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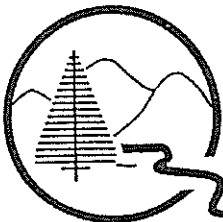
STREAM WATER QUALITY
ASSOCIATED WITH FOREST FERTILIZATION
IN THE UPPER KETTLE RIVER WATERSHED

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1 BACKGROUND

This report summarizes the results of stream water quality monitoring in, adjacent to and downstream of a forest fertilization project in the Penticton Forest District (Fig. 1).

Numerous studies regarding the impacts of fertilization on the aquatic environment are reported in the literature. Most of these studies have focused on agricultural applications. In the forested environment, research has shown that the most significant mechanism by which fertilizer can enter a stream is through direct application and to a lesser extent through off-site drainage during major storm events. Nitrogen which does enter a stream is rapidly depleted through utilization by aquatic organisms, adsorption by suspended and bottom sediments or, through dilution. With the possible exception of situations in which fertilizer has been applied directly into a stream, studies have shown that downstream water quality is unlikely to be affected by forest fertilization (USDA-FS 1980).

Nevertheless, concern regarding local forest fertilization projects and the potential for off-site movement of nitrogen prompted this water quality monitoring project. Forestry grade urea was applied to a number of juvenile lodgepole pine (Pinus contorta) stands in the Upper Kettle River watershed (Fig. 2) between October 26 and 29, 1990. This fertilizer is predominantly nitrogen (41%) and some sulfur (12%) (per Cominco Chemicals and Fertilizers). The fertilizer was spread aerially at a rate of 435 kg/ha resulting in the addition of 180 kg of nitrogen per hectare to each stand.

In an attempt to detect any changes which might be associated with fertilization, spring and fall stream water quality was monitored in 1989 and 1990 in the Upper Kettle River and several of its tributaries.

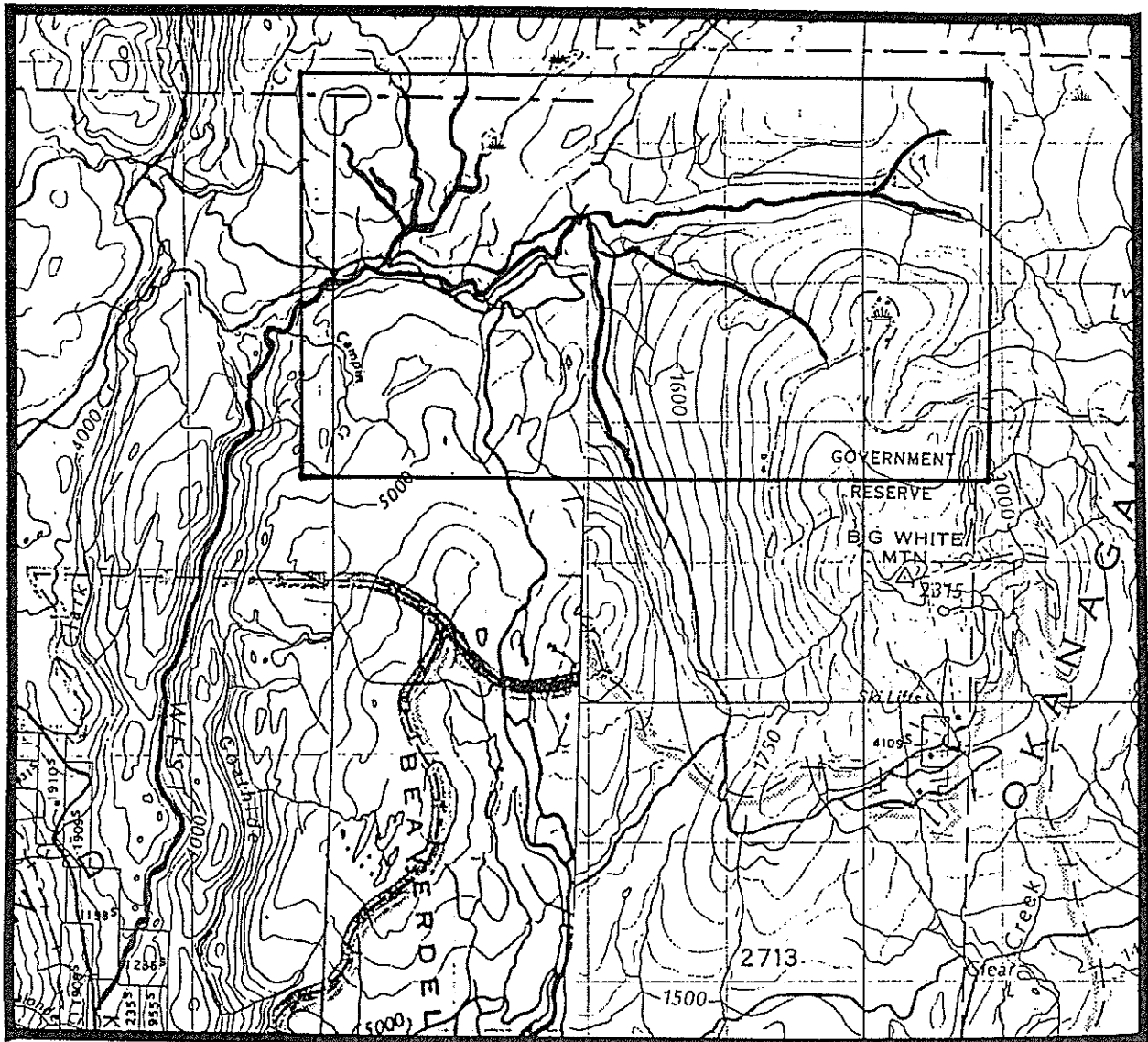


Figure 1. The study area.

Figure 2. Water quality sampling site locations.

2 FERTILIZER NITROGEN AND WATER QUALITY

Urea is produced by reacting ammonia with carbon dioxide, under pressure and at high temperatures (Tisdale and Nelson 1975). In moist conditions, urea is hydrolyzed to ammonium carbonate by the soil enzyme urease in approximately 4 to 7 days (Moore, Currier and Norris 1980). If moisture is limited, the rate at which this process occurs is reduced leading to an increase in soil surface pH and a loss of ammonia by volatilization. Volatilization losses are thought to be in the range of 20 to 30% when urea fertilizer is applied during extended periods of drought (Marshall 1986). Marshall (1986) suggests that these losses could be minimized by applying urea during autumn to early spring under moist conditions.

Ammonia released through hydrolysis is either utilized by soil microorganisms and/or vegetation, adsorbed to soil particles, retained in soil water (Moore, Currier and Norris 1980) or is oxidized to nitrite (NO_2^-) and finally nitrate (NO_3^-) by nitrifying bacteria (Hem 1970). Generally this latter process, referred to as nitrification, depends on soil pH (becoming negligible at a pH of 5 (Moore, Currier and Norris 1980)), soil moisture and temperature. Consequently, the rate of nitrification is significantly reduced during the winter months (Moore 1975). Silvicultural activities also influence the processes just described (by reducing vegetative cover leading to increased soil moisture and temperature which in turn increases microbial activity and reduces the vegetative uptake of nitrogen) and the timing of increased nitrogen loads on-site.

Nitrite and nitrate are the principal forms in which nitrogen is removed from forested ecosystems. Ammonium ions, which are readily adsorbed onto soil particles, especially in clay soils and soils with high cation exchange capacities, are not readily leached (Moore, Currier and Norris 1980). Leaching losses of nitrogen depend on all of

the processes outlined above, as well as on the nutrient uptake capacity of the vegetation remaining on-site. Any excesses of nitrogen contained in soil water may then be lost through subsurface and/or surface flow. It is these losses of nitrogen from a fertilized area which may impact on water quality.

Fertilizer nitrogen may enter water courses through surface runoff, subsurface drainage and/or direct application. Locally, surface runoff rarely occurs except from severely compacted areas such as skid trails and landings during major storm events. The greatest potential for increasing nitrogen concentrations exists by directly overspraying exposed surface water (Moore 1971, Neary and Leonard 1978, Brown 1980). Overspraying of larger streams can generally be avoided by marking a buffer zone and providing appropriate instructions to the applicator. However, it may be impossible to avoid smaller headwater streams.

Urea which falls directly into open water is subject to processes described previously. The ammonia produced through hydrolysis may subsequently be adsorbed on suspended solids or bottom sediments or, may remain in solution (Brown 1980). Nitrogen detected as ammonia in stream water samples is generally a result of direct application into the water course (Meehan, Lotspeich and Mueller 1975).

Nitrogen may also enter streams and lakes through subsurface flow. Nitrogen transferred in this way will generally be detected in stream water samples as nitrate. Nitrite nitrogen is seldom present in well-aerated streams (Hem 1970) in the Pacific Northwest (Brown 1980) and is, therefore, rarely separated from nitrate nitrogen in chemical analysis.

Studies of forest fertilization and water quality indicate short-lived increases in urea, ammonia and nitrate nitrogen concentrations. These monitoring studies range in length

from several weeks to 6 months and, in several cases, an entire year. The results of many of these studies are summarized by Moore, Currier and Norris (1980) and cited in Table 1.

Increased concentrations of urea nitrogen are largely caused by direct application (Moore, Currier and Norris 1980), the magnitude of these increases being directly proportional to the area oversprayed. Concentrations of up to 5 mg/l have been recorded in areas where no buffer strips were established but these levels only persist for a few hours (Moore, Currier and Norris 1980). Moore, Currier and Norris (1980) state that 3 to 5 days after fertilization urea nitrogen concentrations in stream water will have returned to pre-treatment levels.

Similarly, ammonium (the aqueous form of ammonia (Hem 1970)) concentrations resulting from overspraying are rapidly reduced through adsorption on stream sediments and uptake by aquatic organisms (Moore, Currier and Norris 1980). Peak concentrations recorded are generally 0.10 mg/l or less. These ammonium nitrogen levels are short in duration, generally only a few hours (Moore, Currier and Norris 1980) or days (Meehan, Lotspeich and Mueller 1975). The magnitude of increases in both urea and ammonia will depend on the presence and width of buffer strips and the number of small unprotected feeder streams (Moore, Currier and Norris 1980).

Increases in nitrate nitrogen concentrations have been recorded within a few days to a week after fertilization (Moore, Currier and Norris 1980). As stated previously, the increased levels of nitrate result largely from subsurface drainage. Peak concentrations are generally reported as less than 1.0 mg/l and decrease to pre-treatment levels within 2 to 4 months (Moore, Currier and Norris 1980). Where sampling was continued through the winter, additional peaks in concentration have been recorded coinciding with intense winter storms (Moore, Currier and Norris 1980) through to

Table 1. Stream water quality associated with forest fertilization throughout the Pacific Northwest.

