

TECHNOLOGY EVALUATION AND DEVELOPMENT SUB-PROGRAM

**THE EFFECT OF CONSERVATION TILLAGE
PRACTICES ON THE LOSSES OF PHOSPHORUS
AND HERBICIDES IN SURFACE AND SUBSURFACE
DRAINAGE WATERS**

A: Soil Erosion, Phosphorus Losses and Corn Yield
B: Herbicide Losses

FINAL REPORT

May, 1992

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for,
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Harrow, Ontario

Under the Direction of: ECOLOGICAL SERVICES FOR PLANNING LIMITED,
Guelph, Ontario - Subprogram Manager For TED

On Behalf of: AGRICULTURE CANADA
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ACKNOWLEDGEMENTS

The Southwestern Ontario Agricultural Research Corporation thanks the field staff of Agriculture Canada for their assistance in field preparation, planting, harvesting and maintenance of the experimental site. Appreciation is expressed to M. Sultani and K. Rinas for technical assistance in report preparation and data analysis; J. Gaynor for technical advice and comments on the report and C. Drury for comments on parts of the report.

PART A - SOIL EROSION, PHOSPHORUS LOSSES AND CORN YIELD

EXECUTIVE SUMMARY

Deterioration of agricultural land by soil erosion and compaction has encouraged the use of conservation tillage with residue management in southwestern Ontario. Many types of conservation tillage systems have been developed but all are characterized by reduced tillage with over 30% crop residue on the soil surface. Zero and ridge tillage are examples of two conservation tillage practices which leave sufficient crop residue to reduce water flow velocities, increase water infiltration and produce less soil compaction. Conservation tillage has been shown to be effective in reducing soil loss by fluvial transport and in some cases increasing crop yield.

Phosphorus (P) in subsurface, surface and lake waters has been linked with algal blooms which impairs water use and can lead to shifts in aquatic species and populations. Phosphorus in subsurface and surface runoff from agricultural activities has been associated with sediment-phase transport. Thus, common belief held that a reduction in sediment transport would result in reduced phosphorus transport.

Southwestern Ontario is characterized as ideally suited for agricultural production because of its proximity to large U.S. and Canadian markets, adequate and well distributed rainfall, fertile soils and favorable climate for crop production. Because of its proximity to large populations and the largest freshwater resource in North America, past and current agricultural practices have been intensively investigated with respect to yield and to a lesser extent on impairment of water quality. A study was begun in 1984 to identify sediment and phosphorus transport from a poorly drained, Brookston clay loam soil, cropped to corn under three tillage practices. Water quality and yield from a conventional (fall plow, spring disk and midseason cultivation) tillage treatment, was compared with that from a zero tillage (no tillage other than that associated with seeding and fertilizer

application) and ridge tillage (ridges reformed in mid-season) treatment. Research results for the contract period January, 1988 to September 30, 1990 are reported herein.

Rainfall was measured with a rain gauge at the site to determine input. Surface and subsurface runoff for each runoff event was quantified from depth of water over a weir. Water samples were collected manually from each treatment throughout the hydrograph for sediment and orthophosphate analysis. Total soluble and sediment P were also determined over the three year period but an error in analysis invalidated the results for the 1988 and 1989 samples. These phosphorus forms were determined for the 1990 season. The sediment and orthophosphate concentrations were averaged within an event and event transport or loss was calculated from the product of average concentration of the component of interest and runoff volume. Annual losses were computed as the sum of event losses for the year. Surface and subsurface amounts were expressed as percent of total loss. The year was divided into three seasons, before planting (or fertilizer application, January 1 to planting), growing season (planting to September 30) and after harvest (October 1 to December 31). The seasonal losses were reported as a percent of total loss.

A wide range in climatic conditions from dry to wet growing season occurred over the duration of the study which affected grain yield, erosion and nutrient transport. Grain yield was similar within years from each of the tillage treatments. In 1988 (a dry year) and 1989 (a wet year) yields were low averaging 6 t/ha. In 1990 (a normal year) grain yield averaged 9 t/ha with slightly greater yield from the conservation tillage treatments than from conventional tillage. Conservation tillage has been reported to increase yield on well drained soil because of moisture conservation from crop residue but yield effects on poorly drained soils have been inconsistent and may be decreased. Excessive soil moisture during crop development as occurred in 1989, has been reported to reduce grain yield on Brookston soil.

Conservation tillage had a variable effect on sediment transport. In two of the three years, sediment transport was reduced by the conservation tillage treatments compared

to that from conventional tillage. No tillage effects on sediment transport were observed in one year (1990) probably because no major runoff producing events occurred in the spring when soil erosion was most susceptible and sampling was terminated in September, 1990. Soil loss averaged over three years was 530 ± 11 kg/ha from ridge tillage, 391 ± 14 kg/ha from zero tillage and 897 ± 14 kg/ha from conventional tillage. Zero tillage was more effective at reducing erosion than ridge tillage over the three years. A greater proportion of sediment transport occurred in surface runoff from the conservation tillage treatments whereas subsurface transport accounted for a greater proportion of sediment loss from conventional tillage. It is possible that much of the sediment transported through subsurface drainage from conventional tillage originated from preferential surface flow through cracks developed when soil moisture content was low.

Generally, dissolved (ortho) phosphorus transport was higher from zero tillage than from ridge or conventional tillage. Dissolved phosphorus transport was lowest from conventional tillage. Annual dissolved phosphorus transport ranged from 2.7 to 10.4 % of that applied from 1988 to 1990. Subsurface drainage accounted for greater than half of the orthophosphate loss from the conservation tillage treatments in two (1988 and 1990) of the three years. In 1989, surface runoff loss exceeded subsurface runoff loss of orthophosphate from zero tillage. Over 74% of orthophosphate transport from conventional tillage was from subsurface drainage in two of the three years. The seasonal loss pattern for dissolved phosphorus and water runoff were similar. The cumulative, three year sum of dissolved phosphorus transport was 74 to 174% higher from the conservation tillage treatments than from conventional tillage (1665 ± 45 g/ha). Orthophosphate transport was 57% higher from zero than ridge tillage (2895 ± 751 g/ha).

Preliminary studies indicated that total soluble P and total phosphorus (sum of sediment P and soluble P) transport was higher from the conservation tillage treatments than from conventional tillage. The proportion of soluble P transported as orthophosphate was less from ridge (47%) and conventional tillage (56%) than zero tillage (80%). Sediment phosphorus loss was similar between ridge and conventional tillage (199 ± 14 and 197 ± 43

g/ha, respectively) but higher from zero tillage (266 ± 33 g/ha). Thus, much (84 to 93%) of the phosphorus transported from the conservation tillage treatments and conventional tillage occurred in the dissolved form. Other studies have shown that up to 98% of phosphorus transport may be associated with the sediment phase but that leachate from crop residue can account for considerable soluble phosphorus transported from conservation tillage treatments. Ridge reforming in ridge tillage may incorporate some of the crop residue with soil allowing for greater residue decomposition which could account for the greater release of soluble P from ridge compared to zero tillage. Sediment P and orthophosphate transport was higher from zero tillage than from ridge tillage because of P enrichment of runoff, but total P (the sum of all P forms) loss was higher from ridge tillage because of the greater proportion of other soluble P forms. Total phosphorus transport, assuming all P originated from fertilizer ranged from $7\pm 0.3\%$ from conventional to $15\pm 7\%$ from ridge tillage. Since total P forms were only determined from January to September, 1990, further research is required to substantiate these results. Tillage effects in this year were not statistically significant because of the high variability.

Phosphorus and sediment transport was also measured from a sod treatment in 1990. Results are not directly comparable to the corn treatments because sod received twice the amount of phosphorus as corn. However, several interesting inferences with the corn treatment can be made. Water runoff from the sod treatment was less than that from the corn treatment and ranged from 14 to 28% of the rainfall. Sediment transport was reduced to 129 kg/ha which was 30 to 37% of that from the conservation tillage treatments. Over 90% of the sediment loss occurred through subsurface discharge compared to 42 to 68% from corn culture. Dissolved orthophosphorus transport from the sod (6.5% of applied) was similar to that from ridge tillage (6.4%). The percentage of total phosphorus loss ($14\pm 1\%$) from the sod treatment was also similar to that from ridge ($15\pm 7\%$) tillage. As noted for ridge tillage, much of the total phosphorus transported from sod was in the soluble form.

This work indicates that for a poorly drained, Brookston clay loam soil, conservation tillage effectively reduced soil erosion but not phosphorus transport. Transport of soluble forms of phosphorus were higher from both conservation tillage treatments than from the conventional tillage treatment indicating that these tillage practices may result in increased phosphorus bioavailability and reduced water quality. Further research will be needed to confirm the result that total phosphorus transport is also increased with conservation tillage. Thus, if the Great Lakes water quality objective with respect to phosphorus is to be met, alternative or modified conservation tillage systems will have to be developed. The introduction of crops which have a low fertility requirement may result in lower recommended rates of fertilizers and hence improved water quality. Research at Agriculture Canada, Harrow is continuing to study alternative crop and soil management practices that affect water quality (herbicides and nitrate) but resources are not available to include phosphorus. The approach is to develop a management system, whereby through water table control, a favorable environment for efficient use of nutrients applied for crop growth will occur.

PART B - HERBICIDES

EXECUTIVE SUMMARY

Conservation tillage with residue management has been proposed as the most effective means to reduce soil deterioration in southwestern Ontario. Residue management with conservation tillage has reduced soil erosion, increased organic matter content and reduced soil compaction. In some situations, impairment of water quality by pesticide contamination has been reduced by conservation tillage treatments. However, increased impairment of water quality has also been observed. A three year study was conducted on a poorly drained, low slope Brookston clay loam soil to investigate the effect of conventional tillage (fall plow, spring disk and mid season cultivation), zero tillage (direct planting in previous crop residue) and ridge tillage (planting in 15 to 20 cm high ridges, reformed in midseason) on surface and subsurface transport of atrazine and metolachlor applied preemergence to corn. Each runoff producing event was monitored to calculate the proportion of rainfall originating as runoff and water samples from the runoff events were collected for determination of herbicide concentration. Herbicide transport in the runoff was then computed for each event from the concentration profiles and runoff volumes. Residues of atrazine and its major dissipation product, des-ethyl atrazine, and metolachlor were determined in soil from the three tillage practices throughout the growing season and related to herbicide transport in the aqueous phase.

The proportion of rainfall originating as runoff was independent of tillage but dependent upon rainfall intensity, duration and antecedent soil moisture content. Less runoff (23% of rainfall) occurred in 1988 which was a dry year, compared to 28% in 1989, a normal year, and 36% in 1990, a wet year. Subsurface runoff exceeded surface runoff in all treatments. A greater proportion of the runoff occurred from the surface of the conservation tillage treatments compared to conventional tillage. The greater proportion of runoff from the surface of the conservation tillage treatments could impact on water quality since herbicide concentrations are higher in surface than subsurface runoff water.

Runoff producing events which occurred soon after herbicide application, transported the largest amount of herbicide. Where surface and subsurface runoff events occurred, herbicide concentration was highest in the surface runoff water and the mean concentrations were higher from the conservation tillage treatments than from conventional tillage. Herbicide concentrations of the runoff water were higher for metolachlor than for atrazine. However, because of the long soil persistence of atrazine and inclusion of the primary metabolite, des-ethyl atrazine, in the amounts, less metolachlor was lost in the runoff water than atrazine. Tillage had no effect on transport quantities of atrazine and its metabolite or metolachlor. Average three year transport quantities for triazine (sum of atrazine and des-ethyl atrazine) were 58 ± 1 g/ha from ridge, 36 ± 3 g/ha from zero and 62 ± 13 g/ha from conventional tillage representing 3 to 4% of total atrazine applied from 1988 to 1990. Up to 25% of the total triazine transported from the tillage treatments was the dealkylated (des-ethyl atrazine) product. Corresponding average transport quantities for metolachlor were 46 ± 3 g/ha from ridge, 48 ± 1 g/ha from zero and 53 ± 6 g/ha from conventional tillage representing 2% of that applied. Atrazine and metolachlor on crop residue were readily leached into soil by rainfall received soon after application.

Minor changes in soil persistence of atrazine and metolachlor were related to tillage. Atrazine and its dissipation product persisted longer than metolachlor in two of three years and in some years both herbicides showed greater persistence on ridge tops than in the valley of ridge tillage. Soil persistence of the herbicides was longer in conventional than zero tillage.

In conclusion, tillage and crop residue did not influence herbicide transport in surface and subsurface runoff from a level plane, poorly drained soil. The proportion of rainfall appearing as runoff was similar among tillage practices. therefore the lack of a herbicide response to tillage was not unexpected. The quantity of herbicide transported from the three tillage treatments was less than 8% of that applied in the worst year while the three year cumulative loss amounted to <4% of that applied. Transport quantities of herbicide were more related to incidence of runoff producing events to herbicide application, rainfall

intensity and duration, and antecedent soil moisture content. Tillage practices which alter the hydrologic response of watersheds will impact more on herbicide transport losses than tillage alone. Thus, tillage combined with other cultural practices such as band application of herbicide over the seed row, intercropping with a grass or legume forage, or adopting post emergence weed control strategies with low persistence herbicides should be investigated to determine their effect on impairment of runoff.

TABLE OF CONTENTS

LIST OF TABLES -PART A	iii
LIST OF TABLES - PART B	iv
LIST OF FIGURES - PART A	v
LIST OF FIGURES - PART B	viii
PART A - SOIL EROSION, PHOSPHORUS LOSSES AND CORN YIELD	1
INTRODUCTION	1
OBJECTIVE	6
MATERIALS AND METHODS	6
Water Analysis	9
RESULTS AND DISCUSSION	10
Precipitation and Yield	11
Surface and Subsurface Runoff	13
Suspended Sediment Concentration and Loss	18
Concentration and Loss	33
Total Phosphorus and Other Forms	45
Sod	50
SUMMARY	52
IMPLICATIONS OF THE RESULTS	52
REFERENCES	55
LIST OF APPENDICES - PART A	63

PART B- HERBICIDES	63
INTRODUCTION	63
OBJECTIVES	67
MATERIALS AND METHODS	68
Herbicide Application and Sampling	68
Soil and Water Analysis	69
Data Analysis	69
RESULTS AND DISCUSSION	70
ATRAZINE	70
Atrazine and Des-ethyl Atrazine Concentration	70
Triazine Transport	92
Soil Persistence	100
SUMMARY	106
METOLACHLOR	107
Concentration in Runoff	107
Amounts Lost	118
Soil Persistence	121
SUMMARY	127
IMPLICATIONS OF THE RESULTS	127
REFERENCES	129

APPENDICES FOR PART A AND B - SEE VOLUME 2.

LIST OF TABLES - PART A

	Page
Table 1A	10
Residue cover \pm standard error of means before planting on three tillage treatments for 1988, 1989 and 1990.	
Table 2A	11
Rainfall deviation from the 33 year average (762 mm) and seasonal distribution at the Totten site.	
Table 3A	13
Grain corn yield \pm standard error of means (at 14% moisture content) from three tillage practices for 1988, 1989 and 1990.	
Table 4A	18
Range and average sediment and orthophosphate concentration of surface and subsurface runoff water from three tillage treatments for 1988. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	
Table 5A	18
Range and average sediment and orthophosphate concentration of surface and subsurface runoff water from three tillage treatments for 1989. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	
Table 6A	19
Range and average sediment and orthophosphate concentration of surface and subsurface runoff water from three tillage treatments from January 1 to September 30, 1990. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	
Table 7A	48
Range and mean total soluble P and sediment P concentration of surface and subsurface runoff from three tillage practices and a sod treatment for 1990.	
Table 8A	49
Subsurface and surface loss of various phosphorus forms lt. standard error from three tillage practices and a sod treatment for 1990.	
Table 9A	51
Runoff and sediment loss \pm standard error from three tillage practices and a sod treatment for 1990.	

