AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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Meadowfoam has been identified as a potential oilseed crop for production on poorly drained soils in areas with cool, moist winters. The effects of N fertilizer on meadowfoam (Limnanthes alba Benth.) have been studied in Oregon and Maryland, but the results have not been consistent with respect to the effects on oil yield: yields were reduced in most cases but significantly increased in another. Excessive lodging and incidence of fungal infection were associated with N fertilization in some studies.

This study evaluated the effects of twelve combinations of N rate and timing on meadowfoam oil yields and on plant growth and development. Meadowfoam selection 703-A received 50, 100, and 200 kg N ha^{-1} applied in fall, winter, spring, and fall/spring application schedules (regimes). Each N treatment and the control were replicated four times in randomized complete blocks on the Hyslop Research Station of Oregon State University in Corvallis, Oregon.

All N treatment means for seed and oil yield were greater than the control mean. Winter applications of N fertilizer increased the efficiency of fertilizer use, increased floral density, produced relatively early dry weight gains and flowering, and increased seed-oil content. Fall-applied fertilizer N responses were reduced by leaching losses, but it appeared that some quantity of N fertilizer should be applied in the fall and another application made in late winter (before March) for optimal seed-oil yields. Fall applications of slow-release forms of N should also be studied.

NITROGEN FERTILIZER RATE AND APPLICATION TIMING EFFECTS ON GROWTH AND SEED-OIL YIELD OF MEADOWFOAM

by

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INTRODUCTION

Meadowfoam (Limnanthes alba Benth.) seed was reported to have unique oil characteristics (Bagby et al., 1961) and was later suggested as a source of industrial oil (Miwa and Wolff, 1962). Its ability to grow on poorly drained soils has made it a potential rotation crop for grass-seed growers in the Willamette Valley of western Oregon, where commercial-scale production began on a limited basis in 1980 (Jolliff, 1981). Meadowfoam has also been cited as a potential crop for areas of Maryland and Alaska (Higgins et al., 1971).

Meadowfoam is a winter annual native to areas of California, Oregon, and British Columbia that have mild, moist winters and dry, warm summers. Meadowfoam generally is planted after mid-September in western Oregon because temperatures above $16^{o}C$ may induce secondary dormancy in imbibed seeds (Toy and Willingham, 1966 and 1967). It overwinters as a rosette, and flower buds appear in early March. Flowering occurs during approximately three weeks in May to early June in Oregon, and seeds fill during June, although temperature influences these developments (Higgins et al., 1971). Harvest maturity generally is reached by the last week of June or the first week of July.

Limnanthes alba, the protandrous species domesticated at Oregon State University, requires bees for pollination. Weather during flowering affects bee foraging, pollination efficiency, and seed set (Jolliff et al., 1984).

Research results from nitrogen (N) fertilization of different meadowfoam selections under various climates and weather conditions have not been conclusive (Jolliff, 1981). Pearson (1983) found a positive seed yield response to spring applications of 50 and 100 kg N ha^{-1} during a dry spring, but no response in a cool, moist spring season. Nitrogen fertilizer was implicated as a contributor to plant lodging and fungal infection which limited yields. Johnson et al. (1980) found seed yields to be lower under N treatments while Crane et al. (1981) found no seed yield differences because of N fertility.

Seed oil yields from other oilseed crops have been found to be influenced by the rate and timing of N fertilizer application (Allen and Morgan, 1972; Osborne and Batten, 1978; Henry and MacDonald, 1978; Mitchell et al., 1974; Holmes and Ainsley, 1978; Johnson and Jellum, 1972; Yermanos et al., 1964; Dybing, 1964; Hill and Knowles, 1968). Oil yields have been found to be influenced also by the timing of both flowering and duration of seed-filling, which can be affected by N fertilizer (Canvin, 1965; Leininger and Urie, 1964; Dybing and Zimmerman, 1965; and Harris et al., 1978).

In view of the potential of N fertilizer to increase seed-oil yield, three N fertilizer rates applied in four schedules (regimes) were tested for effects on seed yield, oil content, seed yield components, plant growth and development, and N uptake by the plant.

MATERIALS AND METHODS

Field Work

Nitrogen fertilizer application timing and rate effects on meadowfoam [Oregon Limnanthes Selection (ORL) 703-A] oil yields were studied in 1982-83 at the Oregon State University Hyslop Crop Science Field Laboratory near Corvallis, Oregon on a Woodburn silt loam (fine-silty, mixed, mesic Aquultic Agrixerolls). Soil analysis showed the following plant nutrient levels: total N, 0.14 %; nitrate-N, ammonium-N, P, and K, 5.2, 5.4, 46, and 164 ppm, respectively; Ca and Mg, 7.7 and 1.3 meq 100 g^{-1}, respectively; and B, Zn, Mn, Cu and SO_4, 0.30, 0.68, 0.80, 12.0, and 8.1 ppm, respectively.

Applications of 2 kg ha^{-1} B, 10 kg ha^{-1} Zn, 200 kg ha^{-1} K_2O, and 200 kg ha^{-1} P_2O_5 were soil-incorporated prior to seeding. Seeds were planted on 15 October at 22 kg ha^{-1} followed by an application of Propachlor (2-chloro-N-isopropylacetanilide) at 4.5 kg ha^{-1} (active ingredient) for weed control. Mustards and vetch were hand-weeded throughout the growing season. Roverall [3-(3,5-dichlorphenyl)-N-(1-methylethyl)-2,4-dioxo-1-imadazolidinecarboxamine], a fungicide, was applied on 20 April, 4 May, 14 May, and 29 May at 0.923 g L^{-1} (active ingredient) for control of *Botrytis cinera*. One hive of bees was placed adjacent to the field plots on 16 May for pollination and removed on 1 June.

The field experiment was a randomized, complete block design with 13 treatments: 50, 100, and 200 kg N ha^{-1} hand-applied as ammonium nitrate for fall, winter, fall/spring and spring application schedules (regimes) and the control (Table 1). Each treatment was replicated four times on 3.05 x 6.1 m plots. The fall regime, hereafter designated 50F, 100F and 200F, received the total amount on 11 November, which was about three weeks after germination. The winter regime (50W, 100W, and 200W) received one-fifth of the total quantity on 11 November and one fifth during each of the first weeks of December, January, February, and March. The fall/spring applications (50FS, 100FS, and 200FS) were evenly split between 11 November and 5 March. The spring regime plots (50S, 100S, and 200S) received the total quantity on 5 March.

Soil N was measured three times on the 100F, 100W, 100F/S, 100S and control plots: 11 November, prior to fall application of fertilizer; 5 March, prior to spring applications; and 11 July, after harvest. The samples were taken from each replicated plot at depths of 0-30, 30-60, and 60-90 cm. The replicated samples were combined for each treatment and analyzed for nitrate-N, ammonium-N, and total N at the Soil Analysis Laboratory, Department of Soil Science, Oregon State University. Statistical analysis was not performed.

Plant growth and development were measured between 24 March and 17 June. Areas of 1000 cm^2 per plot were harvested biweekly for total above-ground plant dry weight on each sampling date except 17 June when two samples were required to determine yield components and dry weight. Triplicate canopy height measurements were taken biweekly from 8 April and averaged for each plot for each date. Canopy densities were calculated as the ratio of dry weight to canopy height. Plant N content was determined from the analysis of dry weight samples of the

Table 1. Treatments included three N rates (50, 100 and 200 kg N ha^{-1}) applied in four regimes (fall, winter, fall/spring, and spring) and the control. Each treatment was replicated four times in a randomized complete block design.

Treatments		Dates of Application				
Regime	Rate	11 Nov	5 Dec	5 Jan	5 Feb	5 Mar
	kg N ha^{-1}	kg N ha^{-1}				
Fall	50	50				
	100	100				
	200	200				
Winter	50	10	10	10	10	10
	100	20	20	20	20	20
	200	40	40	40	40	40
Fall/Spring	50	25				25
	100	50				50
	200	100				100
Spring	50					50
	100					100
	200					200
Control	0					

100F, 100W, 100FS, 100S, and control treatments. The plant tissue was analyzed for total N, nitrate-N, and ammonium-N by the Soil Analysis Laboratory, Department of Soil Science, Oregon State University.

Plant N uptake was calculated as the product of the tissue N content and dry weight. Maximum N uptake (MNU) was determined as the maximum amount of tissue N for each regime and N uptake efficiency (NUE) was calculated as follows:

$$\mathrm{NUE} = (\mathrm{MNU} - \mathrm{CN}) / 100$$

where CN = Tissue N content in the control plants.

Floral phenology was monitored between 12 May and 29 May. A 1000 cm^2 quadrat was framed in each plot at the beginning of flowering (12 May), and a daily count of floral openings was made. Flowers within the quadrat which opened before 3:00 pm were tallied each day and removed. Lodging scores were assigned to each plot on 21 June using a scale of 0 to 10 with 0 indicating no lodging and 10 signifying full lodging.

Yield component samples and final total above-ground plant dry weight measurements were taken as the average of two 1000 cm^2 samples harvested on 17 June. The components sampled were seeds per flower, floral density (flowers per 1000 cm^2), and 1000-seed weight. (Note that floral density measurements were made from two samples per plot on 17 June while floral phenology was a daily measurement from one quadrat over the entire flowering period.)

Seeds were harvested 30 June from a 4.46 m^2 sampling area within each plot with a flail-chopper (Carter Manufacturing, Brookston, IN 47923). A 30 cm strip between the harvested area and the edge of the plots was maintained to prevent border effects. Shattered seed from the harvested area was collected with a vacuum and added to the harvested plot material which was then air-dried and threshed for seed yield and seed-oil content determinations. A rain storm interrupted the harvest and prevented the completion of the uniform harvest of 19 of 52 plots. Therefore, the statistical analyses on seed and oil yield data were performed with only the 33 plots harvested before the storm. Because of the unequal number of replications making up each treatment mean, a regression model was used to determine appropriate error terms for statistical comparisons of oil and seed yields (Engelstad, 1968 and 1969).

Seed oil content was determined on a dry-weight basis by a hexane solvent extraction method (Comstock and Culbertson, 1958). The average of two subsamples was recorded as the oil percentage for each plot. Oil yield was calculated as the product of seed yield and oil percentage.

Statistical Analyses

Analysis of variance was performed to evaluate differences among means for the measurements of seed-oil content, floral density, seeds per flower, 1000-seed weight, dry weight, canopy height, lodging score, canopy density, and plant N uptake. Student's t-test was used for mean separation of seed and oil yields.

Mean separations for seed-oil content, floral density, seeds per flower, and 1000-seed weight and lodging score were tested for statistical significance by the LSD as follows:

1. all N treatment means were compared with the control mean,
2. treatment means which received the same rate of fertilizer were arrayed and adjacent values were compared,
3. treatment means within each regime were arrayed and adjacent values were compared (Little and Hills, 1978).

One experiment-wise error term was calculated to determine the LSD for each factor measured above, and all mean comparisons were made at the 0.05 level of probability unless otherwise stated.

Statistical comparisons of means for dry weight, canopy height, canopy density and N uptake treatment means were performed as follows:

1. all N treatment means were compared to the control mean for the same date,
2. means within each regime were arrayed for each date and adjacent means were compared, and
3. means across dates for the same treatment were arrayed and adjacent means compared.

Comparisons were made using the LSD value at the 0.05 level unless otherwise stated.

Regression analyses for seed and oil yields were performed by fitting the data to the following first order multiple regression model (Engelstad, 1968, 1969; Neter et al., 1983):

$$Y = a + b_1X_1 + b_2X_2 + \dots + b_{15}X_{15}$$

The b_i are linear regression coefficients and the x's are indicator variables for replications, the control, N rates, regimes, and N rate and regimes interaction (see appendix 1). Student's t-test was performed to determine significance using the estimated means and standard error of the difference.

RESULTS AND DISCUSSION

Oil Yield Components

Seed Yield. Seed yields under all N treatments were significantly greater than the control (Fig.1, Table 2). Three distinct N response patterns were evident among the four regimes. First, the treatment mean for 200F was significantly larger than the 50F and 100F means. Secondly, the 100FS mean was significantly greater than both the 50FS and 200FS means. Thirdly, N applied in the winter and spring regimes at rates above 50 kg N ha^{-1} had no significant additional impact on seed yields relative to the 50W and 50S treatments, respectively.