Treatment: Aerial application of urea.											
Site:	Rate of application lb-N/ac kg-N/ha		Date of appli- cation	Treatment area		Peak Concentration					
						Urea-N		NH ₃ -N		NO ₃ -N	
						Pre- treatment	Post- treatment	Pre- treatment	Post- treatment	Pre- treatment	Post treatment
				ac	ha	-----mg/l-----					
Burns Creek ¹	50	56	Nov 1970	1390	562	0	0	0	0	0	0.068
Canyon Creek	200	224	Nov 1969	3325	1346	0.005	15.20	nd	nd	0.005	0.80
Coyote Creek	200	224	Mar 1970	170	68	0.006	1.39	0.005	0.048	0.002	0.177
Crabtree Creek	200	224	May 1969	570	230	---	24.00	0	0.080	0	0.25
Dollar Creek	200	224	Apr 1971	85	34	0.016	44.40	0.030	0.490	0.060	0.13
Elochoman Creek	200	224	Nov 1969	735	297	0.073	19.10	nd	nd	nd	4.00
Fairchild's Creek	200	224	Apr 1972	475	192	0.008	23.40	0.009	0.280	0.030	0.828
Falls Creek	190	213	May 1970	650	263	nd	nd	0.020	1.28	0.015	1.67
Jackson Creek	150	168	May 1969	235	95	0.007	0.09	0.004	0.044	0.065	0.116
Jimmycomelately Creek	200	224	Apr 1970	120	49	0.002	0.71	0	0.040	0.005	0.042
McCree Creek	50	56	Oct 1970	1265	513	0	0.62	0	0	0	0.210
Mica Creek	200	224	Sep 1972	115	47	0	0.30	0	0	0.15	0.28
Mill Creek	200	224	Dec 1969	565	228	0.02	0.68	0	0.12	0.02	1.32
Nelson Creek	200	224	Apr 1970	95	38	0.016	8.60	0.010	0.32	0.290	2.10
Newaukum Creek	150	168	Sep 1971	6085	2463	0.009	0.26	0	0.008	0.011	0.438
Pat Creek	200	224	Apr 1972	600	243	0.003	3.26	0.007	0.079	0.061	0.388
Quartz Creek	200	224	May 1972	125	51	0.004	1.75	0	trace	0.120	0.70
Roaring Creek	200	224	Mar 1972	660	267	0.007	0.76	0.004	0.040	0.017	0.210
Row Creek	150	168	Oct 1972	6500	2630	0.006	0.13	0.005	0.022	0.004	0.044
Skookumchuck Creek	150	168	Sep 1969	470	191	0	2.63	0.004	0.026	0.005	0.085
Spenser Creek	200	224	Nov 1972	7680	3108	0.019	0.37	0.041	0.123	0.005	0.005
Tahuya Creek	200	224	Oct 1972	4005	1620	0.01	27.20	0	1.40	0.01	1.83
Thrash Creek ²	200	224	May 1974	300	121	---	---	nd	0.06	nd	1.88
Three Lakes Creek	190	213	May 1970	170	69	nd	nd	0.015	0.13	0.003	2.36
Trapper Creek	200	224	Apr 1970	160	64	0.008	0.70	0	0.010	0.034	0.121
Trout Creek	200	224	Mar 1968	1600	648	0.10	14.00	0.12	0.700	0.03	0.160
Turner Creek	200	224	Mar 1972	870	352	0.004	4.36	0	0.046	0.032	0.243
Waddel Creek	200	224	Dec 1969	1480	600	0.01	2.48	0	0.340	0.02	0.99
Wishbone Creek	200	224	May 1972	115	46	0	0.30	0	0	0.12	0.28

¹(NH₄)₂ SO₄ applied

²NH₄NO₃ applied

nd = no data available or not determined

the following year (Meehan, Lotspeich and Mueller 1975). These concentrations tend to decrease with each successive storm. Again all peak concentrations were well below the acceptable limits for drinking water (Moore, Currier and Norris 1980).

Hetherington (1984) reports similar trends in two coastal British Columbia streams where urea was applied in mid-September. The fertilizer was applied during dry weather which continued until early November. Nitrogen losses, in the form of nitrate, were greatest during the rainy period which followed. Increased concentrations of nitrate nitrogen persisted slightly above background levels for approximately one year. Urea concentrations returned to pre-treatment levels within 6 days in one stream but persisted for 4 weeks in the second sample stream. Ammonia concentrations decreased to near pre-treatment levels in 13 days with minor increases during several major rainstorms within the two months following fertilization.

Total losses of nitrogen after forest fertilization are estimated to be 2 to 3 percent of the total applied where buffer strips were not established. Where buffer strips were established and overspraying was avoided losses are less than 0.5 percent (Neary and Leonard 1975; Moore, Currie and Norris 1980). Any of this total nitrogen which does enter the aquatic system is rapidly decreased through adsorption on stream sediments, biological utilization and dilution through natural stream mixing and increased water volumes downstream of the area fertilized (Brown 1980; Moore, Currier and Norris 1980). The actual concentrations of nitrogen, in its various forms, becomes important in assessing the potential for accelerated lake eutrophication and/or toxicity.

Hetherington (1984) cites guidelines for the protection of freshwater life as 0.02 mg/l un-ionized ammonia (NH_3). At the relatively low pH and temperatures commonly found in

local forest streams, Hetherington (1984) states that "over 99% of ammonia N is actually in the form of the ammonium ion and very little as un-ionized ammonia". Hetherington (1984) also cites toxicity levels of urea and nitrate nitrogen as 7500 mg/l and 90 mg/l respectively.

For drinking water, maximum acceptable levels have been defined by the B.C. Ministry of Health (1982). This limit is that beyond which greater concentrations of a given substance are capable of producing deleterious health effects or are aesthetically objectionable. For sulphate the maximum acceptable concentration is 500 mg/l. For ammonia, the maximum acceptable level originally cited is 0.5 mg/l. However, in a 1986 Ministry of Environment report by Norden and Pommen, dealing with revisions to water quality criteria, the authors state that insufficient data exist to define an ammonia concentration at which aesthetic, health or disinfection problems occur. Ammonia reacts readily with chlorine limiting its disinfecting efficiency in community water supplies. It may further promote the growth of organisms and corrosion in distribution lines (Health and Welfare Canada 1968). For nitrite plus nitrate nitrogen, the maximum acceptable concentration is 10 mg/l. Nitrates can "produce an irritation of the mucous membrane of the stomach, and diuresis (increased excretion of urine) accompanied by irritation of the mucous membrane of the urinary bladder" (Health and Welfare Canada 1968). Infants are particularly susceptible to high nitrate concentrations since nitrate can be converted to nitrite in the blood. This causes "an anemic condition resulting from the reaction of nitrite (NO_2^-) ions with haemoglobin" (Neary and Leonard 1978) producing methemoglobin which doesn't absorb oxygen (Nordin and Pommin 1986). Health and Welfare Canada (1968) cite that most reported cases of this disease (infantile methaemoglobinemia) have been associated with groundwater nitrate concentrations greater than 45 mg/L.

3 METHODS

Water samples were collected at 6 sites along the Upper Kettle River and two of its tributaries as shown in Figure 2. Three sampling sites (Stations 1, 2 and 4) were located upstream of the fertilized area and three sites (Stations 3, 5 and 6) were situated within or just downstream of the area treated.

Water samples were collected prior to fertilization during the spring peak and fall lowflow periods of 1989 and again following fertilization in the fall of 1989 and spring 1990. In total 19 pre and 14 post fertilization samples were obtained at each site as indicated in Figures 3 through 12. Pre fertilization collection dates were as follows: May 18, 25, Jun 1, 8, 15, 22, 29, Sep 18, 21, 25, 28, Oct 2, 6, 10, 13, 16, 19, 23 and 26, 1989. Post fertilization collection dates were: Oct 30, Nov 2, 4, 5, 6 and 11, 1989 and Apr 10, 17, 24, May 1, 8, 15, 22, 28 and Jun 5, 1990. The number of samples collected during each phase of this project are cited in Table 2. The exception to this was total Kjeldahl nitrogen which was not included in the study until the fall pre-fertilization sampling phase. The sample period included periods of no precipitation as well as periods of heavy rainfall. Sampling was most intense - every 2 days - immediately following fertilization. Water sampling was carried out in accordance with procedures established by the Water Quality Branch of Environment Canada (1983).

All water samples were delivered to Chemac Environmental Services in Kelowna within 5 hours of collection. Chemac Environmental Services then analyzed the samples for ammonia, nitrite plus nitrate and total Kjeldahl (includes both organic and inorganic) nitrogen, sulfate and acidity. Detection limits were 0.1 mg/L for ammonia, 0.01 for nitrite plus nitrate, 0.1 in 1989 and 0.01 in 1990 for total Kjeldahl nitrogen, and 1 mg/L for sulfate.

4 RESULTS

The results of water quality analyses for the samples collected during the Upper Kettle River fertilization project are presented in Figures 3 to 8 and summarized for the study period in Table 2. It should be noted that all concentrations below the detection limit have been recorded as "0" for graphing purposes.

For most parameters the range of pre/post fertilization and outside/inside the treatment area concentrations overlapped indicating no significant alteration in the range of test parameters resulting from the application of urea. Further, on several occasions samples collected at sites outside the fertilized area had higher concentrations following fertilization than those obtained at the treated sites. This is particularly evident in the data for sulfur and indicates the importance of considerable background data prior to developing conclusive statements.

Stream temperatures at all stations were below 7 °C throughout the study period and pH values ranged from 6.08 to 7.86 with no noticeable variation between pre and post fertilization data. This would indicate that most (over 99% according to Hetherington (1984)) of the ammonia nitrogen in the study streams would occur in the form of the ammonium ion and should, therefore, not pose a hazard to aquatic life. All values were below the recommended drinking water limit.

A comparison of pre and post fertilization data indicates that nitrite plus nitrate nitrogen concentrations were higher following fertilization. Elevated levels of nitrite plus nitrate nitrogen were observed in both the fall and during the peak spring runoff period following fertilization. Nitrite plus nitrate peaked at 0.18 mg/l at Station 3 and 0.13 mg/l at Station 5, compared to a pre-treatment maximum of 0.06 mg/l, during the week following

fertilization. At Station 6, nitrite plus nitrate concentrations peaked at 0.18 mg/l two weeks following fertilization. These peaks occurred during the first post-fertilization period of increased moisture - snowfall and melt (all sample streams were reported as having high water levels). In roughly one week, nitrite plus nitrate concentrations at Stations 3 and 5 had decreased to approximately pre-fertilization levels. Sampling was discontinued for the winter on Nov. 11, 1989 as a result of snow. Concentrations at Station 6 were increasing at this time. The delayed peak at this station could have been a result of its downstream location. It seems reasonable to assume that the overall pattern of increase and subsequent decrease in nitrite plus nitrate levels at Station 6 followed a similar pattern to trends observed at Stations 3 and 5.