LIST OF TABLES - PART B

		Page
Table 1B	Range and average atrazine and des-ethyl atrazine concentration of surface and subsurface runoff water from three tillage treatments for 1988. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	89
Table 2B	Range and average atrazine and des-ethyl atrazine concentration of surface and subsurface runoff water from three tillage treatments for 1989. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	89
Table 3B	Range and average atrazine and des-ethyl atrazine concentration of surface and subsurface runoff water for three tillage practices from January to September 30, 1990. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	91
Table 4B	Adjusted coefficient of determination (R^2), slope and half life of triazine in Brookston clay loam from three tillage treatments.	105
Table 5B	Range and average metolachlor concentration of surface and subsurface runoff water from three tillage treatments for 1988. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	108
Table 6B	Range and average metolachlor concentration of surface and subsurface runoff water from three tillage treatments for 1989. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	108
Table 7B	Range and average metolachlor concentration of surface and subsurface runoff water for three tillage treatments from January to September 30, 1990. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.	118
Table 8B	Adjusted coefficient of determination (R^2), slope and half life of metolachlor in Brookston clay loam from three tillage treatments.	126

LIST OF FIGURES - PART A

		Page
Fig. A1A.	Site layout, treatment and sampling monitoring locations at the Totten experimental site, Woodslee, Ontario	7
Fig. 1 A	Precipitation for (a), 1988 (b), 1989 and (c), 1990 at the Totten site.	12
Fig. 2A	Tile water discharge and surface water runoff from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.	14
Fig. 3A	Surface and tile loss of water as a percent of total water loss from three tillage systems on Brookston soil.	15
Fig. 4A	Seasonal water loss as a percent of total water loss from three tillage practices on Brookston soil.	17
Fig. 5A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1988. Arrow denotes planting date May 11, 1988.	20
Fig. 6A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date May 11, 1988.	21
Fig. 7A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date May 11, 1988.	22
Fig. 8A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1989. Arrow denotes planting date May 10, 1989.	23
Fig. 9A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date May 10, 1989.	24
Fig. 10A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date May 10, 1989.	25
Fig. 11A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	26
Fig. 12A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	27

	Page	
Fig. 13A	Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	28
Fig. 14A	Soil loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.	29
Fig. 15A	Surface and tile loss of soil as a percent of total soil loss from three tillage practices on Brookston soil.	31
Fig. 16A	Seasonal soil loss as a percent of total soil loss from three tillage practices on Brookston soil.	32
Fig. 17A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1988. Arrow denotes planting date May 11, 1988.	34
Fig. 18A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date May 11, 1988.	35
Fig. 19A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date May 11, 1988.	36
Fig. 20A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1989. Arrow denotes planting date May 10, 1989.	37
Fig. 21A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date May 10, 1989.	38
Fig. 22A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date May 10, 1989.	39
Fig. 23A	Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	40

	Page
Fig. 24A	41
<p>Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.</p>	
Fig. 25A	42
<p>Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.</p>	
Fig. 26A	44
<p>Orthophosphate loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.</p>	
Fig. 27A	46
<p>Surface and tile loss of orthophosphate as a percent of total orthophosphate loss from three tillage practices on Brookston soil.</p>	
Fig. 28A	47
<p>Season orthophosphate loss as a percent of total orthophosphate loss from three tillage practices on Brookston soil.</p>	

LIST OF FIGURES - PART B

		Page
Fig. 1B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1988. Arrow denotes planting date May 11, 1988.	71
Fig. 2B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date May 11, 1988.	72
Fig. 3B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date May 1, 1988.	73
Fig. 4B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1988. Arrow denotes planting date May 11, 1988.	74
Fig. 5B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date May 11, 1988.	75
Fig. 6B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date May 11, 1988.	76
Fig. 7B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1989. Arrow denotes planting date May 10, 1989.	77
Fig. 8B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date May 10, 1989.	78
Fig. 9B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date May 10, 1989.	79
Fig. 10B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1989. Arrow denotes planting date May 10, 1989.	80
Fig. 11B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date May 10, 1989.	81

	Page	
Fig. 12B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date May 10, 1989.	82
Fig. 13B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	83
Fig. 14B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	84
Fig. 15B	Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	85
Fig. 16B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	86
Fig. 17B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	87
Fig. 18B	Precipitation (a), total runoff (surface and tile) (b), and des-ethyl atrazine concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till from January 1, to September 30, 1990. Arrow denotes planting date June 1, 1990.	88
Fig. 19B	Total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.	93
Fig. 20B	Des-ethyl atrazine loss as a percent of total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil.	94
Fig. 21 B	Surface and tile loss of triazine as a percent of total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil.	95
Fig. 22B	Surface and tile loss of water as a percent of total water loss from three tillage systems on Brookston soil.	97
Fig. 23B	Seasonal triazine loss as a percent of total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil.	98
Fig. 24B	Seasonal water loss as a percent of total water loss from three tillage practices on Brookston soil.	99

	Page
Fig. 25B	101
Triazine (atrazine and des-ethyl atrazine) soil residues in Brookston soil from three tillage practices, in 1988. Vertical bars are standard error of sample means.	
Fig. 26B	102
Triazine (atrazine and des-ethyl atrazine) soil residues in Brookston soil from three tillage practices, in 1989. Vertical bars are standard error of sample means.	
Fig. 27B	103
Triazine (atrazine and des-ethyl atrazine) soil residues in Brookston soil from three tillage practices, in 1990. Vertical bars are standard error of sample means.	
Fig. 28B	109
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1988. Arrow denotes planting date May 11, 1988.	
Fig. 29B	110
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date May 11, 1988.	
Fig. 30B	111
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date May 11, 1988.	
Fig. 31 B	112
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till for 1989. Arrow denotes planting date May 10, 1989.	
Fig. 32B	113
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date May 10, 1989.	
Fig. 33B	114
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date May 10, 1989.	
Fig. 34B	115
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	
Fig. 35B	116
Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge(c)and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	

		Page
Fig. 36B	Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date June 1, 1990.	117
Fig. 37B	Total Metolachlor loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.	119
Fig. 38B	Surface and tile loss of Metolachlor as a percent of total Metolachlor loss from three tillage practices on Brookston soil.	120
Fig. 39B	Seasonal metolachlor loss as a percent of total metolachlor loss from three tillage practices on Brookston soil.	122
Fig. 40B	Metolachlor soil residues in Brookston soil from three tillage practices in 1988. Vertical bars are standard error of sample means.	123
Fig. 41 B	Metolachlor soil residues in Brookston soil from three tillage practices in 1989. Vertical bars are standard error of sample means.	124
Fig. 42B	Metolachlor soil residues in Brookston soil from three tillage practices in 1990. Vertical bars are standard error of sample means.	125

PART A-

SOIL EROSION, PHOSPHORUS LOSSES AND CORN YIELD

INTRODUCTION

Concern over deterioration of the agricultural resource by soil erosion has resulted in widespread adoption of conservation tillage. Conservation tillage includes those practices with over 30% crop residue on the soil surface (Unger, 1990). Residue cover reduces runoff through increased water infiltration by dissipation of rainfall energy and reduced flow rate. Soil erosion is also reduced through less aggregate dispersion by impacting raindrops (Zobeck and Onstad, 1987; McGregor et al., 1990). However, the full extent of conservation tillage on nutrient transport requires further study.

An increase in infiltration rate by conservation tillage may result in transport of water soluble chemicals to groundwater. Groundwater provides about 95% of the rural US (Helling and Gish, 1986) and much of the rural population in Canada (Frank et al., 1990) with drinking water. The increasing occurrence of nutrients in groundwater is cause for concern (Sharpley *et al.*, 1987; Hanway and Laflen, 1974). The health advisory level for NO₃-N in drinking water is 10 mg/L (National Health and Welfare, 1987). Concentrations of 0.02 mg of phosphorus/L are associated with accelerated eutrophication of surface waters (Sharpley *et al.*, 1987).

Long term tillage trials have recorded increased corn yields with zero tillage compared to conventional tillage (Griffith *et al.*, 1988; Dick and VanDoren, 1985). Yield with zero tillage is most consistently increased on well drained soils and may be depressed on poorly drained soils (Dick and VanDoren, 1985; Cox *et al.*, 1990; Coote and Malcolm-McGovern, 1989; Stone and Heslop, 1987; Vyn *et al.*, 1990; Ketcheson *et al.*, 1983; Vyn *et al.*, 1983). The yield response on well drained soil is primarily attributed to

higher soil water content because of reduced evaporation from the crop residue (Hill et al., 1985). Higher crop yields are also associated with better utilization of fertilizer and reduced potential to leach. Reduced yield on poorly drained soils is attributed to increased disease incidence and decreased germination and plant development from lower soil temperature (Vyn et al., 1990; Cox *et al.*, 1990; Coote and Malcolm- McGovern, 1989; VanDoren et al., 1976; Burrows and Larson, 1962; Fortin and Pierce, 1991). Current research is directed at overcoming these problems by planting disease resistant varieties or encouraging greater use of crop rotation (Dick and VanDoren; 1985; VanDoren et al., 1976; Griffith *et al.*, 1988).

Chemical and physical properties of soil may be altered by tillage. Many of these changes are manifest primarily in the top 30 cm of the soil profile. Reduced tillage results in an increase in organic matter and nutrient content of surface soil (Dick *et al.*, 1991). Two years of zero tillage after 10 yr of conventional mold board tillage increased organic matter content 15% (Lal *et al.*, 1990). Higher concentration of phosphorus and base cations were extracted from the top 5 cm of soil under zero tillage compared to conventional tillage. Micromorphometric analysis of soil from zero tillage treatments revealed half as many macropores (pores >200 μm diameter) in the Ap horizon compared to conventional tillage (Shipitalo and Protz, 1987; Hill et al., 1985). Bioporosity from earth worm activity was two to nine times greater with zero tillage than conventional tillage and was thought to compensate for the loss of macropores. Biomass, as inferred from an increase in enzyme activity, was three to five times greater in zero tillage compared to conventional tillage (Dick, 1983). Nutrient cycling and fertilizer use efficiency could be modified by tillage induced changes on nutrient mineralization (Tracy *et al.*, 1990)

The role of conservation tillage in phosphorus transport has been studied under simulated and field conditions. Phosphorus transport as a function of residue cover, slope length and degree, rainfall intensity, fertilizer application technique and rate, and soil roughness was compared under simulated conditions from conventional and conservation tillage treatments (Ahuja *et al.*, 1982; 1983; Andraski *et al.*, 1985; Reddy *et al.*, 1978;

Romkens and Nelson, 1974; Sharpley *et al.*, 1985; Sharpley, 1980a and b; Mostaghimi *et al.*, 1988). Phosphorus transport from all treatments increased with increasing soil slope and rainfall intensity. Phosphorus concentration in the runoff increased with rate of P fertilization. Phosphorus losses were reduced by contour practices and from soil where surface roughness was increased. However, comparisons of phosphorus loss between conservation tillage and conventional tillage treatments are less definitive. Phosphorus in runoff was associated with sediment transport but soluble P concentrations can be higher under conservation tillage because of leaching of orthophosphate from residue cover (Mostaghimi *et al.*, 1988; Sharpley *et al.*, 1981b) or enrichment of soil P on the soil surface (Sharpley, 1980a; Sharpley, 1985; Sharpley *et al.*, 1985). Conservation tillage may reduce phosphorus loss compared to conventional tillage because of a reduction in sediment transport and runoff. However, reactive and dissolved phosphorus transport was found to be 15% higher from ridge tillage than from conventional tillage treatments because of a 12% increase in surface area of the ridges (Ahuja *et al.*, 1983). Mueller *et al.* (1984b) reported no differences in dissolved reactive phosphorus loss from conservation and conventional tillage treatments in one of two years. Ridge tillage was not one of the conservation tillage treatments included in their study. Lindstrom and Onstad (1984) found higher erosion from zero tillage compared to conventional tillage on a loam soil with 2% slope which they attributed to low saturated hydraulic conductivity, high runoff velocities and low volume of macropores in the zero tillage treatment. Subsurface banding of fertilizer with conservation and conventional tillage on a silt loam reduced the differences in dissolved phosphorus transport but zero tillage reduced total phosphorus loss 81% compared to conventional tillage (Andraski *et al.*, 1985).

Phosphorus transport measured from field watershed studies showed similar trends to the simulated runoff studies. Phosphorus losses were related to sediment losses. Surface applied phosphorus fertilizer had a greater tendency to be transported in runoff than incorporated fertilizer. Phosphorus losses increased with rainfall intensity, and

phosphorus content of surface soil was higher from zero tillage than that from conventional tillage (Alberts *et al.*, 1978; Blevins *et al.*, 1990; Angle *et al.*, 1984; Romkens *et al.*, 1973; Rousseau *et al.*, 1988). Generally phosphorus loss is low with <5% of applied phosphorus appearing in runoff (Olness *et al.*, 1980; Gaynor, 1979). Zero tillage reduces erosion and may reduce phosphorus loss relative to conventional tillage (Mueller *et al.*, 1984b; Angle *et al.*, 1984; McDowell and McGregor, 1984; Mutchler *et al.*, 1985; Yoo and Touchton, 1988) but bioavailability of phosphorus may be higher from zero tillage than from conventional tillage (Mueller *et al.*, 1984a). About 21 to 25% of sediment phosphorus was found to be bioavailable in an algal bioassay (Dorich *et al.*, 1980; 1984; 1985). Sorbed phosphorus associated with amorphous Fe and Al oxides was more biologically available than that associated with Ca constituents (Hegemann *et al.*, 1983; Huettl *et al.*, 1979). Soils in southwestern Ontario are derived from calcareous parent material which could increase their capacity to retain phosphorus.

Tile discharge contributes significantly to phosphorus levels of receiving waters. More than 50% of phosphorus loss occurred through tile water discharge from conservation tillage on poorly drained Brookston soil of low slope (Culley *et al.*, 1983). About 34% of the phosphorus appearing in the drain discharge was sediment related. In another study, phosphorus concentration of tile discharge was related to fertilizer rate, tile depth and rainfall (Calvert, 1975). Phosphorus concentration of surface runoff is higher than that in tile discharge (Hanway and Laflen, 1974; Hergert *et al.*, 1981a and b; Baker *et al.*, 1975). However, a larger proportion of total phosphorus loss may occur through tile discharge because the volume of water in tile discharge usually exceeds the volume of surface runoff. Where soil loss was high, 90 to 98% of phosphorus loss was associated with sediment but during winter months 33% of phosphorus loss may occur as dissolved or soluble phosphorus (Hubbard *et al.*, 1982). Rain and snow may contribute significantly to phosphorus loading of receiving streams or waterways (Nicholaichuk and Read, 1978; Menzel *et al.*, 1978; Culley and Bolton, 1983) but phosphorus derived from these sources

are less than those from agricultural sources. Natural geologic sources may contribute 45% to the total phosphorus load (Johnson *et al.*, 1976).

About 7% of the area of Canada (922×10^6 ha) is suitable for agriculture (Dumanski *et al.*, 1986). Of this area, 5% is considered class 3 or better land. Ontario has 14% of Canada's arable land and over 50% of the class 1 capability soils (Ketcheson, 1980). Thus, to ensure continued productivity of soils in Canada, conservation methods need to be developed.

Approximately 23×10^6 ha of the area bordering the Great Lakes basin (43% of the total area draining into the lakes) lies in Canada (Coote *et al.*, 1982). Of this area, 22% is agricultural land residing in the drainage basins of Lakes Erie, Huron and Ontario. Essex County lies in the Lake Erie basin and is extensively cultivated predominantly to corn, wheat and soybeans (88% of the farm area, Anonymous, 1990). Drainage flows north to Lake St. Claire or west to the Detroit River which discharges to Lake Erie or south directly to the lake. The major clay and clay-loam soil type is the Brookston series (Evans and Cameron, 1983) which represents 89% of the soil type in the county, and is about 80% artificially drained by subsurface drains. The Brookston series is classified as poorly drained, and has a high surface pollution potential index (0.8, Coote *et al.*, 1982). Estimated soil loss from this soil type is 6500 kg/ha/yr with total P loss 1500 g/ha/yr. Approximately 80% of the soil and phosphorus loss occurs from September to April. Average precipitation in the study area is 762 mm/yr with 27% appearing as stream discharge. Average rainfall is distributed throughout the year with 35% falling from January to April, 41% from May to August and 24% from September to December (Coote *et al.*, 1982).

OBJECTIVES

Conservation tillage with residue management is considered the best management practice in Ontario to control soil erosion from agricultural land (Ketcheson *et al.*, 1983; Vyn *et al.*, 1983). However, little is known about the effects of conservation tillage on nutrient losses from level plane, poorly drained soil. Because Brookston clay loam is the predominant soil type under intensive agriculture in Essex County, a study was initiated to compare soil and nutrient losses from three tillage practices.

MATERIALS AND METHODS

The study area was located south of the 42° 30' north Latitude and 82° 30' west Longitude in Essex County. The area was tiled longitudinally in 1969 with one tile in the centre of each 0.1 ha plot at 0.6 m depth . The three tillage practices established in 1984 were i) fall plow, spring disk, and one midseason cultivation (referred to as conventional tillage), ii) ridge tillage with ridges 15 to 20 cm high reformed in midseason with a Hiniker[®] soil ridger and, iii) zero tillage, no tillage other than that associated with planting and fertilizer incorporation (Fig. Al A). A blue grass sod treatment was included for comparison. Each tillage plot was graded (<0.5% slope) to the centre and longitudinally to the north in each plot for surface runoff measurement.

Precipitation was measured at the site with a Belfort[®] rain gauge which records the weight of rain or snow as inches or mm of rainfall. A catchment basin was installed downslope where runoff was channelled to a 0.23 m H flume. Stage height for each runoff event was recorded on a Belfort[®] water level recorder. Tile discharge was directed through a 3.8 cm proportional logarithmic weir and stage height recorded on a Stevens[®] water level recorder.

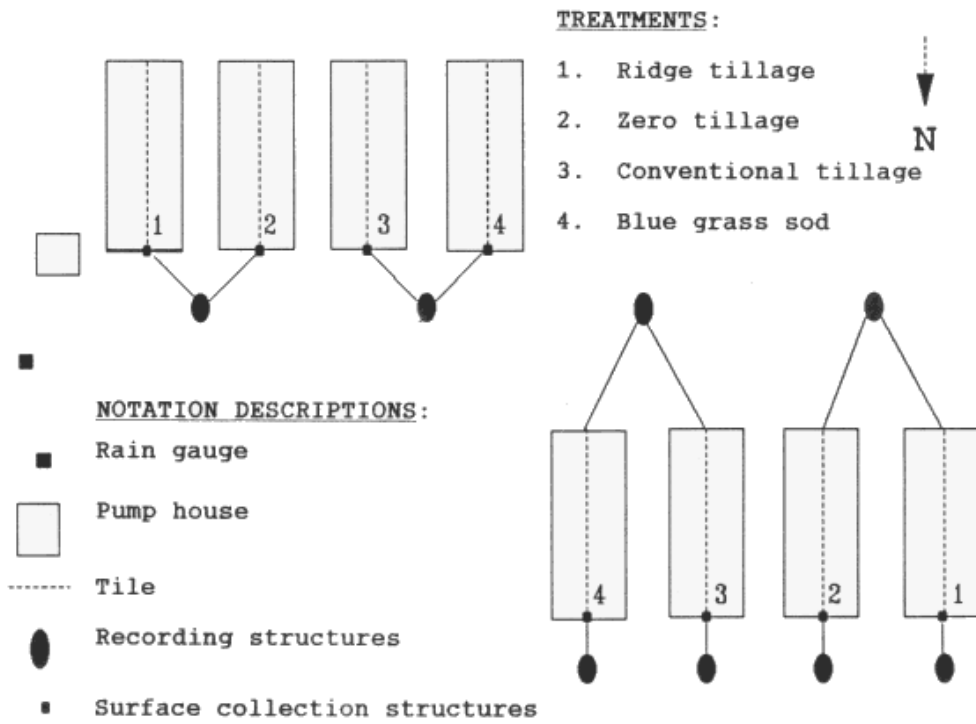


Fig. A1A. Site layout, treatment and sampling monitoring locations at the Totten experimental site, Woods lee, Ontario.

Manual monitoring of tile flow rate for each event throughout the hydrograph provided verification of calibration of the weir. The surface runoff flumes were calibrated independently, such that the total flow was the product of the unit area paper weight of the hydrograph and a calculated calibration factor. Tile discharge volume was calculated from the area of the hydrograph by integration of the tile flow rate throughout the hydrograph using Simpsons Rule algorithm. Grab samples from surface runoff and tile discharge were manually collected throughout the hydrograph for suspended sediment, nutrients and herbicide analysis. Samples were stored at 4°C and analyzed within 2 to 4 months of collection.

