1.00	1.21	0.79	0.86	0.96	0.73	0.14	0.25	0.06
0.80	1.00	1.17	0.83	0.89	0.99	0.79	0.11	0.18	0.04
0.85	1.00	1.13	0.87	0.93	1.01	0.84	0.07	0.12	0.03
0.90	1.00	1.08	0.92	0.95	1.01	0.90	0.05	0.07	0.02

75 percent irrigation adequacy

UC_H	*Gross Chemical Application* mean application	upper quartile	lower quartile	*Net Chemical Application* mean application	upper quartile	lower quartile	*Deep Percolation Loss* mean loss	upper quartile	lower quartile
0.65	1.00	1.30	0.70	0.91	1.07	0.70	0.09	0.22	0.00
0.70	1.00	1.25	0.75	0.92	1.07	0.75	0.08	0.18	0.00
0.75	1.00	1.21	0.79	0.94	1.07	0.79	0.06	0.14	0.00
0.80	1.00	1.17	0.83	0.95	1.06	0.83	0.05	0.11	0.00
0.85	1.00	1.13	0.87	0.97	1.05	0.87	0.03	0.08	0.00
0.90	1.00	1.08	0.92	0.98	1.04	0.92	0.02	0.05	0.00

effects of increasing the design chemical adequacy to these levels. As the relative differences in distributions in response to changing the adequacy was already discussed with regard to irrigation distributions, we will present a practical application of nitrogen requirements in response to various levels of adequacy when using chemigation for fertilizer application. For the purpose of this example, we will consider the chemigation of peppermint, a high-value specialty crop that commonly receives nitrogen through irrigation. The recommended annual nitrogen application requirement of peppermint ranges in the literature from 202 kg/ha (Court et al., 1993) to 336 kg/ha (University of Idaho). Assuming that the entire annual application of the lowest of these two estimates was supplied through chemigation, a mean chemical application of 297 kg/ha would be required to achieve a net chemical mass application of 202 kg/ha at a design chemical adequacy of 90 percent and through an irrigation system with a reasonable uniformity coefficient of 0.80. By reducing the uniformity coefficient to 0.65, the required mean chemical application would be increased to 461 kg/ha. We can see here how chemical application could be increased to unreasonable levels by taking the approach of increasing the design chemical adequacy.

CONCLUSIONS

Given the estimated effects of irrigation uniformity and adequacy on the distribution of applied chemical, it is important that only highly efficient irrigation systems be used for chemigation. Since the simple soil water and solute balance model used here did not account for the cumulative effects of successive irrigation events on solute transport or the effects of preferential flow, chemical loss to deep percolation may be significantly worse than predicted here. When soils are favorable to preferential flow, the option to use chemigation should be carefully considered against the potential results. Such soils include swelling clay soils where shrink/sell phenomena produce cracks and all other soils with significant macro-pore structure, coarse-textured soils in dry climates where fingered flow may be a factor, and soils consisting of strong bedding patterns of alternating coarse and fine materials, which may induce funneled flow. Each of these types of preferential flow can be minimized to some degree by the method of irrigation (Selker, 1996).

This study and the majority of other irrigation modeling studies have used field averaged distribution parameters to characterize irrigation dependent variables such as soil water and solute distributions, crop yields, and irrigation economics resulting from non-uniform irrigation. It has been shown, however, that the AWD is not homogenous on a field scale, and that field averaged parameters may not represent true water distributions (Mallawatantri and Mulla, 1996). Stochastic modeling techniques can be used to simulate irrigation depths based upon random samples from an irrigation distribution. A distinct advantage of this approach is the production of a distribution of outputs rather than one deterministic result. More flexibility is also available in maintaining independence of successive irrigation events and accounting for a heterogeneous AWD in time as well as in space. Before a stochastic modeling effort can be employed however, the probability distribution of inputs must be characterized. Given the mathematical scheme presented here, the distribution of such inputs can be characterized from common irrigation design parameters.

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Chapter 5

General Summary

Three separate investigations were conducted to answer questions about irrigation and nitrogen management for peppermint production. In the first of these, structured field experiments were designed and conducted to isolate potential environmental, management, and sampling influences on stem nitrate test results. The most significant effects observed were those of the type of stem material collected (a 441% effect at $p < 0.001$) and the number of stems collected to estimate the field mean concentration. It was found that the variance of the sample population and the number of stems required for a given sampling error could be greatly reduced by only collecting stems from within the plant canopy. Collecting only these stems, 30 stems were found to be adequate to estimate the field mean concentration within 10 to 15 percent of the true population mean ($p < 0.05$). Less pronounced but statistically significant differences in stem nitrate concentrations were produced by variations in solar radiation on hourly ($p < 0.05$) and day length ($p < 0.01$) scales. For the diurnal response, a 17 percent reduction in stem nitrate concentration was observed over a nine-hour period from 12:00 hours to 21:00 hours. On the day length scale, an 80 percent reduction in incoming solar radiation produced a 29 percent increase in stem nitrate concentrations after three days of shading. In the analysis of stem nitrate spatial variability, no discernable range of autocorrelation was detected indicating a purely random distribution of stem nitrate concentrations on the 1-150 m scale. Given this finding and under the conditions of the analyses (late season with stem nitrate in excess of critical levels), it is not important that samples collected for this test fully cover the field being assessed, despite the intuitive appeal of full-field sampling as a standard procedure. The response of stem nitrate concentrations to soluble nitrogen application was minimal, probably due to plant nitrogen status in the test plots being well above the critical deficiency content prior to application. With the data produced from these investigations, users of the peppermint stem nitrate test are presented with a method to collect data in the field whereby nitrogen management interpretations of the test can be more consistent and reliable. In addition, these results indicate the need for researchers to fully report the method of sampling employed when presenting finding for stem tissue tests.

For the second investigation, a field study was conducted to measure the consumptive use of peppermint in the post-harvest period and to develop crop coefficients used to predict evapotranspiration (ET) rates. The soil water balance was measured on two fields with a neutron moisture meter over an 80 day period from July 29, 1997 to October 17, 1997. Over the 49 day period following harvest, a consumptive use of 96 mm was observed. Basal crop coefficients increased from near zero to approximately 0.40 within 40 days post-harvest. When these crop coefficients are used for irrigation scheduling, instead of full irrigation at pre-harvest levels (0.90 ET_r), an estimated 175 mm of water over the 60 day period following harvest can be saved and the nutrient loss associated with excess irrigation can be avoided.

The third, and final investigation employed a simple heuristic statistical model to explore the effective adequacy of chemical application as influenced by the uniformity of irrigation. To perform this analysis, an expression was presented whereby irrigation distribution parameters for the normal, or Gaussian, model could be derived from common irrigation design terms. The results of this model indicate that the effective chemical adequacy is greatly compromised when the irrigation uniformity coefficient is low and/or the design irrigation adequacy is high. Although not included in the model, preferential flow is expected to increase chemical loss to deep percolation greatly from what was predicted. Consequently, peppermint growers employing chemigation for in-season nitrogen application should be particularly conscious of potential preferential flow problems within their fields and should refer to Selker (1996) for methods of irrigation to minimize preferential flow.

The above results present new information that can help to increase irrigation and nitrogen management efficiency within peppermint production. In doing so, nitrate loading to groundwater can be further reduced. Without extension of this information directly to the community of peppermint producers however, this information may have little impact. The next step in this effort therefore, is to distribute this information through meetings with grower groups and through university extension publications.

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