Increased concentrations of total Kjeldahl nitrogen were recorded for several days following fertilization, likely a result of overspray or drift into the stream. Within one week this parameter had returned to pre-treatment levels. Spring post-fertilization concentrations were again above pre-treatment levels at Stations 5 and 6 but had returned to well within the pre-treatment range by May 1, 1990. These observations are in keeping with trends reported in the literature.

All concentrations at all sites, during all phases of this study were well below the drinking water quality standards cited earlier.

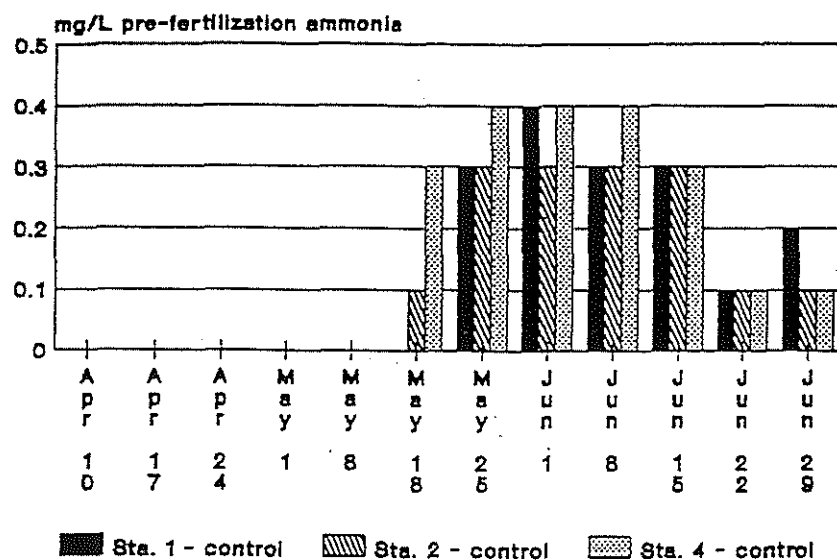
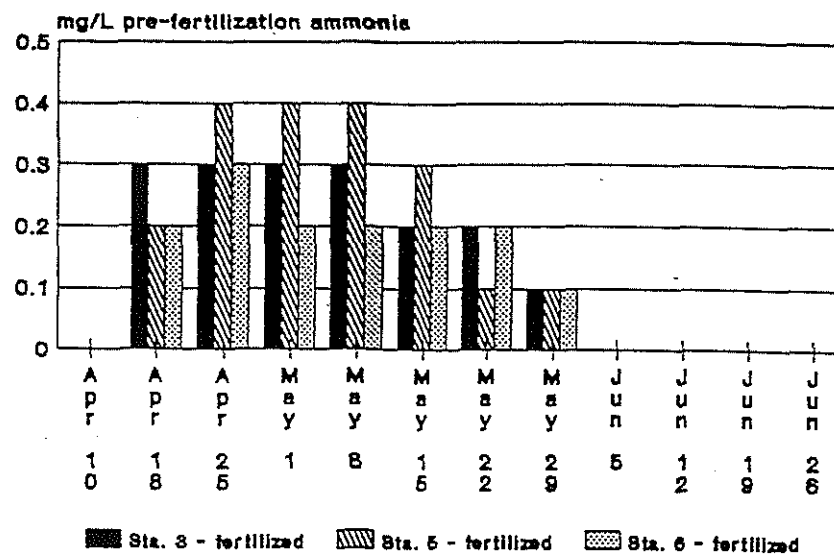
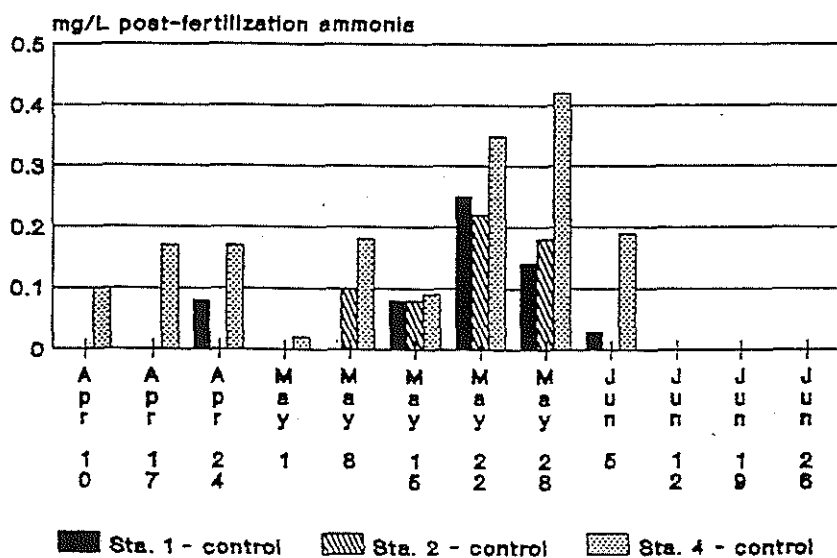
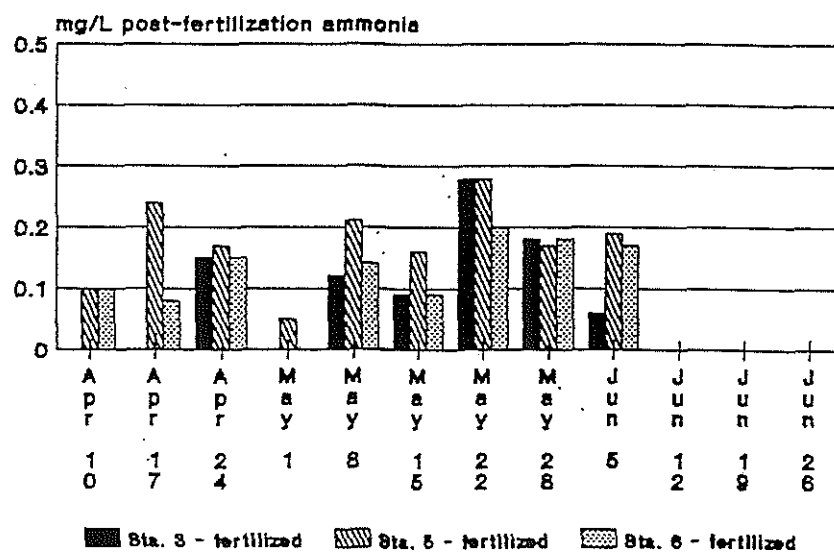


Figure 3. Spring pre and post fertilization ammonia.

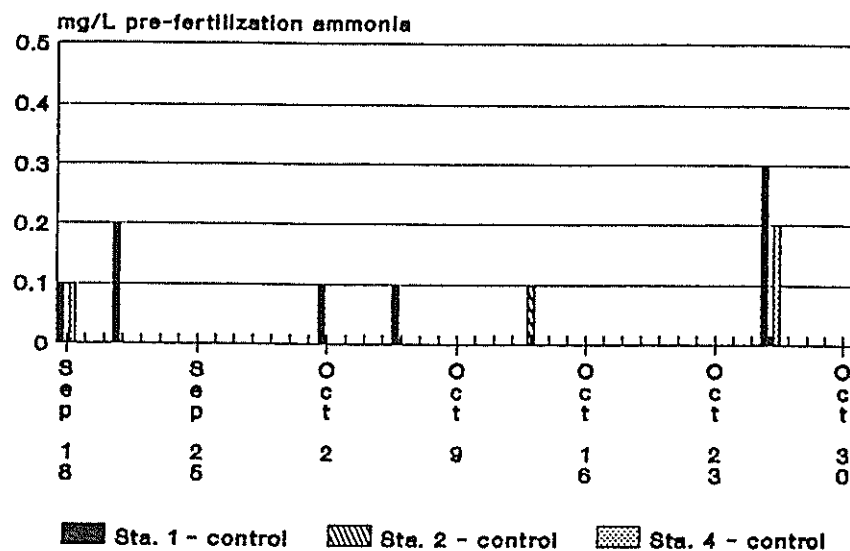
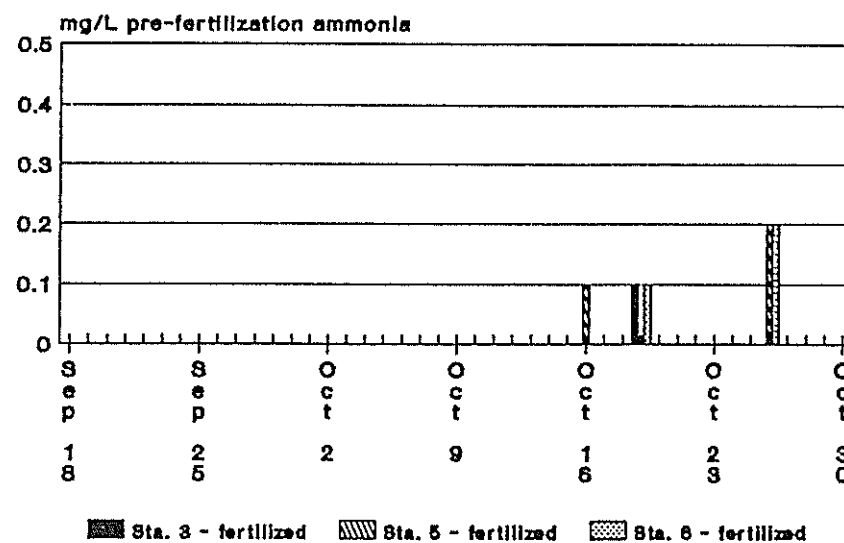
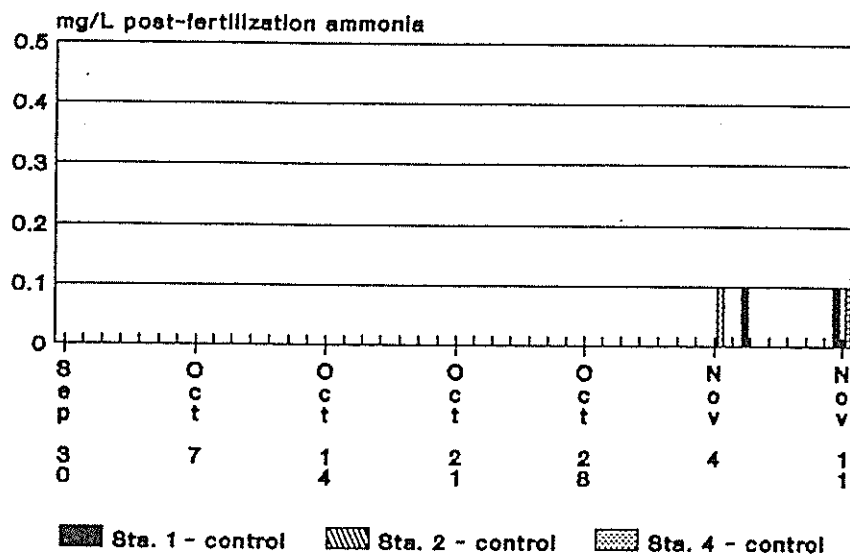
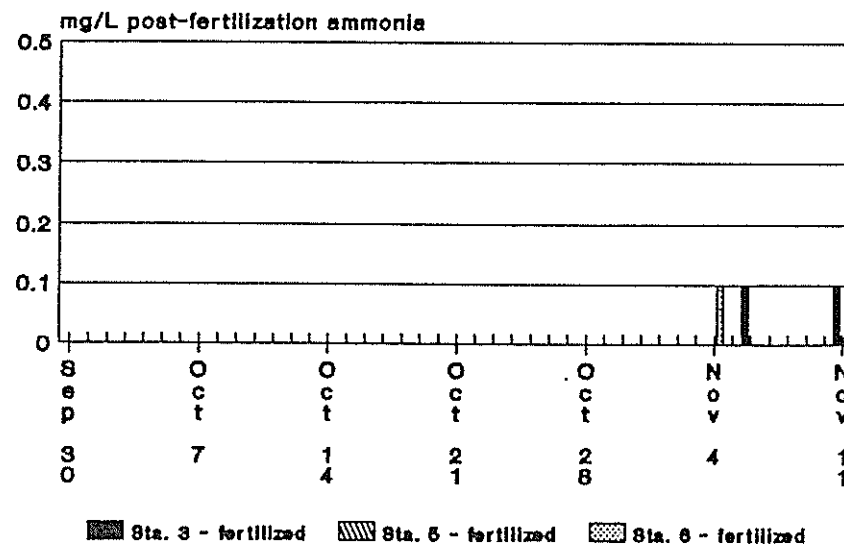


