CHAPTER THREE

THE EFFECTS OF NITROGEN PLACEMENT AND WATER INJECTION CULTIVATION ON CREEPING BENTGRASS PUTTING GREENS

ABSTRACT

Nitrogen is usually the most limiting nutrient in turfgrass growth. Food and forage crops have benefited from receiving subsurface nitrogen fertilization. Subsurface fertilization in turfgrass had not been feasible until the development of high pressure water injection cultivation (WIC). Previous research showed that applying nitrogen with WIC increased turf color ratings, clipping yields, and nitrogen content compared to surface fertilization, but the effects of nitrogen placement and cultivation were confounded. In addition, turf injected with nitrogen exhibited occasional dark green striping that would be unacceptable in a putting green situation. The objectives of this research were to evaluate (i) the separate effects of nitrogen application method and WIC on growth, nitrogen content in the plant tissue, turf color, and turf quality and (ii) the effects of several alternative methods of injecting nitrogen on uniformity of color response. In a nitrogen injection – management practice study, four combinations of nitrogen injection, WIC, and surface fertilization were applied at 2.4 and 4.8 g N m^{-2} application^{-1}. In 1997, nitrogen injection increased turf color and quality ratings, clipping yields and leaf nitrogen content, but in 1998 only increased turfgrass color. In both years, WIC alone had no significant effect on any turfgrass evaluations. In an application uniformity study, an application method providing

both injection and surface application of nitrogen provided superior color, quality, and uniformity of putting green turf. If injecting nitrogen improves turf responses compared to surface applications, less overall nitrogen may be needed to maintain a healthy turf stand.

INTRODUCTION

Nitrogen is usually the limiting nutrient for turfgrass growth. It is an essential component of chlorophyll, other proteins, genetic material, and many other plant substances. Turfgrass plants normally contain more nitrogen, 3 to 5 percent, than any other mineral nutrient. Responses to nitrogen by turf include darker green color and increased growth and density. Too much nitrogen can be detrimental by enhancing some diseases or causing osmotic burn (Emmons, 1995).

Turfgrass fertilization is traditionally accomplished through surface applications. This is primarily due to the unavailability of equipment capable of placing fertilizers below the soil surface without causing significant turf disruption. Subsurface applications of nitrogen increase plant nitrogen use efficiency in the food and forage crop industries (Mengal et al., 1982; Stecker et al. 1993).

Rapid suburban growth and golf course construction has increased nitrogen fertilizer use in the turfgrass industry during recent decades. More efficient nitrogen application methods on turfgrass, and the subsequent conservation of nitrogen in the turfgrass industry, could save energy and reduce risks of environmental pollution.

The introduction of water injection cultivation (WIC) (Murphy and Rieke, 1994) to the turfgrass management marketplace makes possible subsurface placement of soluble materials in established turf. Although WIC was introduced purely as a tool for soil cultivation, previous studies have concluded that injecting soluble nutrients with WIC may be beneficial to turf (Miller, 1994).

Most literature available on fertilizer placement in turfgrass concerns turfgrass establishment, i.e. fertilizer placement effects on seed germination or sod establishment (Jackson and Burton, 1962; King and Skogley, 1969; King and Beard, 1972) This work has shown minimal differences in turfgrass establishment with regard to fertilizer placement. In contrast, Murphy and Zaurov (1994) observed in a greenhouse study that perennial ryegrass (*Lolium perenne* L.) receiving subsurface nitrogen injections (urea) had higher clipping yields, greater root mass, higher nitrogen accumulation in plant tissues, and higher water use rate efficiency than turfgrass receiving surface applications of nitrogen.

Studies examining the effects of injecting nitrogen with WIC on fairway and putting green turfs were conducted in 1994 (Karcher, 1997). Treatments included three rates of urea, either injected or surface applied. Plots injected with urea had consistently higher clipping yields, nitrogen content in plant tissues, and color ratings than plots receiving surface applications. One possible explanation for these differences could have been as a result of ammonia volatilization from surface applications, even though plots were irrigated shortly after application. This hypothesis was tested by repeating the study in 1995 using ammonium nitrate as the nitrogen source, which is much less susceptible to volatilization than urea. Results from the 1995 study were very similar to those recorded in 1994. Clipping yields, nitrogen content in plant tissues and color ratings were all increased by injecting ammonium nitrate. Plots injected with nitrogen had a longer duration of a dark green turf response than plots receiving surface applications during both years. Additionally, turf injected with nitrogen was less susceptible to moisture stress than turf receiving surface applications.

These results suggest that by injecting nitrogen, a turfgrass manager may be able to use less total nitrogen and increase water use efficiency when compared to making surface applications. Plots receiving surface applications of nitrogen in these studies were not subjected to WIC treatment with water alone. Therefore, the effects of placement of nitrogen beneath the surface, and soil aerification from WIC could not be separated.

In previous studies involving application of nitrogen with WIC, the turf exhibited striping due to the nozzle alignment of the WIC unit on some dates. Striping was most evident on closely mowed putting green turf, 5 to 14 days following application. Turf striping occasionally reduced surface uniformity on putting green turf to a level likely considered unacceptable by most turf managers.

A group of studies were initiated in 1997 to compare the effects of surface application and subsurface injection of nitrogen. The overall objective of these studies was to determine if nitrogen application via injection is a practical and improved means of fertilizing turfgrass. More specifically, they were to compare injection and surface application of nitrogen by evaluating: (i) the separate effects of nitrogen application method and WIC on growth, nitrogen content in the plant tissue, turf color, and turf quality in **a nitrogen injection – management practice study** and (ii) the effects of several alternative methods of injecting nitrogen on uniformity of turf color and quality in an **application uniformity study.**

MATERIALS AND METHODS

Nitrogen Injection - Management Practice Study

Experimental Area

The nitrogen injection - management practice study was initiated in May 1997 at the Hancock Turfgrass Research Center (East Lansing, MI) on a one year old 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) putting green established on a root zone meeting USGA specifications (96% sand, 3% silt, 1% clay) (Hummel, 1993). The experimental area was mowed at 4 mm and maintained under typical putting green management practices. Pesticides were applied on a curative basis and phosphorus and potassium were applied as recommended from soil test values. Light sand topdressing applications were made monthly with sand matching the texture of the root zone. Irrigation was applied to approximate water loss due to average daily evapotranspiration.

Treatment Structure

This study contained two treatment factors, management practice and nitrogen rate. There were four management practices: 1) surface applied nitrogen without supplemental WIC, 2) surface applied nitrogen with supplemental WIC using a standard, #53 nozzle (approximately 15 cm injection depth), 3) nitrogen injected using a #56 nozzle (approximately 7.5 cm injection depth), and 4) nitrogen injected using a #53 nozzle. There were two nitrogen rates: 1) 2.4 g m^{-2} $application^{-1}$ and 2) 4.8 g m^{-2} $application^{-1}$. Combining the two factors yielded eight individual treatments (Table 9). This treatment arrangement allowed specific and separate analyses of the effects of nitrogen placement and WIC. The effects of nitrogen placement were tested by contrasting treatments #1, #2, #3, and #4 vs. #5, #6, #7, and #8. The effects of WIC were tested by contrasting treatments #1 and #2 vs. #3 and #4.

Table 9. Summary of treatments comprising the nitrogen injection - management practice study.

Treatment No.	Management Practice	Nitrogen Rate
		g m^{-2} $application^{-1}$
1.	N applied on surface with no WIC	2.4
2.	N applied on surface with no WIC	4.8
3.	N applied on surface plus WIC	2.4
4.	N applied on surface plus WIC	4.8
5.	N injected with #56 nozzle	2.4
6.	N injected with #56 nozzle	4.8
7.	N injected with #53 nozzle	2.4
8.	N injected with #53 nozzle	4.8

The nitrogen source for all applications was ammonium nitrate. Nitrogen applications were made once a month throughout the growing season. Fertilizer injections and WIC were done with a HydroJect 3000® provided by the Toro Co. of Minneapolis. Nitrogen injections were achieved by pumping dissolved ammonium nitrate solution from a mounted tank to the intake line of the HydroJect. The HydroJect was operated at the closest hole spacing (approximately 7.5 cm x 2.5 cm). Surface applications were made using a CO_2 powered sprayer designed specifically for small plot applications. Approximately 5 mm of water were applied to the experimental area immediately following nitrogen applications. On plots receiving surface applications of nitrogen plus WIC, WIC was applied immediately following irrigation. Treatments were replicated four times in a randomized complete block design. Individual plot sizes were 3.6 by 1.7 m.