Pioneer 3707 corn at 67,000 seeds/ha was seeded in 75 cm rows on May 11, 1988 with a Buffalo® till planter, on May 10, 1989 with a Hiniker Econ-o-till (model 7430) planter and on June 1, 1990 with a Kinzie planter. In 1990 Pioneer 3707 was no longer available and Pioneer® 3475 was substituted, a variety with similar heat unit requirements. The planters were outfitted with 10 cm fluted coulters to cut the thatch for the seed drill. Fertilizer (132 kg/ha 8-32-16) was side dressed at planting with the Hiniker in 1989 and the Kinzie in 1990. A brush applicator was used in 1988 and for the midseason fertilizer application of 168 kg/ha 34-0-0. A Gandy® spreader was used on the sod plots which received the same rates of fertilizer as the corn plots in addition to 132 kg/ha 8-32-16 in the fall. All treatments were replicated twice.

Grain yield was measured from the weight of threshed ears hand harvested from each treatment in two, 15 m rows. Harvest dates were October 17, 1988, October 12, 1989 and October 31, 1990. Grain moisture content was determined with a Dicky John moisture meter and grain weight at 14% moisture content calculated.

Residue cover on each tillage treatment was calculated from the average of three determinations per plot using the marked rope technique as described by Stone and Heslop (1987). Basically a 15 m rope was marked at 50 equally spaced points and diagonally laid

across the plot. The number of marks that intercepted residue were summed and expressed as percent residue cover.

Water Analysis

A 250 mL aliquot from each water sample was filtered under vacuum through a pre-weighed 0.45 µm filter (Millipore Cat. No. HAWP 047 AO). The filter was dried 2 h at 105°C and sediment weight determined gravimetrically (Anonymous, 1979). The sediment and filter were retained in 1990 for P analysis.

An aliquot of the filtered water sample was analyzed for orthophosphate on a Technicon® auto analyzer using the ammonium molybdate, stannous chloride method (Anonymous, 1979). Orthophosphate concentration in the water was determined from a linear calibration curve developed for each analysis. Total soluble phosphorus concentration was determined on samples from 1990 by reducing a 50 mL aliquot of the filtered water sample to 10 mL and digesting the residue on a hot plate after adding three drops of sulphuric acid, one mL perchloric acid and five mL of a nitric, perchloric acid solution (44 mL perchloric acid in 2 L nitric acid). The digested residue was fumed to emit the perchloric acid, acidified to pH 3 then analyzed on the Technicon® analyzer for orthophosphate.

Total phosphorus on the sediment from 1990 was digested on a hot plate in an acid environment similar to that for total soluble phosphorus, the residue fumed to emit perchloric acid then dissolved in 50 mL water adjusted to pH 3 and filtered to remove undissolved residue. Phosphorus concentration in the acidified filtrate was determined on the auto analyzer as noted for orthophosphate. Because of an error in analysis of the samples for total soluble and sediment phosphorus for 1988 and 1989, only orthophosphate concentration and losses are reported for these years. In 1990 orthophosphate, total soluble P and sediment phosphorus concentrations were determined.

Event losses of sediment and orthophosphate were calculated as the product of the average event concentration for sediment or orthophosphate and event volume loss of water. Phosphorus loss associated with the sediment for 1990 was the product of soil loss and sediment phosphorus concentration averaged for the event. For the 1990 water samples, total soluble phosphorus transport was the product of the average soluble phosphorus concentration and event volume. Organic phosphorus was the difference between soluble phosphorus and orthophosphate, and total phosphorus loss was the sum of soluble phosphorus and sediment phosphorus loss for each event. Annual sediment and phosphorus loss was the sum of event losses for each parameter.

Data for treatments within years are reported with standard error of sample means. Seasonal distribution and source losses (surface or tile) are reported as a percent of total loss without standard errors since statistical analysis of percent data requires special procedures. Statistical analysis of data were performed with MEANS and ANOVA procedures (SAS, 1989).

RESULTS AND DISCUSSION

The two conservation tillage treatments had >86% crop residue before planting (Table 1 A). Residue cover was higher with zero (95%) than with ridge tillage (88%). Conventional tillage had <10% crop residue as a result of fall plowing and spring disking operations. Reridging in midseason lowered residue cover on the ridge tillage treatment.

Table 1A. Residue cover \pm standard error of means before planting on three tillage treatments for 1988, 1989 and 1990.

Tillage	Residue cover, %		
	1988	1989	1990
Ridge	89 \pm 1	86 \pm 1	89 \pm 2
Zero	96 \pm 1	95 \pm 2	93 \pm 1
Conventional	<10	<10	<10

Precipitation and Yield

Rainfall was 16% less than the 33 yr average of 762 mm in 1988, 7% less in 1989 and 43% greater in 1990 (Table 2A). Rainfall was fairly evenly distributed in 1988 with 31% received before planting (January to planting, May 11), 37% in the growing season (May 12 to September 30) and 32% after harvest (October 1 to December 31, Table 2A). More rainfall (61%) was received in the growing season (May 10 to September 30) in 1989 than before planting (January 1 to May 10, 24%), and after harvest (October 1 to December 31, 15%). Rainfall in 1990 was distributed with 47% falling in the growing season (June 1 to September 30) and 33% before planting (January 1 to June 1). Water sampling was completed after September 30, 1990 because of termination of the field phase of the project.

Table 2A. Rainfall deviation from the 33 year average (762 mm) and seasonal distribution at the Totten site a.

Year	Total, mm	Deviation from normal, %	BA ----- % -----	GS ----- % -----	AH ----- % -----
1988	638.9	-16.2	31	37	32
1989	708.8	- 7.0	24	61	15
1990	1092.0	+43.3	33	47	20

^a BA = January 1 to planting; GS = planting to September 30; AH = October 1 to December 31.

Little rain fell in the early stages of crop development during the growing season (Julian day 132 to 200) in 1988 (Fig. 1 Aa) which resulted in poor corn growth and reduced yields (Table 3A). Heavy rainfall came after planting in 1989 (Julian day 130, Fig. 1Ab) and seemed to have affected plant growth and reduced yields. High soil moisture content from excessive rainfall around planting can reduce corn yield on poorly drained soil because of poor aeration and low soil temperature (Stone and Heslop, 1987; Vyn et al, 1990).

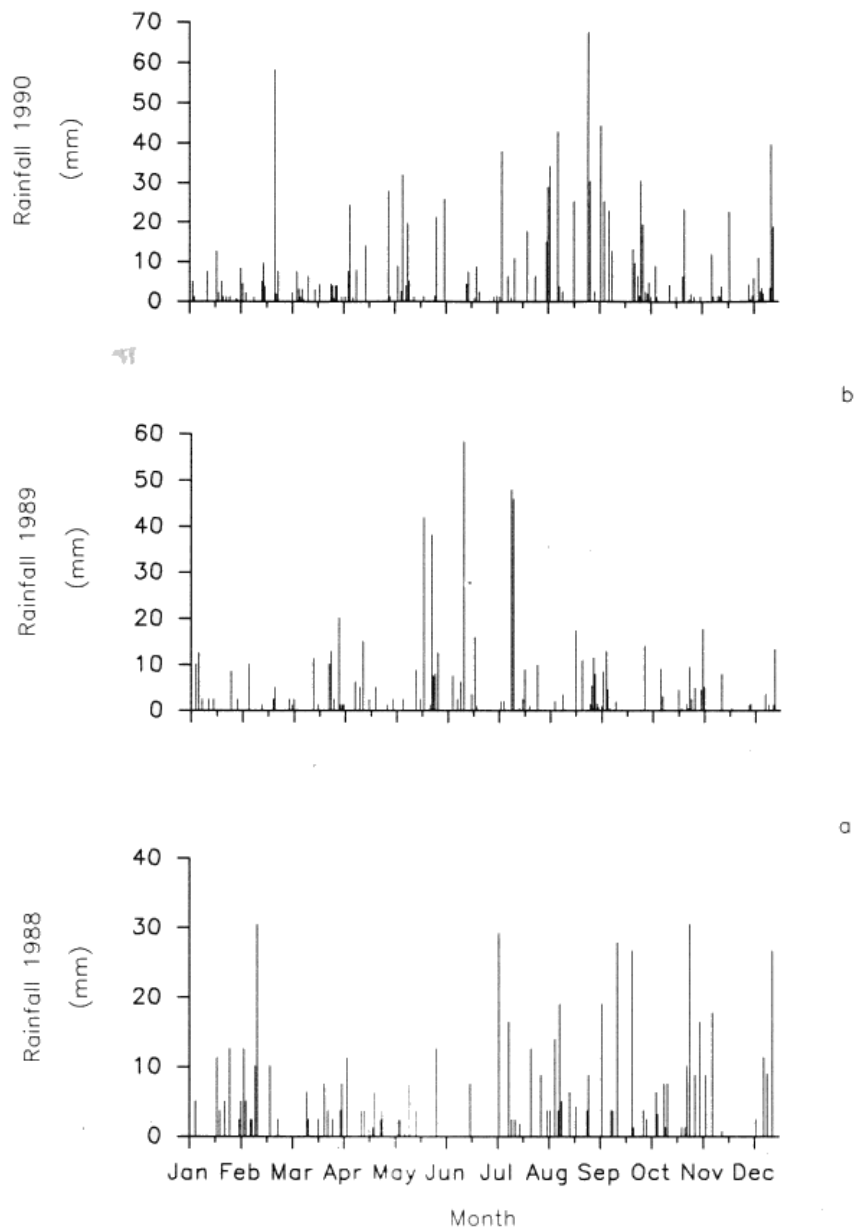


Fig 1A. Precipitation for 1988 (b), 1989 and ©), 1990 at the Totten site.

Rainfall distribution and quantity were adequate in 1990 (Fig. 1 Ac) producing good grain yield (Table 3A). Tillage method had no significant effect on grain yield in any of the years. Average grain yield for the three years was 7.0 t/ha from ridge, 6.9 t/ha from zero and 6.5 t/ha from conventional tillage.

Table 3A. Grain corn yield \pm standard error of means (at 14% moisture content) from three tillage practices for 1988, 1989 and 1990.

Tillage	Yield, t/ha		
	1988	1989	1990
Ridge	5.49 \pm 0.43	5.89 \pm 0.61	9.72 \pm 0.20
Zero	5.38 \pm 0.48	6.29 \pm 0.81	9.14 \pm 0.09
Conventional	5.93 \pm 0.70	5.50 \pm 0.38	8.13 \pm 0.37

Surface and Subsurface Runoff

Water loss by surface runoff and subsurface tile flow was similar from the three tillage treatments but yearly differences occurred (Fig. 2A). Total water loss was 23% of rainfall in 1988, 28% in 1989 and for the first nine months in 1990, 36%. Coote *et al.* (1982) estimated 26% runoff of annual rainfall in this area for the Brookston clay loam. Rainfall was near the long term average in 1989 and runoff was similar to that reported by Coote *et al.* (1982) whereas rainfall was 43% higher than normal in 1990 thus accounting for the higher runoff. The absence of a tillage response on total runoff losses is not unexpected since all treatments received the same water input and the slope of the plots was <0.5%. However, tillage had an effect on the source of runoff, ie. tile discharge or surface runoff.

Over the three years of the study tile discharge exceeded surface runoff for all treatments (Fig. 3A). Surface runoff was greater from the conservation tillage treatments than from conventional tillage in all years. In two of the three years (1988 and 1990)

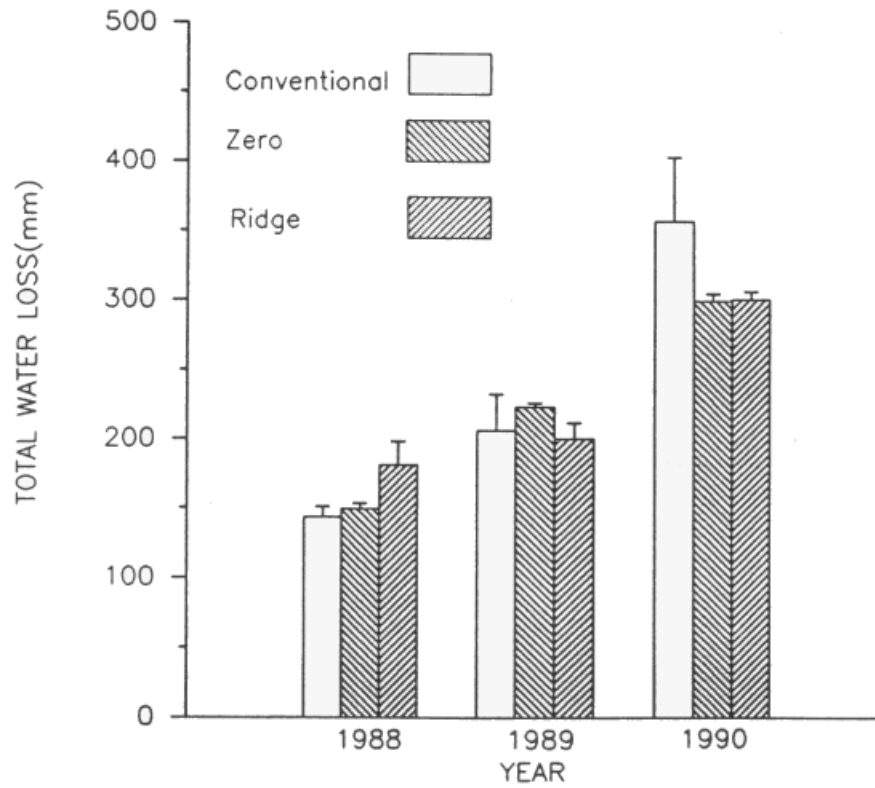


Fig. 2A Tile water discharge and surface water runoff from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.

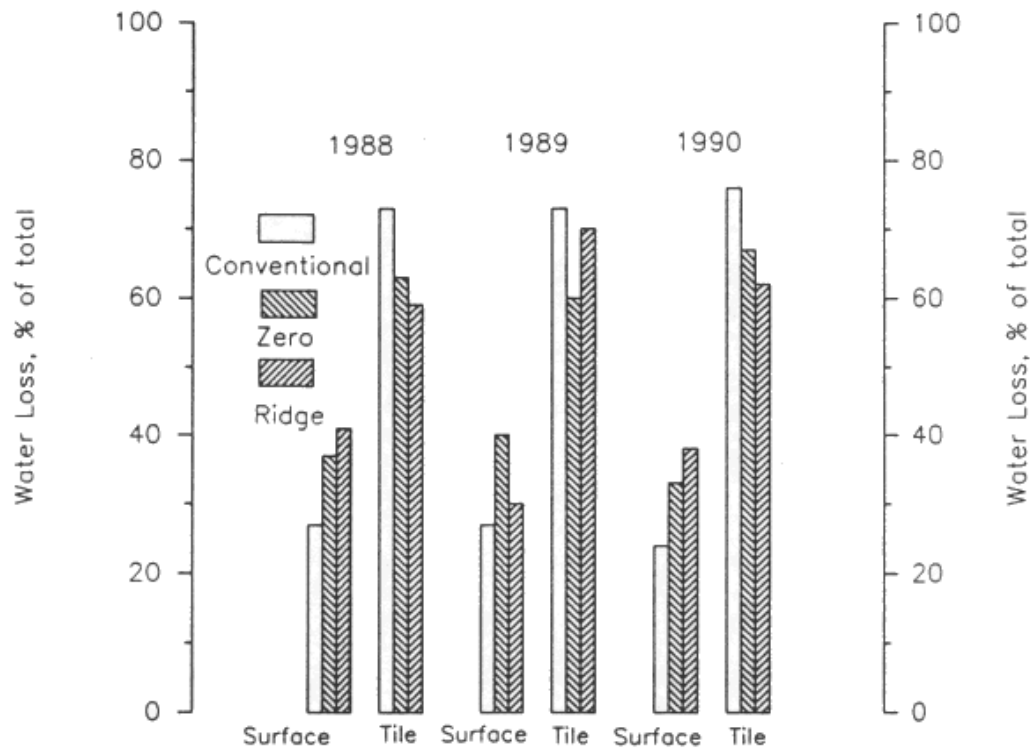


Fig. 3A Surface and tile loss of water as a percent of total water loss from three tillage systems on Brookston soil.

surface runoff was greater from ridge than zero tillage. This could relate to differences in surface topography between ridge tillage and zero tillage, however, antecedent soil moisture content, residue cover, rainfall intensity and duration will affect runoff (Ahuja *et al.*, 1983; Mostaghimi *et al.*, 1988; Unger, 1990). Subsurface runoff accounted for 58 to 75% of the total runoff. Drain discharge amounts under these treatments were similar to those reported by Culley *et al.* (1983). Our results demonstrate that on low slope, poorly drained soil, tillage has no effect on total runoff but can affect whether runoff occurs from the surface or through drains. This could have a significant effect on nutrient transport. Phosphorus concentrations of surface runoff water were higher in 1988 and 1989 than concentrations of tile discharge. Similar results for other nutrients and phosphorus have been reported (Laflen and Tabatabai, 1984; McDowell and McGregor, 1984; Mostaghimi *et al.*, 1988).

The proportion of runoff was higher before planting (January to planting) than for the growing season for all treatments in 1988 and 1990 (Fig. 4A). The proportion of runoff from conventional and zero tillage was similar before planting and in the growing season in 1989, while a much greater proportion of runoff occurred during the 1989 growing season from the ridge tillage treatment. Generally, runoff in southwestern Ontario is higher in spring and fall because evaporative losses are low, soil is frozen and soil moisture content remains high (Madramootoo, 1988). Very little runoff occurred during the growing season in 1988 because soil moisture was low and rainfall was insufficient to exceed the infiltration rate and storage capacity of the soil. A greater proportion of runoff occurred during the growing season in 1989 because rainfall events were more intense and occurred closer together. About 30% of the January to September runoff for 1990 occurred during the growing season. Tillage had no effect on the seasonal proportion of runoff in 1988 and 1990. The proportion of runoff was higher before planting and lower in the growing season for zero tillage than for the other tillage systems in 1989. The higher residue cover associated with zero tillage and accompanying increased moisture content of soil because of reduced evaporative losses (Dick *et al.*, 1991) appears to have little consistent effect on seasonal distribution of runoff for this soil type.