Figure 4. Fall pre and post fertilization ammonia.

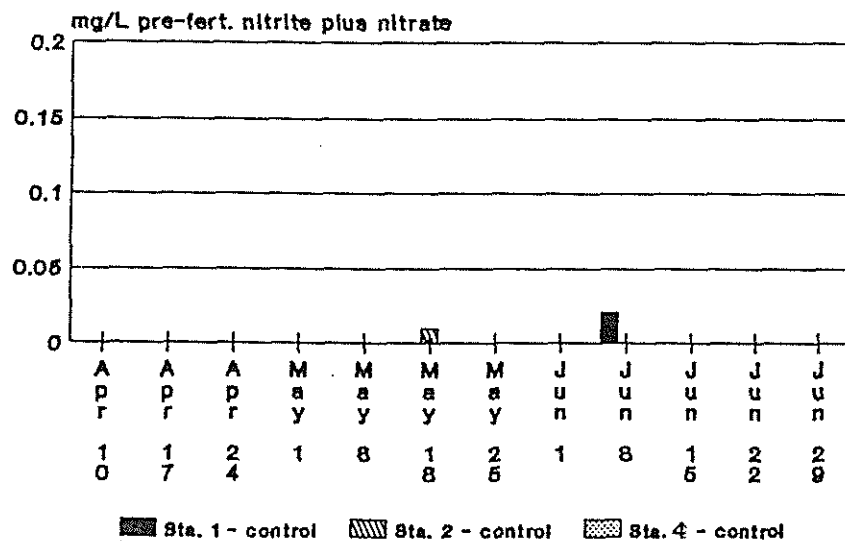
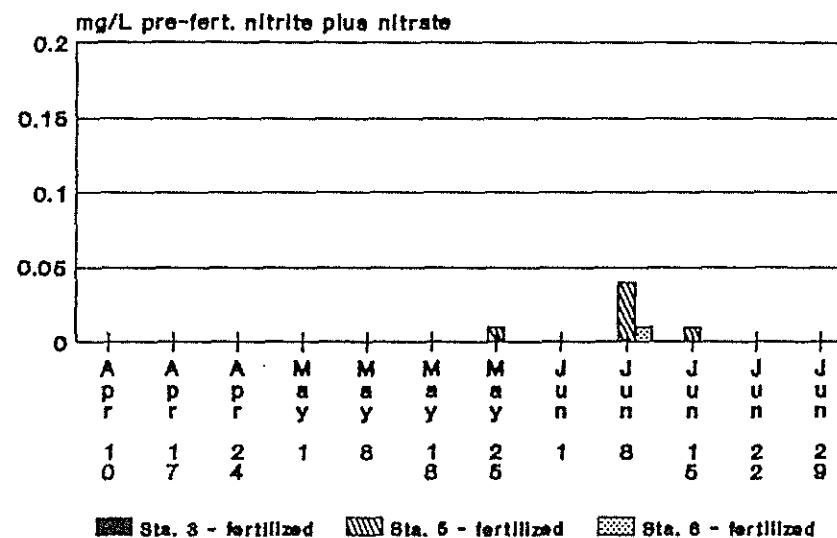
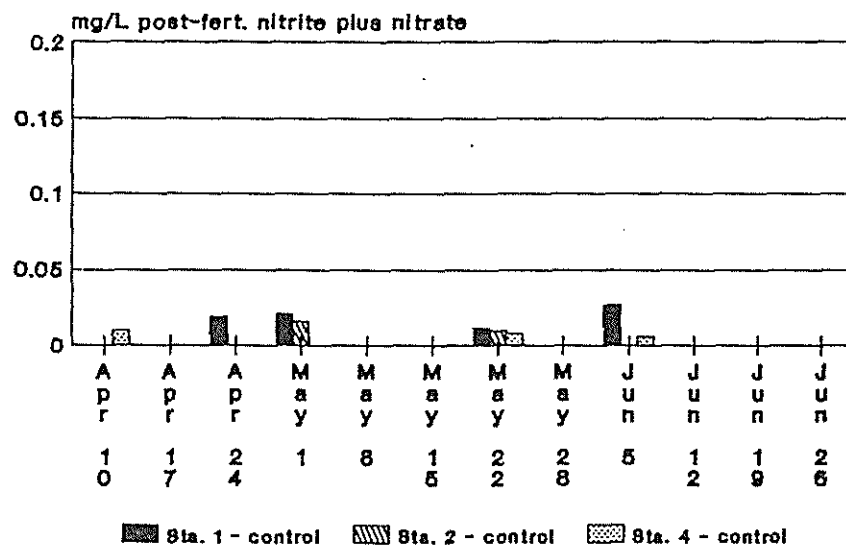
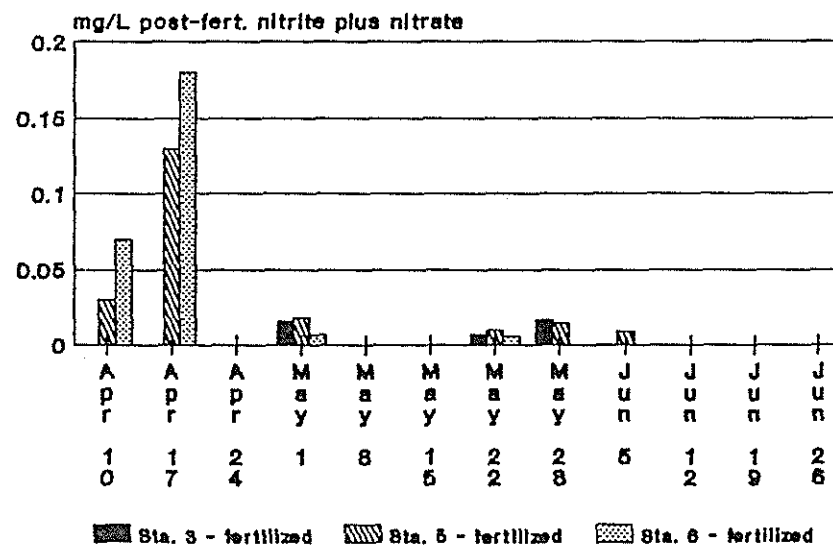


Figure 5. Spring pre and post fertilization nitrite plus nitrate nitrogen.