Since the experimental area was extremely nitrogen deficient at the beginning of the study, 38 g m^{-2} nitrogen was applied in 1997, whereas 24 g m^{-2} was applied in 1998. Treatments were applied on 2 May, 28 May, 27 Jun., 31 July, 25 Aug., 25 Sep., and 12 Nov in 1997 and 9 May, 5 Jun, 10 July, 9 Aug., and 15 Sep. in 1998. The November 1997 application was a double rate late fall application.

TREATMENT EVALUATIONS

Clippings were collected by mowing two passes lengthwise on each plot with a greens mower once a week from May through October. Clippings were dried at 60° C and weighed to determine yield. Clipping yields were evaluated on 22 dates in 1997 and 18 dates in 1998.

Plant tissue nitrogen content was determined from the dried clippings using a Karsten Model 591 NIRS analyzer (Karsten Inc., Phoenix, AZ). Leaf nitrogen content was evaluated on 15 dates in 1997 and 18 dates in 1998.

Turfgrass quality and color ratings were taken weekly throughout the growing season. The rating scale for quality was from 1 to 9 (1=dead, 2=mostly dead, 3=severely flawed, 4=flawed, 5=slightly flawed, 6=acceptable, 7=good, 8=excellent, 9=ideal) and for color was from 1 to 9 (1=tan, 2=greenish yellow, 3=yellowish green, 4=light green, 5=medium light green, 6=medium green, 7=medium dark green, 8=dark green, 9=extremely dark green). Turf quality and color were evaluated on 21 dates in 1997 and 17 dates in 1998.

Application Uniformity Study

EXPERIMENTAL AREA

The application uniformity study was conducted in June through October in 1997, and September through October in 1998 at the Hancock Turfgrass Research Center on a 14-year old annual bluegrass (*Poa annua* L. *reptans*) turf established on a fine-loamy, mixed, mesic Typic Hapludalf (68% sand, 19% silt, 13% clay). The experimental area was mowed at 4 mm and managed under typical putting green management practices. Pesticides were applied on a curative basis and phosphorus and potassium were applied as recommended from soil test values. Light sand topdressing applications were made monthly (96% sand, 3% silt, 1% clay) and irrigation was applied to approximate water loss due to average daily evapotranspiration.

TREATMENT STRUCTURE

Seven nitrogen application methods are evaluated in the 1997 study, whereas nine were evaluated in 1998 (Table 10). Alternative application treatments were chosen based on their potential to reduce the appearance of green stripes following nitrogen injection. Nitrogen injections were made with a HydroJect 3000. Nitrogen injections were achieved by pumping dissolved ammonium nitrate from a mounted tank to the intake line of the HydroJect. The HydroJect was operated at the closest hole spacing (approximately 7.5 cm x 2.5 cm).

Treatments #4 and #5 used experimental nozzles manufactured by the Toro Co., with 2 orifices and 3 orifices, respectively. The orifices on these nozzles were arranged to affect the largest volume of soil possible. Treatments #6 and #8 involved turning on the roller washers of the HydroJect, which resulted in approximately half of the nitrogen being applied on the turf surface. This was determined by comparing the volume of water entering the roller washer to the volume of water entering the HydroJect. The normal function of the roller washers is to clean the rollers on which the unit rides during WIC.

The application rate for all treatments was 4.8 g N m^{-2}. Treatments were replicated four times in a completely randomized design. In 1997, treatments were applied on 25 June, 15 Aug., and 25 Sep. The direction of nitrogen injection was alternated 180 degrees between consecutive application dates. Treatments were applied only on 10 Sep. in 1998. In both years, nitrogen was applied on the experimental area at 3.6 g m^{-2} every six weeks, from early May until one month prior to treatment applications.

Table 10. Treatments comprising the application uniformity study.

Treatment No.	Application Method
1.	Surface application
2.	Injected with #53 nozzle (approximately 15 cm depth)
3.	Injected with #56 nozzle (approximately 7.5 cm depth)
4.	Injected with 2 orifice prototype nozzle
5.	Injected with 3 orifice prototype nozzle
6.	Injected with #53 nozzle while surface roller washers on (using nitrogen solution)
7.	Injected with #53 nozzle at half rate making two passes in perpendicular directions
8.	Injected with #56 nozzle while surface roller washers on (using nitrogen solution)†
9.	Injected with #56 nozzle at half rate making two passes in perpendicular directions†

† Treatments were only applied in 1998 study.

Visual quality, color, and stripe ratings were taken weekly following treatment applications. Quality and color ratings were taken in the same manner described in the nitrogen injection - management practice study. A scale of 1 to 5 was used to evaluate turfgrass striping with 1 representing no discernible striping, 2 representing barely discernible striping, 3 representing fairly discernible striping, 4 representing easily detected striping, and 5 representing obvious striping with sharp contrasting stripe borders. Ratings were taken on 13 dates in 1997 and 6 dates in 1998.

Statistical Analyses

Visual rating data for both studies were analyzed using the proportional odds model that is incorporated into the Rating Data Analysis File Package (Karcher, 2000). Treatment separation was done with pairwise chi-square tests of the treatment parameter estimates. Probability distributions were constructed to represent the odds of a treatment level to be rated in a particular category. These distributions were constructed by inserting the appropriate combination of parameter estimates into the logit-link function.

For the application uniformity study, maximum likelihood calculation errors occurred using the full model. This was due to a relatively large ratio of model parameters to experimental units. Therefore, a reduced model was used by dropping the application method x rating date interaction term from the model, and subsequently, only estimates of main effects were possible.

All other data were analyzed with ANOVA. If treatment effects were significant, means were separated using LSD at the 0.05 probability level. Where repeated measures were made on the same experimental units, time was analyzed as a sub-plot factor of the experiment. The best fitting covariance model among compound symmetry, first order auto-regressive, and spatial exponential was used to fit correlations among time points. The best fitting covariance model was determined by the highest Akaike's Information Criteron value (Littell et al., 1996).

RESULTS AND DISCUSSION

Nitrogen Injection – Management Practice Study

Treatment main effects, nitrogen placement contrasts, and ANOVA results are summarized in Table 11 (1997) and Table 12 (1998). The higher nitrogen rate significantly increased the probability of the turf to be rated high in color and quality, clipping yields, and leaf nitrogen content in both years. Management practices effects were significant for all evaluations in 1997, but only color and quality in 1998. The management practice x nitrogen rate interaction was significant for all evaluations in 1997 and 1998, with the exception of leaf nitrogen content in 1997. The nitrogen placement contrast was significant for all evaluations in 1997, but only turfgrass color in 1998. Significant interactions involving rating date resulted from the lack of treatment effects on a few rating dates throughout the year. However, within years, treatment separation was consistent on rating dates when treatment effects were significant.

Color Ratings

Fertilizing turf with the high nitrogen rate increased the probability of being rated as medium green or better by approximately 85% over the low rate in both years (Figure 19 and Figure 20). Much previous research has demonstrated that creeping bentgrass has a dark color response to increased rates of nitrogen (Landschoot and McNitt, 1997; Powell et al., 1967, Brauen et al., 1975).

Table 11. Treatment main effects, and nitrogen placement contrast for turf quality, color, clipping yields, and nitrogen content. 1997.

Effect	df	Color Parameter	df	Quality Parameter	df	Clipping Yield	df	Nitrogen Content
		estimate		estimate		$g\ m^{-2}\ day^{-1}$		%
Management practices								
surface N, no WIC		0.98 D†		3.00 D		2.84 B		4.02 B
surface N, + WIC		0.31 C		2.08 C		2.69 B		4.04 B
injected N to 7.5 cm		-5.00 A		-1.72 A		4.40 A		4.41 A
injected N to 15 cm		-3.92 B		-1.17 B		4.26 A		4.42 A
Nitrogen rate								
2.4 $g\ m^{-2}\ app^{-1}$		0.66 B		2.67 B		2.83 B		3.96 B
4.8 $g\ m^{-2}\ app^{-1}$		-4.47 A		-1.57 A		4.27 A		4.48 A
Nitrogen placement contrast								
surface		0.65 B		2.54 B		2.76 B		4.03 B
injected		-4.46 A		-1.44 A		4.33 A		4.41 A
				ANOVA				
Source of variation								
Block	3	***	3	***	3	**	3	*
Management practice (mp)	3	***	3	***	3	***	3	***
Nitrogen rate (nr)	1	***	1	***	1	***	1	***
mp x nr	3	***	3	***	3	***	3	NS
Date (d)	20	***	20	***	21	***	14	***
mp x d	60	***	60	***	63	***	42	***
nr x d	20	***	20	***	21	***	14	***
mp x nr x d	60	***	60	***	63	***	42	**

† Within effects, means sharing a letter are not significantly different.

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 12. Treatment main effects, and nitrogen placement contrast for turf quality, color, clipping yields, and nitrogen content. 1998.