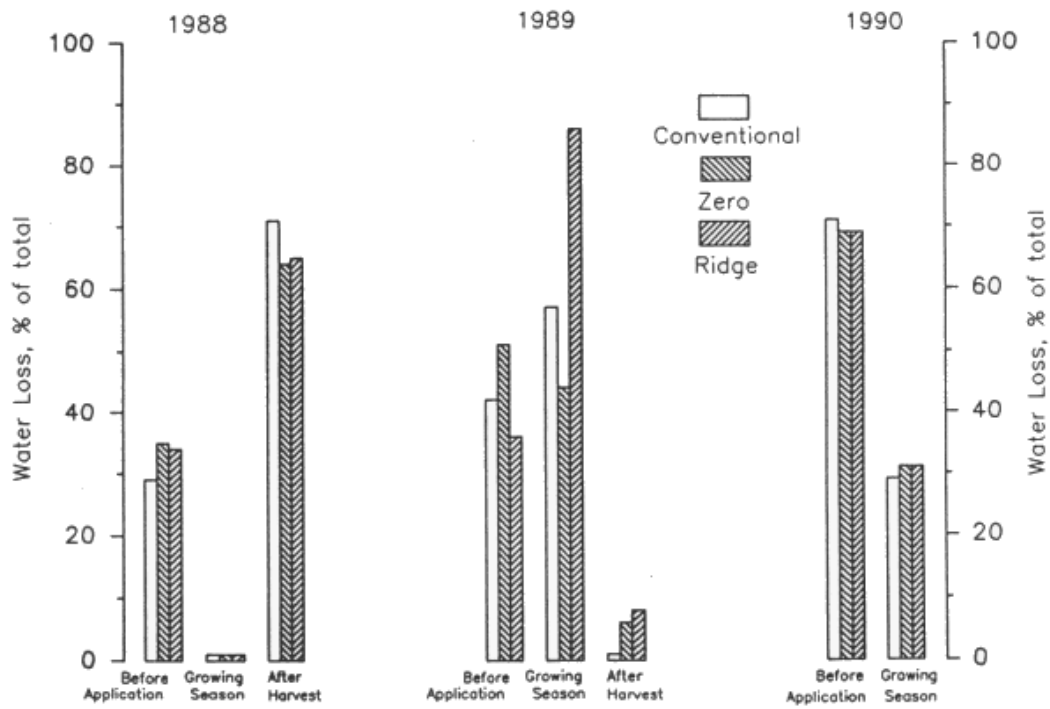


Fig. 4A Seasonal water loss as a percent of total water loss from three tillage practices on Brookston soil.

Suspended Sediment Concentration and Loss

The range and average sediment concentration in the runoff was similar for 1988 and 1990 but runoff from conventional tillage had higher average sediment concentration than the conservation tillage treatments (Table 4 to 6A). Generally, sediment concentrations were higher in surface runoff than drain discharge and runoff from conventional tillage had higher sediment concentrations in surface and subsurface runoff than did runoff from the conservation tillage treatments. Runoff from zero tillage had lower sediment concentration than ridge tillage.

Table 4A. Range and average sediment and orthophosphate concentration of surface and subsurface runoff water from three tillage treatments for 1988. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Tillage	Source	Sediment conc, g/L		Orthophosphate conc, mg/L	
		Range	Mean	Range	Mean
Ridge	Surface	0.08 - 1.86	0.42 ± 0.03	0.17 - 1.91	0.58 ± 0.07
	Tile	0.00 - 0.75	0.15 ± 0.01	0.03 - 1.00	0.39 ± 0.02
Zero	Surface	0.08 - 0.69	0.25 ± 0.01	0.19 - 1.92	0.74 ± 0.06
	Tile	0.00 - 0.70	0.11 ± 0.01	0.07 - 1.02	0.51 ± 0.03
Conventional	Surface	0.18 - 2.02	0.98 ± 0.05	0.18 - 0.65	0.35 ± 0.04
	Tile	0.00 - 3.69	0.45 ± 0.02	0.05 - 0.94	0.33 ± 0.02

Table 5A. Range and average sediment and orthophosphate concentration of surface and subsurface runoff water from three tillage treatments for 1989. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Tillage	Source	Sediment conc, g/L		Orthophosphate conc, mg/L	
		Range	Mean	Range	Mean
Ridge	Surface	0.14 - 3.14	0.73 ± 0.22	0.12 - 3.48	0.67 ± 0.04
	Tile	0.01 - 1.19	0.28 ± 0.02	0.05 - 1.24	0.37 ± 0.04
Zero	Surface	0.02 - 0.42	0.12 ± 0.01	0.13 - 7.10	2.12 ± 0.45
	Tile	0.00 - 0.24	0.05 ± 0.01	0.08 - 3.45	0.80 ± 0.04
Conventional	Surface	0.14 - 3.64	0.87 ± 0.18	0.08 - 3.62	0.46 ± 0.12
	Tile	0.01 - 1.52	0.37 ± 0.06	0.04 - 1.15	0.24 ± 0.02

Table 6A. Range and average sediment and orthophosphate concentration of surface and subsurface runoff water from three tillage treatments from January 1 to September 30, 1990. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Tillage	Source	Sediment conc, g/L		Orthophosphate conc, mg/L	
		Range	Mean	Range	Mean
Ridge	Surface	0.02 - 1.26	0.24 ± 0.03	0.07 - 5.30	0.56 ± 0.31
	Tile	0.01 - 0.41	0.10 ± 0.01	0.03 - 5.97	0.45 ± 0.11
Zero	Surface	0.06 - 0.45	0.17 ± 0.01	0.09 - 1.71	0.43 ± 0.01
	Tile	0.01 - 0.28	0.09 ± 0.01	0.04 - 9.73	0.96 ± 0.03
Conventional	Surface	0.04 - 1.50	0.32 ± 0.02	0.09 - 0.65	0.19 ± 0.02
	Tile	0.01 - 0.35	0.10 ± 0.01	0.03 - 3.98	0.25 ± 0.04

The relationship between rainfall, runoff and sediment concentration in surface and subsurface runoff is shown in Figures 5 to 13A. No significant runoff producing events occurred during the growing season in 1988 (Fig. 5 to 7A). Generally sediment concentrations were higher in surface than subsurface runoff. Also, higher sediment concentrations were observed in runoff which occurred after harvest because of more intense rainfalls and absence of crop canopy. Major runoff producing events occurred during the growing season in 1989 and sediment concentrations in the runoff were high (Fig. 8 to 10A). Only one runoff producing event (Julian day 320) occurred after harvest which did not contribute substantially to sediment transport. The runoff producing events in 1990 had low sediment concentrations (<1.5 g/L) compared to 1989 (<3.6 g/L, Fig. 8 to 13A). Runoff events in 1990 occurred when the soil was susceptible to erosion, however, their intensity was low thus sediment concentrations were low. Water sampling was completed after September 30, 1990.

Soil erosion was reduced with the conservation tillage treatments in each of the three years investigated (Fig. 14A) attesting to the value of residue cover on reducing rainfall energy (Unger, 1990; Johnson and Moldenhauer, 1979; Coote and Malcolm-McGovern, 1989;

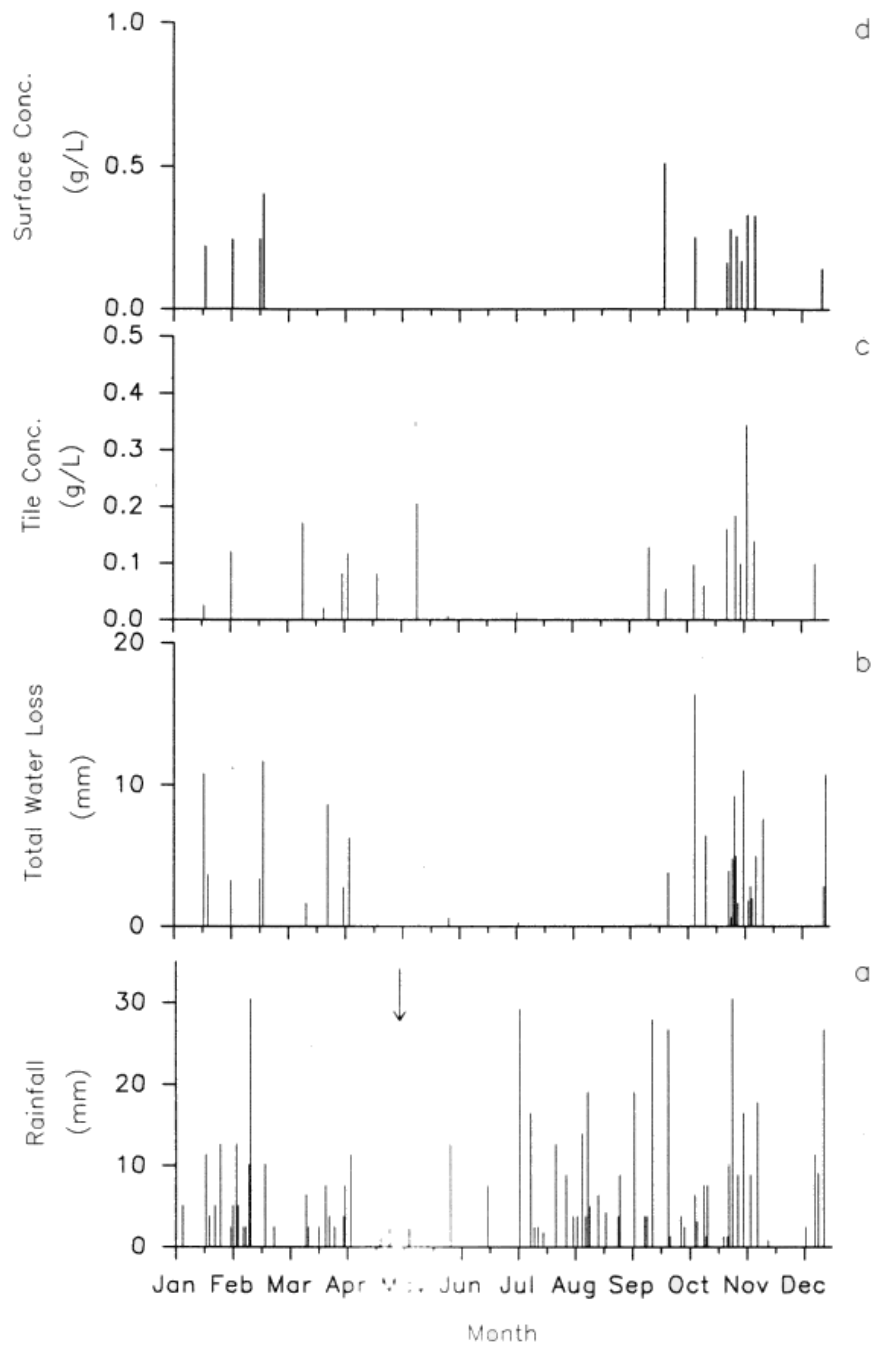


Fig 5A Precipitation (a) total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d) from zero till for 1988. Arrow denotes planting date on May 11, 1988

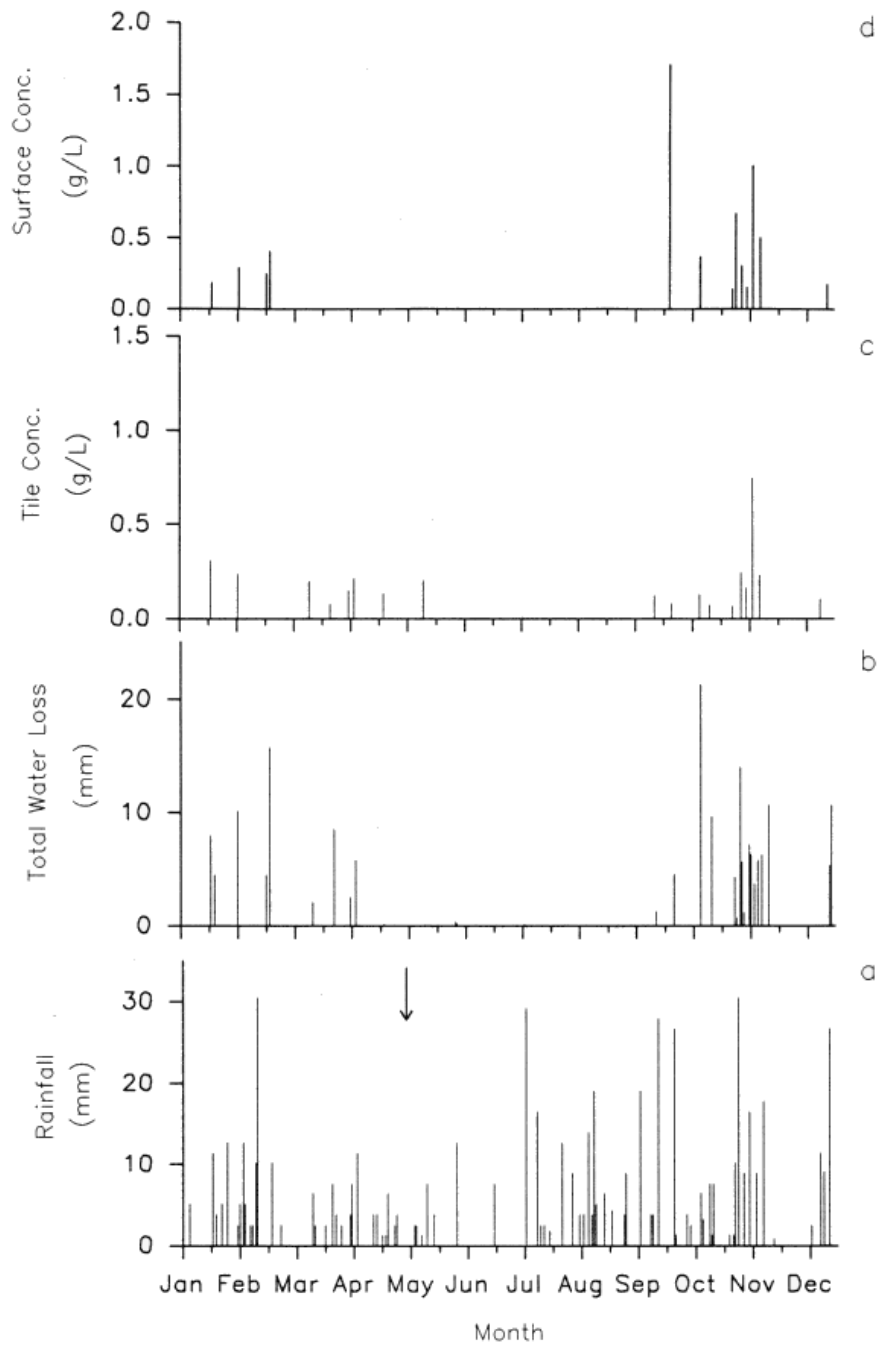


Fig 6A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date on May 11, 1988.

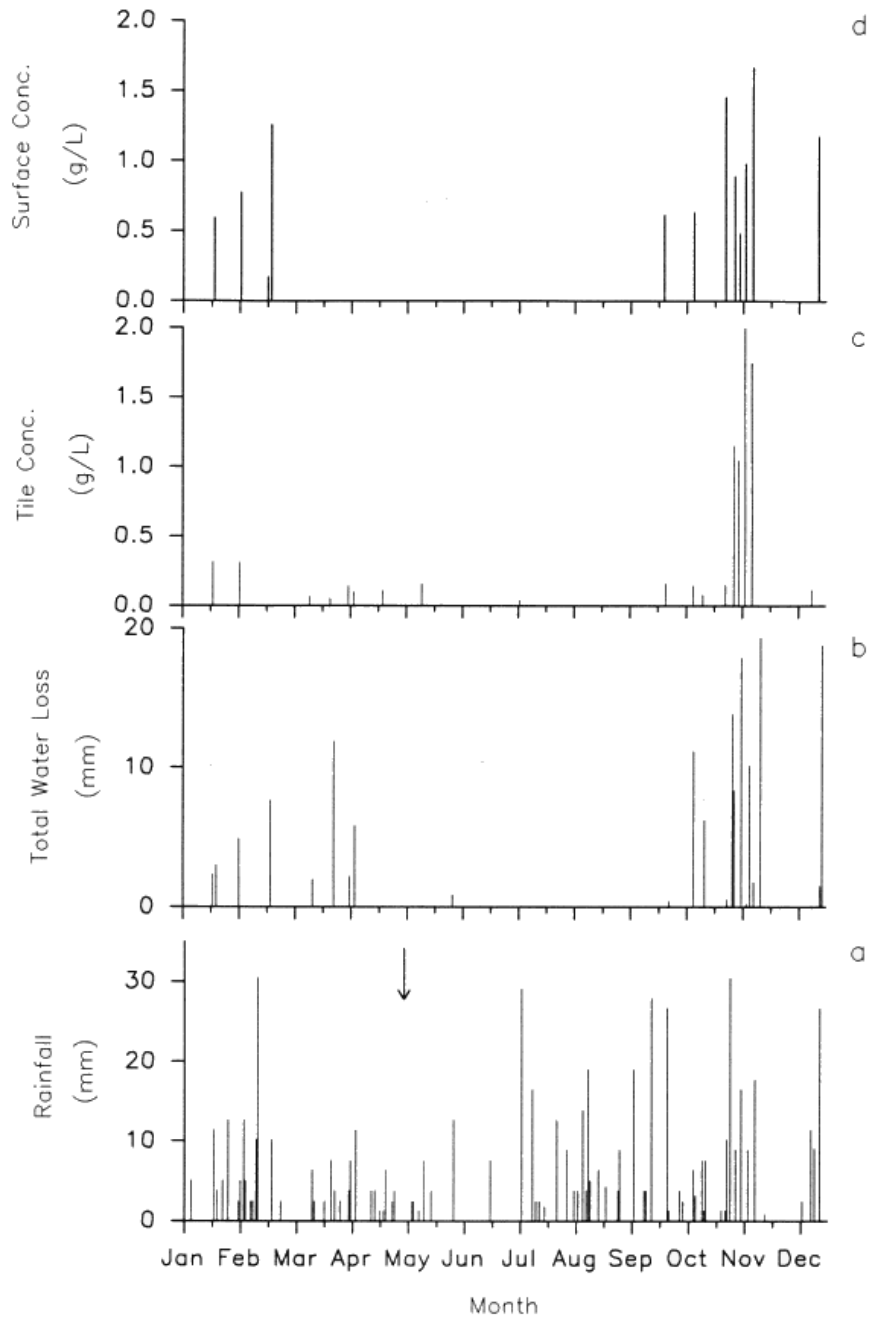


Fig 7A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date on May 11, 1988.