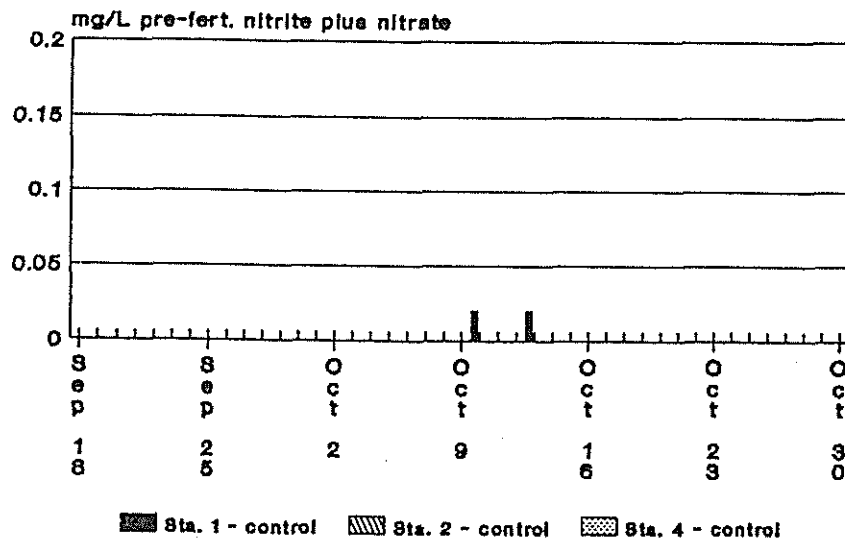
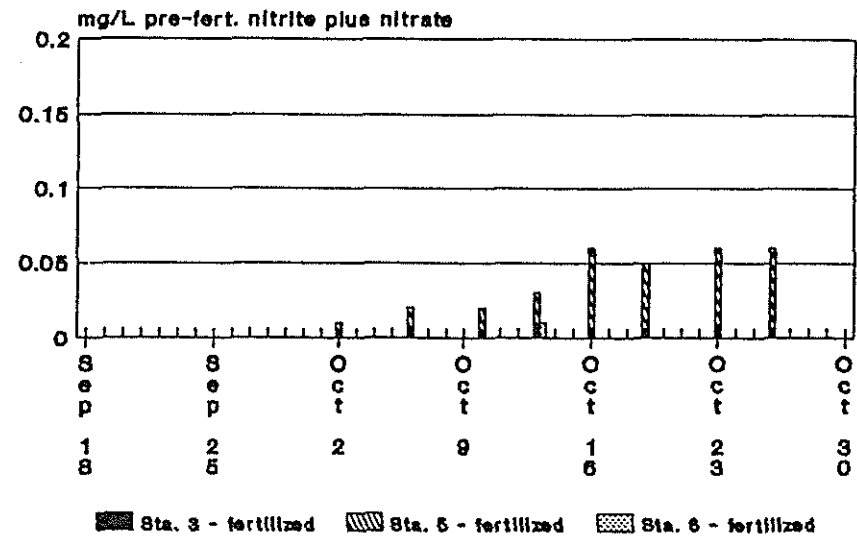
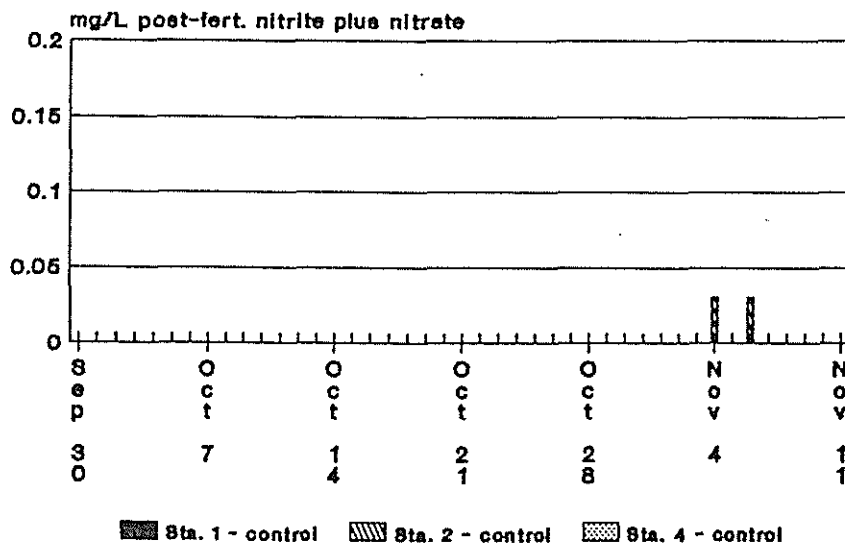
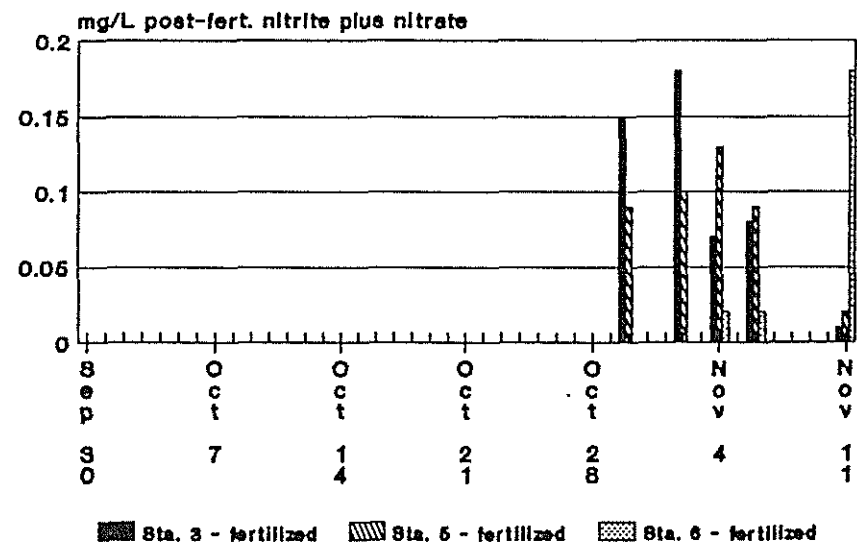


Figure 6. Fall pre and post fertilization nitrite plus nitrate nitrogen.

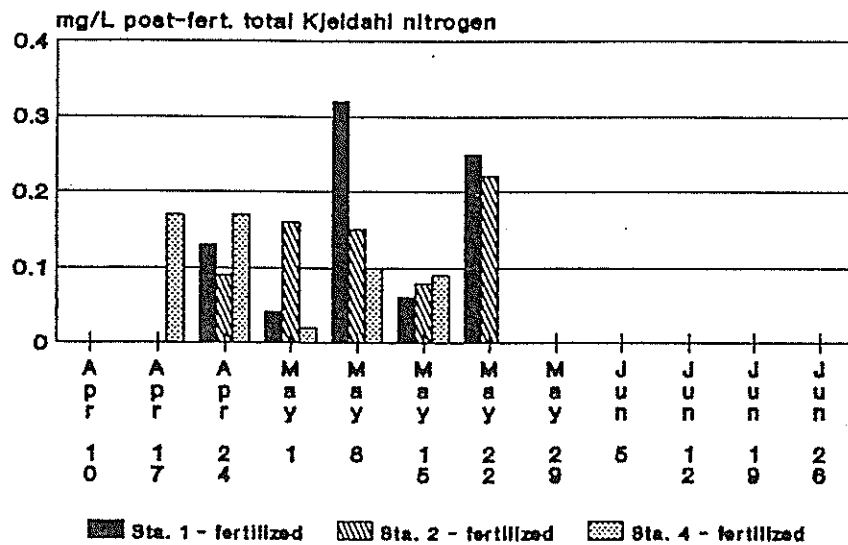
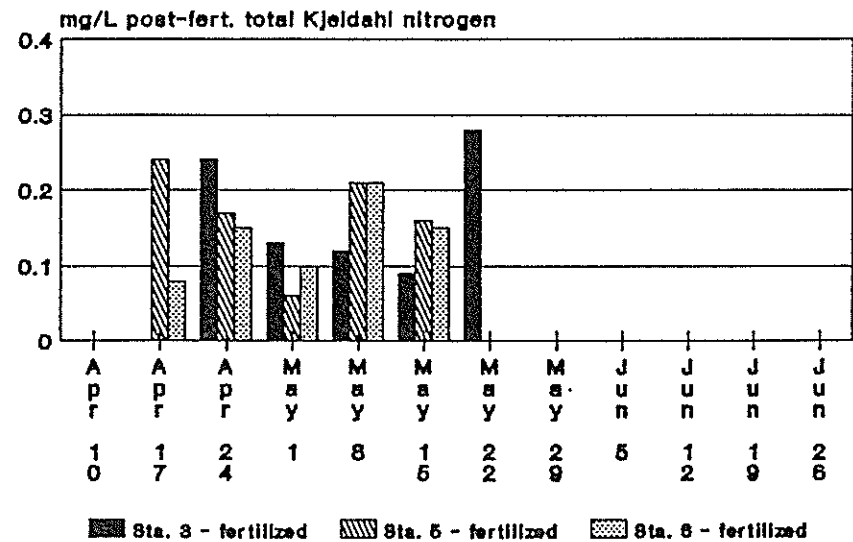


Figure 7. Spring pre and post fertilization total Kjeldahl nitrogen.

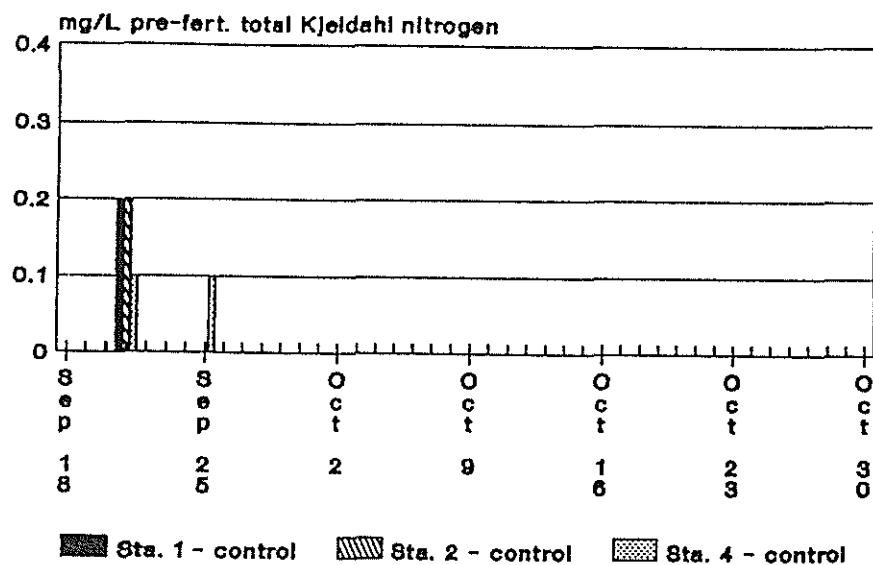
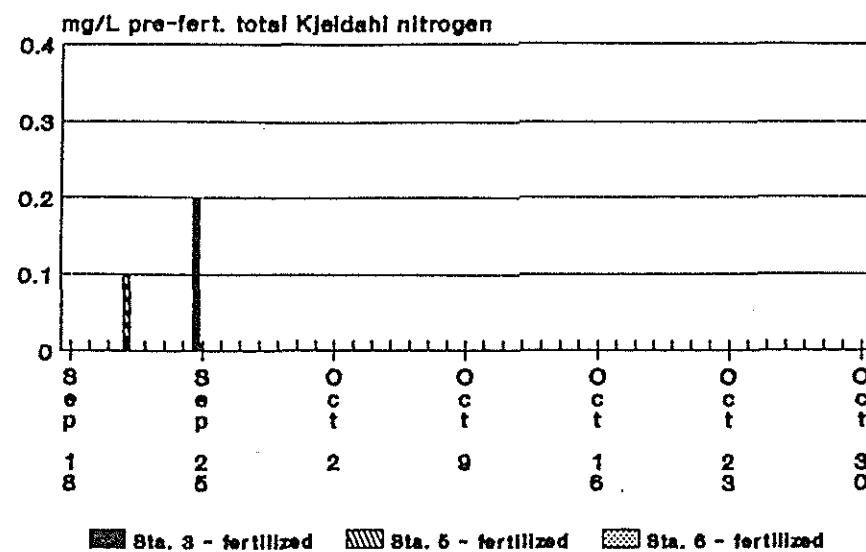
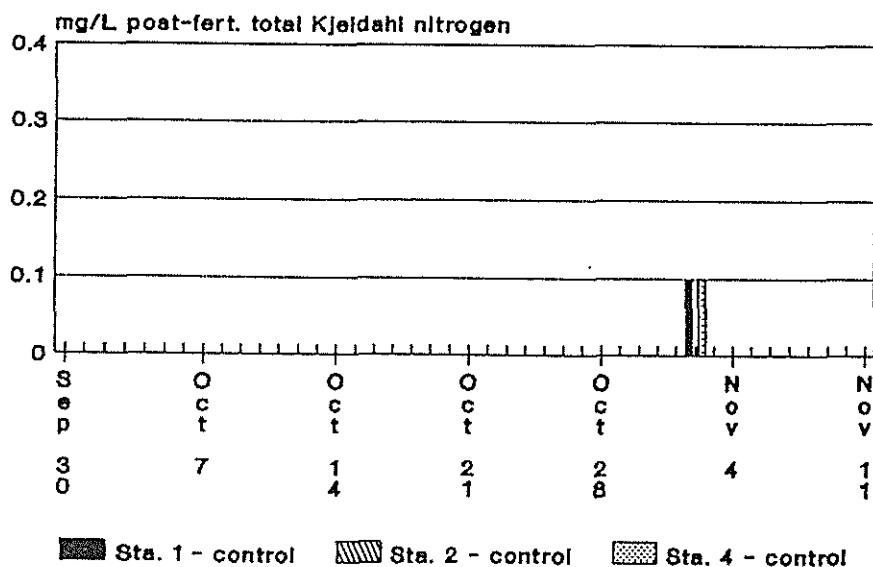
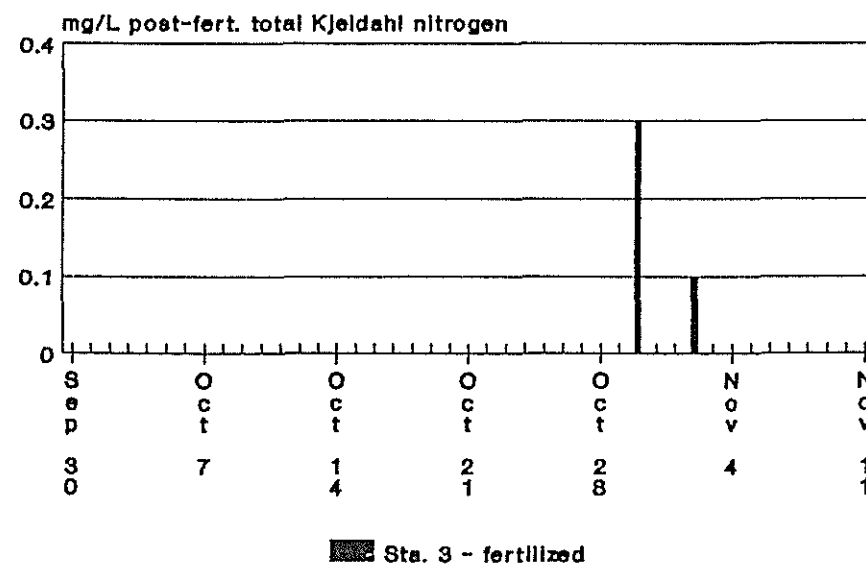