Effect	df	Color Parameter	df	Quality Parameter	df	Clipping Yield	df	Nitrogen Content
		estimate		estimate		$g\ m^{-2}\ day^{-1}$		%
Management practices								
surface N, no WIC		0.16 C†		0.12 C		5.24 A		4.57 A
surface N, + WIC		-0.71 B		-1.51 A		5.24 A		4.57 A
injected N to 7.5 cm		-1.57 A		-1.12 AB		4.98 A		4.53 A
injected N to 15 cm		-0.74 B		-0.88 B		5.10 A		4.51 A
Nitrogen rate								
2.4 $g\ m^{-2}\ app^{-1}$		1.02 B		0.76 B		4.18 B		4.38 B
4.8 $g\ m^{-2}\ app^{-1}$		-2.46 A		-2.46 A		6.10 A		4.72 A
Nitrogen placement contrast								
surface		-0.28 B		-0.70 A		5.24 A		4.57 A
injected		-1.16 A		-1.00 A		5.04 A		4.52 A
				ANOVA				
Source of variation								
Block	3	NS	3	**	3	***	3	NS
Management practice (mp)	3	***	3	***	3	NS	3	NS
Nitrogen rate (nr)	1	***	1	***	1	***	1	***
mp x nr	3	***	3	***	3	***	3	*
Date (d)	16	***	16	***	17	***	17	***
mp x d	48	***	48	***	51	NS	51	NS
nr x d	16	***	16	***	17	***	17	***
mp x nr x d	48	NS	48	*	51	*	51	NS

† Within effects, means sharing a letter are not significantly different.

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

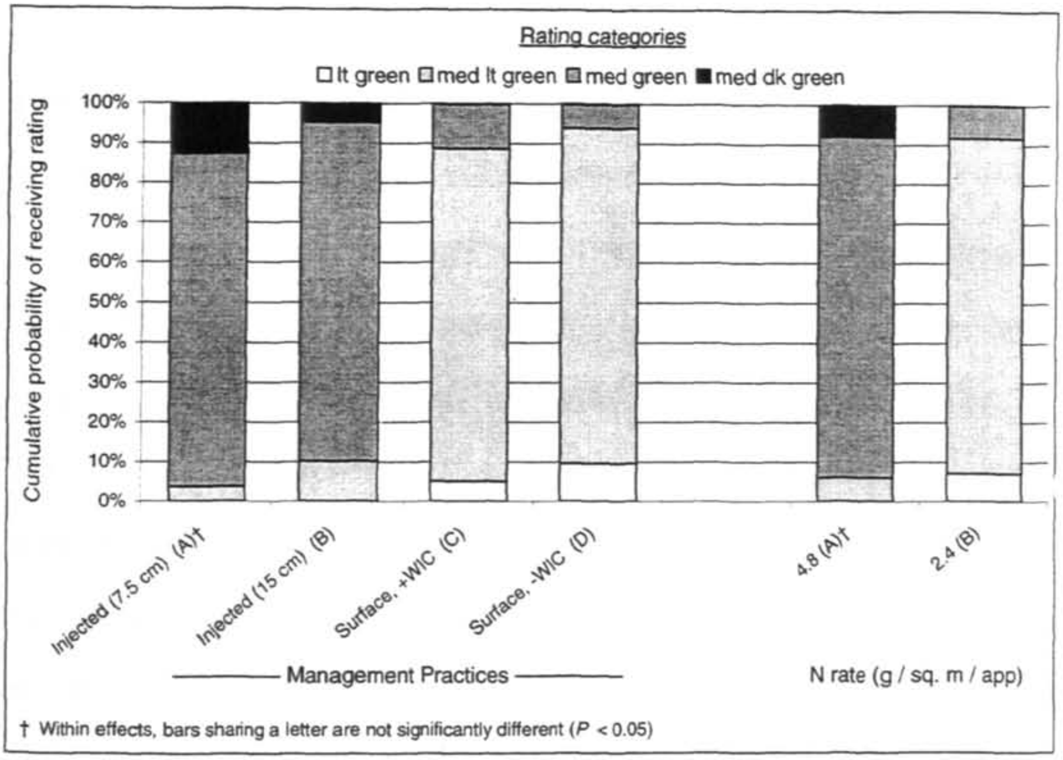


Figure 19. Color rating probability distributions for management practice and nitrogen rate main effects. 1997.

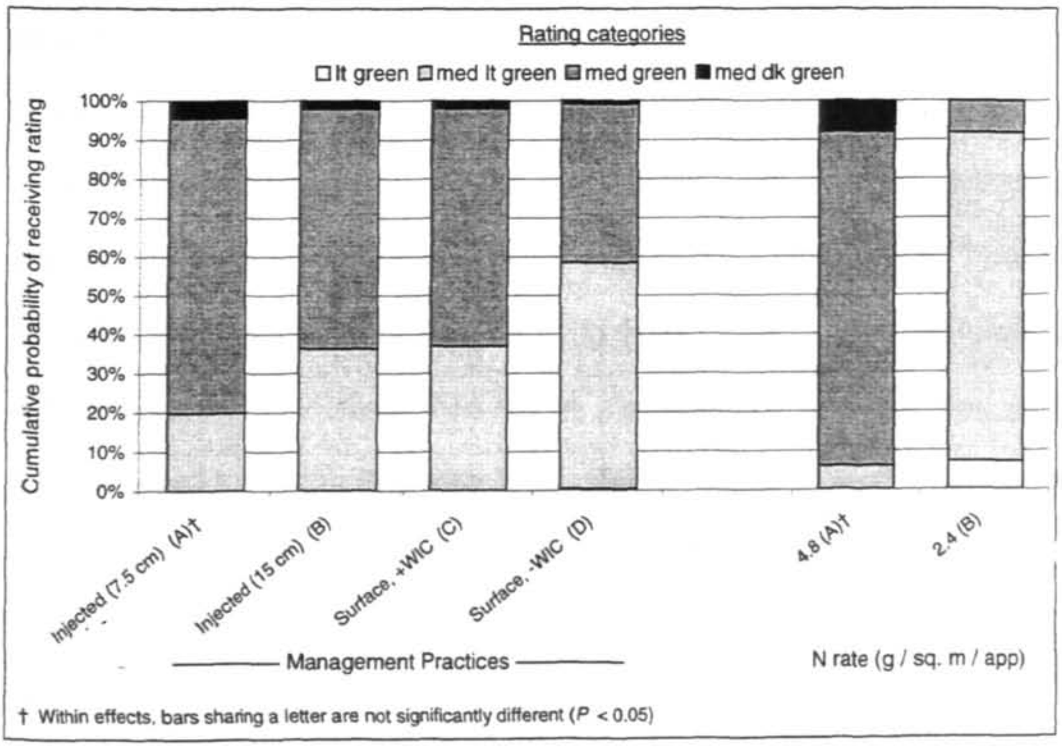


Figure 20. Color rating probability distributions for management practice and nitrogen rate main effects. 1998.

In both years, turf injected with nitrogen to a 7.5 cm depth had the highest probability to be rated dark in color, followed by turf injected with nitrogen to a 15 cm depth, turf fertilized on the surface with nitrogen plus WIC, and turf fertilized on the surface without additional WIC. The differences among treatments were greatest in 1997. There is an extremely small amount of published work regarding the effects of nitrogen placement in turf on color and quality. In previous studies, Karcher (1997) found that injecting creeping bentgrass putting green turf with urea or ammonium nitrate resulted in darker green turf compared to surface applications. Injection to 7.5 cm probably concentrated the nitrogen solution in closer proximity to the majority of the creeping bentgrass roots, allowing for greater cumulative uptake compared to surface applications or injection to a 15 cm depth. Previous rooting studies on creeping bentgrass turf have determined the majority of the root mass is within 10 cm of the turf surface (Cooper et al., 1998). Surface applications may have resulted in more microbial immobilization compared to nitrogen injection since microbial populations are greater near the turf surface than at soil depths of 7.5 cm or more. Thatch was found to contain up to 1600, 600, and 100 times as many bacteria, fungi, and actimomycetes, respectively than soil on a creeping bentgrass putting green with a sand based root zone (Mancino et al., 1993). Harper et al. (1996) discovered that a significant amount of nitrogen applied to a perennial ryegrass pasture was immobilized by microbes, and remobilized at insufficient rates to avoid nitrogen stress by the grass.

The significant management practice x nitrogen rate interaction in 1997 resulted from nitrogen injected to a 7.5 cm depth increasing turf color compared to the 15 cm depth at the low nitrogen rate, but not at the high rate (Figure 21). These results suggest that nitrogen placement to an optimum depth is more critical when fertilizing at relatively low rates. The significant management practice x nitrogen rate interaction in 1998 resulted from WIC significantly increasing turf color on turf receiving surface fertilization at the low nitrogen rate, but not at the high rate (Figure 22).