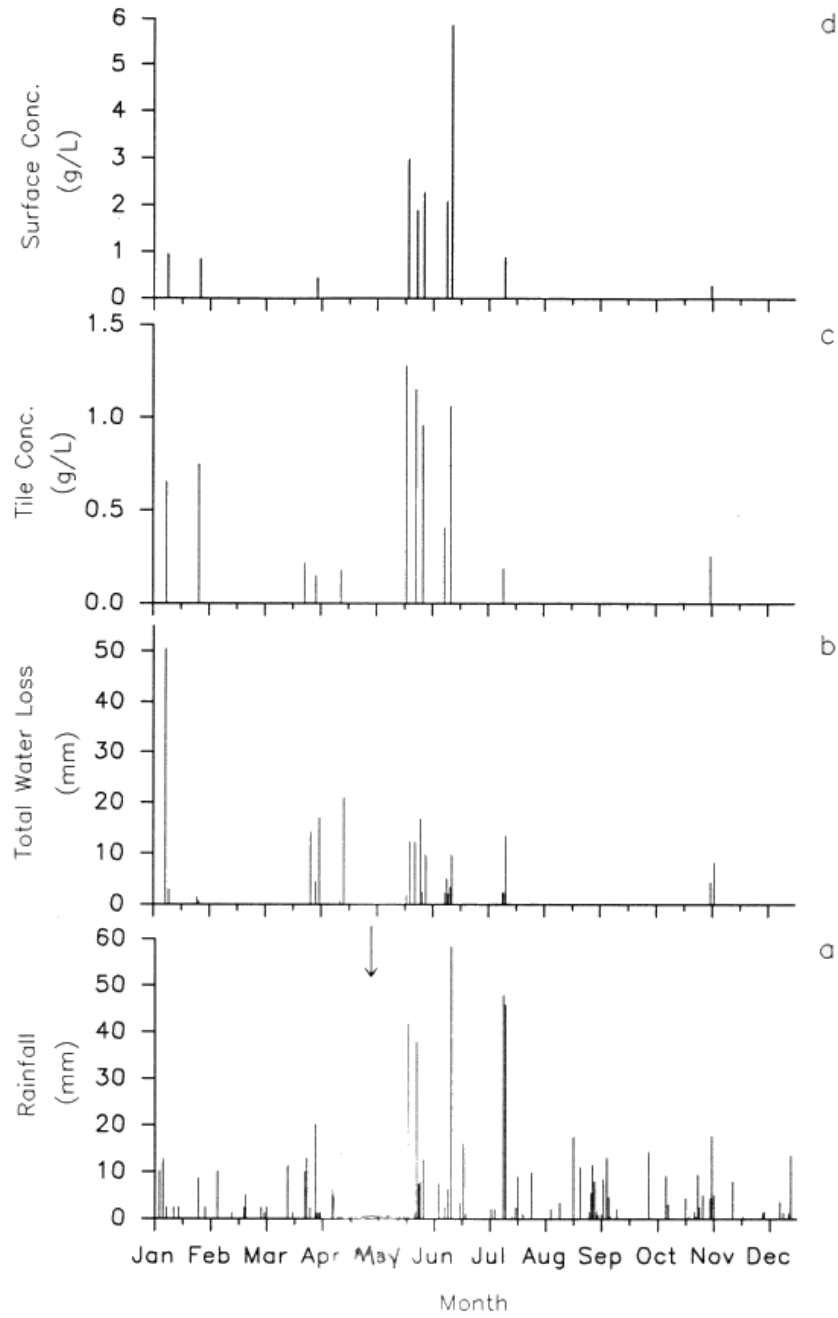


Fig 8A Precipitation (a) total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d) from zero till for 1989. Arrow denotes planting date on May 10, 1989.

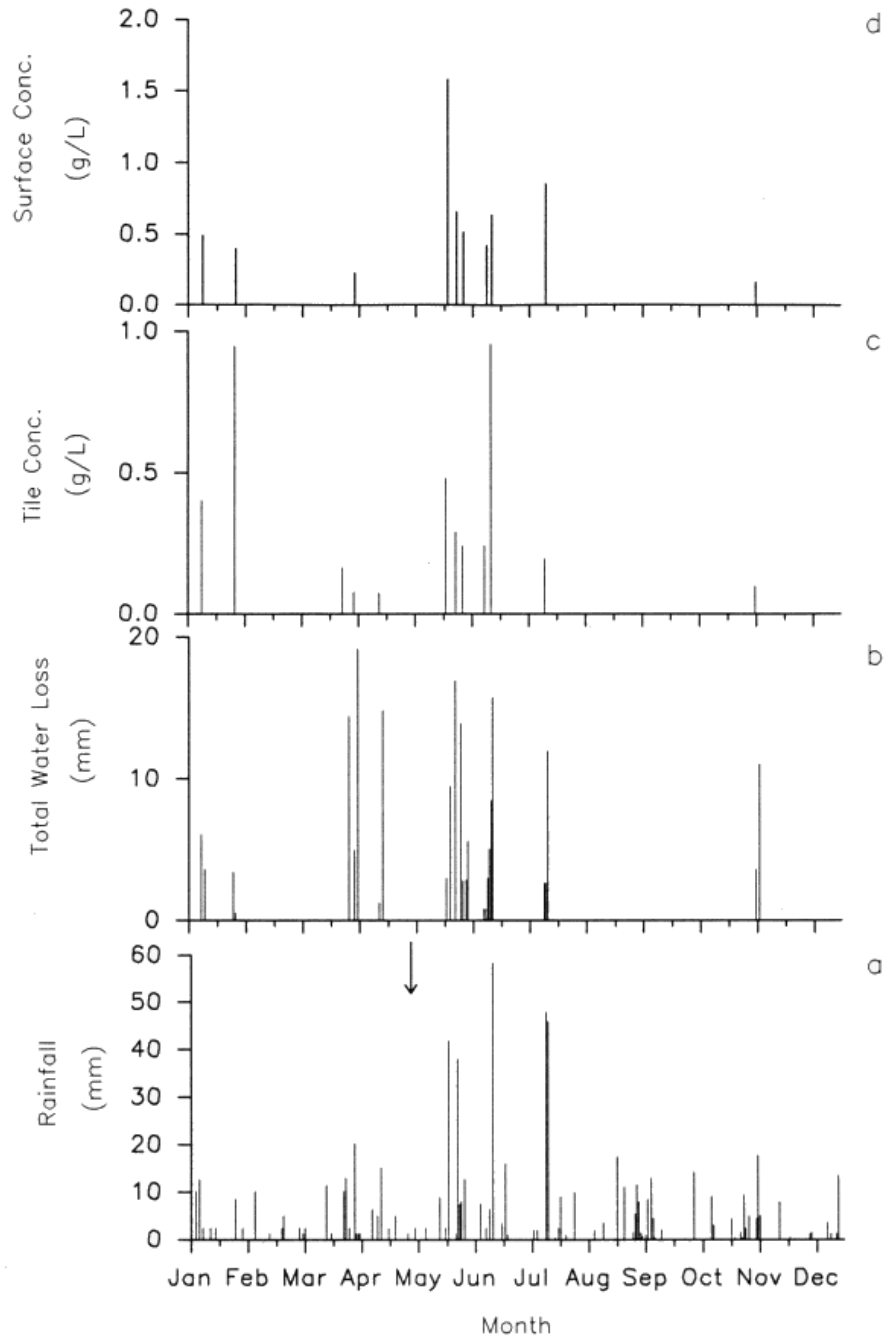


Fig 9A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date on May 10, 1989.

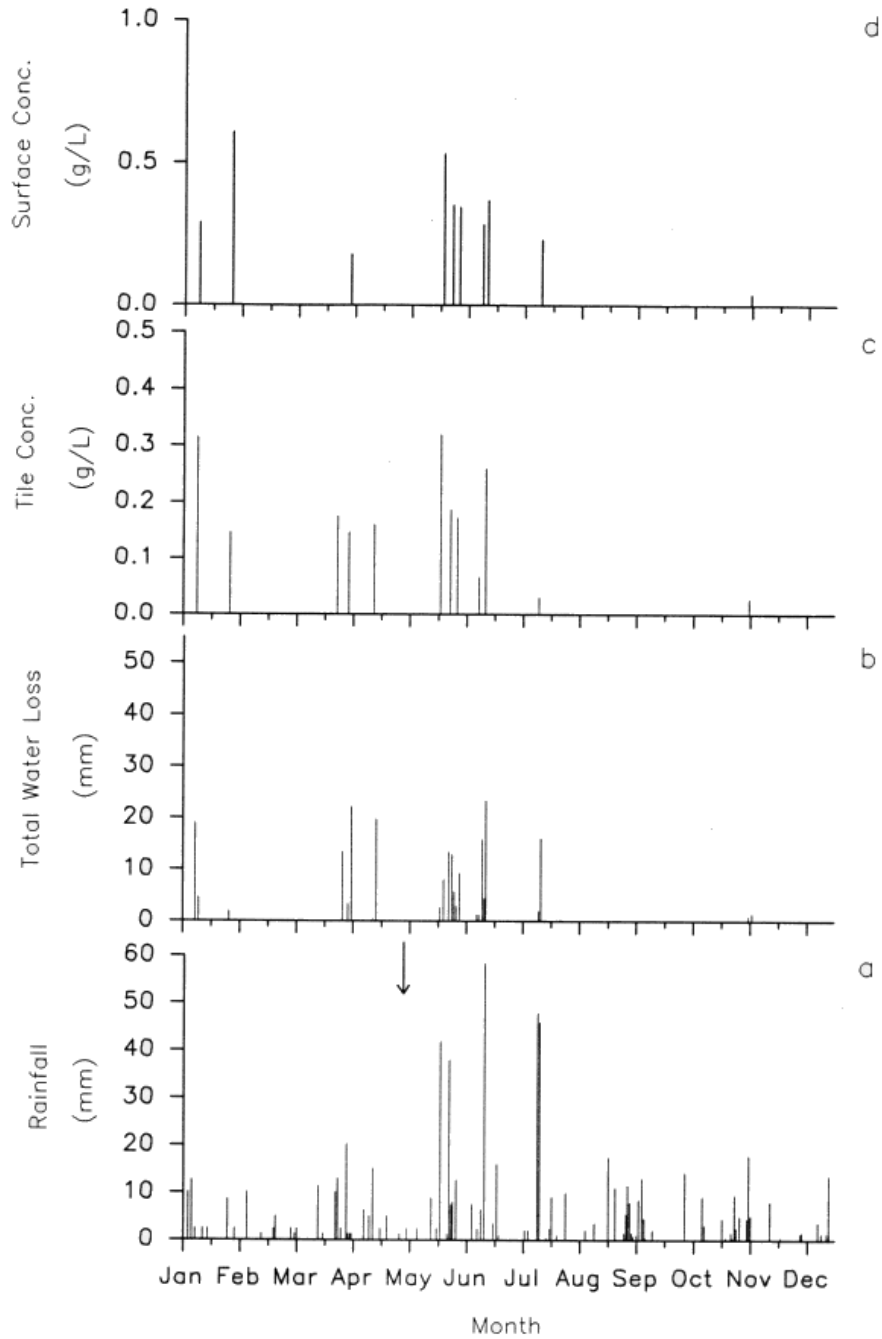


Fig 10A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date on May 10, 1989.