Figure 8. Fall pre and post fertilization total Kjeldahl nitrogen.

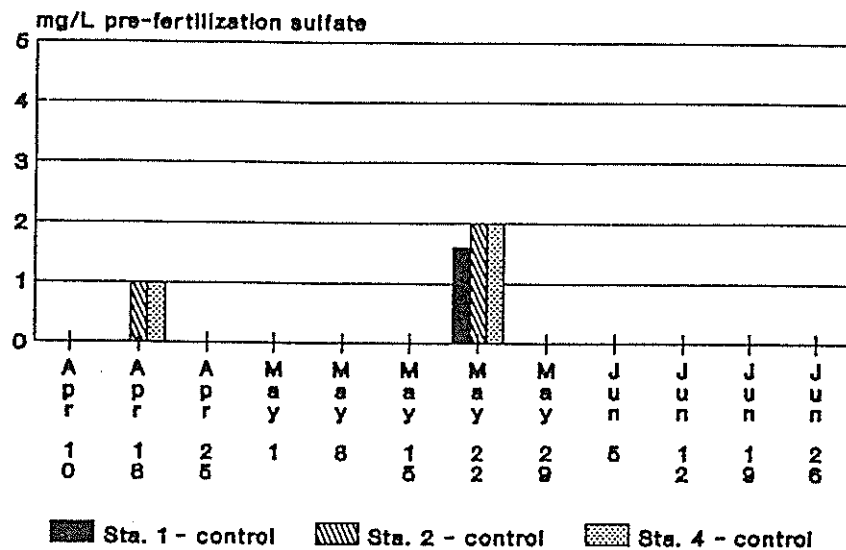
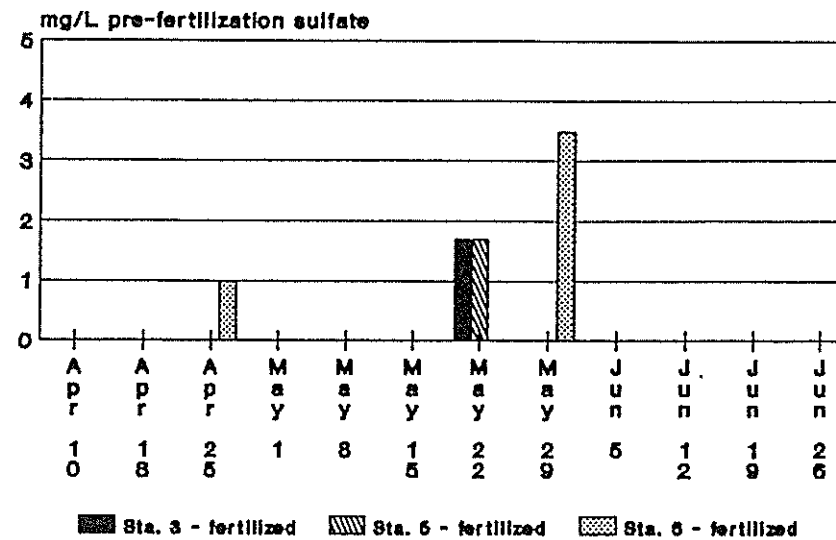
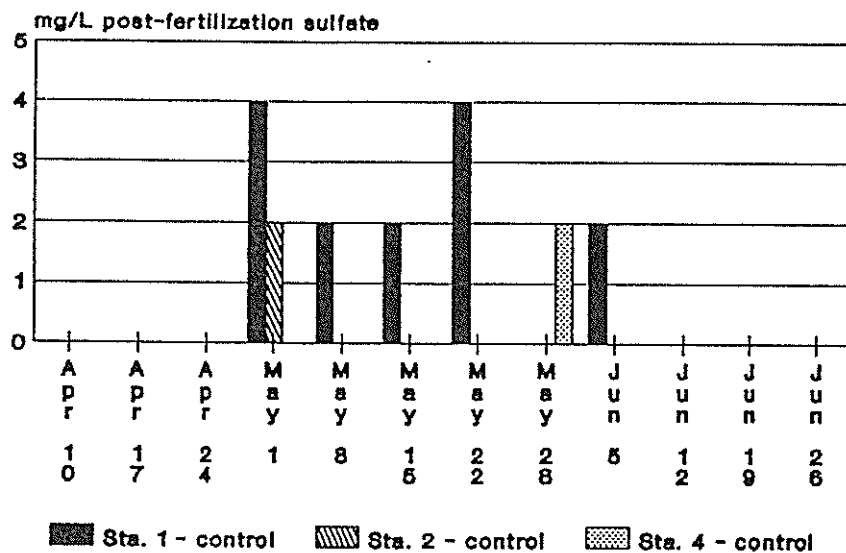
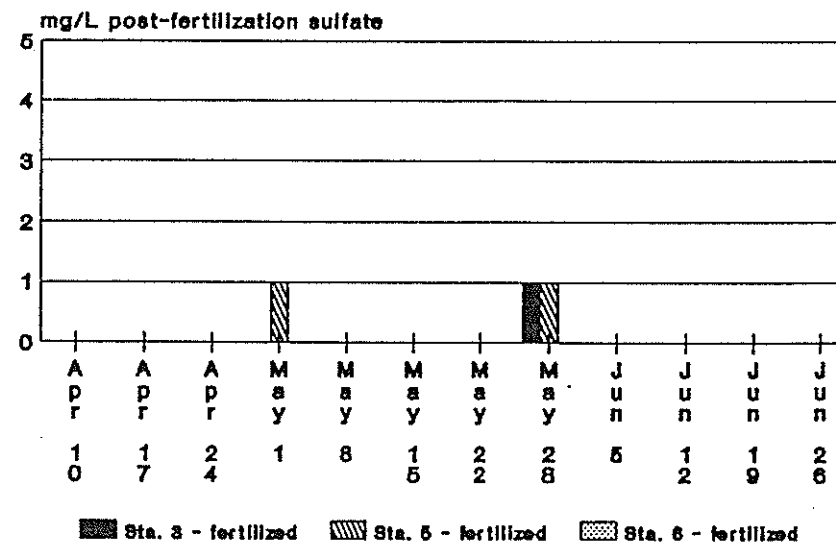


Figure 9. Spring pre and post fertilization sulfate.