QUALITY RATINGS

Turf fertilized with the high nitrogen rate increased the probability of being rated as acceptable or better by approximately 55% in 1997 (Figure 23) and 85% in 1998 (Figure 24) over the low nitrogen rate. Similar results were reported in previous studies examining the effects of nitrogen on creeping bentgrass quality (Waddington et al., 1978; Christians et al., 1981).

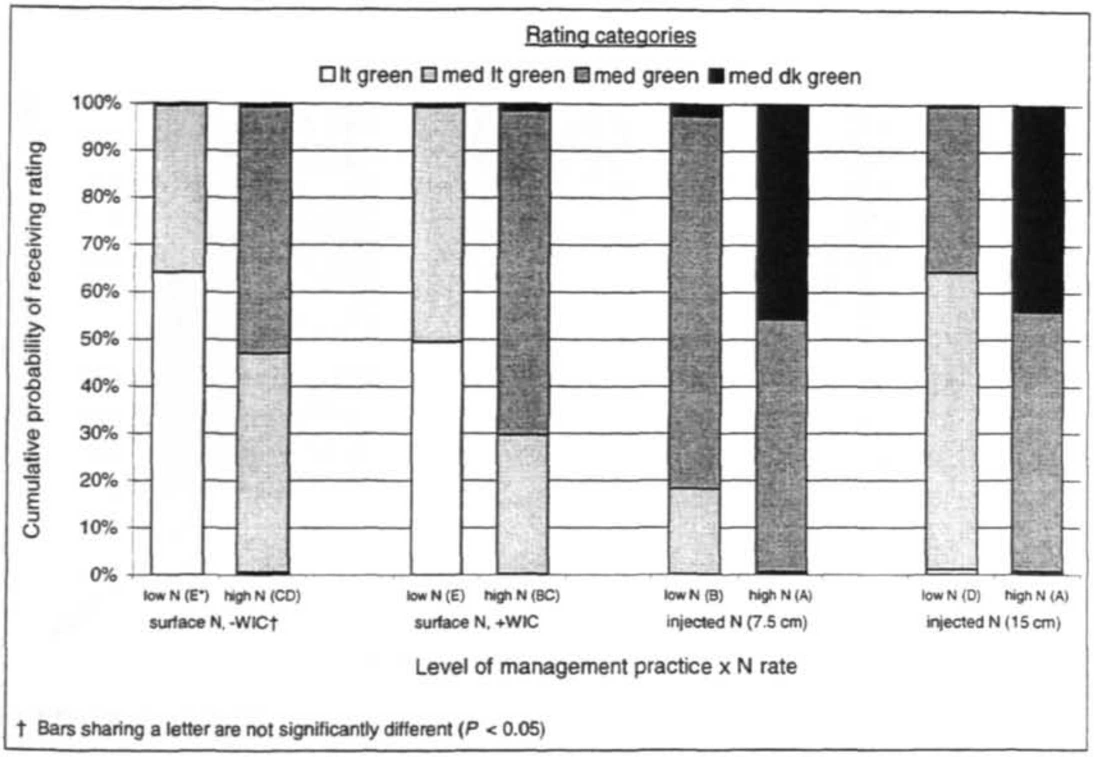


Figure 21. Color rating probability distributions for the management practice x nitrogen rate interaction. 1997.

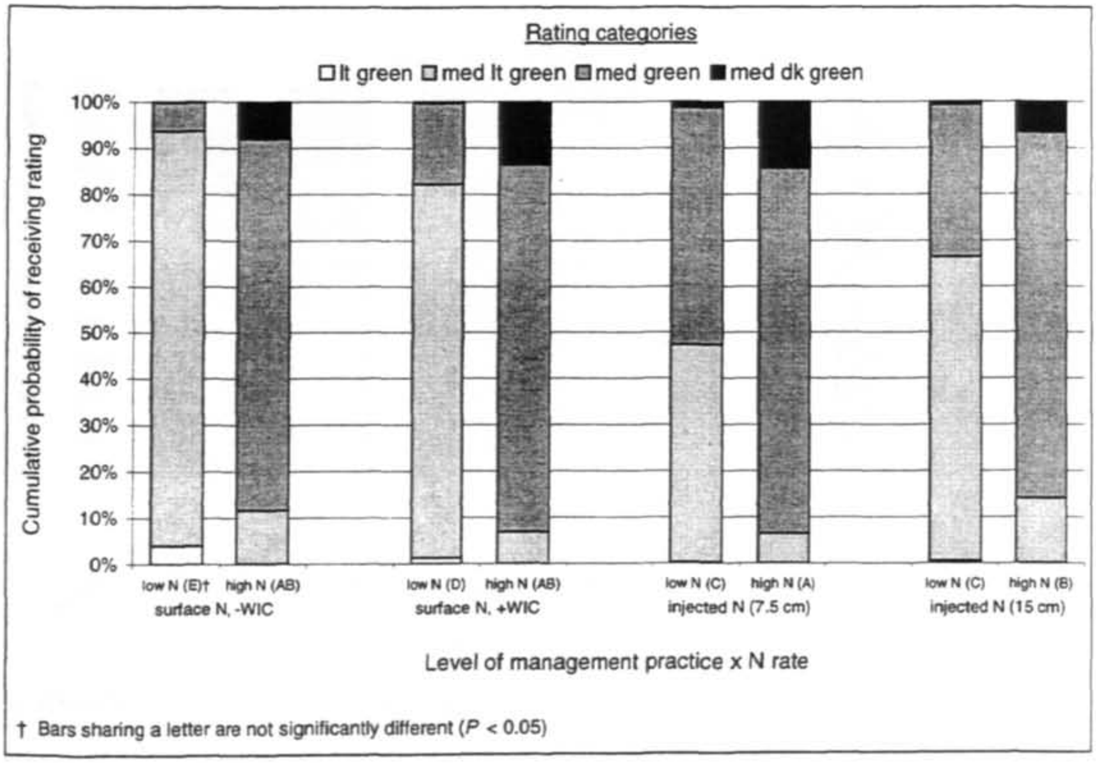


Figure 22. Color rating probability distributions for the management practice x nitrogen rate interaction. 1998.

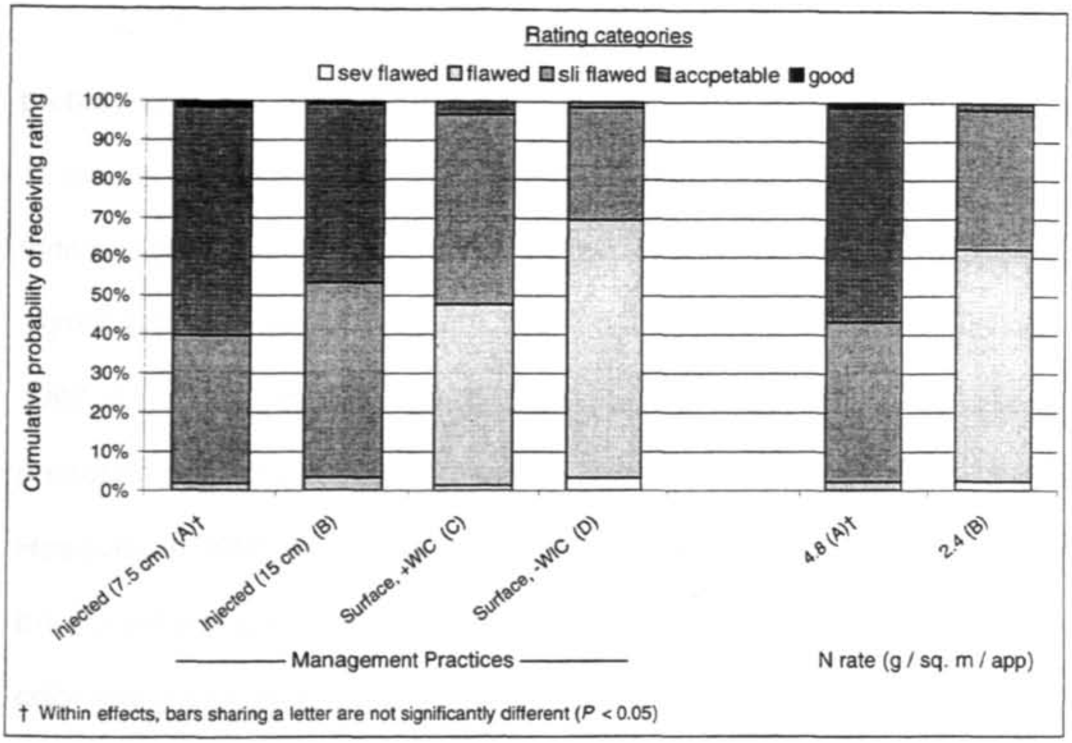


Figure 23. Quality rating probability distributions for management practice and nitrogen rate main effects. 1997.