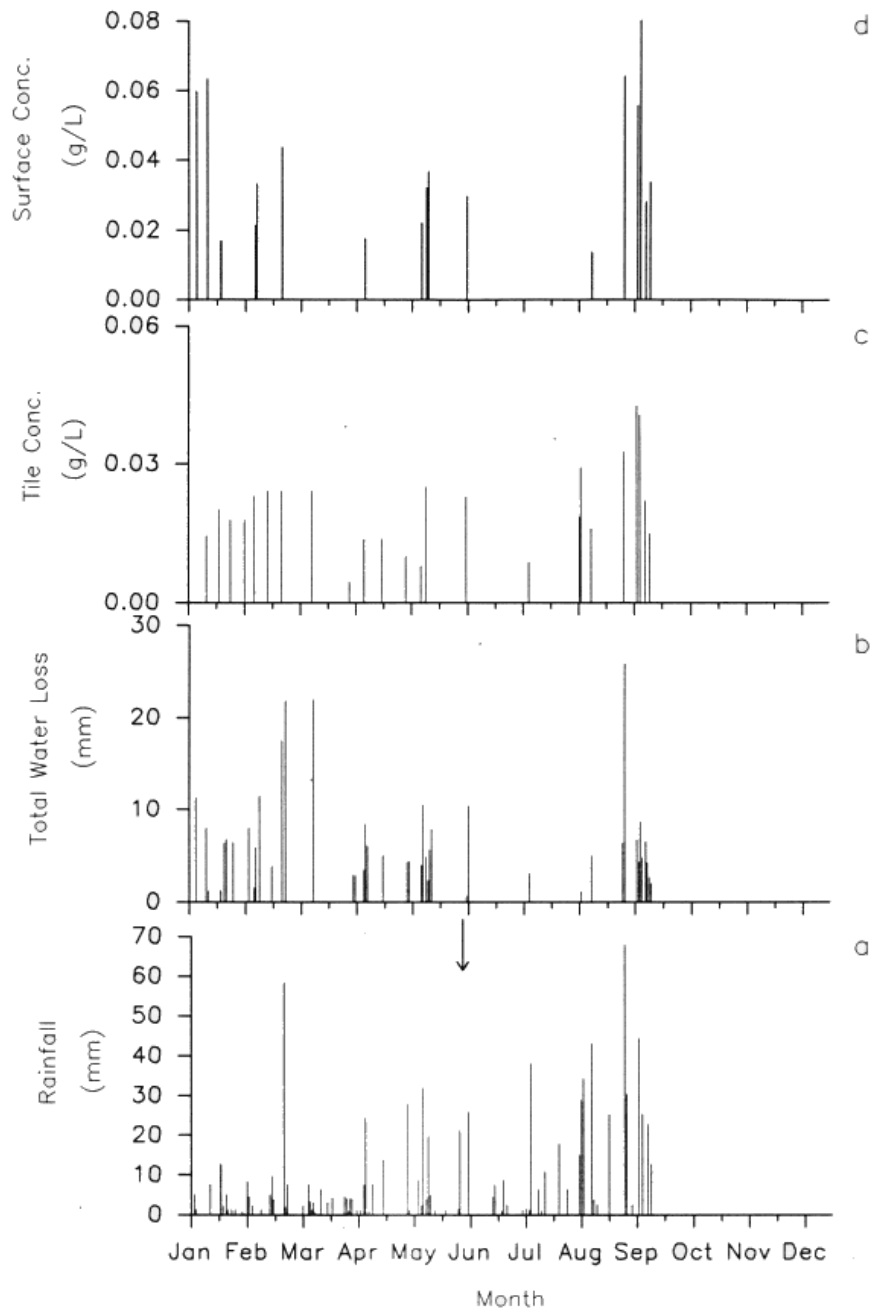


Fig 11A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

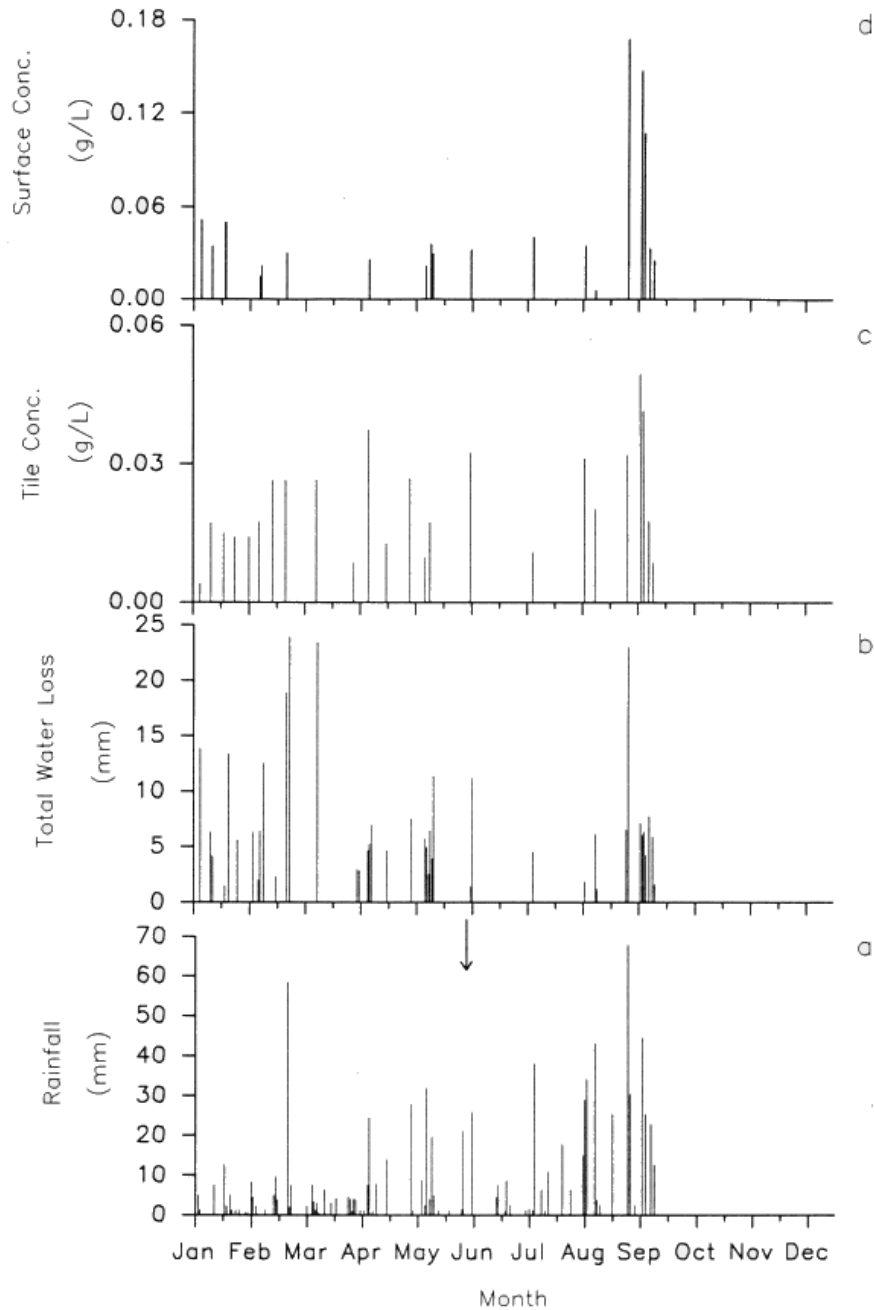


Fig 12A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

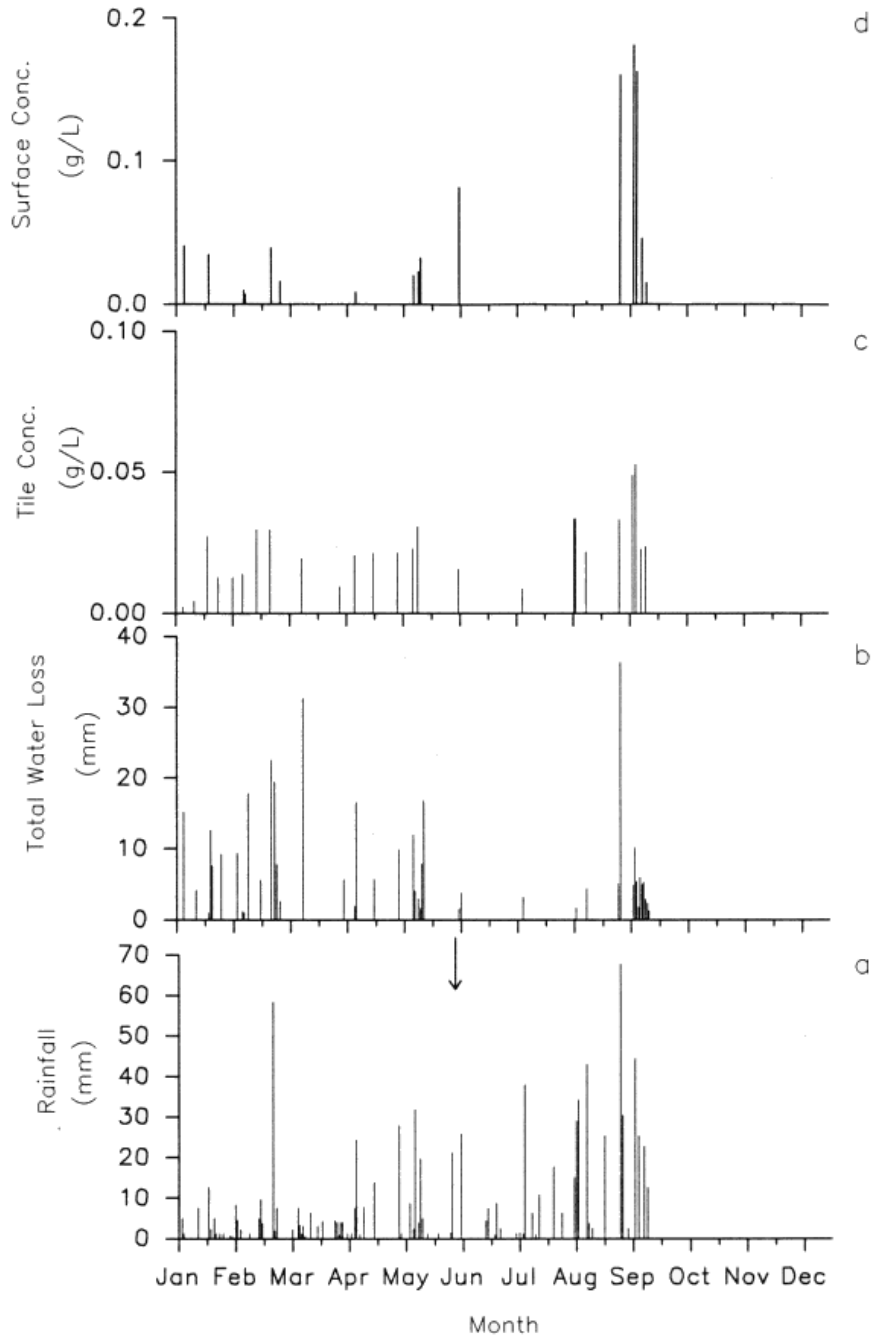


Fig 13A Precipitation (a), total runoff (surface and tile) (b), and soil sediment concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

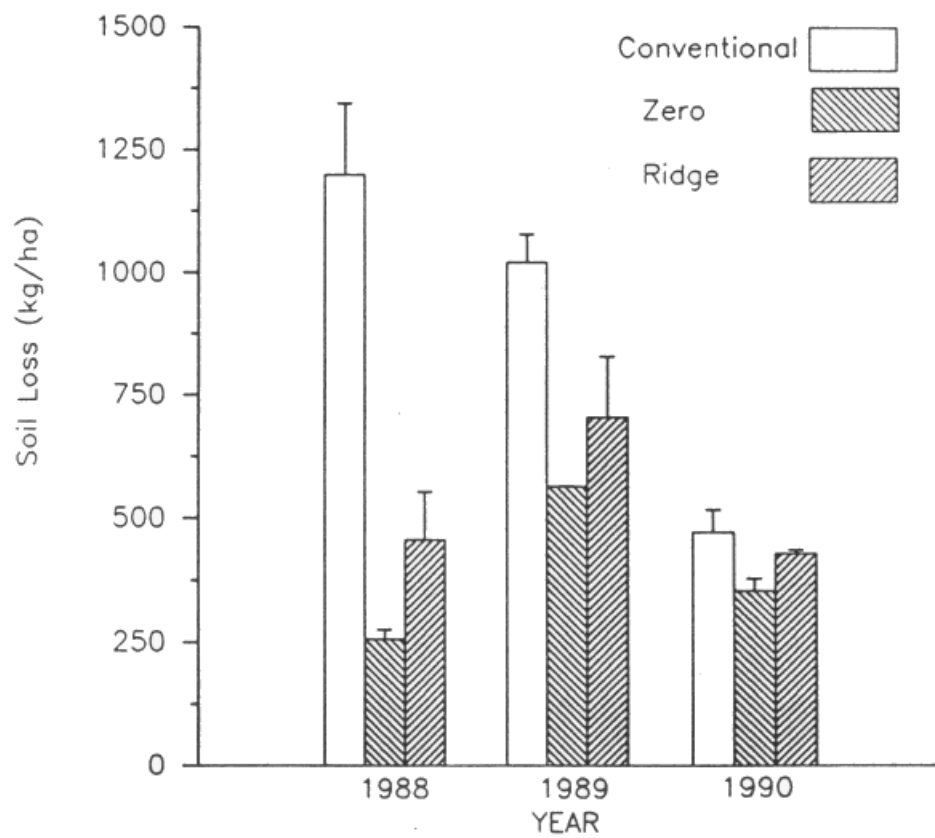


Fig. 14A Soil loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.

Mutchler *et al.*, 1985). The proportion of water loss attributed to surface runoff was greater from the conservation tillage treatments compared to the conventional tillage treatments (Fig. 3A) yet sediment losses on the conservation tillage treatments were low, possibly because of the residue cover. Residue cover reduces runoff velocity, and the destructive impact of raindrops on soil dispersion and hence dislodgment and transport of soil particles. Over three years, sediment losses averaged were 530 ± 11 kg/ha from ridge tillage, 391 ± 14 kg/ha from zero tillage and 897 ± 14 kg/ha from conventional tillage. The sediment loss from conventional tillage is 5600 kg/ha/yr less than that estimated by Coote *et al.* (1982) from a watershed of similar soil type and slope. Their losses included ditch and stream bank erosion which could amount to 32% of the total loss (Culley and Bolton, 1983; Rousseau *et al.*, 1988). Culley *et al.* (1983) reported sediment loss in the order of 400 kg/ha from this soil which is closer to losses measured from the conservation tillage treatments and from all treatments in the first 9 months of 1990 (Fig. 14A).

Suspended sediment loss was similar through surface and subsurface runoff from the conservation tillage treatments whereas sediment loss by subsurface runoff exceeded surface runoff loss in all years from conventional tillage (Fig. 15A). Subsurface runoff contributes significantly to soil erosion from this soil, probably because of preferential flow of surface sediments to the drains through extensive cracking of the soil (McKeague *et al.*, 1987).

Seasonal sediment loss (Fig. 16A) followed the pattern for seasonal water runoff (Fig. 4A). A larger proportion of sediment was lost after harvest in 1988 and during the growing season in 1989. Equal amounts of sediment were lost before planting and during the growing season in 1990. Erosion of this fine textured soil may occur throughout the year with losses more dependent upon rainfall intensity, duration and antecedent soil moisture content than crop canopy cover.

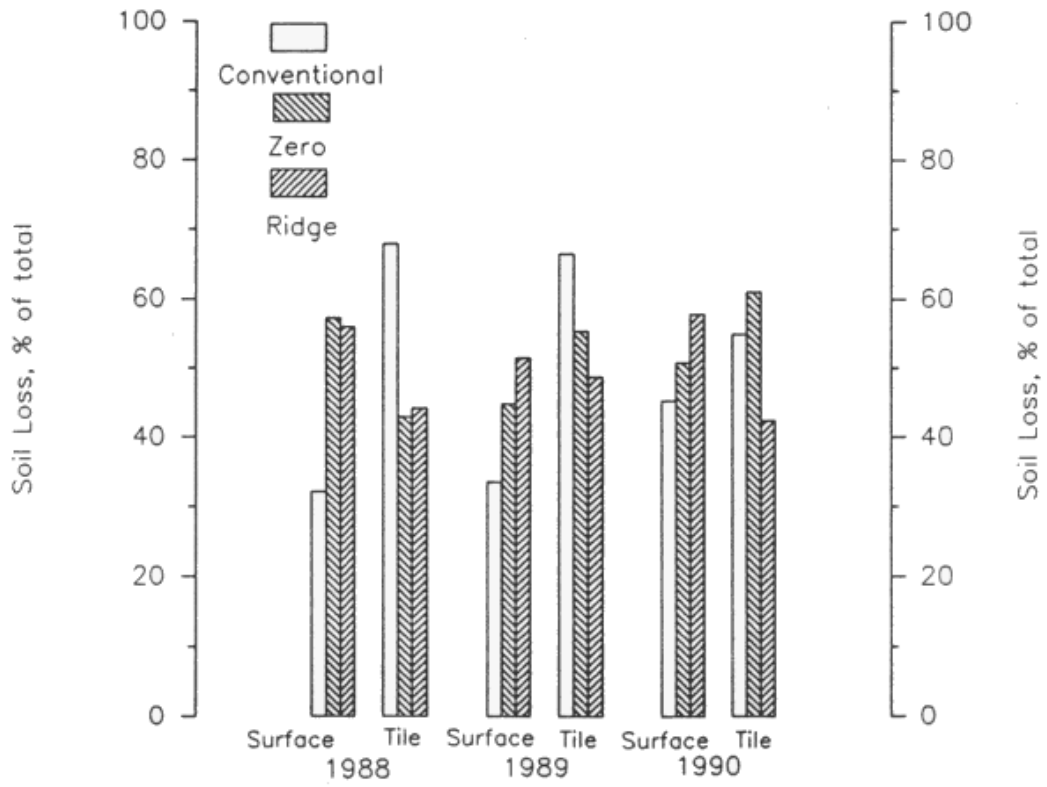


Fig. 15A Surface and tile loss of soil as a percent of total soil loss from three tillage practices on Brookston soil.

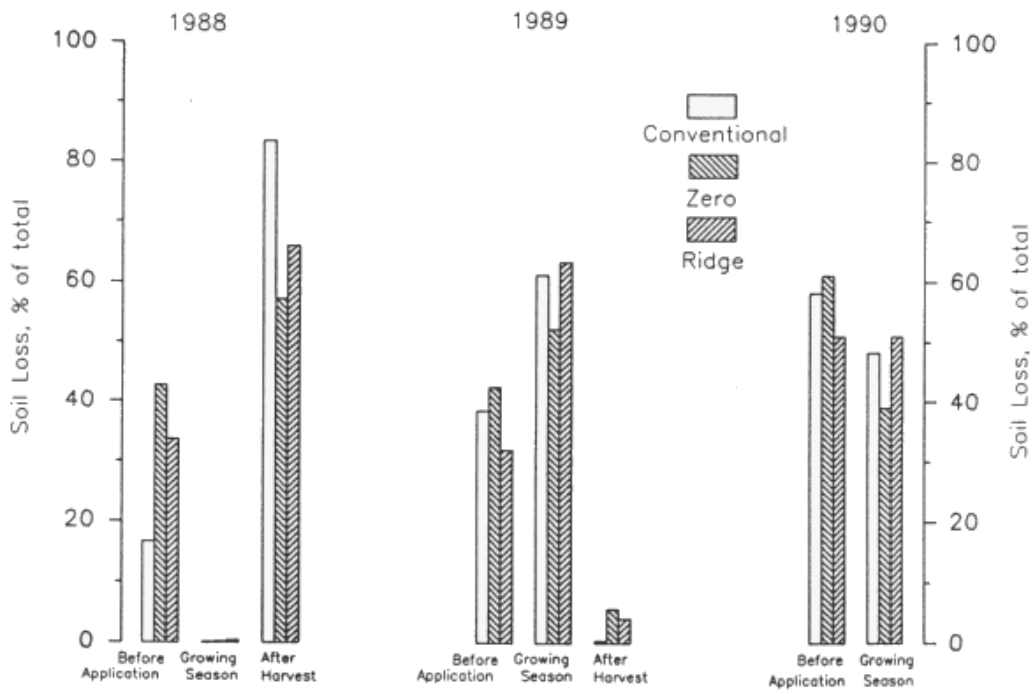


Fig. 16A Seasonal soil loss as a percent of total soil loss from three tillage practices on Brookston soil.

Residue cover may affect the magnitude and source of sediment loss but appeared to have little effect on the seasonal distribution of sediment loss.

Orthophosphate Concentration and Loss

The relationship between precipitation, runoff, and surface and subsurface orthophosphate concentration for the three tillage practices and years is shown in Figures 17 to 25A. Orthophosphate concentration ranged from 0.03 to 9.7 mg/L. Higher orthophosphate concentrations were observed in 1989 and 1990 (Table 6A) than in 1988 (Tables 4A and 5A). Greater runoff occurred in 1989 which may have diluted the orthophosphate concentration of the runoff whereas runoff volumes and intensities were low in 1988. Orthophosphate concentration of the runoff was more variable in 1990 than in the preceding years. One event after planting in 1990 produced a high orthophosphate concentration in runoff from the conservation tillage treatments, however, the high concentration only occurred in one replicate of the conservation tillage treatments because the intensity and duration of the rainfall was not sufficient to cause runoff on the second replicate. Orthophosphate concentration of the replicate which had low runoff from ridge tillage was <0.6 mg/L compared to 10 mg/L in the other replicate. The average concentration of the two replicates for the ridge and zero tillage treatments are reported in Table 6A.

Runoff from the conservation tillage treatments had higher orthophosphate concentration than that from conventional tillage (Tables 4 to 6A). Higher maximum concentrations were observed in surface runoff than drain discharge in two of three years. Phosphorus concentrations were higher in subsurface than surface runoff from all treatments in 1990 and concentrations were higher from the conservation tillage treatments than conventional tillage. The higher orthophosphate concentrations in runoff from the conservation tillage treatments could relate to phosphorus leaching from crop residue or soil enrichment (Sharpley, 1981; Sharpley, 1985; McDowell and McGregor 1984; Mostaghimi *et al.*, 1988). Sodium bicarbonate extractable phosphorus ranged from

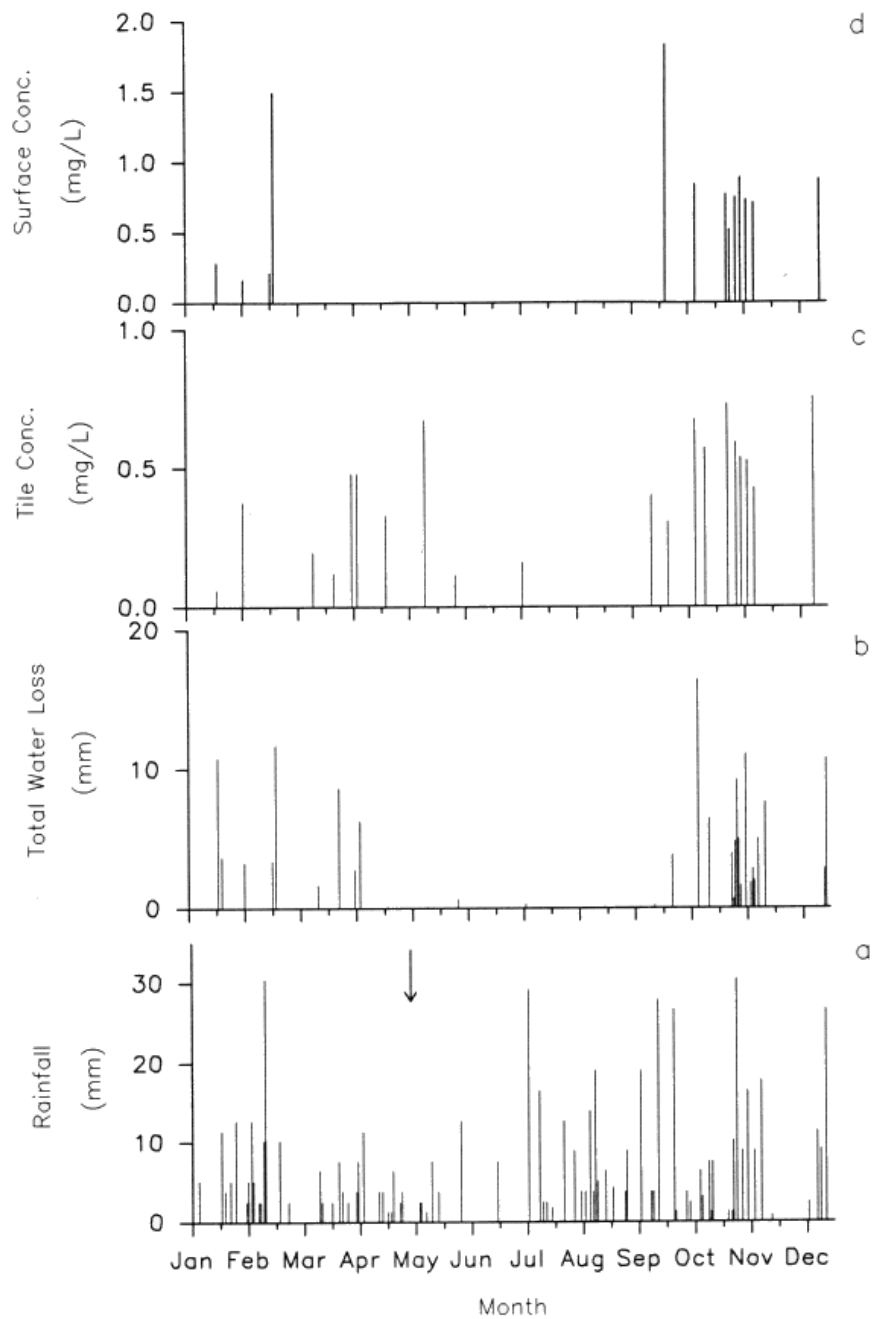


Fig 17A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1988. Arrow denotes planting date on May 11, 1988.