Deleterious and yield-limiting effects of N fertilizer on meadowfoam seed yield as seen on the 200FS plots were also observed by Pearson (1983). Lodging and incidence of fungus were high in the plots receiving applications of spring-applied N during a cool, moist spring. Pearson observed that yield responses to N fertilizer varied according to the yearly weather conditions. The spring of the second year of Pearson's study was relatively dry and warm, and he reported no lodging, low incidence of fungus, and yields from N fertilizer treatments which were significantly greater than the control.

Nitrogen applied only in the fall in this experiment at the 100 and 200 kg rates was relatively ineffective. The low response from the fall-applied fertilizer may be attributed to leaching or

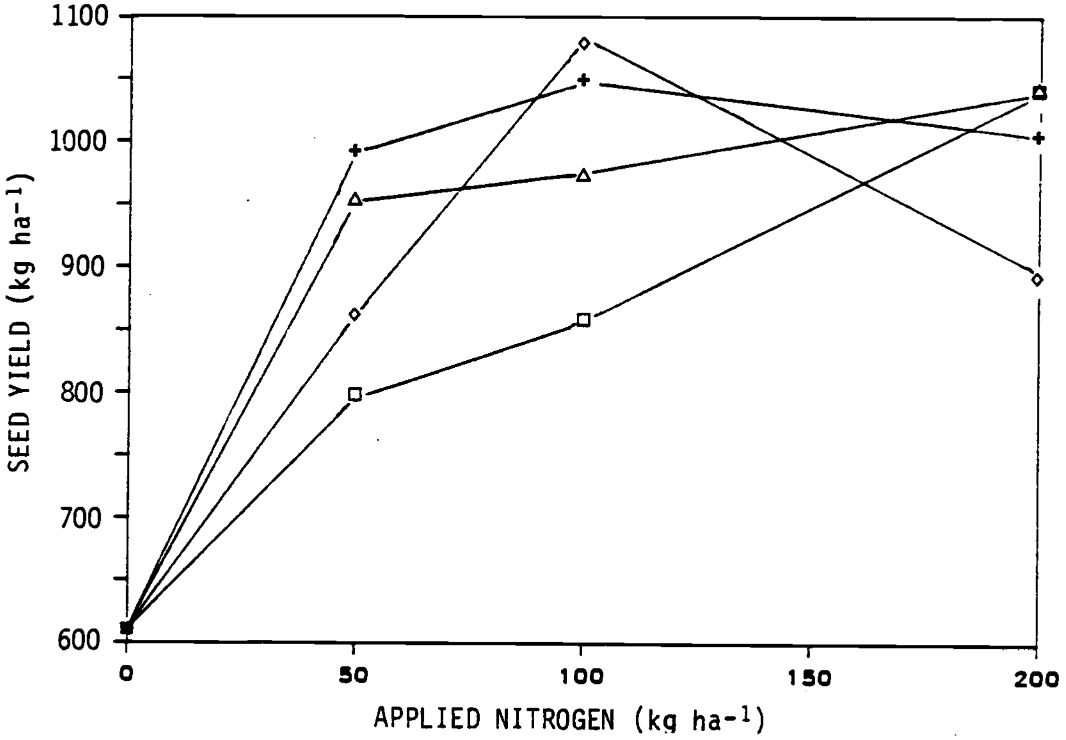

Figure 1. Seed yield as affected by N fertilizer. The lines were fitted to point estimates from the regression model for the fall (□), winter (+), fall/spring (◇), and spring (△) regimes. Comparisons for statistical difference are found on table 2.

Table 2a. Effects of N treatments on seed yields. Listed are the point estimates from regression analysis of seed yield means. Yields were arrayed by magnitude within each regime. Mean separation was performed by the Student's t-test between (1) adjacent means within each regime, (2) adjacent means within each rate, and (3) all N treatment means and the control mean. Results of the comparisons are shown in table 2b.

	Nitrogen fertilizer rate, kg ha^{-1}			
Regime	0	50	100	200
	kg ha^{-1}			
Fall		796	857	1040
Winter		992	1048	1003
Fall/spring		863	1083	894
Spring		953	976	1039
Control	611			

Table 2b. Mean separations for seed yield.

		C	Fall			Winter			Fall/Spring			Spring	
Regime	Rates	0	50	100	200	50	100	200	50	100	200	50	100
	200	**	-	-	-	-	-	ns	-	-	ns	ns	ns
Spring	100	**	-	ns	-	-	ns	-	-	-	-	ns	
	50	**	-	-	-	ns	-	-	ns	-	-		
	200	**	-	-	-	-	-	-	ns	*			
FS	100	**	-	-	-	-	ns	-	*				
	50	**	ns	-	-	-	-	-					
	200	**	-	-	ns	ns	ns						
Winter	100	**	-	-	ns	ns							
	50	**	-	-	-								
	200	**	*	*									
Fall	100	**	ns										
	50	**											

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

ns = Not significantly different at the 0.05 level.

\- = Mean comparisons not appropriate.

C = Control treatment.

volatilization losses during the cool winter months when the soil was saturated and poorly aerated.

Oil Content. Oil content was significantly greater than the control in seven out of twelve treatments (Table 3). All winter treatment means were significantly greater than the control, but none in the spring regime were observed to be different from the control (Table 3). Rate of fertilizer application did not statistically affect oil content within regimes except in the spring, where additional N over the 100S treatment produced a decrease (Fig. 2).

No previous studies were found which reported an increase in seed-oil content with the addition of N such as was observed in the fall, winter, and fall/spring regimes of this study. In contrast, the negative response of oil content to N fertilizer found in the spring regime was consistent with findings of others (Pearson, 1983). Johnson et al. (1980), working with fall, fall/spring, and spring applications of N, found a linear and negative seed-oil content response to N applications. The time of application did not significantly affect the response. Crane et al. (1981) found seed-oil content to decrease with N fertilization.

Seed-oil content has been reported to be negatively correlated with N fertility rates in flax (Dybing, 1964) and safflower (Yermanos et al., 1964). But, neither Hoag et al. (1968) nor Gilbert and Tucker (1967) found any correlation between safflower seed-oil content and rate or timing of N fertilization.

Dybing (1964) observed the oil content of flax seeds which developed from late-blooming flowers to be lower than the oil content

Table 3. Nitrogen treatment effects on three seed yield components and seed oil content. Means are the average of four replications. Means were arrayed by magnitude within each rate and within each regime, and mean separations for statistical significance were tested by the LSD. Comparisons were made between (1) means within each regime, (2) means within each rate of N, and (3) all N treatment means and the control mean. Only the third comparison is indicated. Effects of blocks, control, N, and interaction were analyzed. Statistical significance is presented at the bottom of the table.

Treatment					
Regime	Rate	Oil content	Floral density	Seeds per flower	1000-seed weight
	kg N ha^{-1}	%	0.1 m^2	no.	g
Fall	50	33.375	777	1.70	6.150
	100	34.750**	844	1.65	6.150
	200	34.500**	1225**	1.53	6.375
Winter	50	33.750*	999*	1.525	6.300
	100	34.625**	1274**	1.408	6.275
	200	34.125*	1687**	1.273**	5.775*
Fall/Spring	50	34.375**	920	1.593	6.225
	100	34.375**	1296**	1.463	6.225
	200	33.125	1414**	1.355*	6.225
Spring	50	33.625	943	1.640	6.200
	100	33.375	1407**	1.378*	6.100
	200	31.750	1308**	1.458	6.100
Control	0	32.125	629	1.548	6.125
LSD	.05	1.53	342	0.167	0.302
	.01	2.08	458	0.224	0.404
Blocks		ns	ns	ns	ns
Control		**	**	ns	ns
Rate		ns	**	**	ns
Regime		ns	*	**	ns
Rate x Regime		ns	ns	ns	*

*,** Significant at the 0.05 and 0.01 levels, respectively.
ns = Not significant at the 0.05 level.

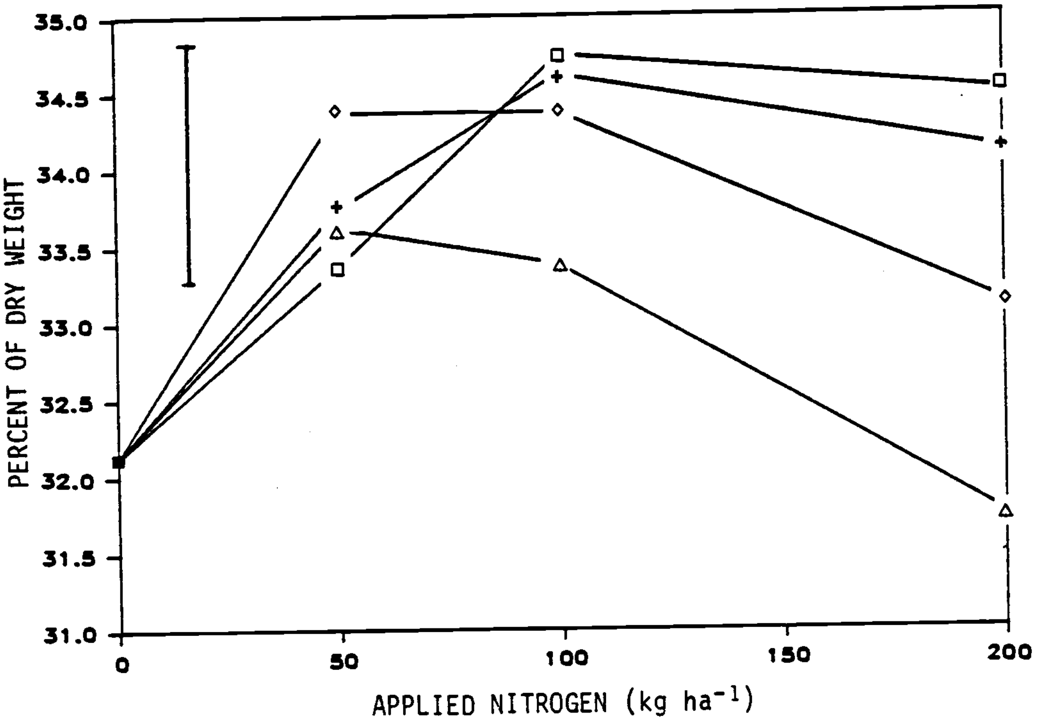

Figure 2. Seed oil content as affected by N fertilizer treatments. Lines represent the response of the fall (□), winter (+), fall/spring (◇), and spring (△) regimes. The vertical bar represents the experiment-wise LSD at the 0.05 level for comparison between (1) all N treatment means and the control mean, (2) means within each rate, and (3) means within each regime.

in seeds from early-blooming flowers. Moisture and temperature stress during the seed-filling period were factors implicated as adversely affecting oil development. Similarly, Leininger and Urie (1964) reported seed-oil content to increase with a longer seed-filling period.

Oil Yield. By definition, oil yield was significantly correlated with both seed yield and seed-oil content, however, variations for oil yield were most closely related to seed yield (Table 4). Yields were increased by all levels of N fertilizer relative to the control (Fig.3, Table 5). The 100FS mean was significantly greater than either the 50FS or 200FS mean, while the 200F mean was significantly greater than the 100F and 50F means. The treatment means did not vary significantly within either the winter or spring regimes.

Seed Yield Components

Floral Density. Floral density was the component most highly correlated with seed yield (Table 4) with eight out of twelve N treatment means greater than the control. The winter regime means were significantly greater than the control at every rate of N fertilizer (Table 3). Less effective were the fall/spring and spring regimes where applications of 100 and 200 kg N ha^{-1} produced significantly greater floral density means than the control, and the fall regime which required the highest rate of N to significantly increase floral density.

Table 4. Correlations between oil yields, seed yields, oil content and seed yield components.

	Oil yield[1]	Seed yield[1]	Oil content	Floral density	Seeds per flower
1000-seed weight	.2644	.2441	.0762	-.0142	-.0954
Seeds per flower	-.2933	-.3633*	.0837	-.7337**	
Floral density	.4599**	.5099**	.2374		
Oil content	.6187**	.4233*			
Seed yield	.9724**				

[1] Correlations in these columns were made from the samples in the 33 plots from which seed was harvested; the remaining correlations involved samples from 52 plots.

*, ** Correlations significant at the 0.05 and 0.01 levels of probability, respectively.