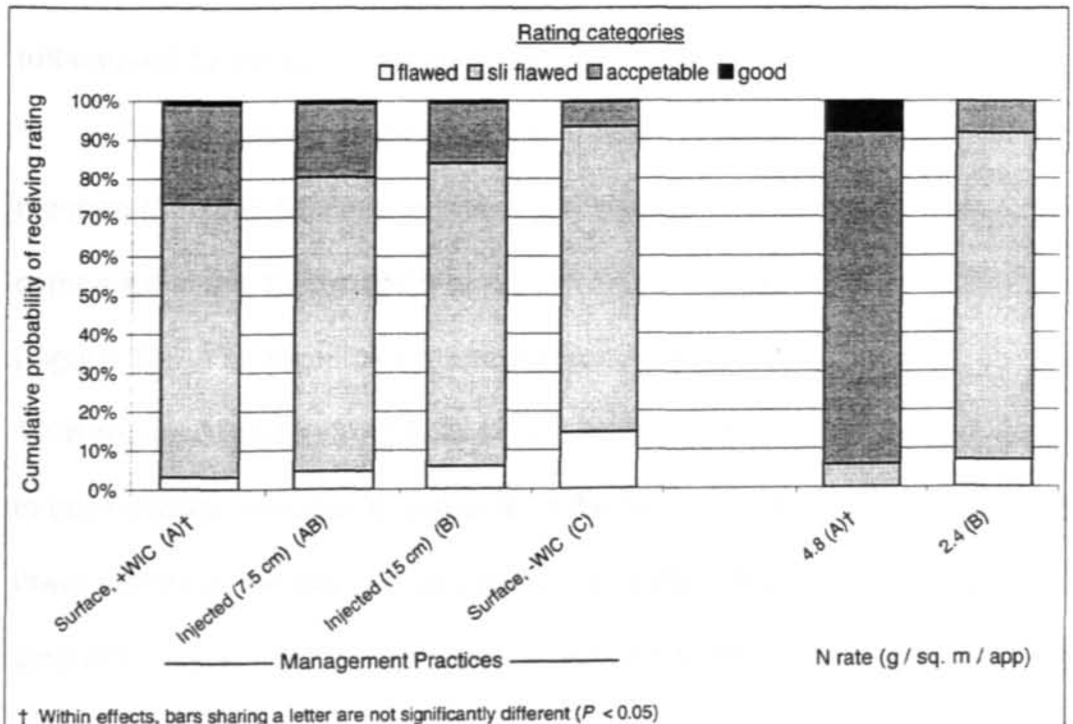


Figure 24 Quality rating probability distributions for management practice and nitrogen rate main effects. 1998.

In 1997, turf injected with nitrogen to a 7.5 cm depth had the highest probability to be rated high in quality, followed by turf injected with nitrogen to a 15 cm depth, turf fertilized on the surface with nitrogen plus WIC, and turf fertilized on the surface without additional WIC. Each management practice was significantly different from the others. More cumulative uptake of nitrogen in 1997 of turf receiving injected nitrogen to a 7.5 cm depth could likely have produced more chlorophyll and increased turf density, improving turf quality. However, in 1998, surface application of nitrogen plus WIC had quality equal to the 7.5 cm injection treatment. Although turf injected with nitrogen had better color than turf receiving surface applications, striping on several dates resulted in equal quality among the application methods. Previous studies have shown variable differences in quality between application methods due to striping of the turf caused by injecting nitrogen (Karcher, 1997).

The significant management practice x nitrogen rate interaction in 1997 resulted from the 7.5 cm injection depth significantly increasing turf quality compared to the 15 cm depth at the low nitrogen rate, but not at the high rate (Figure 25). The significant management practice x nitrogen rate interaction in 1998 resulted from turf fertilized on the surface with nitrogen having quality equal to both injected nitrogen treatments at the high nitrogen rate, but significantly lower quality at the low nitrogen rate (Figure 26). These results suggest with extended use at low nitrogen rates, injecting nitrogen to a 7.5 cm depth may result in optimal quality, whereas at high nitrogen rates application method has little effect on turf quality.

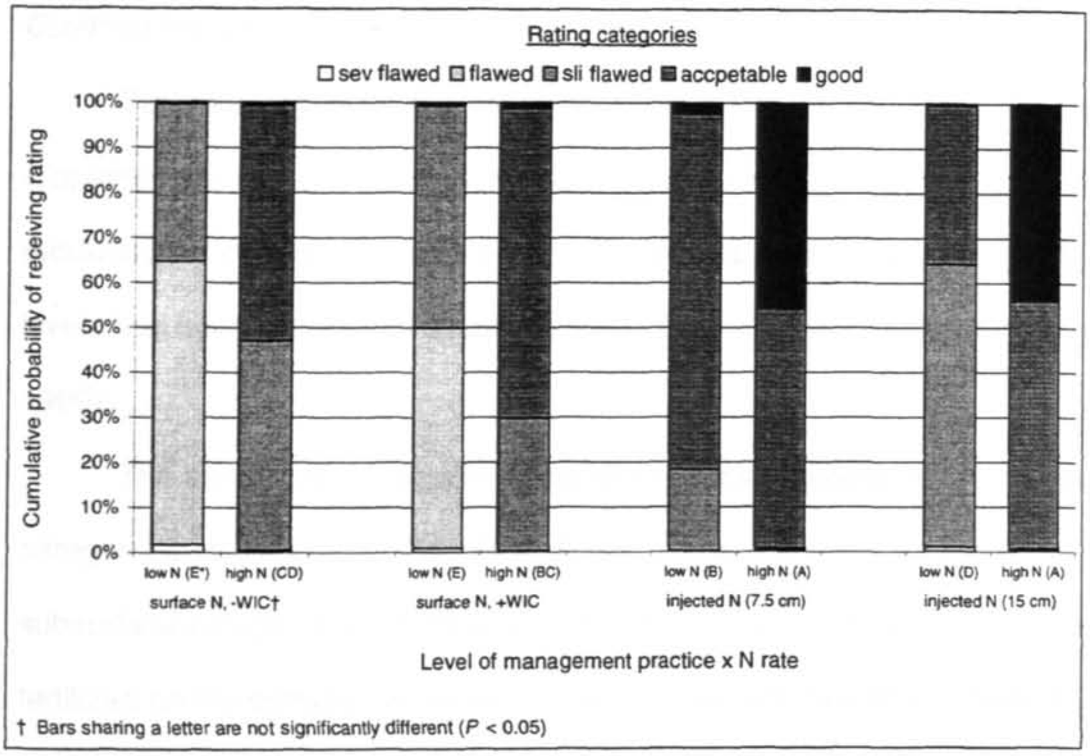


Figure 25. Quality rating probability distributions for the management practice x nitrogen rate interaction. 1997.

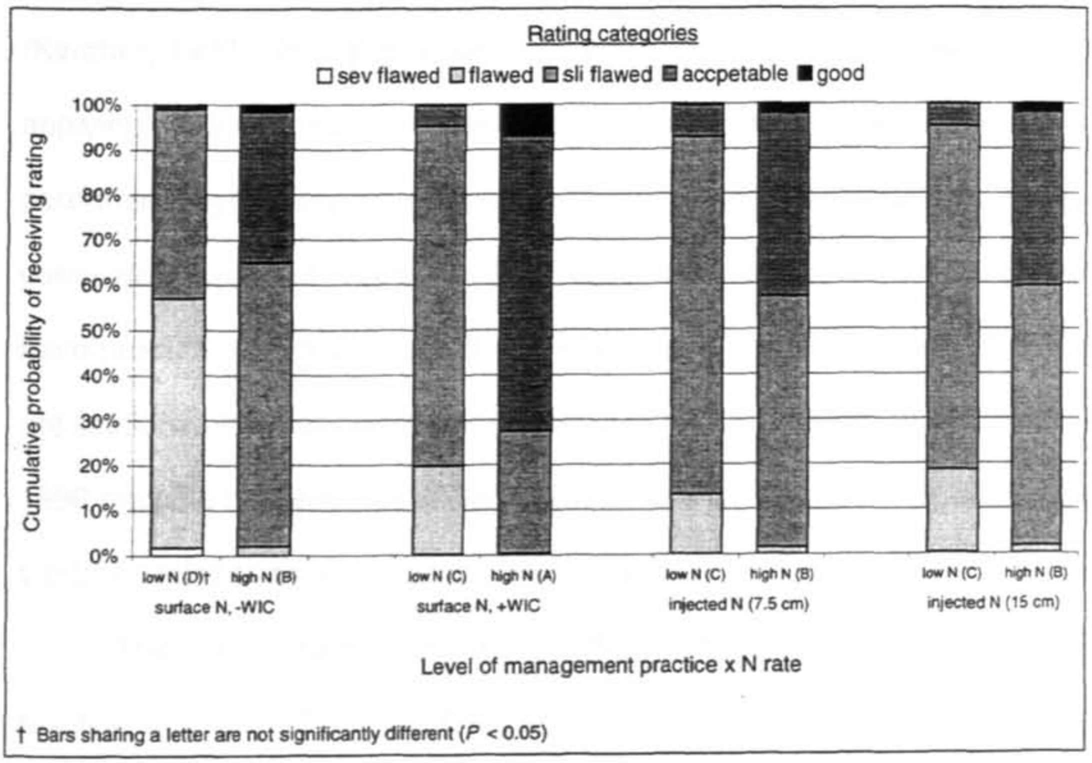


Figure 26. Quality rating probability distributions for the management practice x nitrogen rate interaction. 1998.