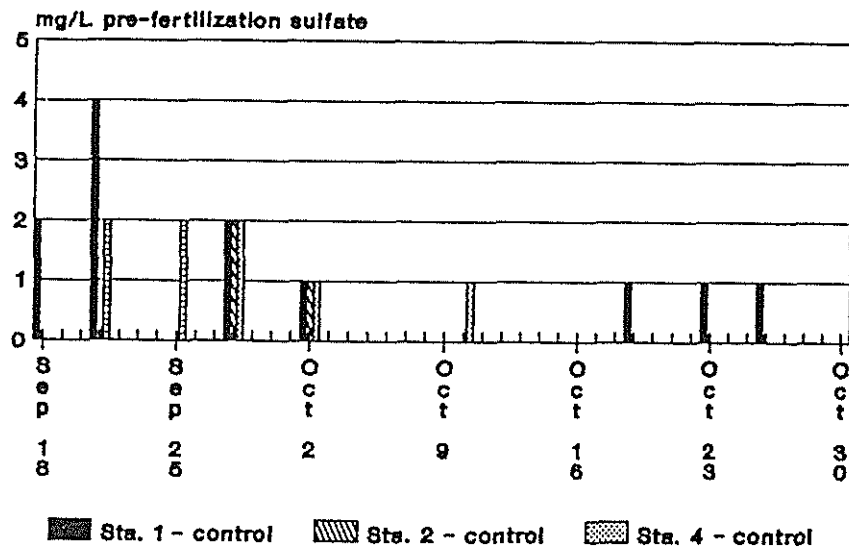
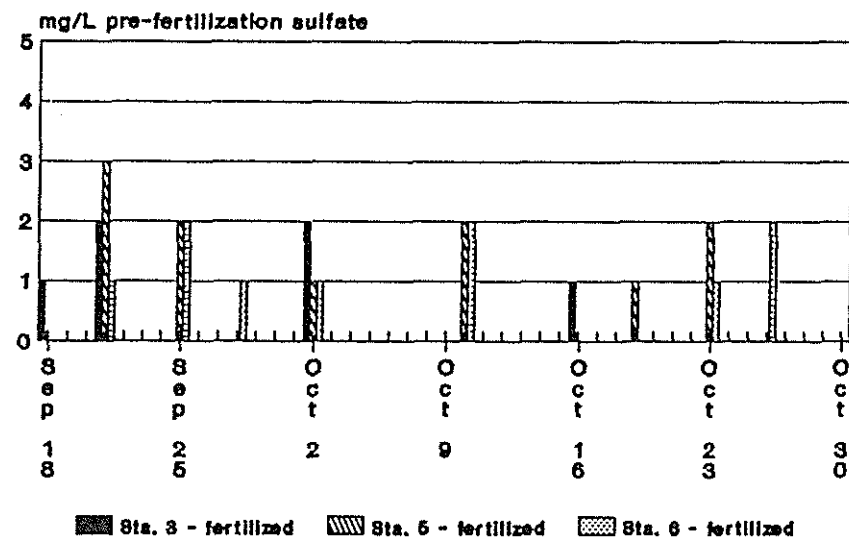
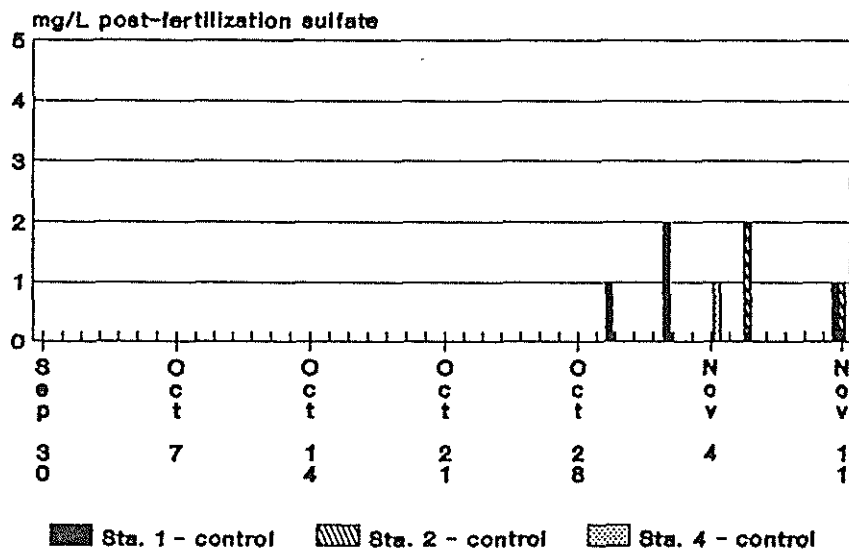
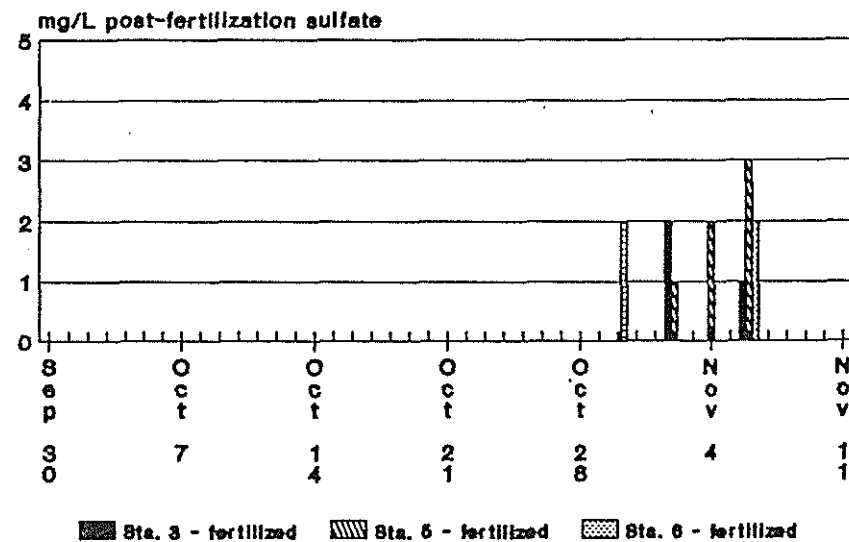


Figure 10. Fall pre and post fertilization sulfate.

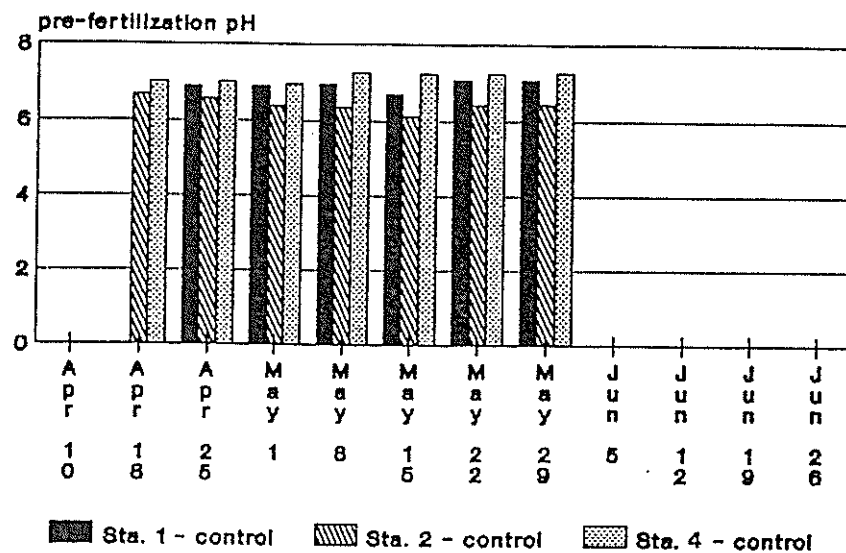
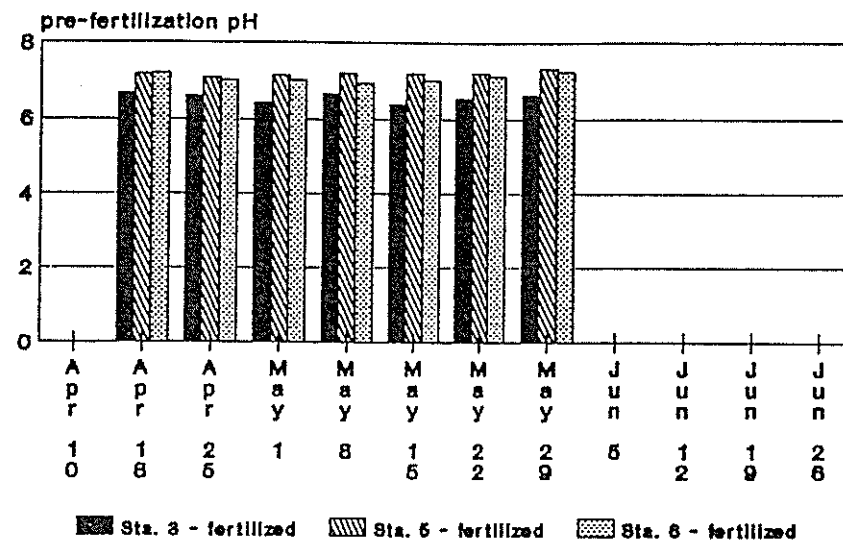
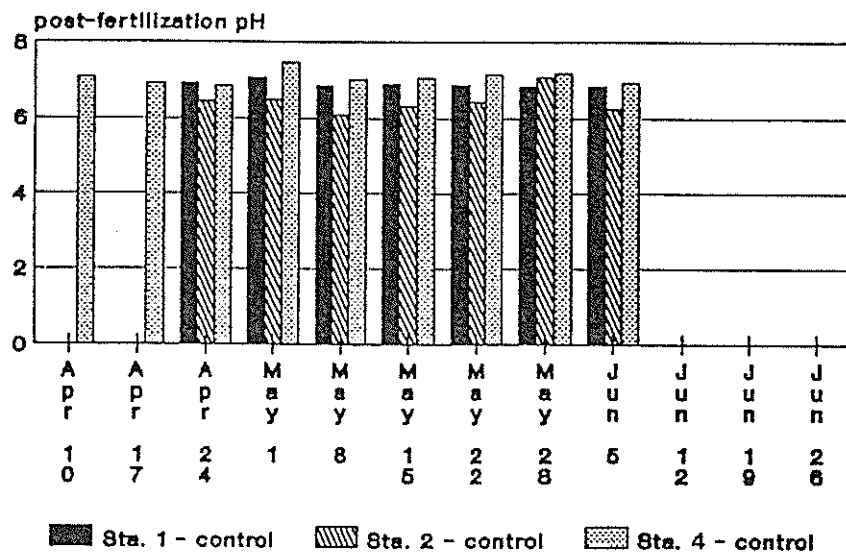
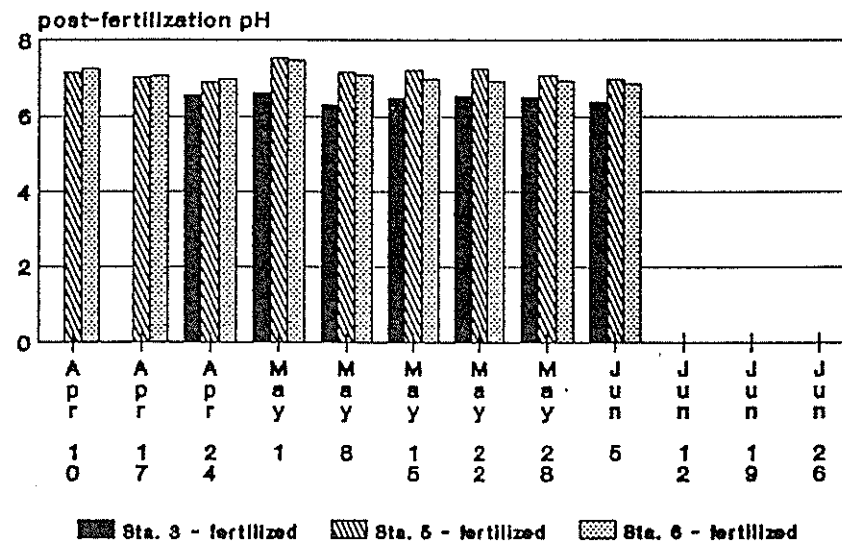


Figure 11. Spring pre and post fertilization pH.