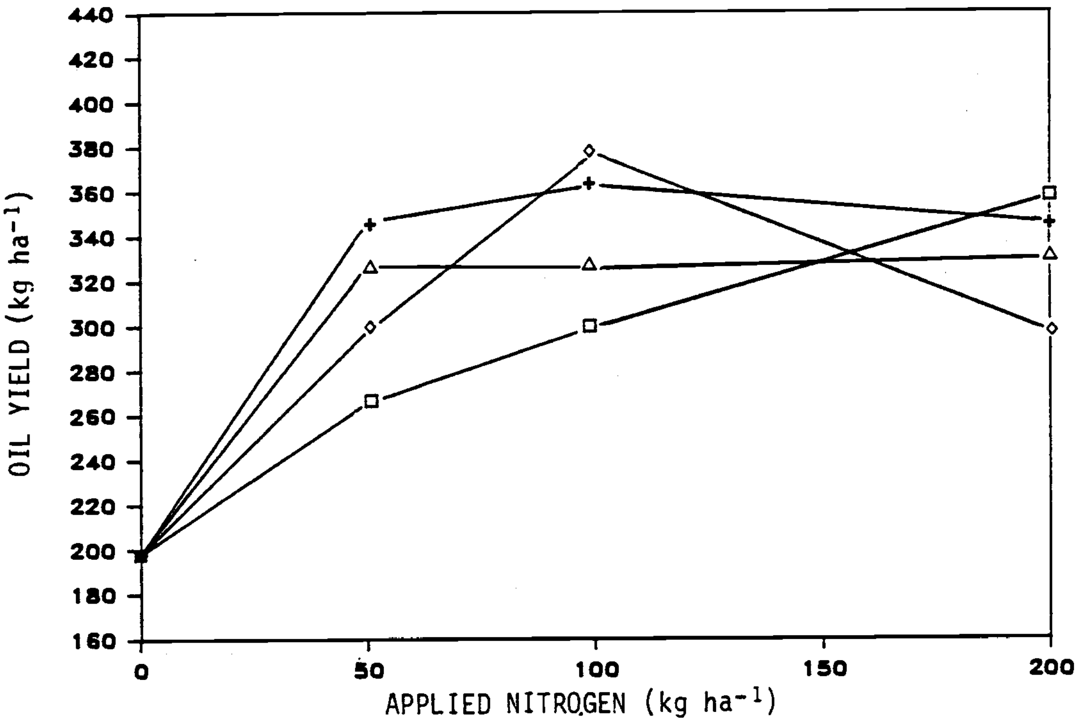

Figure 3. Oil yields as affected by N fertilizer. The lines were fitted to point estimates from the regression model for the fall (□), winter (+), fall/spring (◇), and spring (△) regimes. Comparisons for statistical difference are found on table 5.

Table 5a. Effects of N treatments on oil yields. Listed are the point estimates from regression analysis of oil yield means. Yield means were arrayed by magnitude within each rate and within each regime. Mean separation was performed by the Student's t-test between (1) adjacent means within each regime, (2) adjacent means within each rate, and (3) all N treatment means and the control mean.

	Nitrogen fertilizer rate, kg ha^{-1}			
Regime	0	50	100	200
		-----------	kg ha^{-1}	-----------
Fall		266	300	358
Winter		347	363	345
Fall/spring		298	377	297
Spring		327	331	326
Control	198			

Table 5b. Mean separation of seed-oil yields.

		C	Fall			Winter			Fall/Spring			Spring	
Regime	Rate	0	50	100	200	50	100	200	50	100	200	50	100
Spring	200	**	-	-	-	-	-	ns	-	-	ns	ns	ns
	100	**	-	ns	-	-	ns	-	-	-	-	ns	
	50	**	-	-	-	ns	-	-	ns	-	-		
FS	200	**	-	-	-	-	-	-	ns	*			
	100	**	-	-	-	-	ns	-	*				
	50	**	ns	-	-	-	-	-					
Winter	200	**	-	-	ns	ns	ns						
	100	**	-	-	ns	ns							
	50	**	-	-	-								
Fall	200	**	*	*									
	100	**	ns										
	50	*											

*,** Significant at the 0.05 and 0.01 levels, respectively.
ns = Not significantly different at the 0.05 level.
- = Mean comparisons not appropriate.
C = Control treatment.

Significant floral density increases in response to additional N application above the 100 N rate were observed in the early regimes (fall and winter), but not in the regimes which received all or half of the fertilizer on 5 March (fall/spring and spring) as shown in figure 4. Apparently, the plants did not respond to additional N fertilizer when applied on the later dates.

Seeds per Flower. Addition of N reduced the number of seeds per flower in three of twelve treatments. While no mean in the fall regime statistically differed from the control mean (Table 3), the 200W treatment mean was less than the control mean at the 0.01 level of probability. The number of seeds per flower was significantly correlated to seed yield at the 0.05 probability level but negatively correlated with floral density at the 0.01 level (Table 4, Fig. 4).

Pearson (1983) found a negative response in number of seeds per flower to spring-applied N during a wet year. He attributed the decrease to increased lodging and disease. Pierce and Jain (1977), working with single plants, reported a negative correlation between the number of seeds per flower and floral density.

Given that floral density was established prior to seed development, it appeared that the number of seeds per flower was limited by the floral density in 1983. Possible reasons for the reduction in seeds per flower in plots with high floral densities in this study include the following:

1. insufficient bee numbers on plots with high floral density;
2. decreased pollinator effectiveness due to reduced flower

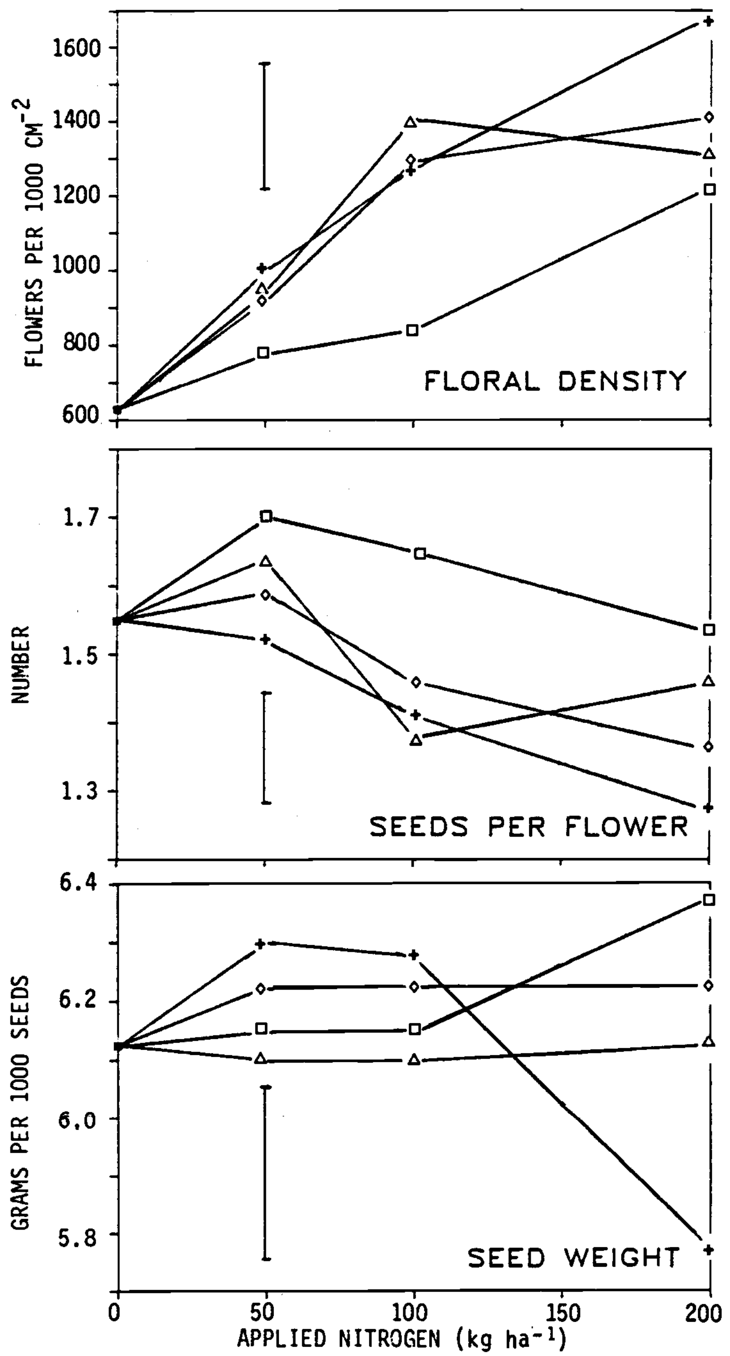

Figure 4. Seed yield components as affected by N fertilizer. Vertical bar reoresents the experiment-wise LSD at the 0.05 level of probability for comparison between (1) all N treatment means and control mean, (2) adjacent means within each rate, and (3) adjacent means within regimes. Lines connect treatment means of the fall (□), winter (+), fall/spring (◇), and spring (△) regimes.

accessibility under lodged conditions;

3. reduced total photosynthate production caused by self-shading; and,
4. destruction of floral parts and photosynthetic leaf area by fungal disease.

Seed Weight. The only significant variation in the 1000-seed weight arose from the 200W treatment which weighed significantly less than either the control or the 100W treatment (Fig. 4 and Table 3).

The lack of variation in meadowfoam seed weight response to N in this study was different from the results Pearson (1983) reported for a wet spring, but it was consistent with findings from a year with a dry period during flowering. Decreased seed weight under N treatments was attributed to increased lodging and fungal disease in the wet season.

Seed weight in this study had no significant correlation with oil content (Table 4). In contrast, Johnson et al. (1980), using another selection of meadowfoam, found a highly significant positive correlation between seed weight and oil content. Pierce and Jain (1977), in a study of five selections, reported that only one produced a significant correlation between seed weight and oil content.

Plant Growth and Development

Dry Weight. Total above-ground dry weight means were greater than the control on every sampling date in all treatments except for the 50F treatment after 8 April and for the 50S and 100S treatments on

24 March (Table 6). Higher rates of N produced greater dry weights in each regime (Fig. 5).

Treatment variations in the fall regime were most evident during the initial measuring periods (Fig. 5). Lack of a response from the 50F treatment with respect to the control after 8 April indicated that 50 kg N ha^{-1} applied in the fall had been sufficiently depleted by the early bud stage to preclude further contributions to plant growth.

Adjacent N treatment means, for a given date, within the spring regime were not significantly different until 22 April, but four of six differences were significant on the last three measuring dates (Table 6) during the periods of late-flowering and early-seed-fill. Thus, application of more than 50 kg N ha^{-1} on 5 March produced very little additional dry weight before flowering.

Differences between adjacent means were found in at least one comparison for every date in the winter and fall/spring regimes (Fig. 5). The winter regime had the most consistent rate effects with 11 out of 14 comparisons being significant. The early and sustained differences between adjacent dry weight means in the fall/spring and winter regimes indicated that these applications produced relatively large plants early in the spring and supported continued plant growth through the remainder of the growing season.

Canopy Height. Canopy height means of all N treatments were significantly greater than the control on the initial measuring date, but variation from the control was not maintained through the measuring period for all treatments (Table 7). The 50F treatment means were significantly different from the control on only two of the

Table 6. Dry weight response of meadowfoam to N fertilizer. Means are the average of four samples collected from 0.1 m^2. Mean separations for statistical significance were tested by the LSD. Comparisons were made between (1) means across dates for each treatment, (2) means within each regime for each date, and (3) between all N treatment means and the control mean for each date.

Treatments		Dates							LSD for dates across each treatment
Regime	Rate	Mar. 24	Apr. 8	22	May 6	20	June 3	17	
	kg N ha^{-1}	g							
Fall	50	12.1**	19.6*	28.8	37.3	43.1	37.6	46.6	9.73
	100	18.0**	25.8**	37.4**	49.5**	50.4**	50.6*	55.4**	10.00
	200	24.9**	35.4**	50.8**	59.1**	73.8**	65.6**	78.4**	11.87
Winter	50	19.4**	34.0**	36.9**	58.9**	61.8**	62.4**	60.4**	5.04
	100	25.4**	38.3**	63.9**	77.2**	77.7**	81.6**	78.0**	11.97
	200	31.4**	48.6**	72.4**	91.1**	105.4**	97.0**	95.9**	9.27
Fall/ Spring	50	13.5**	24.0**	38.4**	43.7*	45.9*	58.4**	52.6**	9.45
	100	18.1**	32.5**	45.4**	64.2**	67.8**	72.6**	75.3**	10.79
	200	18.5**	38.7**	62.6**	74.0**	83.6**	99.2**	91.5**	11.79
Spring	50	10.2	21.2*	36.2**	53.0**	46.1*	47.0*	54.3**	9.24
	100	10.4	25.7**	45.1**	61.6**	70.4**	73.5**	75.8**	9.66
	200	10.9*	24.5**	55.9**	67.5**	92.2**	87.6**	82.5**	20.56
Control	0	6.62	12.58	22.50	27.02	29.12	30.70	33.55	7.00
LSD for each date									
.05		3.8	6.4	10.0	12.8	14.9	15.9	13.2	
.01		5.1	8.6	13.4	17.2	20.0	21.3	17.7	

*,** Significant at the 0.05 and 0.01 probability level,respectively for comparisons between N treatment means and the control for each date.