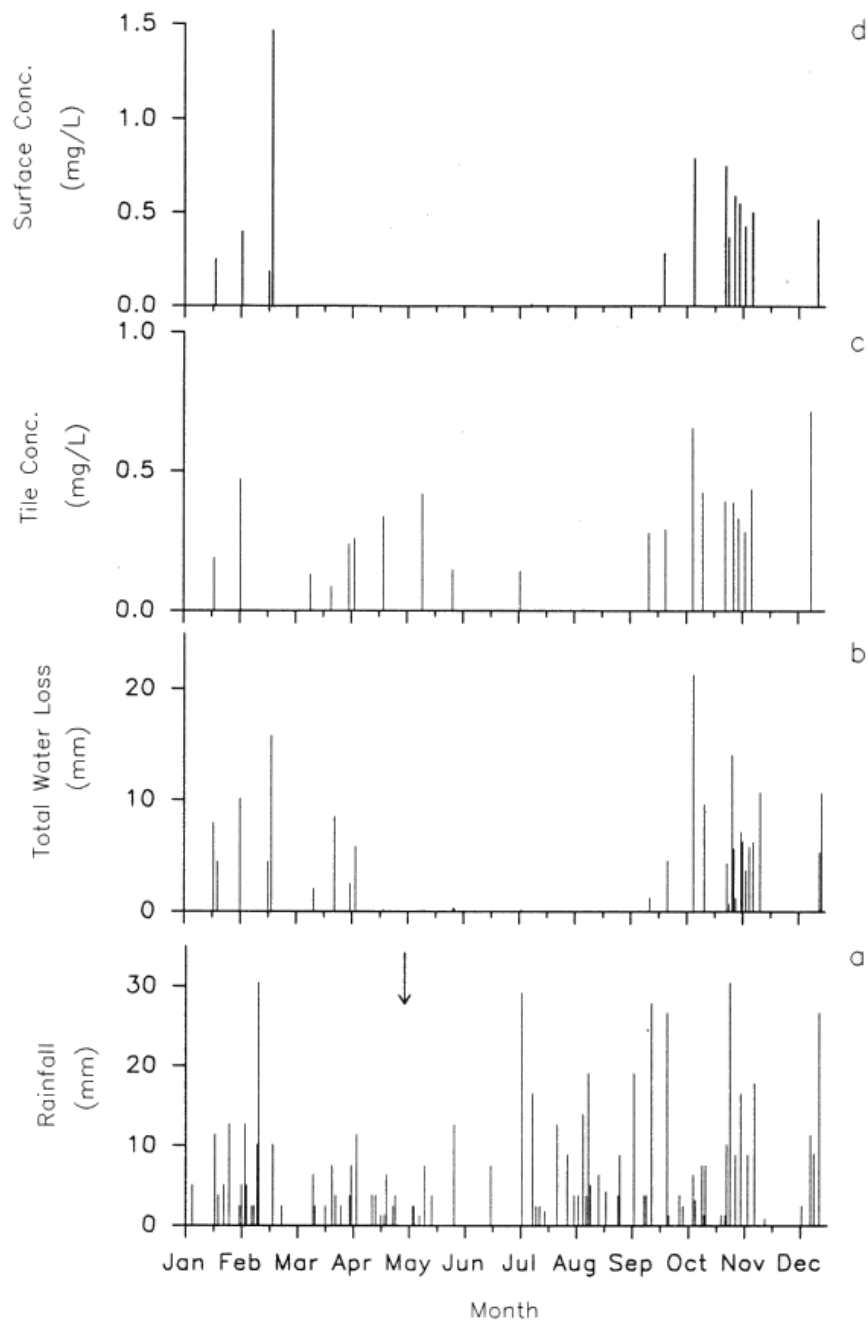


Fig 18A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date on May 11, 1988.

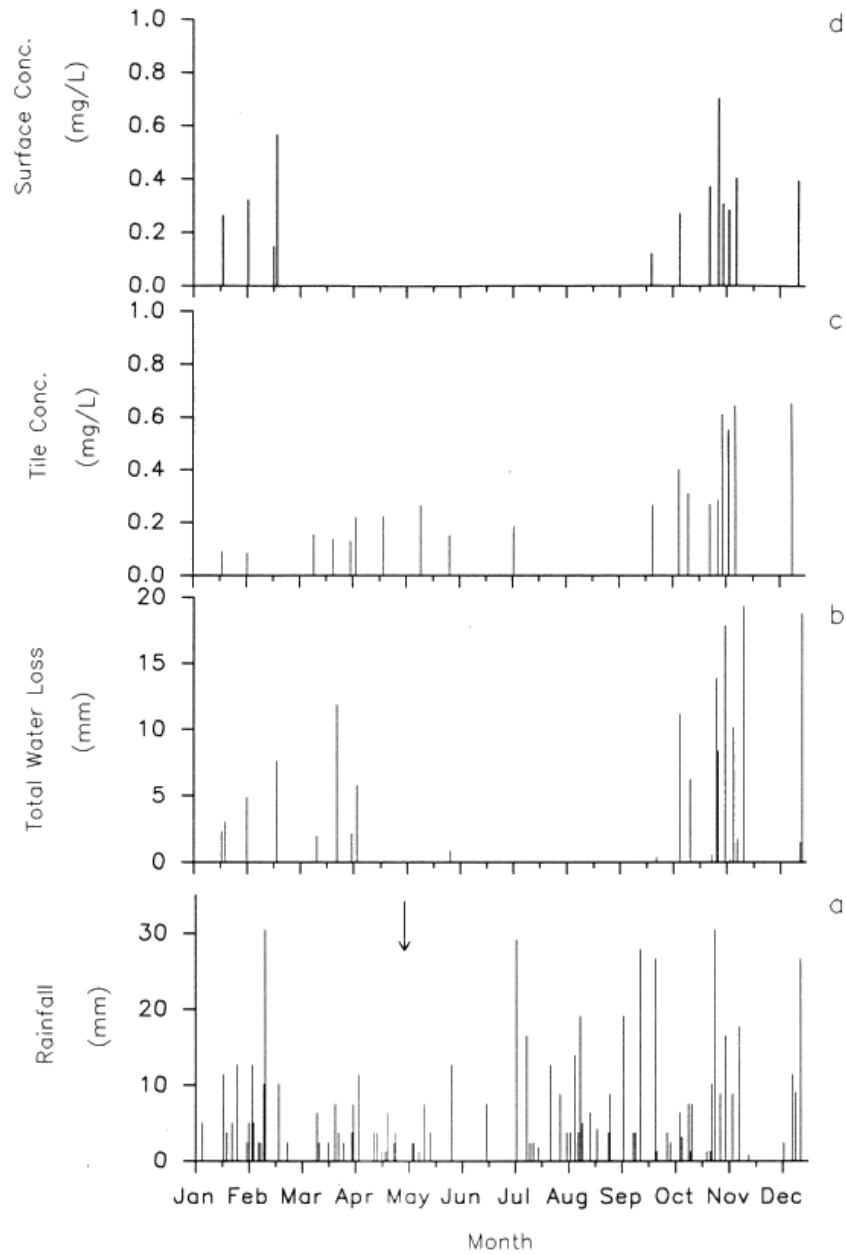


Fig 19A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date on May 11, 1988.

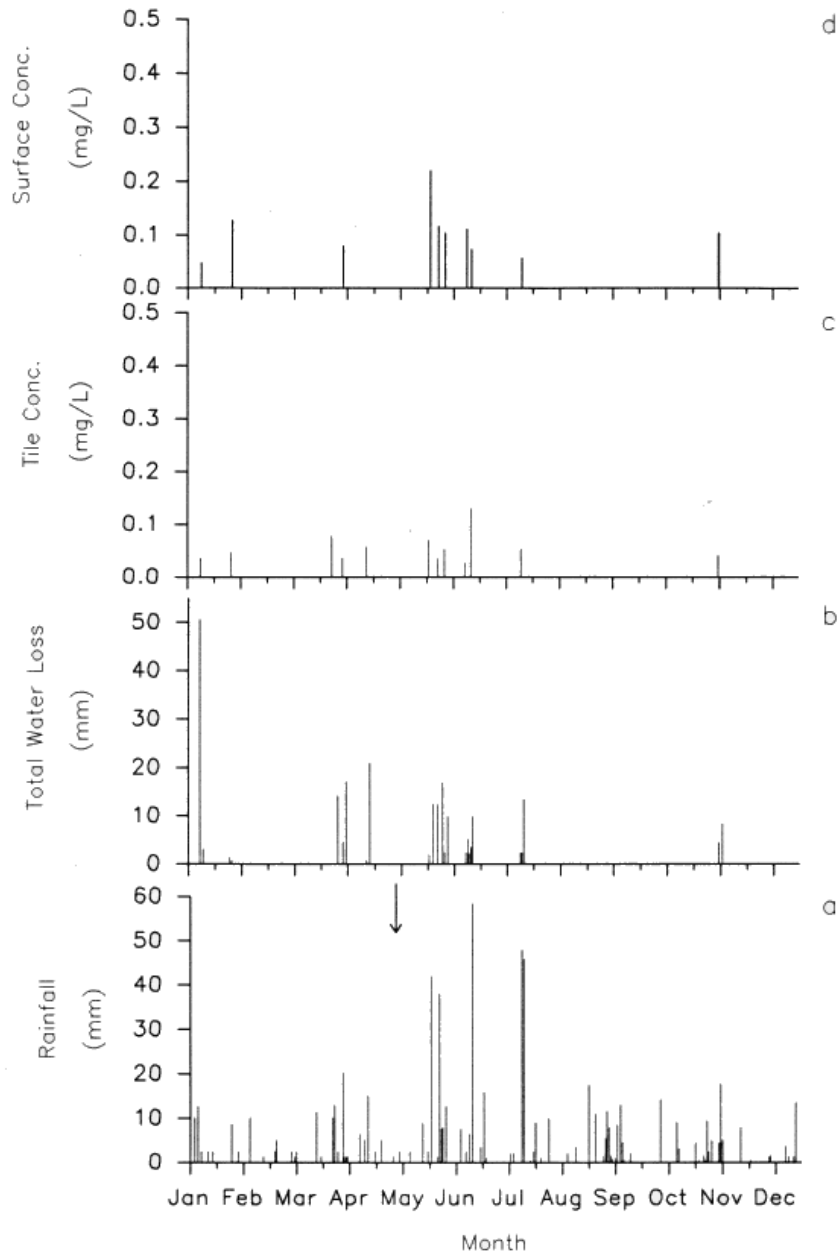


Fig 20A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1989. Arrow denotes planting date on May 10, 1989.

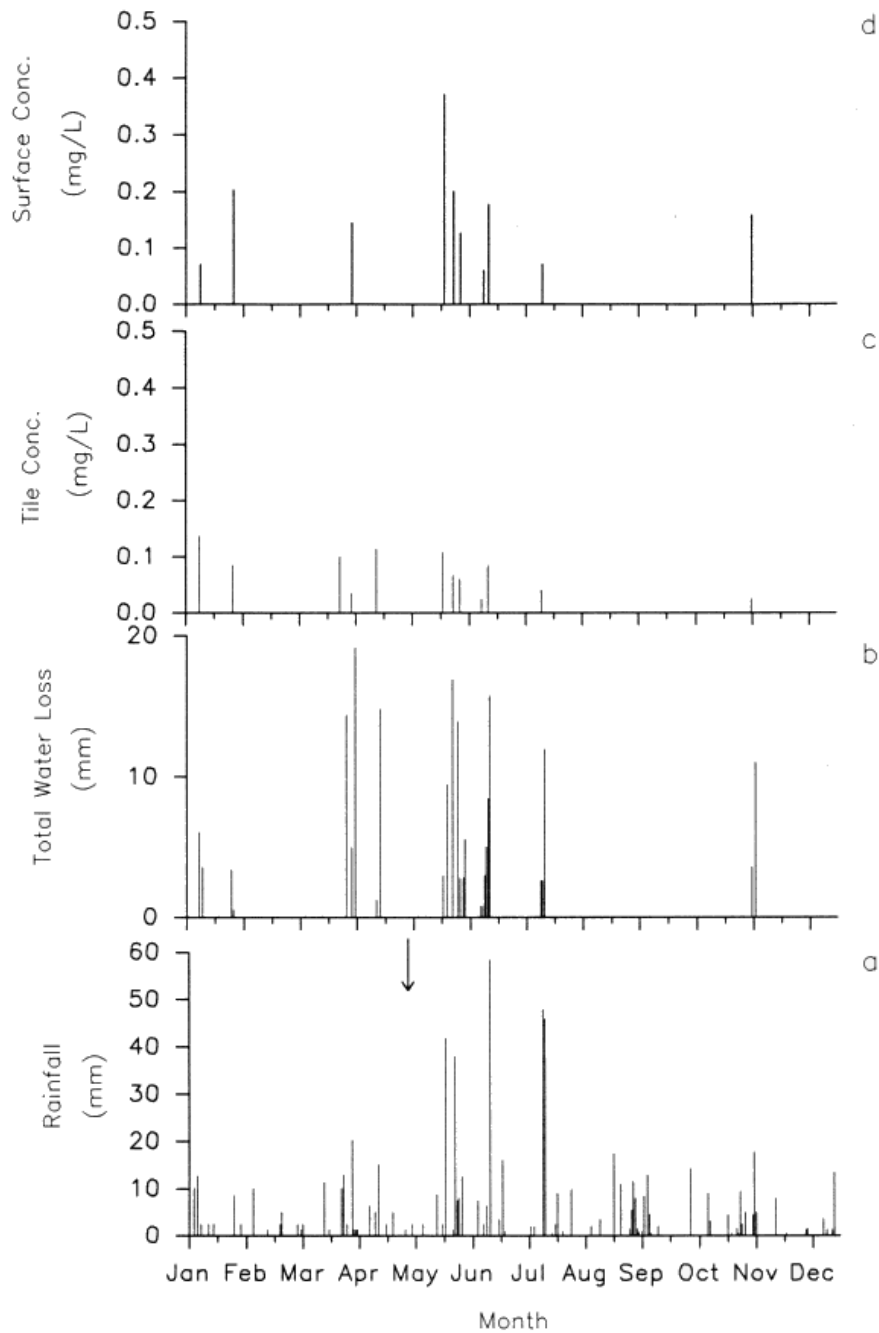


Fig 21A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date on May 10, 1989.

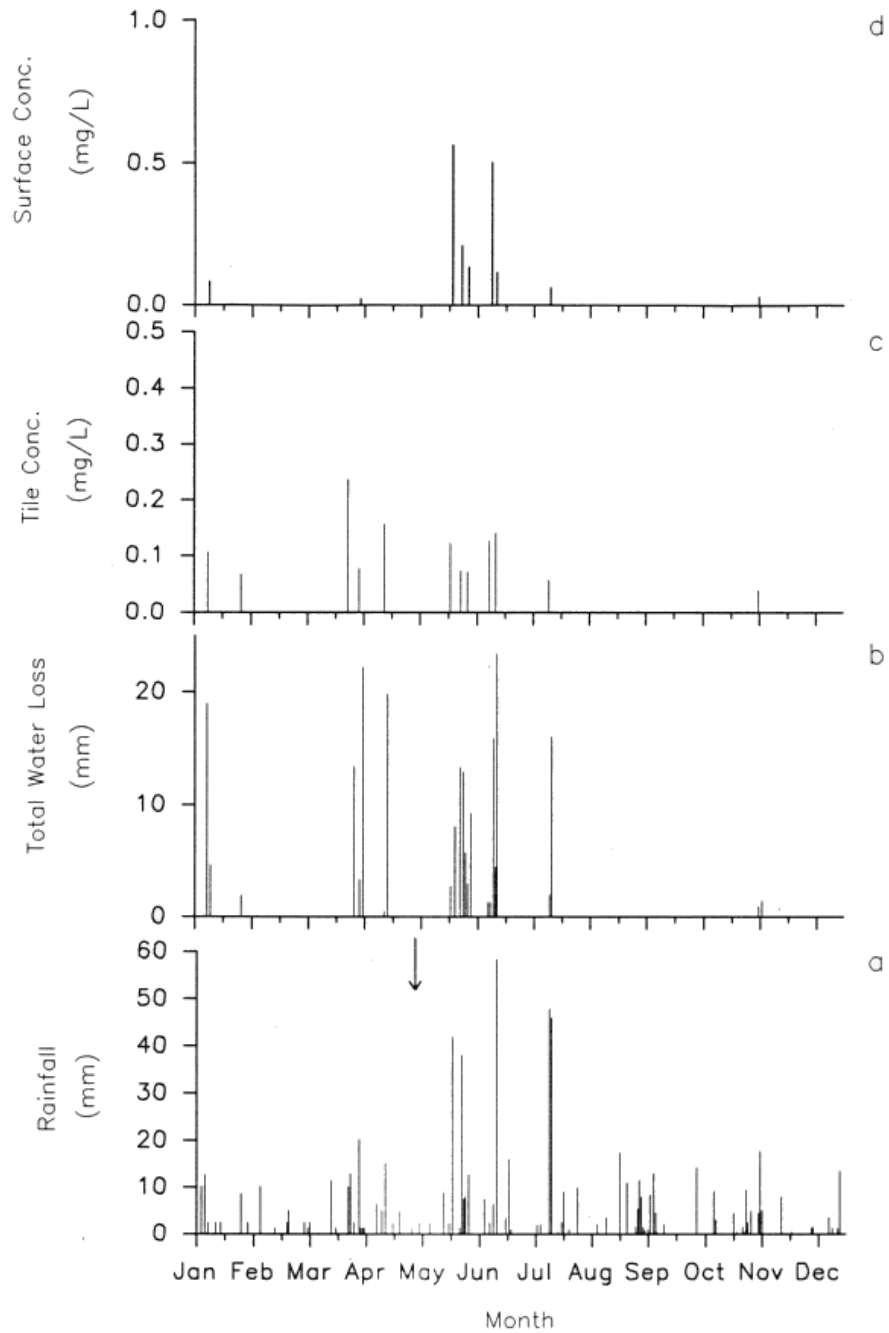


Fig 22A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date on May 10, 1989.