Clipping Yields

Turf fertilized at the high nitrogen rate had 1.4 and 1.9 g m^{-2} day^{-1} more clippings than the low rate in 1997 and 1998, respectively. A significant production of creeping bentgrass leaf tissue in response to increasing nitrogen levels has been previously reported (Carroll and Petrovic, 1991; Sheldrick et al., 1990).

The significant management practice effect on clipping yields was due to nitrogen placement rather than WIC (Table 11). In 1997, turf receiving subsurface nitrogen placement averaged 1.6 g m^{-2} day^{-1} more clippings than turf fertilized on the surface. However, this effect was not apparent in 1998, possibly as the result of remobilized nitrogen in turf receiving surface applications. The clipping yield effect seen in 1997 is similar to previous nitrogen injection studies (Karcher, 1997). In a greenhouse study, Murphy and Zaurov (1994) found that applying nitrogen, potassium, and phosphorous at a 5 cm depth increased perennial ryegrass clipping yields compared to surface fertilizations. More cumulative uptake of nitrogen in 1997 by turf receiving injected nitrogen could have produced more chlorophyll and increased turf growth compared to surface applications. It is possible that nitrogen immobilized in 1997 was remobilized in 1998 causing turf receiving surface applications of nitrogen to produce clipping yields equal to turf receiving injected nitrogen.

The significant management practice x nitrogen rate interaction in 1997 resulted from the 7.5 cm injection depth significantly increasing turf clipping yield compared to the 15 cm depth at the low nitrogen rate, but the reverse effect occurred at the high rate (Table 13). The significant management practice x nitrogen rate interaction in 1998 resulted from turf fertilized on the surface with nitrogen causing higher clipping yields than turf injected with nitrogen to a 7.5 cm depth at the high nitrogen rate, but not at the low nitrogen rate.

Table 13. Clipping yields as affected by management practice x nitrogen rate. 1997 and 1998.

	Management practice			
Nitrogen rate	surface N, no WIC	surface N, + WIC	injected N to 7.5 cm	injected N to 15 cm
	$g\ m^{-2}\ day^{-1}$			
	1997			
$2.4\ g\ m^{-2}\ app^{-1}$	2.3 E†	2.1 E	3.7 C	3.1 D
$4.8\ g\ m^{-2}\ app^{-1}$	3.4 D	3.2 D	5.0 B	5.4 A
	1998			
$2.4\ g\ m^{-2}\ app^{-1}$	4.1 CD	4.0 D	4.3 C	4.3 C
$4.8\ g\ m^{-2}\ app^{-1}$	6.4 A	6.5 A	5.6 B	5.9 B

† Within years, means sharing a letter are not significantly different ($P < 0.05$).

Leaf Nitrogen Content

The high nitrogen rate increased nitrogen content in the leaf tissue 0.5 and 0.4 % in 1997 and 1998, respectively. Significant differences in leaf nitrogen content among management practices in 1997 were the result of nitrogen placement rather than WIC (Table 11). In 1997, injecting nitrogen resulted in a 0.4% increase in leaf nitrogen content compared to surface applications. A 0.4% increase in leaf nitrogen content over surface applications is very similar to previous nitrogen injection studies (Karcher, 1997). Murphy and Zaurov (1994) reported significant increases in nitrogen accumulation in perennial ryegrass leaf tissue when fertilizer was placed at 5 or 10 cm depths compared to on the surface. There was no management practice effect in 1998.

A significant management practice x nitrogen rate interaction in 1998 resulted from surface applications significantly increasing leaf nitrogen content compared to injecting nitrogen at the high fertilization rate, but not at the low nitrogen rate (Table 14).

Table 14. Leaf nitrogen content as affected by management practice x nitrogen rate. 1998.

	Management practice			
Nitrogen rate	surface N, no WIC	surface N, + WIC	injected N to 7.5 cm	injected N to 15 cm
	%			
$2.4\ g\ m^{-2}\ app^{-1}$	4.4 C	4.4 C	4.4 C	4.4 C
$4.8\ g\ m^{-2}\ app^{-1}$	4.8 A	4.8 A	4.6 B	4.7 B

† Within years, means sharing a letter are not significantly different ($P < 0.05$).

Application Uniformity Study

Application method significantly affected turf color, quality, and striping in both years (Table 15). Since parameter estimate calculation by maximum likelihood was not possible with the full statistical model, no information was available regarding the application method x rating date interaction.

Color Ratings

Turf injected with nitrogen and with the roller washers turned on had the highest probability of being rated dark in color during both years. In 1997, (Figure 27), surface applications of nitrogen were equal to injecting with the roller washers on, whereas in 1998 (Figure 28) a standard injection and injecting at a half rate in two directions were equal to injecting with the roller washers on. Surface application and injection with a 3 orifice prototype nozzle resulted in significantly poorer color ratings than all other treatments in 1998.

QUALITY RATINGS

Turf injected with nitrogen with the roller washers on had the highest probability to be rated high in quality in 1997 (Figure 29) and 1998 (Figure 30). The multiple orifice nozzles ranked relatively poor in quality among all treatments across both years. Although turf receiving surface application of nitrogen had equal quality to turf injected with nitrogen with roller washers on in 1997, turf treated with surface applications had relatively low probability to be rated high in quality in 1998.

STRIPE RATINGS

Turf injected with the standard nozzle (15 cm depth) and the 7.5 cm depth nozzle had the highest probabilities to be rated high in surface striping in both years (Figure 31 and Figure 32). Turf injected with nitrogen and with the roller washers on had an equal probability of striping to turf receiving surface applications in both years. Turf fertilized with the multiple orifice nozzles had more striping than turf fertilized with surface applications in 1997, but was rated equal in striping to turf fertilized with surface applications in 1998.

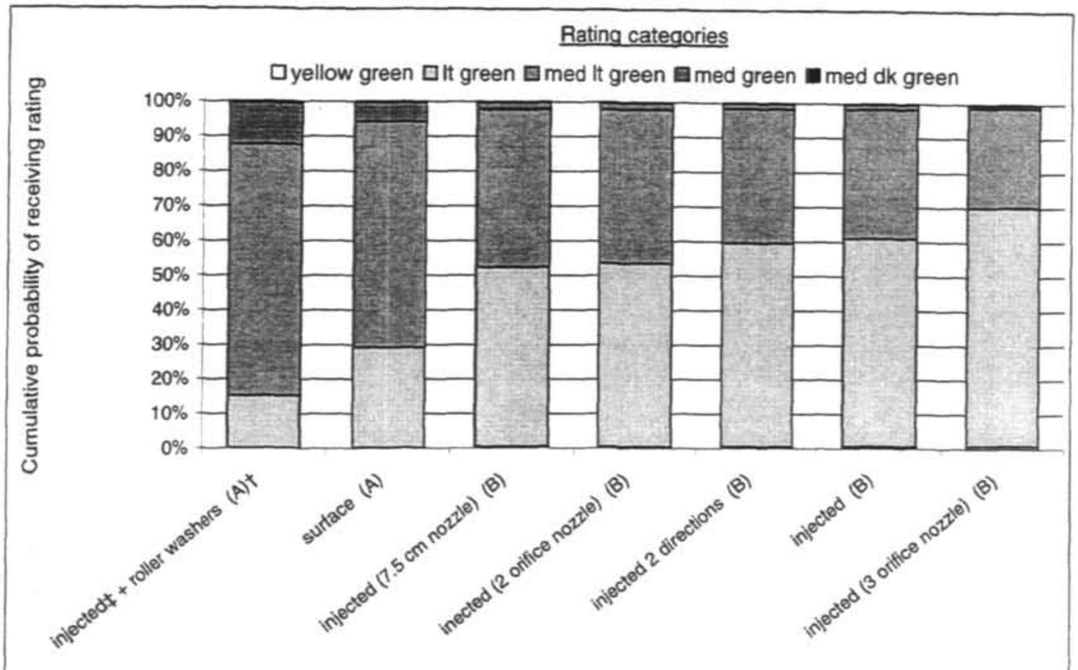
Table 15. Application method effects on turf color, quality, and stripe ratings. 1997 and 1998.