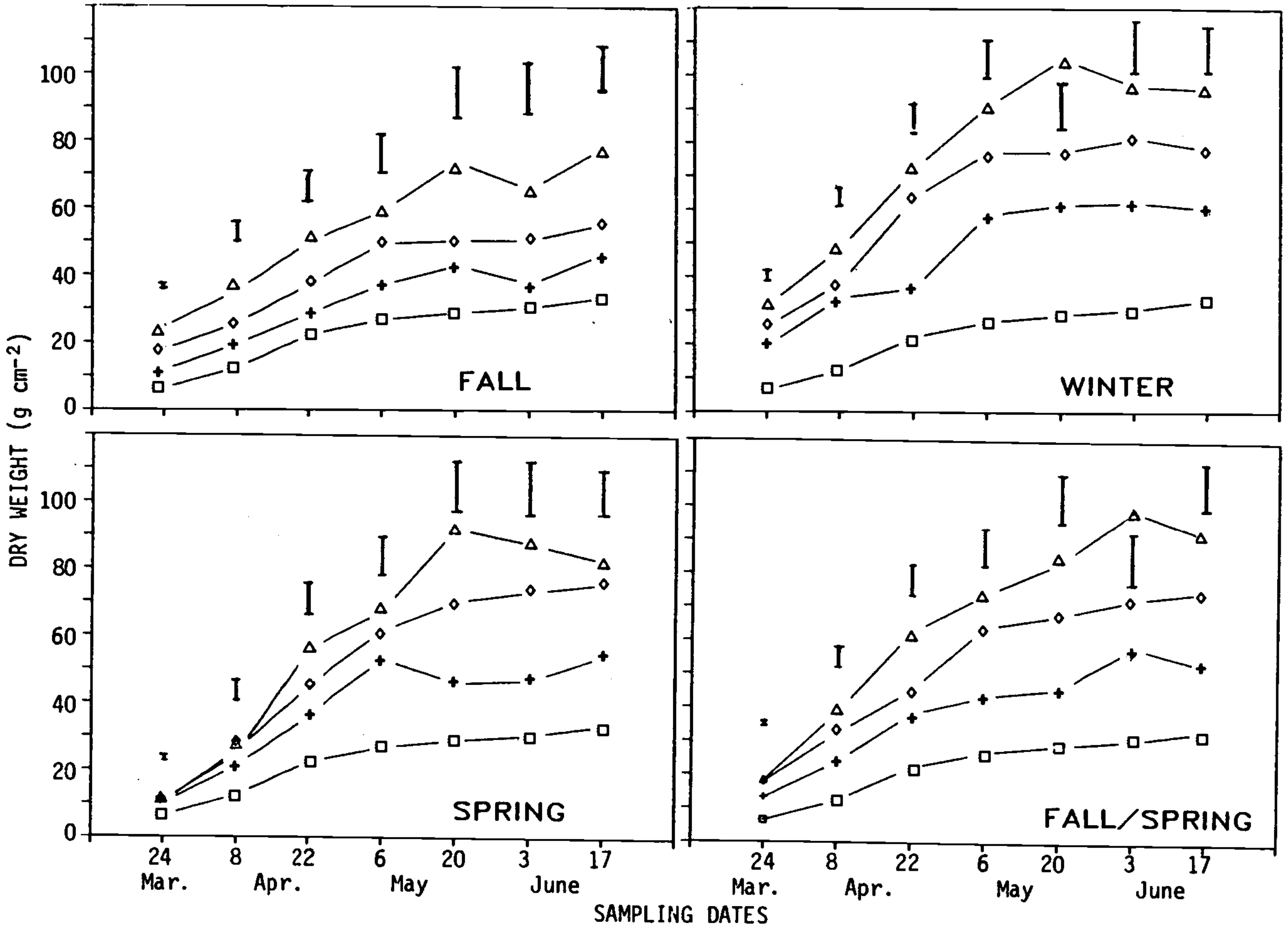

Figure 5. Dry weight as affected by nitrogen fertilizer treatments. Statistical comparisons of adjacent means within each regime were performed at each date by LSD at the 0.05 level. The bar above each date represents the LSD for that date. Lines connect treatment means which received rates of 0 (□), 50 (+), 100 (◇), and 200 (△) kg ha^{-1}.

Table 7. Canopy height response of meadowfoam to N fertilizer. Means are the average of four samples collected from 0.1 m^2. Mean separations for statistical significance were tested by the LSD. Comparisons were made between (1) means across dates for each treatment, (2) means within each regime for each date, and (3) all N treatment means and the control mean for each date.

Treatments		Dates						LSD for dates across each treatment
		Apr.		May		June		
Regime	Rate	8	22	6	20	3	17	
	kg N ha^{-1}	cm						
Fall	50	11.5**	13.0	18.0	30.8**	32.3**	30.0	4.70
	100	14.0**	15.0**	21.8**	32.0	34.8**	34.0**	1.00
	200	15.8**	19.0**	26.0**	35.0**	38.3**	37.8**	1.72
Winter	50	14.0**	15.0**	23.3**	33.3*	36.8**	36.0**	2.08
	100	16.3**	19.0**	27.8**	36.3**	40.8**	39.5**	3.33
	200	21.0**	25.0**	34.0**	34.0*	30.3	23.3*	3.98
Fall/ Spring	50	11.8**	14.0*	20.3**	29.3	33.8**	33.0**	2.40
	100	13.8**	16.3**	25.0**	35.35*	37.8**	37.8**	1.14
	200	16.8**	22.5**	29.5**	39.8**	38.5**	35.35**	4.05
Spring	50	11.3**	14.0*	18.8	31.5	32.3**	33.0**	2.97
	100	12.5**	15.3**	22.3**	33.3*	37.0**	35.8**	1.81
	200	13.5**	18.5**	25.8**	36.0**	30.8	28.8	4.55
Control	0	9.00	11.75	16.50	28.00	28.00	27.00	3.42
LSD for each date								
.05		1.30	1.97	2.48	4.96	3.07	3.15	
.01		1.74	2.64	3.33	6.65	4.12	4.22	

*,** Significant at the 0.05 and 0.01 probability level, respectively for comparisons between N treatment means and the control for each date.

five remaining dates and the 200W and 200S means declined significantly after 3 June and 20 May respectively (Fig. 6). The decline in canopy height, which reflected lodging, began during the flowering period and may have affected pollination on the 200W and 200S plots.

Lodging Scores. There was very little lodging in the control or the 50 kg N ha^{-1} plots on 21 June, but significant differences from the control were observed for seven of eight treatments receiving 100 and 200 N treatments (Fig. 7 and Table 8).

Significant differences between regime means for a given rate occurred only at the 200 N rate. The 200FS score was significantly greater than 200F, and the 200S score was significantly greater than the 200FS score.

Each increment of N above 50 kg ha^{-1} applied in the winter and fall/spring regimes produced a significant increase in lodging for the respective regime, and an addition to the 100S treatment significantly increased lodging in the spring regime. The adjacent treatment mean differences within the fall regime were non-significant.

Canopy Density. Canopy density was calculated throughout the growing season as dry weight/canopy height as a parameter to monitor the occurrence of lodging over time. Lodging scores taken on 21 June were most closely correlated with the densities on the last three measuring dates (Table 9); therefore, only the densities from 20 May, 3 June, and 17 June are discussed with respect to lodging. On these dates, the winter, fall/spring and spring means were significantly different from the control in eight, seven, and six comparisons,

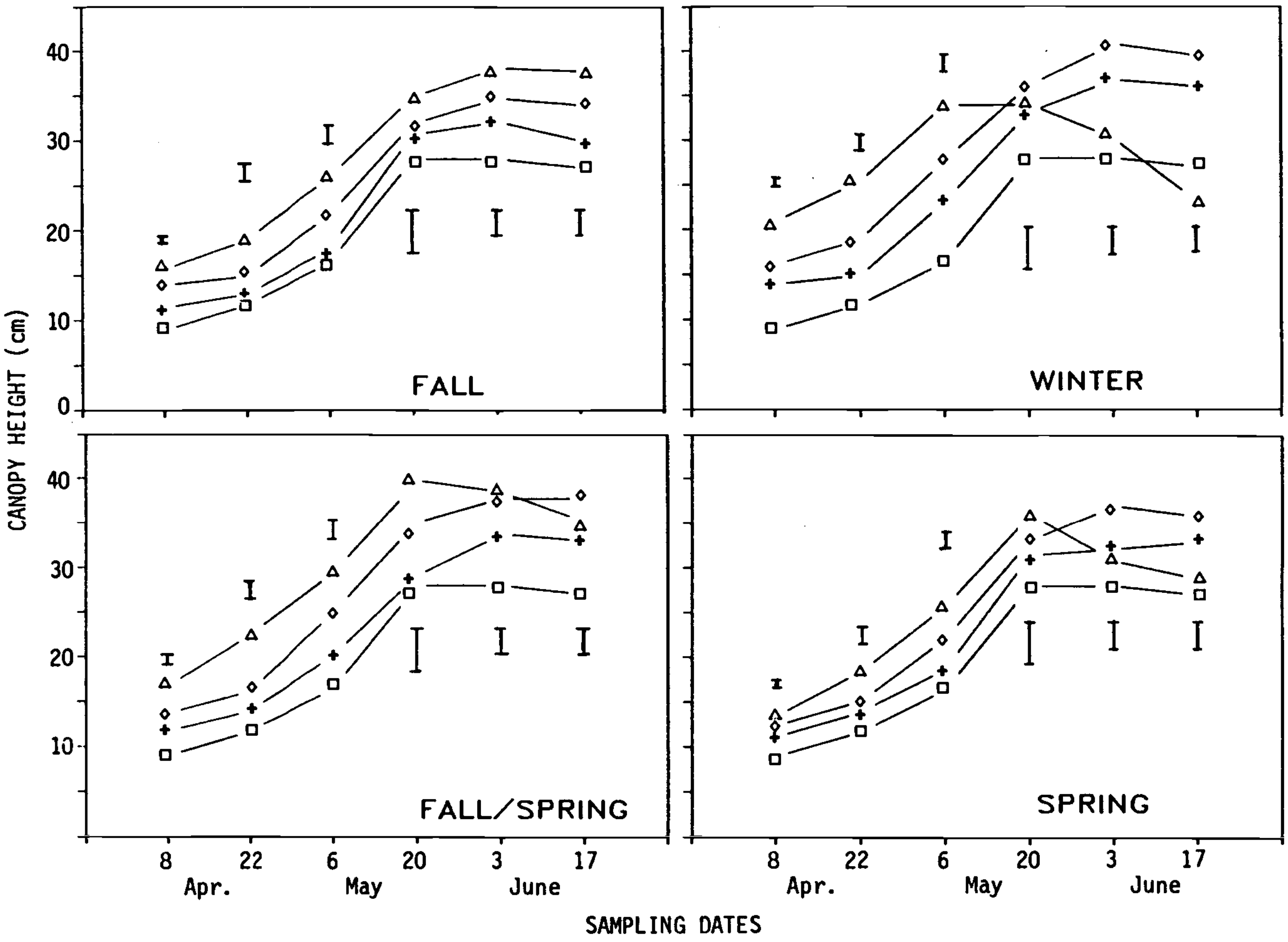

Figure 6. Canopy height as affected by N fertilizer treatments. Statistical comparisons of adjacent means within each regime were performed at each date by the LSD at the 0.05 level. The bar above each date represents the LSD for that date. Lines connect treatment means which received rates of 0 (□), 50 (+), 100 (◇), and 200 (△) kg N$^-$.