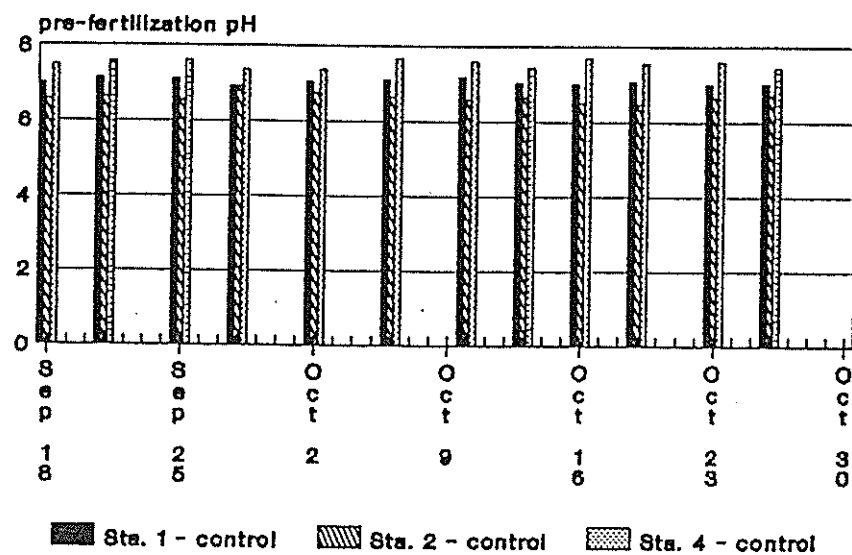
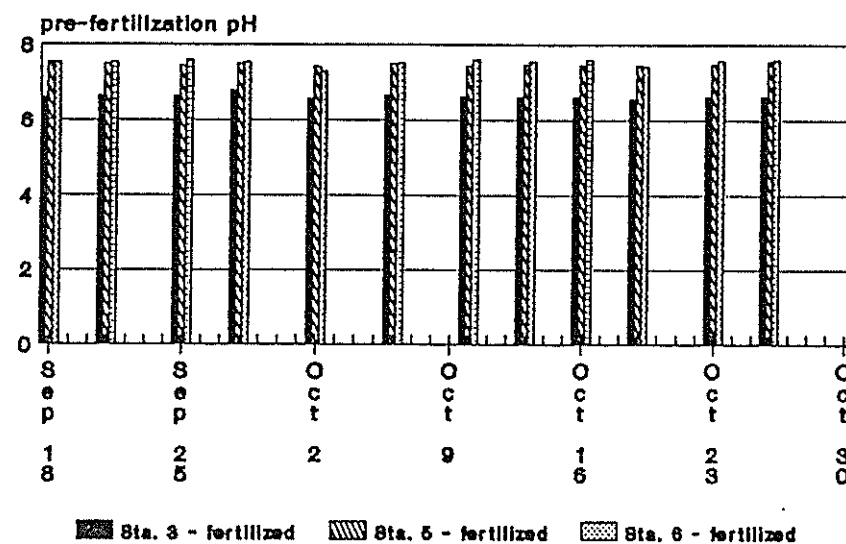
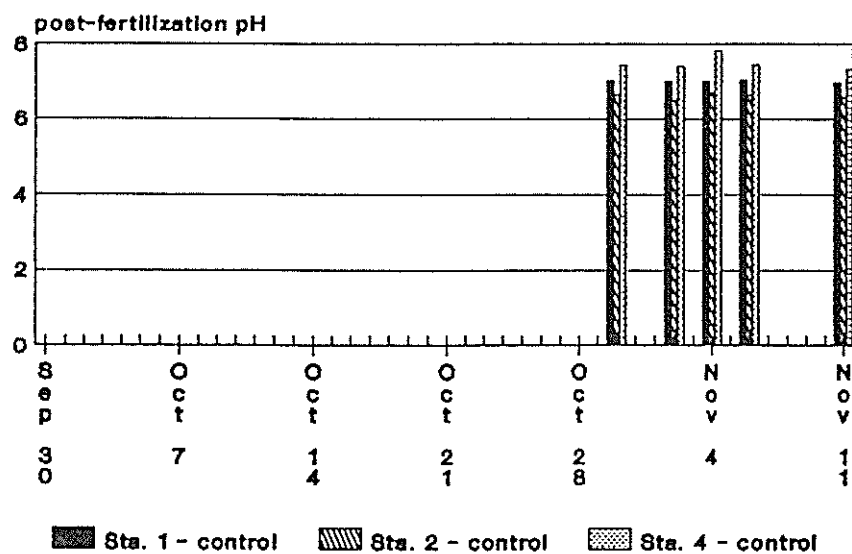
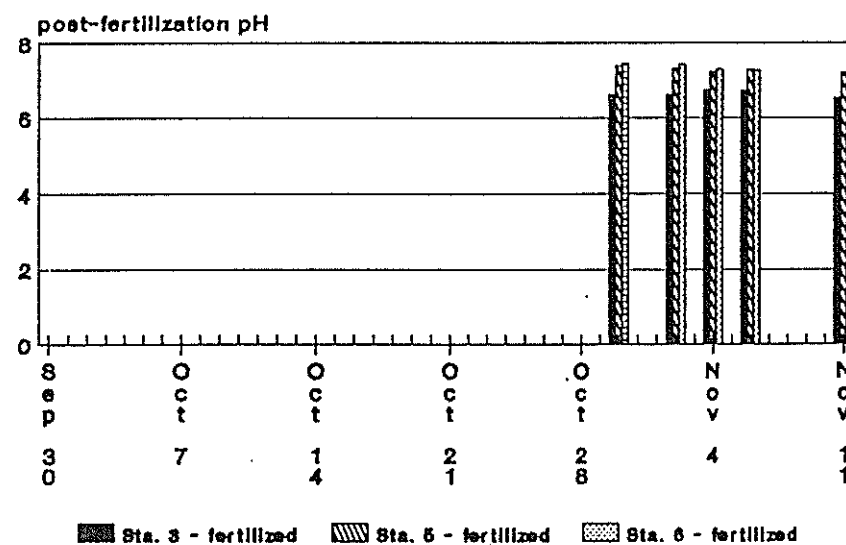


Figure 12. Fall pre and post fertilization pH.

Table 2. Stream water quality associated with forest fertilization in Oct. 1989 in the Upper Kettle River watershed.

	Stations Outside Fertilized Area (1,2,4)				Stations Within Fertilized Area (3,5,6)			
	Spring		Fall		Spring		Fall	
	Pre-Fert.(7)	Post-Fert.(9)	Pre-Fert.(12)	Post-Fert.(5)	Pre-Fert.(7)	Post-Fert.(9)	Pre-Fert.(12)	Post-Fert.(5)
Ammonia N (mg/L)	.1 - .4	.02 - .42	<.1 - .3	<.1 - .1	.1 - .4	.05 - .28	<.1 - .2	<.1 - .1
Nitrite + Nitrate N (mg/L)	<.01 - .04	<.01 - .02	<.01 - .02	<.01 - .03	<.01 - .04	<.01 - .04	<.01 - .06	<.01 - .18
Total Kjeldahl N (mg/L)		.02 - .25	<.1 - .2	<.1 - .1		.08 - .28	<.1 - .2	<.1 - .3
Sulfate (mg/L)	<1 - 2	<1 - 4	<1 - 2	<1 - 2	<1 - 3.5	<1 - 1	<1 - 3	<1 - 3
pH	6.12 - 7.27	6.08 - 7.45	6.46 - 7.66	6.5 - 7.86	6.54 - 7.18	6.28 - 7.52	6.57 - 7.66	6.53 - 7.44
(n) = number of samples collected								

5 CONCLUSIONS

Water quality data obtained during this study, as well as data from a similar study at Bigg Creek in the Vernon Forest District (Eremko 1986) and another at Maka Creek in the Merritt Forest District (Eremko 1987), indicate that concentrations of nitrite plus nitrate nitrogen can be expected to increase slightly during the first major storm or snowmelt event following the application of urea fertilizer. However, peak concentrations observed during all three local studies, as well as those reported in the literature, are well below the maximum acceptable for drinking water. The increases in nitrite plus nitrate nitrogen observed were of short duration and appeared to return to pre-treatment levels within one week of both the fall 1989 and spring 1990 "flush". Post-fertilization concentrations of the other parameters measured in this study remained within the range of pre-treatment levels.

In summary, it appears that forest fertilization with urea, under environmental and application conditions similar to those occurring in the study area, does not have a significant, lasting, deleterious impact on stream water quality. The results of this monitoring project are also consistent with results reported in the literature.

6 LITERATURE CITED

- B.C. Ministry of Health. 1982. British Columbia drinking standards. Prov. of B.C. Victoria, B.C.
- Brown, G.W. 1980. Forestry and water quality. School of Forestry Oregon State Univ., O.S.U. Book Stores Inc. Corvallis, Oreg.
- Environment Canada. 1983. Sampling for water quality. Inland Waters Directorate, Water Quality Branch. Ottawa, Ont.
- Eremko, R.D. 1986. Stream water quality associated with forest fertilization in the Bigg Creek watershed near Vernon, B.C. Report prepared for the B.C. Min. For., Vernon, B.C.
- Eremko, R.D. 1987. Fall 1986 and spring 1987 stream water quality associated with forest fertilization in the Maka Creek watershed near Merritt, B.C. Report prepared for the B.C. Min. For., Merritt, B.C.
- Health and Welfare Canada. 1968. Canadian drinking water standards and objectives. Queen's Printer for Canada. Ottawa, Ont.
- Hem, J.D. 1970. Study and interpretation of the chemical characteristics of natural water (2nd edition). Geological Survey - Water Supply Paper 1473. U.S. Gov't Printing Office. Washington, D.C.
- Hetherington, E.D. 1984. Streamflow nitrogen loss following forest fertilization in a southern Vancouver Island watershed. Can. J. For. Res. 15:34-41.
- Marshall, V.G. 1986. Environmental fate of nitrogenous fertilizers. In: Procs. of the interior forest fertilization workshop. Kamloops, B.C.
- Meehan, W.R., F.B. Lotspeich and E.W. Mueller. 1975. Effects of forest fertilization on two southeast Alaska streams. J. Environ. Qual. Vol. 4, No. 1:50-55.

- Moore, D.G. 1971. Fertilization and water quality. USDA Forest Service. Portland, Oreg.
- Moore, D.G. 1975. Effects of forest fertilization with urea on stream water quality - Quilcene Ranger District, Wash. USDA Forest Service Res. Note PNW-241. Portland, Oreg.
- Moore, D.G., J.B. Currier and L.A. Norris. 1980. Introduced chemicals. In: An approach to water resources evaluation of non-point silvicultural sources - a procedural handbook. EPA 600/8-80-012. Athens, GA. Chapt. XI.
- Neary, D.G. and J.H. Leonard. 1978. Effects of forest fertilization on nutrient losses in streamflow in New Zealand. N.Z. J. For. Sci. 8(1):189-205 (1978).
- Nordin, R.N. and L.W. Pommen. 1986. Water quality criteria for nitrogen (nitrate, nitrite and ammonia). Report prepared for the B.C. Min. Environ. and Parks, Water Mgmt. Br., Victoria, B.C.
- Tisdale, S.L. and W.L. Nelson. 1975. Soil fertility and fertilizers (3rd edition). Macmillan Publ. Co. Inc. New York, N.Y.
- U.S.D.A. - F.S. 1980. An approach to water resources evaluation of non-point silvicultural sources. EPA-600/8-80-012. Environ. Res. Lab, Athens, GA.