Effect	df	1997 Color Parameter	df	1997 Quality Parameter	df	1997 Stripe Parameter	df	1998 Color Parameter	df	1998 Quality Parameter	df	1998 Stripe Parameter
		estimate		estimate		estimate		estimate		estimate		estimate
Application Method												
surface		2.49 A†		-2.71 A		19.85 D		5.78 D		6.17 F		21.62 C
injected‡		3.83 B		-1.09 BC		1.62 B		-5.10 A		-2.24 CD		4.14 A
injected (7.5 cm nozzle)		3.47 B		-0.46 C		0.61 A		-5.58 A		-2.80 BC		4.33 A
inected (2 orifice nozzle)		3.52 B		-1.55 B		4.85 D		-1.87 C		0.42 E		9.66 C
injected (3 orifice nozzle)		4.23 B		-1.40 B		5.61 D		5.34 D		5.81 F		10.46 C
injected + washers		1.66 A		-3.47 A		5.95 D		-5.95 A		-4.65 A		10.47 C
injected 2 directions		3.77 B		-1.62 B		3.22 C		-5.93 A		-3.48 AB		6.22 B
injected (7.5 cm nozzle) + washers		---		---		---		-5.85 A		-3.68 AB		10.32 C
injected (7.5 cm nozzle) 2 directions		---		---		---		-3.54 B		-1.35 D		9.51 C
LOGISTIC REGRESSION												
Source of variation												
Application Method	6	***	6	***	6	***	8	***	8	***	8	***
Date	12	***	12	***	10	***	5	***	5	***	5	***

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

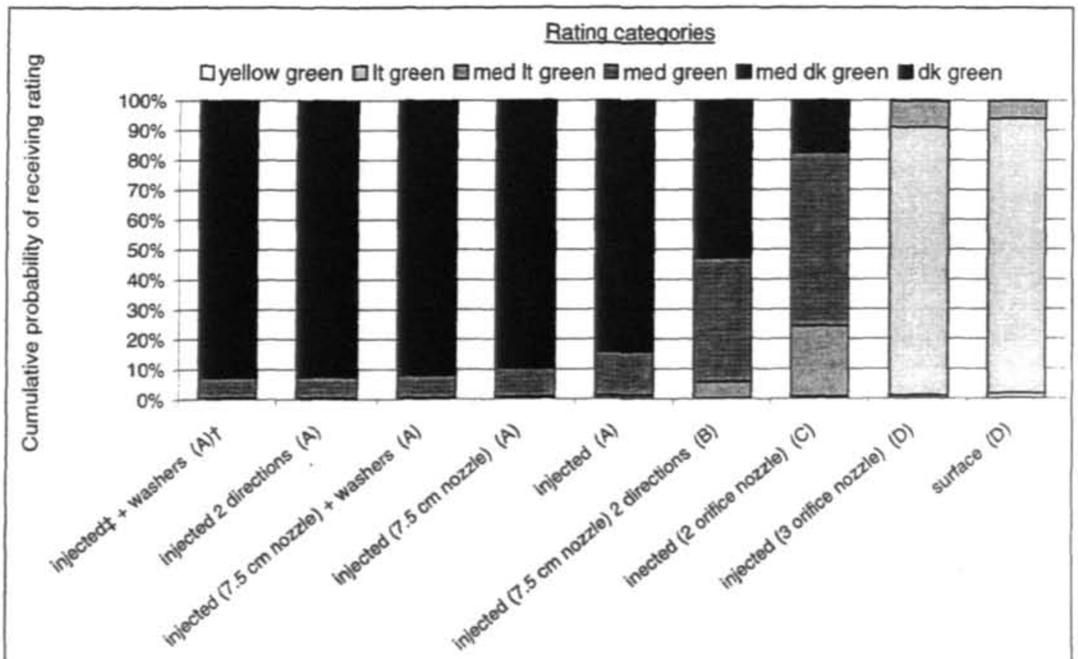
† Within columns, means sharing a letter are not significantly different ($P < 0.05$).

‡ Unless noted otherwise, injected treatements done with standard nozzle (15 cm depth).



† Bars sharing a letter are not significantly different ($P < 0.05$).
‡ Unless noted otherwise, injected treatements done with standard nozzle (15 cm).

Figure 27. Color rating probability distributions for application method effects. 1997.



† Bars sharing a letter are not significantly different ($P < 0.05$).
‡ Unless noted otherwise, injected treatements done with standard nozzle (15 cm).

Figure 28. Color rating probability distributions for application method effects. 1998.

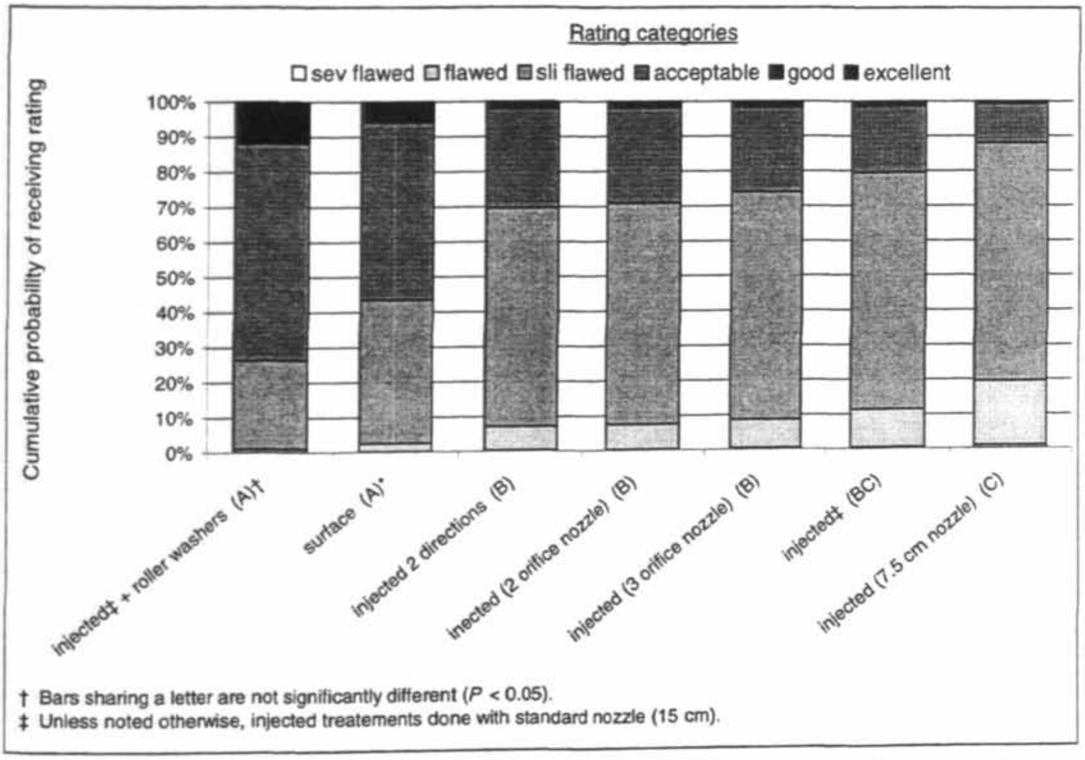


Figure 29. Quality rating probability distributions for application method effects. 1997.