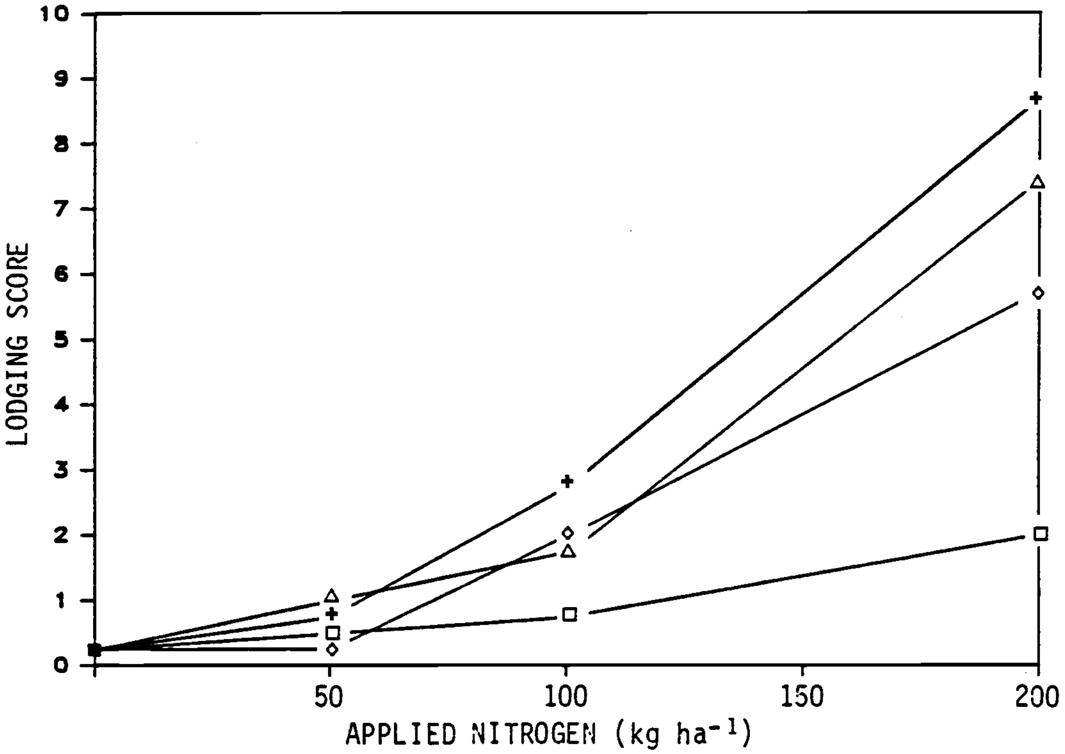

Figure 7. Lodging scores on 21 June as affected by N fertilizer. Scores of zero and ten indicate no lodging and complete lodging, respectively. The bar represents the experiment-wise LSD at the 0.05 level and was used for statistical comparison between (1) adjacent rate means within each regime, (2) between adjacent regime means within each rate, and (3) between all N treatment means and the control mean. Lines connect means within the fall (□), winter (+), Fall/spring (◇), and spring (△) regimes.

Table 8. Lodging scores on 21 June 1983 for each treatment. Each score is the mean of four replications. Mean separation was performed by use of the LSD. Scores were arrayed by magnitude within each rate and within each regime. Comparisons were made between (1) adjacent means within each regime, (2) adjacent means within each rate and (3) all N treatment means and the control mean.

	Nitrogen fertilizer rate, kg ha^{-1}			
Regime	0	50	100	200
Fall		.50	.75	2.00**
Winter		.75	2.75**	8.75**
Fall/spring		.25	2.00**	5.75**
Spring		1.00	1.75*	7.50**
Control	.25			

*,** Nitrogen treatment lodging scores significantly different from the control at the 0.05 and 0.01 levels, respectively.

Table 9. Correlations between lodging scores and canopy densities for each measuring date.

Date	Correlation coefficient
8 April	.2319
22 April	.2690
6 May	.2803*
20 May	.7362**
3 June	.8304**
17 June	.8702**

*,** Correlations significant at the 0.05 and 0.01 levels, respectively.

respectively, out of a possible nine comparisons for each regime (Table 10, Fig. 8). The fall regime canopy density scores were different from the control at only the 200 N rate during the same period.

The 200W means were greater than the 100W means for each of the last three dates (Fig. 8). The same comparisons were significantly different only for the last two dates in the fall/spring and spring regimes, and differences between rate means in the fall regime were not seen during this time.

Lodging as monitored by canopy density calculations occurred earliest in the 200W treatment. Early lodging may have decreased pollinator effectiveness. High canopy density probably maintained a higher relative humidity that favored the germination of _Botrytis cinera_ (Jarvis, 1977) and increased the probability of fungal infection.

Floral Phenology. Flowering in the control plots was delayed relative to the N treated plots (Table 11) which was contrary to findings of Pearson (1983), Johnson et al. (1980), and Ayres (1975). Application of the fungicide Roverall was a major difference between this study and the other three and may have affected phenology. Meadowfoam maturity was markedly delayed by four applications of Roverall, based upon visual comparisons between the experimental plots and the adjacent area. Therefore, while these floral phenology data may serve as a baseline for other studies, application of these data without reference to another year's study would be of questionable value.

Table 10. Canopy Density response of meadowfoam to N fertilizer in 1983. Means are the average of four samples collected from 0.10 m^2. The LSD was used to test for statistical difference between means. Mean comparisons were made between (1) means across dates for each treatment, (2) means within regimes for each date, and (3) between all N treatment means and the control mean for each date.

Treatments		Dates						LSD for dates across each treatment
		Apr.		May		June		
Regime	Rate	8	22	6	20	3	17	
	kg N ha^{-1}	---------------		g cm^{-3}		---------------		
Fall	50	1.7	2.2	2.1	1.4	1.2	1.6	.57
	100	1.8	2.5	2.3*	1.6	1.5	1.6	.49
	200	2.3**	2.7*	2.3*	2.1**	1.7*	2.1**	.49
Winter	50	2.4**	2.5	2.5**	1.9**	1.7*	1.7	.40
	100	2.4**	3.4**	2.8**	2.2**	2.0**	2.0**	.56
	200	2.3**	2.9**	2.7**	3.1**	3.2**	4.2**	.54
Fall/ Spring	50	2.1*	2.8*	2.2	1.6	1.7*	1.6	.50
	100	2.4**	2.8*	2.6**	1.9**	1.9**	2.0**	.40
	200	2.3**	2.8*	2.5**	2.1**	2.6*	2.6**	.50
Spring	50	1.9	2.6*	2.8**	1.5	1.5	1.6	.58
	100	2.1*	3.0**	2.8**	2.1**	2.0**	2.1**	.39
	200	1.8	3.0**	2.6**	2.6**	2.9**	3.0**	1.01
Control	0	1.42	1.88	1.67	1.05	1.10	1.24	.49
LSD for each date								
.05		0.54	0.71	0.57	0.57	0.54	0.56	
.01		0.72	0.95	0.76	0.76	0.72	0.75	

*,** Significant at the 0.05 and 0.01 probability level respectively as different from the control for the same date.

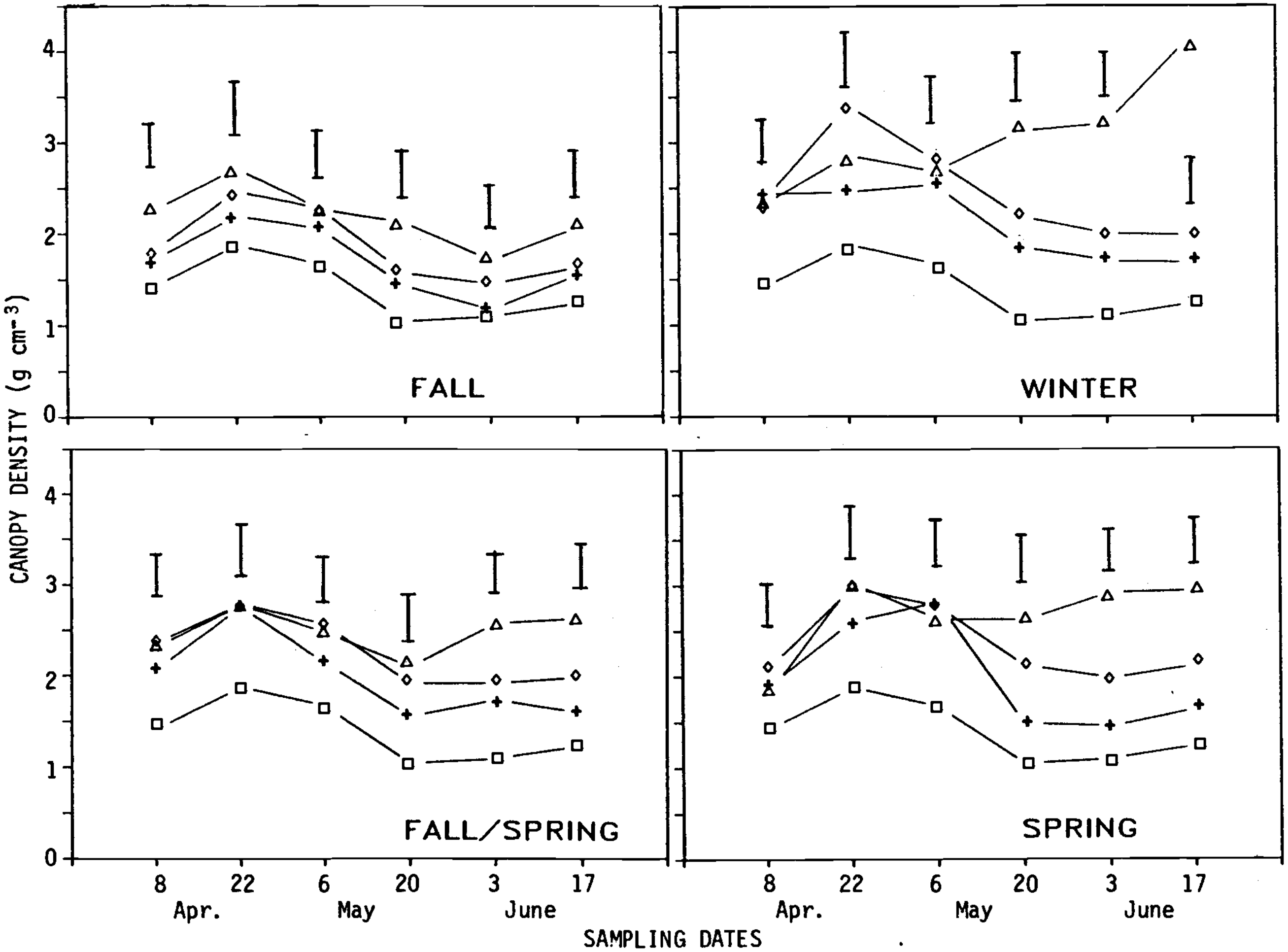

Figure 8. Canopy densities as affected by N fertilizer. Statistical comparisons of adjacent means within each regime were performed at each date by the LSD at the 0.05 level. The bar above each date represents the LSD for that date. Lines connect treatment means which received rates of 0 (□), 50 (+), 100 (◇), and 200 (△) kg N ha^{-1}.

Table 11. Percentage of flowers opening on 22 May 1983 and day of peak flowering for each treatment.

Regime	Nitrogen treatment	Percentage opening after 22 May Treatment	 Regime	Day of peak flowering
	kg ha^{-1}	--------- %	---------	
Fall			25.9	
	50	29.4		22/5
	100	21.4		20/5
	200	27.0		22/5
Winter			26.4	
	50	25.0		21/5
	100	20.2		20/5
	200	34.2		22/5
Fall/spring			29.0	
	50	28.0		20/5
	100	30.3		21/5
	200	28.6		22/5
Spring			40.2	
	50	28.7		21/5
	100	40.2		22/5
	200	51.6		21/5
Control	0	40.0		22/5

Forty and fifty-two percent of floral openings in the 100S and 200S treatments, respectively, occurred after peak flowering (date at which half the flowers on all plots had opened) compared to 26, 26, and 29 percent for the fall, winter, and fall/spring regimes, respectively (Table 11). Although not analyzed statistically, it appeared that applying N in the spring delayed flowering relative to the other regimes (Fig. 9).

Spring applications also produced the lowest seed-oil content (Fig. 2). Dybing and Zimmerman (1965) reported that oil content of flax seed which developed from late flowers was significantly lower than from seed which developed from early flowers. They suggested that seed which developed later in the season was under moisture and temperature stress. Hill and Knowles (1968) reported that safflower seed-oil increased when the seed-filling period was longer. Data from this study suggest that timing of N fertilizer application affects time of flowering which may influence the time and duration of the seed-filling period, and the oil content.

Plant Nitrogen

Plant Tissue Content. Tissue N content on the initial measuring day was greatest in the samples from the 100S and 100FS treatments which had received all or half the N application less than three weeks before sampling (Fig. 10A).

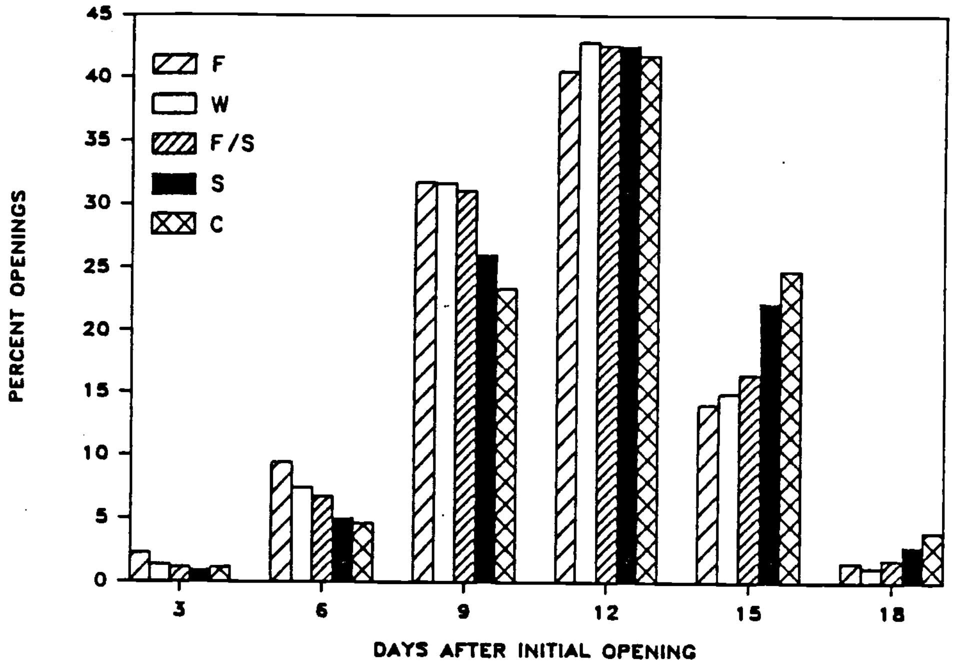

Figure 9. Percentage of floral openings during flowering stage as affected by N regime. Bars are means of regime treatments for each three day period. Regimes were fall (F), winter (W) fall/spring (F/S), spring (S), and control (C).

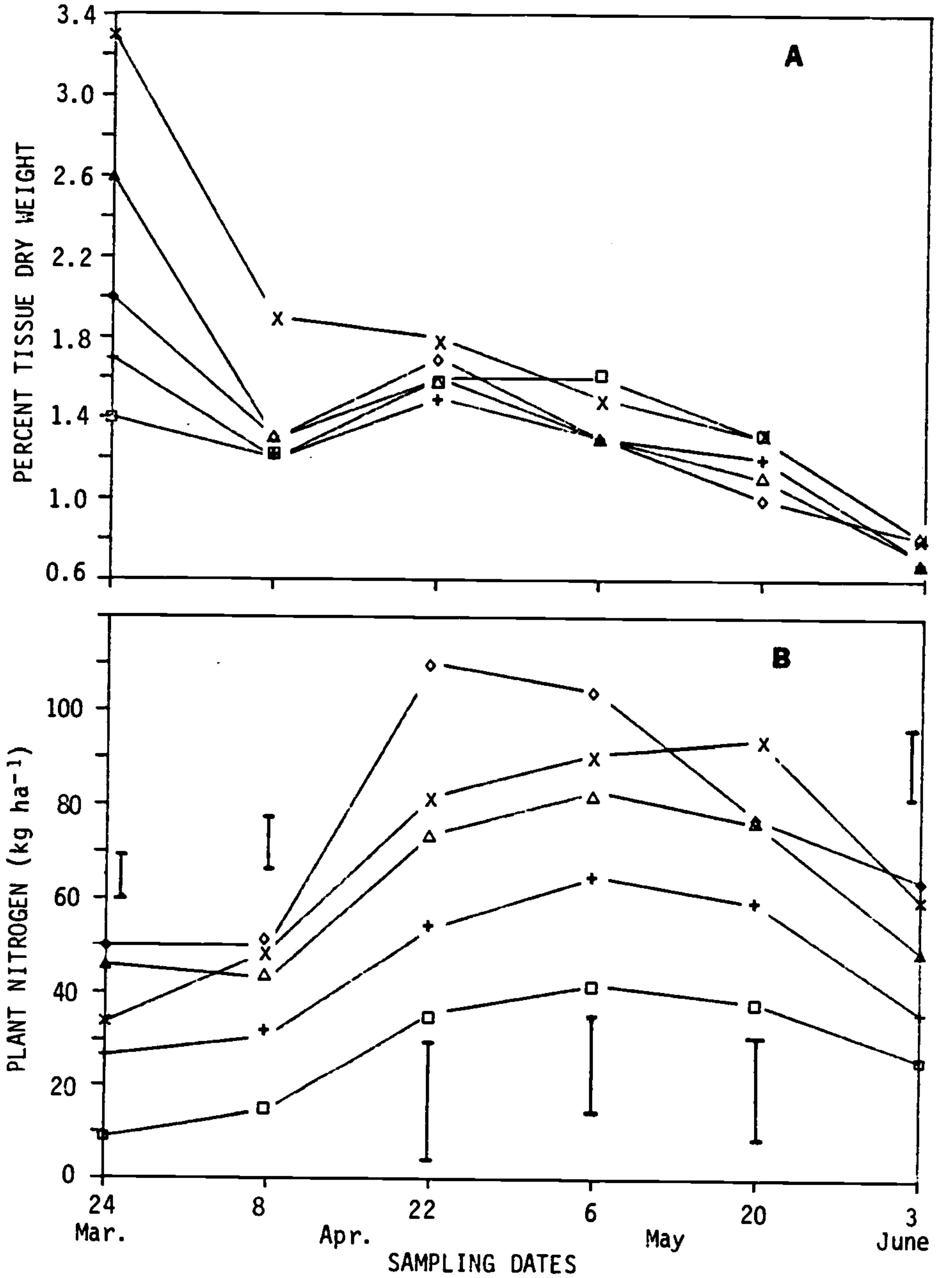

Figure 10. Effects of N on (A) tissue nitrogen content as percent of total above-ground dry weight, and (B) plant nitrogen in kilograms per hectare. Lines connect means of the control (□), fall (+), winter (◇), fall/spring (△), and spring (x). Bars above each date in B represent the LSD for comparison of adjacent means for each date.

Plant Nitrogen Uptake. Total N uptake was most efficient and occurred earliest in the the winter regime (Fig. 10B, Table 12). Approximately 40% of the N applied in the 100W treatment had been incorporated into plant material by the first measuring date. Tissue N peaked at 74 percent of the applied N in the 100W treatment by the mid-bud stage (22 April). Plant N in the other treatments peaked two to four weeks later during the late-bud and early-flowering stages. The relatively high and early uptake of N associated with winter application indicated that meadowfoam absorbed available N when soil temperatures were lowest and soil moisture had surpassed field capacity, and it suggested early establishment of a well-developed root system capable of using nutrients from a large portion of the soil profile.

The high N uptake of the 100W treatment was reflected in the dry weight means. Dry weight means from the 100W treatment were significantly greater than other 100 N treatments on three of the seven measuring dates (Table 6). But, the 100W lodging score mean, a concern associated with greater dry weight, was not significantly different than the other 100 N treatment means (Fig. 7).

Tissue N decreased in all five treatments over the last measurements. Daigger et al. (1976), working with wheat, found that N mineralized within the plant and escaped as ammonia gas if the plant vascular system was destroyed before the N was translocated. No data were taken in this experiment to test for the occurrence of this phenomenon, but Daigger's study provides a possible explanation. Roots and senesced leaves, which were not collected, were other

Table 12. Nitrogen uptake efficiency as affected by timing of N fertilizer.

Treatments*	Nitrogen uptake maximum	Nitrogen uptake efficiency
	kg ha^{-1}	%
Control	42	-
100F	65	23
100W	110	74
100FS	83	41
100S	94	56

* The treatments tested for tissue N were the control, and those receiving 100 kg ha^{-1} N fertilizer in the fall, winter, fall/spring, and spring regimes.

possible sources of tissue N loss. The large loss of N reflected a loss of plant tissue and photosynthetic area during stages critical for floral and seed development.

Soil Nitrogen

Soil Nitrogen Changes. The status of available N in the soil has been recognized as being difficult to assess relative to other plant nutrients such as P and K (Stanford, 1982). Transformations between available and organic forms of N are numerous and vary in rate according to soil type, weather, and farming systems. Given the volatile state of soil N, numerous samples would be required to make reliable interpretations. Soil sampling in this study was not replicated, therefore, only very general observations were made.

Ammonium and nitrate are generally considered the N ion species available to plants in the soil (Olson and Kurtz, 1982). Sources of soil ammonium include addition of fertilizer, and mineralization of organic matter (Stevenson, 1982). Nitrates are increased by fertilization and by conversion from ammonium by aerobic bacteria (Lynch, 1979). Nitrate is generally more readily leached, and is reduced by anaerobic bacteria to gaseous forms that are volatilized.

Soil nitrate decreased (beyond the amounts applied as fall, winter, and fall/spring treatments) on all plots between 11 November and 5 March (Fig. 11). Given the mobility of soil nitrate and the moist conditions, most of the loss was probably from leaching or denitrification. The greatest apparent change occurred on the 100F

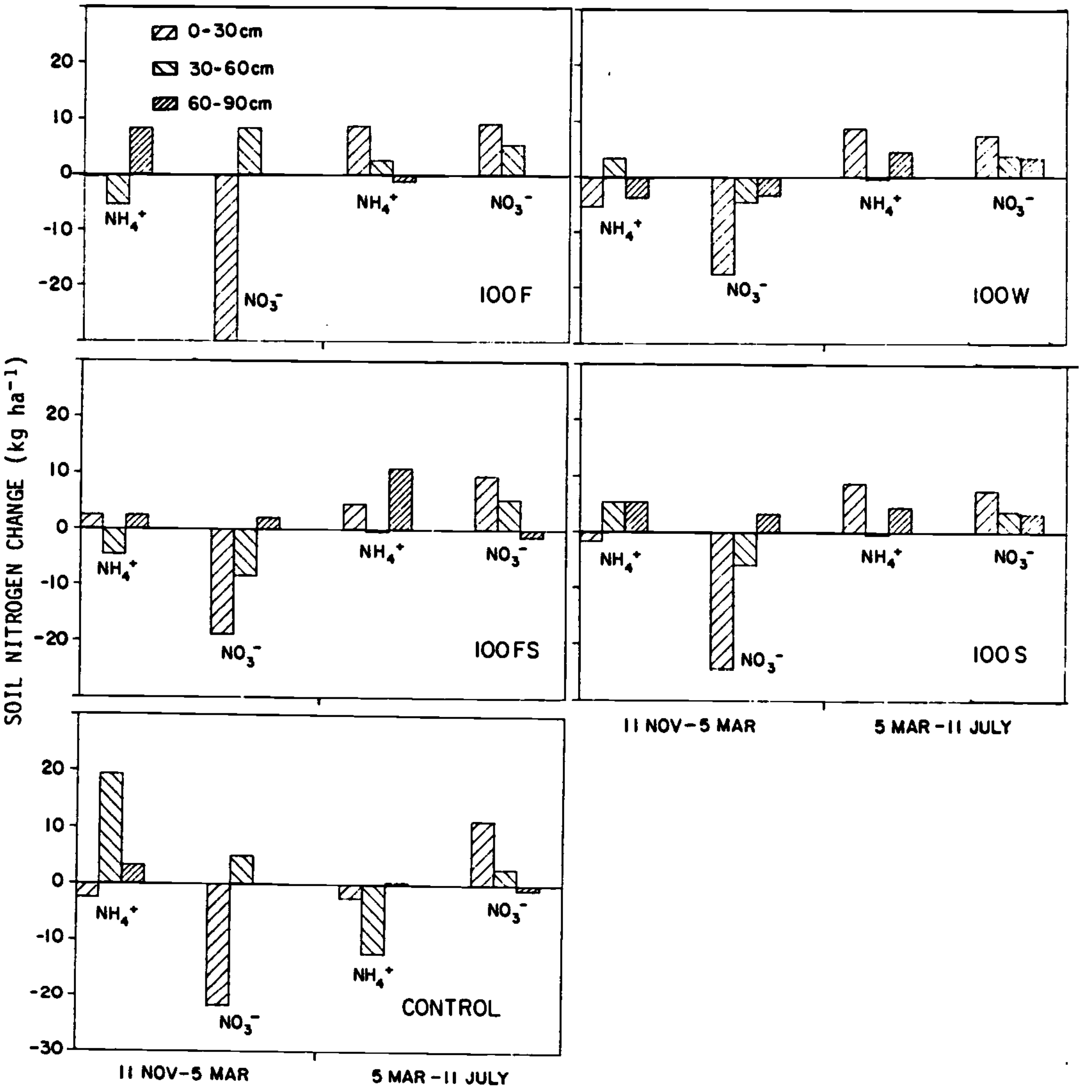

Figure 11. Soil ammonium-N and nitrate-N changes between 11 Nov. and 5 Mar. and between 5 Mar. and 11 July in plots receiving the 100F, 100W, 100FS, 100S and control treatments. The bars represent amount of change at depths of 0-30, 30-60, and 60-90 centimeters during each period.

plots which lost about 10 kg nitrate-N ha^{-1} more than the control despite the addition of 50 kg ha^{-1} nitrate-N. Some of the difference was accounted for in plant N which was about three times greater in the 100F plants than in the control plants on 24 March (Fig. 10B) and in the gain in nitrate seen in the 0.3-0.6 meter depth which was greater for the 100F plots than for the control (Fig. 11). The remaining difference between the amount applied and the amount measured was probably lost to denitrification or leached beyond the measurement depth.