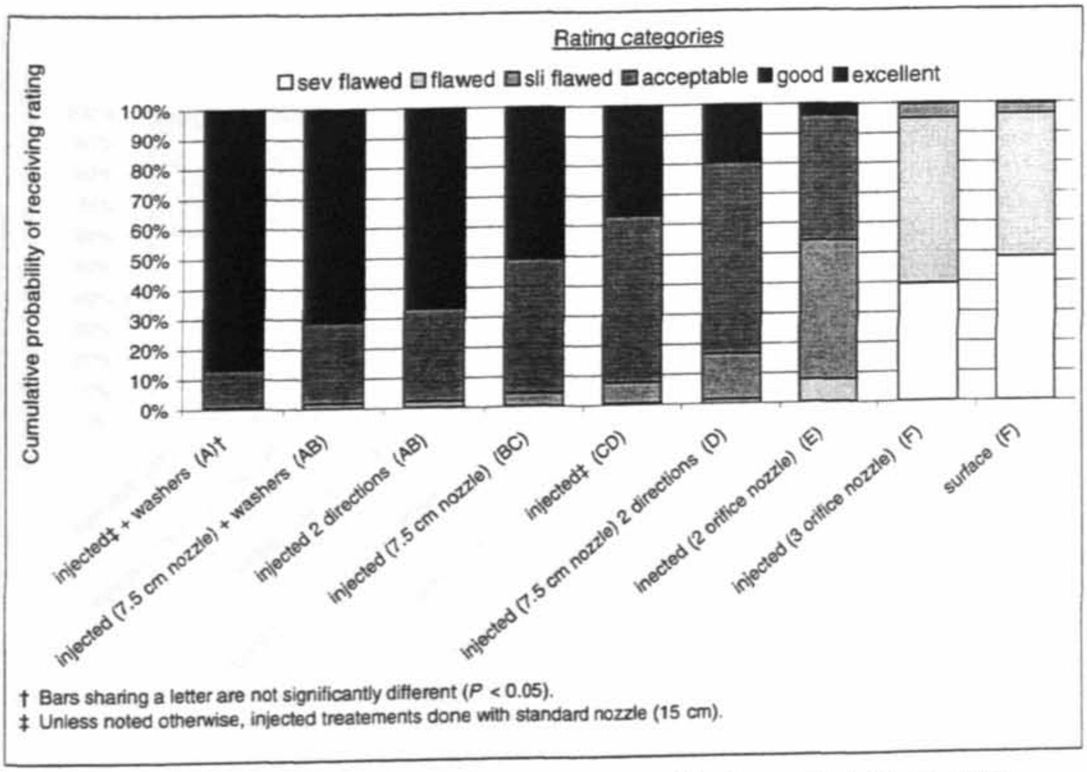


Figure 30. Quality rating probability distributions for application method effects. 1998.

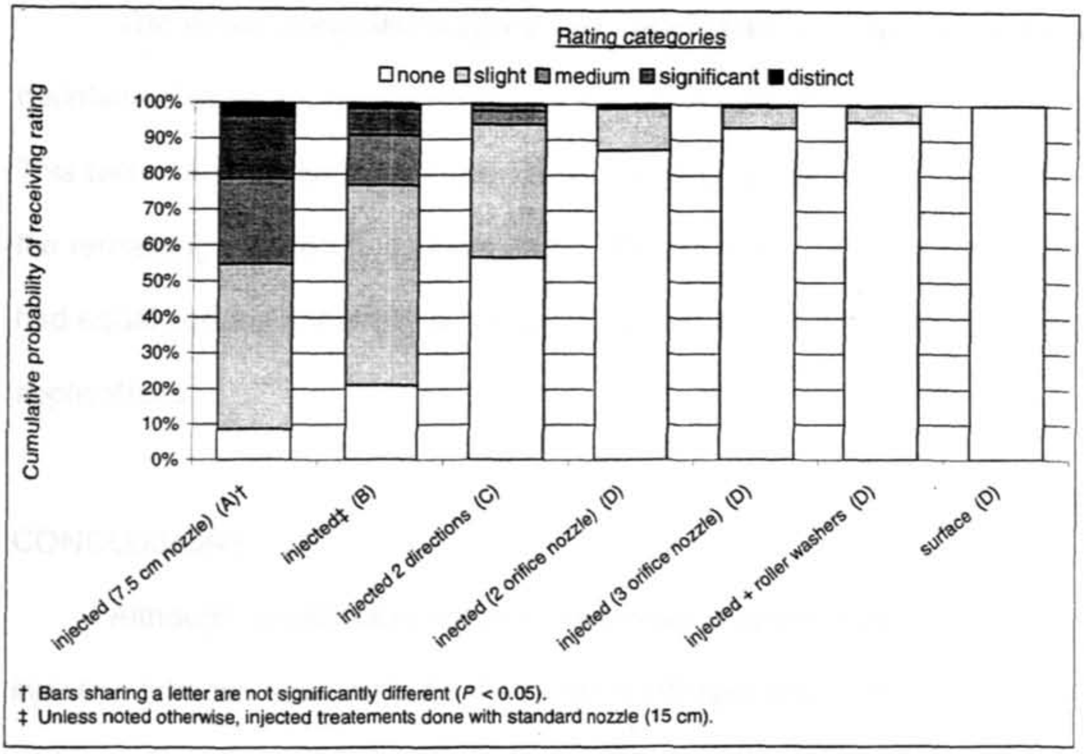


Figure 31. Stripe rating probability distributions for application method effects. 1997.

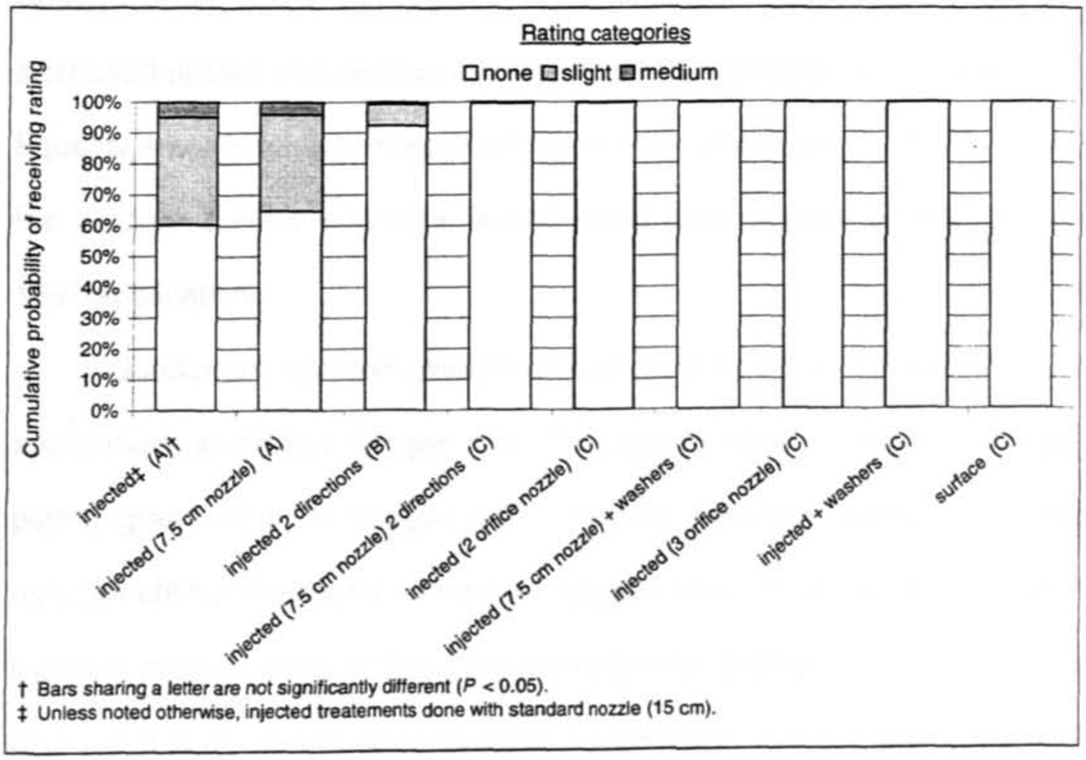


Figure 32. Stripe rating probability distributions for application method effects. 1998.

The visual rating data suggest that putting green surface uniformity can be maintained when applying nitrogen via WIC by leaving the roller washers on. This technique applies nearly one half the nitrogen on the surface while injecting the remaining nitrogen to a 15 cm depth. Across years, this application method had equal surface uniformity and superior quality and color compared to surface applications.

CONCLUSIONS

Although results were variable, improved turfgrass responses from injecting nitrogen seemed to be the result of nitrogen placement beneath the surface rather than WIC. This is probably the result of concentrating nitrogen in close proximity to the majority of active creeping bentgrass roots, resulting in increased uptake and decreased opportunity for microbial immobilization. Equality among management practices in 1998 with regard to clipping yields and leaf nitrogen content may have resulted from remobilization of nitrogen from 1997 applications.

Subsurface nitrogen placement was most beneficial compared to surface applications at the low nitrogen rate. The current trend in nitrogen fertilization of putting greens is a low nitrogen rate. From the data here, subsurface fertilization may benefit turf managers using low nitrogen rates. However, the nitrogen injection process used in these experiments was relatively labor intensive and time consuming compared to traditional application methods and would likely be considered impractical by turf managers.

The unacceptable surface uniformity seen in previous nitrogen injection studies can be remedied by injecting a half rate of nitrogen while applying the remainder on the surface. This was accomplished by injecting nitrogen with the HydroJect while using the roller washers.

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