Only the winter treatment decreased in soil nitrate-N at all three levels during the period of 11 Nov. - 5 March (Fig. 11). Much of the loss could have occurred from leaching and denitrification, but this observation may indicate that plants which received winter N extracted N from all three measuring depths.

Statistical Methods

The loss of 19 of 52 plots resulted in an imbalance among the number of replications making up each treatment mean and required the use of least squares methods in the form of a regression model. An example of the importance of the model in this case is seen by comparing the treatment means of 100W and 100FS (Table 13). The two samples which made the 100W mean were from higher-yielding blocks I and III while the 100FS samples were from the lower yielding blocks II and IV. The 100W mean was larger if the harvested samples were simply averaged, but the 100FS was estimated to be greater in the regression

Table 13. Individual samples of oil yields which make up the thirteen treatment means. The missing plots are indicated by (---). The harvested means are the simple averages of the plots for each treatment and the point estimates are the estimated yields from the regression model. Tests of statistical significance were performed on point estimates.

Treatments		Oil yields					
		Blocks				Treatment means	
Regime	Rate	I	II	III	IV	Harvested	Point estimate
	kg N ha^{-1}	kg ha^{-1}					
Fall	50	280	---	306	234	273	266
	100	298	310	306	---	305	300
	200	---	323	378	357	353	358
Winter	50	389	318	---	313	340	347
	100	421	---	342	---	382	363
	200	315	326	---	373	338	345
Fall/Spring	50	316	276	---	---	296	298
	100	---	353	---	365	359	377
	200	288	---	318	304	304	297
Spring	50	376	---	---	278	327	327
	100	---	---	351	---	351	331
	200	332	279	382	---	331	326
Control	0	---	193	215	168	192	198
Block means		335*	297*	325*	299*		

* Means of blocks I and III greater than blocks II and IV at the 0.06 level of probability.

model. While the model does not replace "lost" data, the least squares method provides a way to properly compare treatment means.

SUMMARY AND CONCLUSION

All N treatment means for seed and oil yields were significantly greater than the control. Winter applications were used most efficiently by meadowfoam, and all three winter rates produced significant increases over the control for oil content and floral density. All dry weight means from winter treatments were greater than the control for every date, but winter lodging score means, a concern related to dry weight production, were not significantly greater than adjacent means of other regimes at the 50 and 100 kg ha^{-1} rates of N fertilization.

Fall applications of N fertilizer were effective in plant establishment, but had marginal impact in terms of dry weight after the early bud stage. Dry weight gains and flowering were delayed by spring applications, and applications before 5 March increased seed-oil content. Fall/spring N applications were not taken-up as efficiently as the winter and spring regimes, but lodging scores for the highest N rate were significantly less than the winter and spring regimes.

Future studies are needed to more clearly identify fertilizer application schedules that would provide optimal yields of seed-oil. It appears that some N should be applied in the fall for plant establishment, but the amount should be limited because of the leaching potential. A second application should be made before March to benefit from uptake efficiency of winter applications and to avoid delayed flowering. From this study it appears that about 40% of the total rate should be applied in the fall (at planting) with the remaining quantity applied in late January or early February. Fall applications of slow-release forms of N should be a part of future studies.

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APPENDICES

App. 1. Regression model of the harvested seed yields. Indicator variables were used to represent each effect. The block within which each sample was measured is represented in columns 1-3, and the control is in column 4. Rates and regimes, the main effects, are represented in columns 5-6 and 7-9, respectively. The interaction variables are represented in columns 10-15. A condition for the variable was either true (1) or not true (0) for each sample, or if the appropriate condition was not listed, the sample was assigned a -1 under the columns for that category. The interaction indicator variables were determined as the product of the variables of the main effects.

Treatments	Blocks			Control	Rates		Regimes			Interactions					
	I	II	III	C	50	100	F	W	FS	50 F	50 W	50 FS	100 F	100 W	100 FS
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
50F	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0
	0	0	1	0	1	0	1	0	0	1	0	0	0	0	0
	-1	-1	-1	0	1	0	1	0	0	1	0	0	0	0	0
100F	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0
	0	1	0	0	0	1	1	0	0	0	0	0	1	0	0
	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0
200F	0	1	0	0	-1	-1	1	0	0	-1	0	0	-1	0	0
	0	0	1	0	-1	-1	1	0	0	-1	0	0	-1	0	0
	-1	-1	-1	0	-1	-1	1	0	0	-1	0	0	-1	0	0
50W	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0
	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0
	-1	-1	-1	0	1	0	0	1	0	0	1	0	0	0	0
100W	1	0	0	0	0	1	0	1	0	0	0	0	0	1	0
	0	0	1	0	0	1	0	1	0	0	0	0	0	1	0
200W	1	0	0	0	-1	-1	0	1	0	0	-1	0	0	-1	0
	0	1	0	0	-1	-1	0	1	0	0	-1	0	0	-1	0
	-1	-1	-1	0	-1	-1	0	1	0	0	-1	0	0	-1	0
50FS	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0
	0	1	0	0	1	0	0	0	1	0	0	1	0	0	0
100FS	0	1	0	0	0	1	0	0	1	0	0	0	0	0	1
	-1	-1	-1	0	0	1	0	0	1	0	0	0	0	0	1
200FS	1	0	0	0	-1	-1	0	0	1	0	0	-1	0	0	-1
	0	0	1	0	-1	-1	0	0	1	0	0	-1	0	0	-1
50S	1	0	0	0	1	0	-1	-1	-1	-1	-1	-1	0	0	0
	-1	-1	-1	0	1	0	-1	-1	-1	-1	-1	-1	0	0	0
100S	0	0	1	0	0	1	-1	-1	-1	0	0	0	-1	-1	-1
200S	1	0	0	0	-1	-1	-1	-1	-1	1	1	1	1	1	1
	0	1	0	0	-1	-1	-1	-1	-1	1	1	1	1	1	1
	0	0	1	0	-1	-1	-1	-1	-1	1	1	1	1	1	1
Control	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
	-1	-1	-1	1	0	0	0	0	0	0	0	0	0	0	0

App. 2. Regression coefficients from the model for oil yields, seed yields and oil content. Coefficients for the seed and oil yields are from the model of the 33 harvested samples, and coefficients for the oil content are from 52 samples. The indicator variables for blocks, control, N rate, application regime, and rate by regime interaction were dropped from the model to test for random variation of each effect.

Effects		Variable	Coefficients		
			Oil yield	Seed yield	Oil content
Constant			327.882	961.997	33.812
Blocks	I	X_1	16.485	25.816	0.817
	II	X_2	-21.312	-39.067	-0.837
	III	X_3	20.014	42.010	0.279
Control		X_4	-130.110	-350.725	-1.688
Nitrogen rates	50	X_5	-18.496	-60.819	-0.313
	100	X_6	15.033	29.000	0.469
Regime	Fall	X_7	-19.934	-64.254	0.396
	Winter	X_8	23.756	52.384	0.354
	Fall/Sp	X_9	-3.824	-15.408	0.146
Interaction	50F	X_{10}	-23.395	-40.546	-0.802
	50W	X_{11}	13.577	38.875	-0.385
	50FS	X_{12}	-7.372	-22.794	0.448
	100F	X_{13}	-23.275	-69.396	0.073
	100W	X_{14}	-3.380	4.356	-0.104
	100FS	X_{15}	38.378	107.325	-0.521

App. 3. Regression analysis for the effects of blocks, N treatment, control, N rate, application regimes, and interaction of rate and regime on oil yields, seed yields, and oil contents. The analysis was performed using the data from 33 samples for seed and oil yield and 52 samples for oil content.

Parameter	Source of variation	Variables	Degrees of freedom	F ratio	Probability of significance
Oil yield					
	Total model	15	17	5.5842	.0005
	Blocks	3	17	2.8443	.0686
	Control	1	17	44.1334	.0000
	Main effects				
	N rate	2	17	2.2009	.1413
	Regime	3	17	2.6117	.0849
	Interaction	6	17	2.6068	.0560
Seed yield					
	Total model	15	17	6.5567	.0002
	Blocks	3	17	1.6235	.2211
	Control	1	17	52.9743	.0000
	Main effects				
	N rate	2	17	4.0674	.0360
	Regime	3	17	3.4184	.0412
	Interaction	6	17	2.8678	.0406
Oil content					
	Total model	15	36	3.5058	.0010
	Blocks	3	36	5.5837	.0030
	Control	1	36	8.9550	.0050
	Main effects				
	N rate	2	36	2.8079	.0736
	Regime	3	36	3.7675	.0189
	Interaction	6	36	1.6605	.1592

App. 4. Statistical comparisons of seed yield means from selected treatments. The F ratio was calculated from the estimated difference of the means and the estimated error of the difference. Both estimates were calculated from the regression model.

Treatments compared	Estimated difference	Estimated error	F-ratio	Probability of significance
Cont X 50F	185.1	64.8	2.857	.0109
100FS X 200FS	189.0	74.1	2.552	.0206
100FS X 50FS	219.9	80.3	2.740	.0140
100F X 100S	118.6	93.1	1.274	.2198
100S X 100W	54.3	116.8	0.648	-----
100F X 200F	182.2	64.8	2.811	.0120
50F X 100F	61.0	64.9	0.940	.3603

App. 5. Analysis of variance for oil content, floral density, seed per flower, 1000-seed weight, and lodging scores for meadowfoam in 1983.

Source of variation	df	MS	F	P value
Oil content				
Treatment	12	3.50641	2.9864	.0055
Block	3	6.55609		
Error	36	0.04413		
Floral density				
Treatment	12	370188	6.5156	.0000
Block	3	24977		
Error	36	56816		
Seeds per flower				
Treatment	12	.064861	4.7994	.0001
Block	3	.010320		
Error	36	.013514		
1000-seed weight				
Treatment	12	.082853	1.8773	.0718
Block	3	.014551		
Error	36	.044134		
Lodging score				
Treatment	12	32.6923	32.8334	.0000
Block	3	5.3846		
Error	36	0.9957		

App. 6. Statistical comparisons of oil yield means from selected treatments. The F ratio was calculated from the estimated difference of the means and the estimated standard error of the difference. Both estimates were calculated from the regression model.

Treatments compared	Estimated difference	Estimated standard error	F ratio	Probability
Cont X 50F	68.29	26.34	2.593	.0190
50F X 100F	33.65	26.36	1.276	.2191
100F X 200F	58.38	26.34	2.216	.0406
100FS X 200FS	80.96	30.11	2.689	.0155
100FS X 50FS	79.28	32.62	2.430	.0265
100F X 100S	31.49	37.84	0.832	.4169

App. 7. Regression coefficients for the floral density, seeds per flower, and seed weight.

Source of variation		Indicator variable	Coefficients		
			Floral density	Seeds/ flower	1000-seed weight
(Intercept)		X_0	1174.3	1.4975	6.1750
Blocks	I	X_1	-20.0	0.0125	0.0442
	II	X_2	-43.8	-0.0090	-0.0173
	III	X_3	58.4	-0.0344	0.0058
Control		X_4	-545.6	0.0500	-0.0500
Rate	50	X_5	-264.7	0.1169	0.0438
	100	X_6	30.8	-0.0225	0.0125
Regime	Fall	X_7	-225.9	0.1292	0.0500
	Winter	X_8	145.5	-0.0958	-0.0583
	Fall/spring	X_9	35.7	-0.2750	0.0500
Inter-action	50F	X_{10}	93.3	-0.4354	-0.1188
	50W	X_{11}	-56.6	-0.0065	0.1396
	50FS	X_{12}	-25.1	0.0056	-0.0438
	100F	X_{13}	-135.7	0.0483	-0.0875
	100W	X_{14}	-77.0	0.0283	0.1458
	100FS	X_{15}	55.5	0.0150	-0.0125

App. 8. Regression analysis for floral density, seeds per flower and 1000-seed weight for meadowfoam.

Source of variation	Variables	df	F	P value	R
Floral density					
Total	15	36	5.3004	.0000	.8297
Blocks	3	36	.4396	.7261	
Control	1	36	19.3426	.0001	
N rate	2	36	17.7037	.0000	
Regime	3	36	5.3125	.0039	
Rate x regime	6	36	1.2499	.3047	
Seeds per flower					
Total	15	36	3.9923	.0003	.7903
Blocks	3	36	0.7636	.5219	
Control	1	36	0.6830	.4140	
N rate	2	36	13.6582	.0000	
Regime	3	36	7.8904	.0004	
Rate x regime	6	36	0.9871	.4485	
1000-seed weight					
Total	15	36	1.5678	.1330	.6286
Blocks	3	36	0.3297	.8039	
Control	1	36	0.2092	.6502	
N rate	2	36	0.3967	.9488	
Regime	3	36	0.9189	.4415	
Rate x regime	6	36	2.9440	.0193	

App. 9. Analysis of variance for meadowfoam dry weight means for dates within each treatment.

Source of Variation		df	MS	F	P value	LSD .05
50 F	Date	6	637.262	14.86	.0000	9.73
	Block	3	25.964			
	Error	18	42.884			
100 F	Date	6	820.716	18.12	.0000	10.00
	Block	3	252.916			
	Error	18	45.301			
200 F	Date	6	1560.550	24.45	.0000	11.87
	Block	3	89.393			
	Error	18	63.817			
50 W	Date	6	1192.170	103.74	.0000	5.04
	Block	3	135.538			
	Error	18	11.492			
100 W	Date	6	2005.460	30.89	.0000	11.97
	Block	3	45.839			
	Error	18	64.915			
200 W	Date	6	3113.260	79.96	.0000	9.27
	Block	3	5.540			
	Error	18	38.935			
50 FS	Date	6	1004.12	25.03	.0000	9.45
	Block	3	90.21			
	Error	18	40.11			
100 FS	Date	6	1945.91	37.17	.0000	10.79
	Block	3	4.88			
	Error	18	52.35			
200 FS	Date	6	3417.38	55.02	.0000	11.79
	Block	3	363.19			
	Error	18	62.11			
50 S	Date	6	1131.56	29.48	.0000	9.24
	Block	3	195.61			
	Error	18	38.35			
100 S	Date	6	2615.86	62.43	.0000	9.66
	Block	3	446.12			
	Error	18	41.90			
200 S	Date	6	4034.43	21.24	.0000	20.56
	Block	3	186.70			
	Error	18	189.93			
Cont.	Date	6	400.805	18.19	.0000	7.00
	Block	3	119.356			
	Error	18	22.037			

App. 10. Analysis of variance for meadowfoam dry weight means for measuring dates.

Source of Variation	df	MS	F	P value	LSD .05
24 March					
Trmt	12	207.075	29.391	.0000	3.8
Block	3	15.035			
Error	36	7.0455			
8 April					
Trmt	12	376.671	19.099	.0000	6.4
Block	3	68.782			
Error	36	19.722			
22 April					
Trmt	12	858.007	17.798	.0000	10.0
Block	3	138.201			
Error	36	48.209			
6 May					
Trmt	12	1182.020	14.771	.0000	12.8
Block	3	80.112			
Error	36	80.022			
20 May					
Trmt	12	1899.950	17.534	.0000	14.9
Block	3	98.226			
Error	36	108.362			
3 June					
Trmt	12	1864.10	15.111	.0000	15.9
Block	3	67.80			
Error	36	123.36			
7 June					
Trmt	12	1381.88	16.275	.0000	13.2
Block	3	107.90			
Error	36	84.95			

App. 11. Analysis of variance for canopy height date means for each treatment.

Source of Variation		df	MS	F	P value	LSD .05
50 F	Date	5	360.667	37.140	.0000	4.70
	Block	3	25.611			
	Error	15	9.711			
100 F	Date	5	365.000	864.474	.0000	1.00
	Block	3	2.389			
	Error	15	0.422			
200 F	Date	5	385.475	297.154	.0000	1.72
	Block	3	8.931			
	Error	15	1.297			
50 W	Date	5	431.875	227.635	.0000	2.08
	Block	3	1.931			
	Error	15	1.897			
100 W	Date	5	447.967	91.838	.0000	3.33
	Block	3	20.278			
	Error	15	4.878			
200 W	Date	5	123.900	17.728	.0000	3.98
	Block	3	1.889			
	Error	15	6.989			
50 FS	Date	5	373.667	147.500	.0000	2.40
	Block	3	3.000			
	Error	15	2.533			
100 FS	Date	5	473.575	823.609	.0000	1.14
	Block	3	2.375			
	Error	15	0.575			
200 FS	Date	5	340.875	47.289	.0000	3.98
	Block	3	1.889			
	Error	15	6.989			
50 S	Date	5	394.942	101.920	.0000	2.97
	Block	3	3.042			
	Error	15	3.875			
100 S	Date	5	464.400	321.508	.0000	1.81
	Block	3	7.444			
	Error	15	1.444			
200 S	Date	5	273.142	29.952	.0000	4.55
	Block	3	5.819			
	Error	15	9.119			
Cont.	Date	5	302.642	58.734	.0000	3.42
	Block	3	8.819			
	Error	15	5.153			

App. 12. Analysis of variance for canopy height treatment means for each measuring date.

Source of Variation	df	MS	F	P value	LSD .05
8 April					
Trmt	12	37.0160	44.9377	.0000	1.30
Blocks	3	2.6154			
Error	36	0.8237			
22 April					
Trmt	12	61.8494	32.8366	.0000	2.00
Block	3	16.4808			
Error	36	1.8836			
6 May					
Trmt	12	98.047	32.7856	.0000	2.50
Blocks	3	7.8653			
Error	36	2.9904			
20 May					
Trmt	12	40.1891	3.3620	.0024	5.0
Block	3	6.6346			
Error	36	11.9541			
3 June					
Trmt	12	58.5481	12.8130	.0000	3.1
Block	3	6.0000			
Error	36	4.5694			
17 June	12	89.2724	18.5234	.0000	3.2
	3	7.3333			
	36	4.8194			

App. 13. Analysis of variance for canopy density date means for each treatment.

Source of Variation		df	MS	F	P value	LSD .05
50 F	Date	5	0.60708	4.2435	.0132	.5696
	Block	3	0.02467			
	Error	15	0.14239			
100 F	Date	5	0.68480	6.4589	.0022	.4907
	Block	3	0.51472			
	Error	15	0.10602			
200 F	Date	5	0.43086	4.1282	.0147	.4868
	Block	3	0.16077			
	Error	15	0.10437			
50 W	Date	5	0.67073	9.6482	.0003	.3973
	Block	3	0.19158			
	Error	15	0.06952			
100 W	Date	5	1.24303	9.1002	.0004	.5569
	Block	3	0.53829			
	Error	15	0.13659			
200 W	Date	5	1.5957	12.6219	.0001	.5358
	Block	3	0.0470			
	Error	15	0.1264			
50 FS	Date	5	0.8298	7.4814	.0011	.5019
	Block	3	0.4220			
	Error	15	0.1109			
100 FS	Date	5	0.5478	7.6683	.0009	.4027
	Block	3	0.0140			
	Error	15	0.0714			
200 FS	Date	5	0.2404	2.2124	.1072	.4967
	Block	3	0.2168			
	Error	15	0.1086			
50 S	Date	5	1.3983	9.4221	.0003	.05805
	Block	3	0.3473			
	Error	15	0.1484			
100 S	Date	5	0.7010	10.3502	.0002	0.3921
	Block	3	0.7110			
	Error	15	0.0677			
200 S	Date	5	0.8082	1.7955	.1743	1.0110
	Block	3	0.5339			
	Error	15	0.4501			
Cont.	Date	5	0.4335	4.1061	.0150	.4896
	Block	3	0.2774			
	Error	15	0.1056			

App. 14. Analysis of variance for canopy density treatment means for six measuring dates.

Source of Variation	df	MS	F	P value	LSD .05
8 April					
Trmt	12	.392117	2.7558	.0093	0.541
Block	3	.334269			
T x B	36	.142288			
22 April					
Trmt	12	.585744	2.3778	.0223	0.712
Block	3	.165083			
T x B	36	.246340			
6 May					
Trmt	12	.460238	2.9354	.0062	0.568
Block	3	.05663			
T x B	36	.156790			
20 May					
Trmt	12	1.18886	7.6213	.0000	0.566
Block	3	0.103483			
T x B	36	0.155992			
6 June					
Trmt	12	1.63378	11.5866	.0000	0.538
Block	3	0.06230			
T x B	36	0.14100			
17 June					
Trmt	12	2.40522	15.9870	.0000	0.556
Block	3	0.112615			
T x B	36	0.15045			

App. 15. Analysis of variance for meadowfoam plant nitrogen uptake.

Source of variation	df	MS	F	P value	LSD
24 March					
Trmt	4	1049.61	18.8366	.0000	11.50
Block	3	15.71			
Error	12	55.72			
8 April					
Trmt	4	877.63	25.4765	.0000	9.04
Block	3	156.69			
Error	12	34.45			
22 April					
Trmt	4	3138.11	11.0011	.0006	26.02
Block	3	50.18			
Error	12	285.25			
6 May					
Trmt	4	2313.94	12.6013	.0003	20.88
Block	3	36.82			
Error	12	183.62			
20 May					
Trmt	4	1837.55	8.4710	.0017	22.69
Block	3	471.35			
Error	12				
3 June					
Trmt	4	1033.33	14.9074	.0005	14.91
Block	3	33.63			
Error	12	93.61			

App. 16. Soil N levels during the growing season in the plots of 100F, 100W, 100FS, 100S and the control treatments. Samples for each treatment were collected from each replicated plot at three depths on 11 Nov., 5 March and 11 July and analyzed for NO_3 (N) and NH_4 (A). The figures are in kg N ha $^{-1}$.

Treatment	Date	Form of N	Depth, cm		
			0-30	30-60	60-90
			----------	kg ha $^{-1}$	--------
100F	11 Nov.	A	10.08	15.96	7.98
		N	34.02	12.18	4.62
	5 Mar.	A	10.50	10.50	16.38
		N	3.78	3.78	4.62
	11 July	A	19.32	13.02	15.12
		N	13.02	9.24	4.62
100W	11 Nov.	A	15.96	10.08	14.28
		N	21.42	9.24	4.62
	5 Mar.	A	10.50	13.44	10.50
		N	3.78	4.62	1.26
	11 July	A	19.32	13.02	15.12
		N	11.34	8.40	4.62
100FS	11 Nov.	A	7.98	18.06	7.98
		N	21.42	12.18	4.62
	5 Mar.	A	10.50	13.44	10.50
		N	2.52	3.78	6.72
	11 July	A	15.12	13.02	21.42
		N	12.18	9.24	5.46
100S	11 Nov.	A	12.18	7.98	15.96
		N	28.14	10.50	4.62
	5 Mar.	A	10.50	13.44	10.50
		N	3.78	4.62	1.26
	11 July	A	19.32	13.02	15.12
		N	11.32	8.40	4.62
Cont.	11 Nov.	A	16.0	5.9	10.1
		N	24.4	10.5	5.5
	5 Mar.	A	13.4	25.2	13.4
		N	2.5	5.5	5.5
	11 July	A	13.9	8.4	4.6