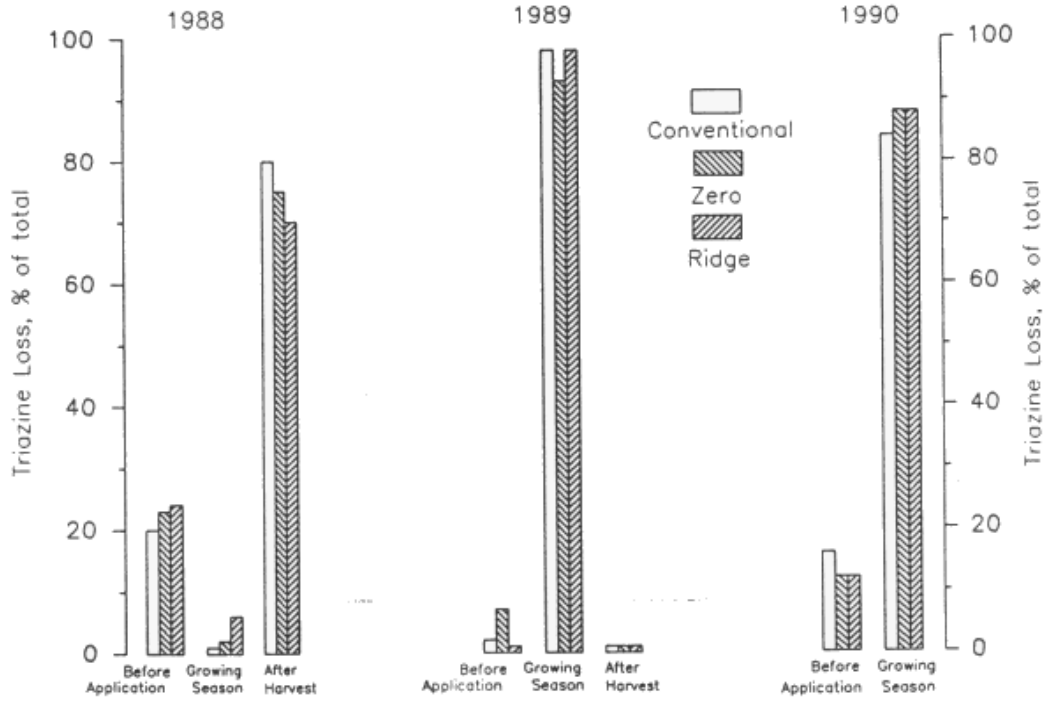


Fig 23A Precipitation (a) total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

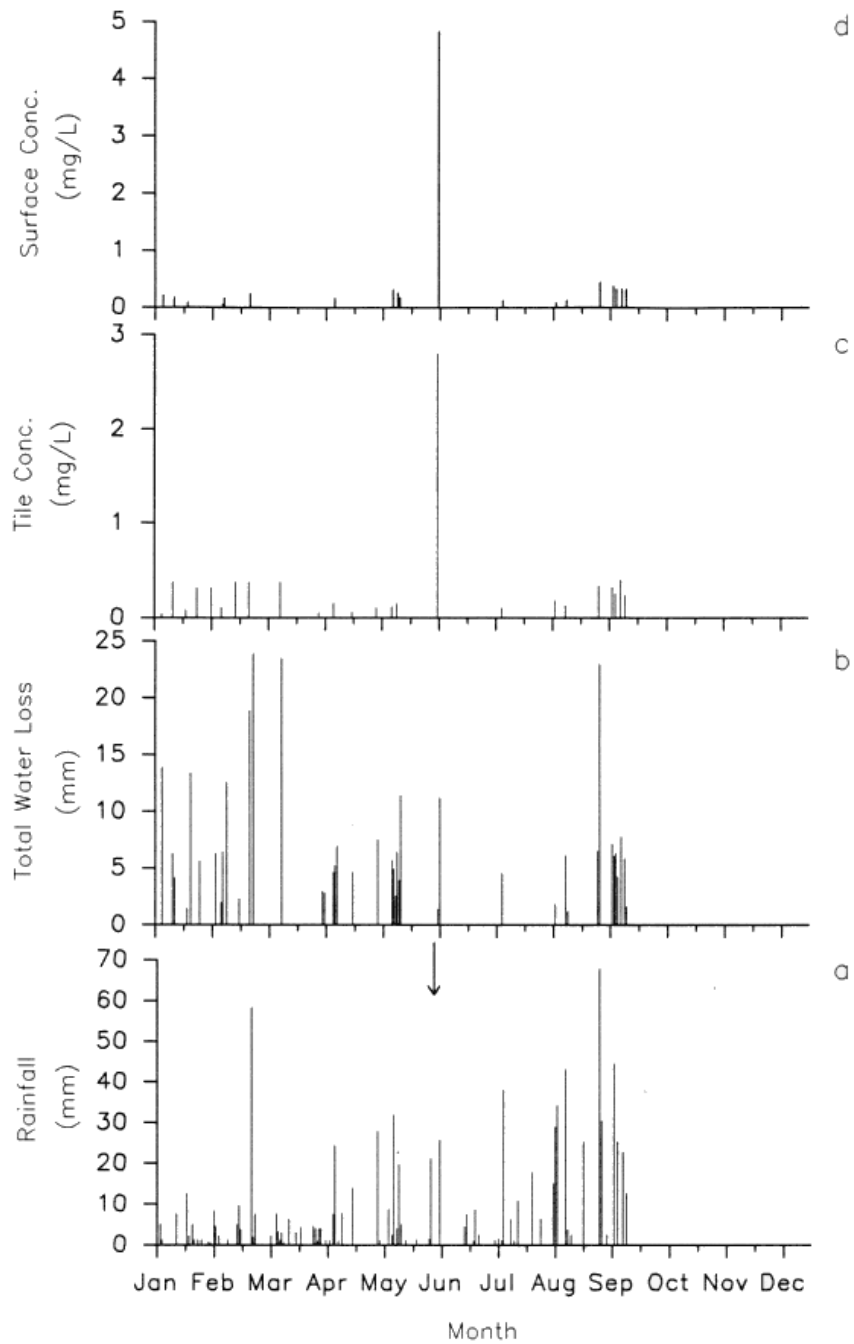


Fig 24A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date on June 1,1990

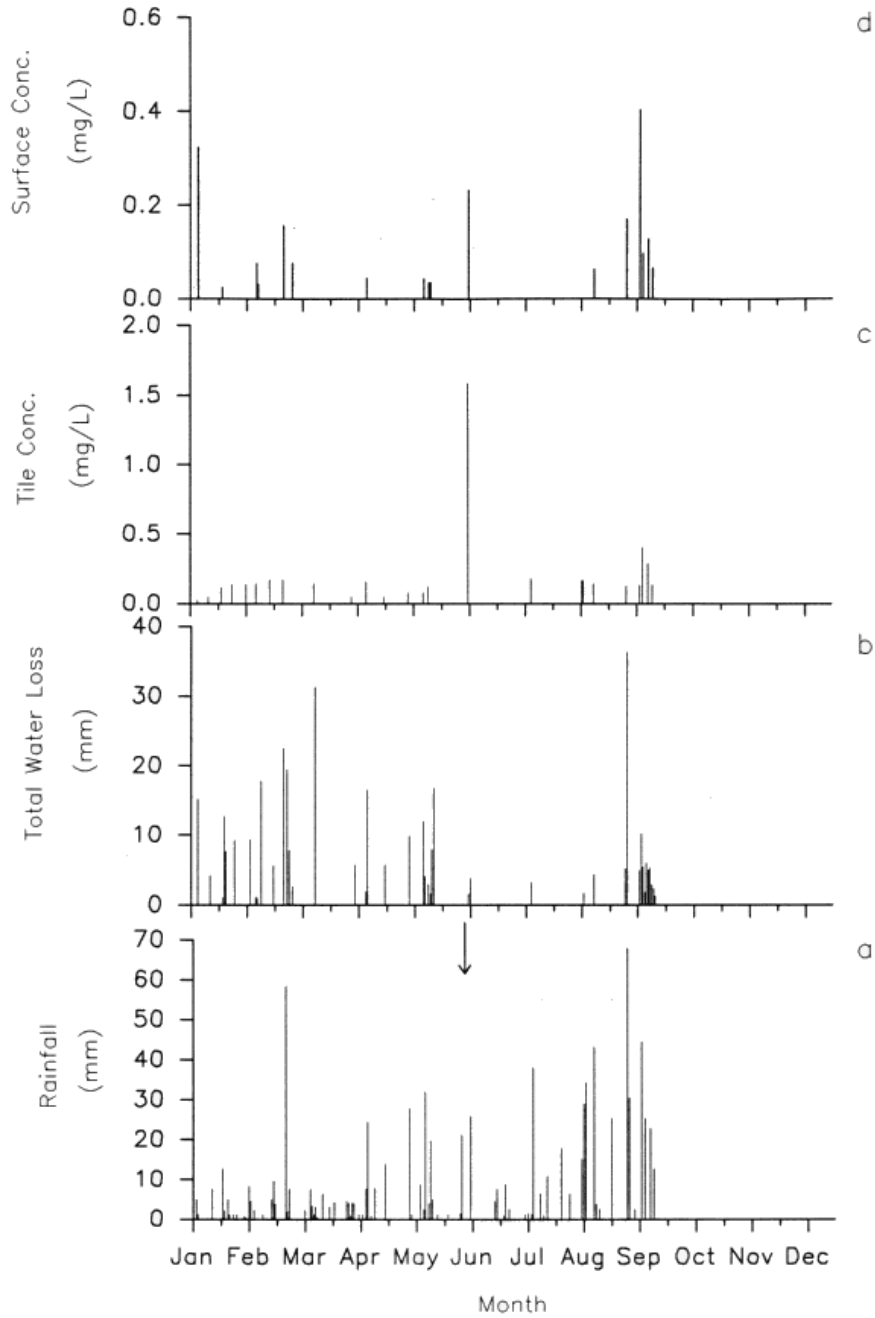


Fig 25A Precipitation (a), total runoff (surface and tile) (b), and orthophosphate concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

31 to 64 ppm in the 0 to 10 cm soil depth. Except for 1988, soil extractable phosphorus did not differ among tillage treatments. In 1988, extractable phosphorus was 64 ppm in zero tillage and 35 ppm in conventional and ridge tillage. Extractable phosphorus averaged 67 ppm in the sod. Soil enrichment of phosphorus in the corn plots may have been masked because of the deep sampling depth (Dick, 1983).

Orthophosphate loss was consistently lower from conventional than from the conservation tillage treatments (Fig. 26A). Losses of orthophosphate were somewhat higher from zero than ridge tillage in two of three years (1989 and 1990). A higher dissolved phosphorus concentration of runoff water from zero tillage could be associated with nutrient leaching from crop residue cover and/or soil enrichment of the sediment (McDowell and McGovern, 1984; Mostaghimi *et al.*, 1988; Sharpley, 1981). Where runoff is high, orthophosphate loss can also be high (Mueller *et al.*, 1984a and b) but most studies which report a reduction in phosphorus runoff from conservation tillage also show reduced water runoff (Blevins *et al.*, 1990; Angle *et al.*, 1984; McDowell and McGovern, 1984). Sharpley (1981) reported that 90% of dissolved phosphorus transported in surface runoff can originate from canopy leachate. Overall, depending upon the age and stage of development of the crop, 20 to 60% of phosphorus transported in surface runoff may originate from plant leachate.

The orthophosphate losses averaged over three years were 555 ± 15 g/ha from conventional tillage, 965 ± 250 g/ha from ridge tillage and 1519 ± 89 g/ha from zero tillage. These losses represent 3.0 to 8.3% of the total phosphorus added (55200 g/ha) to the soil over the three years. The Great Lakes water quality strategy is to reduce phosphorus discharge from diffuse sources to the lower Great Lakes by 30% (DePinto *et al.*, 1986). It is estimated that 70% of the nonpoint source phosphorus load from agriculture is derived from cropland (Miller *et al.*, 1982). Thus, based on the orthophosphate losses reported here, the phosphorus objectives of the Great Lakes Water Quality strategy will only be achieved through further modification of conservation tillage practices. For example, phosphorus concentration in runoff may be reduced by lime application (Hergert *et al.*, 1981) Minor tillage to reduce the soil enrichment ratio as evidenced in this study with reduced orthophosphate

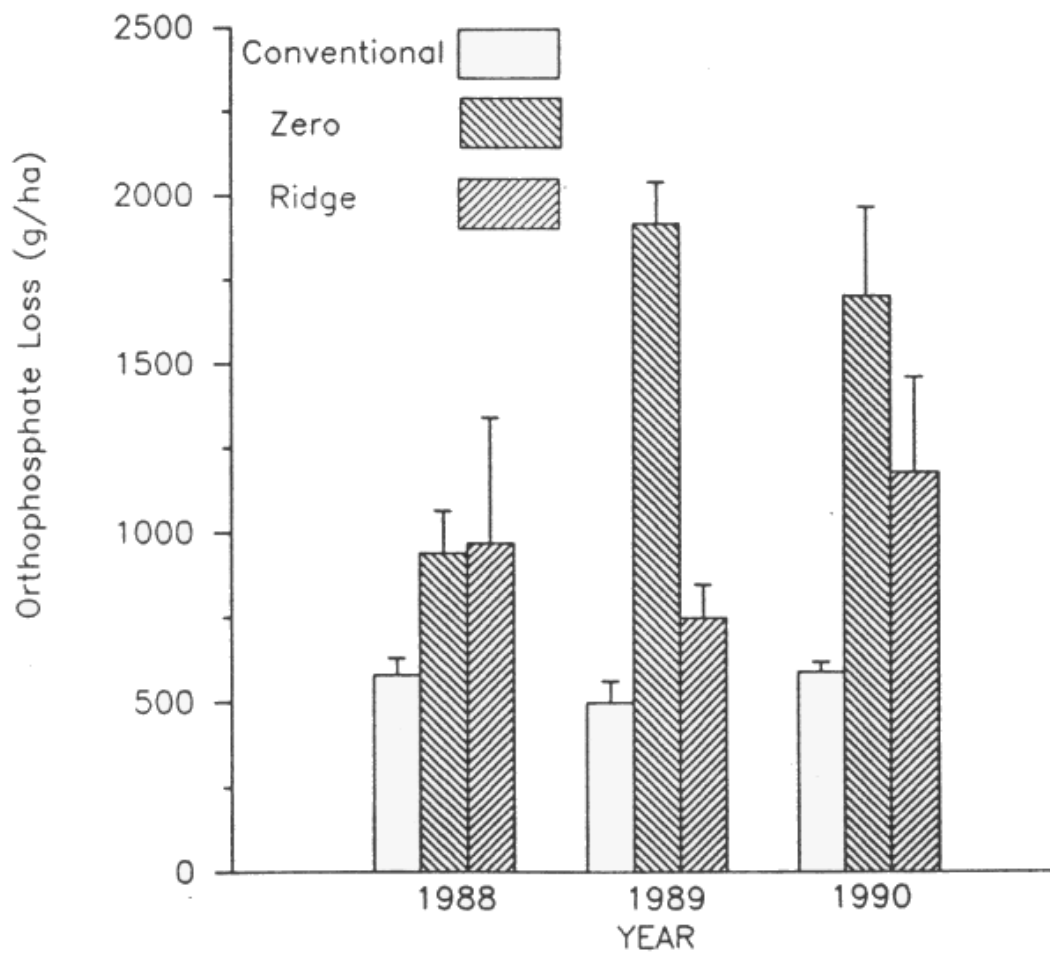


Fig. 26A Orthophosphate loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.

loss from ridge tillage compared to zero tillage (Sharpley *et al.*, 1981a and b). Intercropping can help to utilize and retain nutrients at the site of application or alter the hydrologic response of the watershed (Lowrance and Leonard, 1988; Dillaha *et al.*, 1989) and greater use of crop rotation (Laflen and Tabatabai, 1984; Dick and VanDoren, 1985; Dick *et al.*, 1991). The effect of various crop management systems on runoff water quality with respect to nitrogen dynamics and herbicide transport are currently being investigated by Agriculture Canada at Woodslee but no resources have been allocated for phosphorus.

Most orthophosphate transport occurred through tile discharge (Fig. 27A). Only from zero tillage in 1989 did orthophosphate transport from surface runoff exceed subsurface transport. Orthophosphate concentration of runoff is usually higher in surface water than drainage discharge (Hanway and Laflen, 1974; Baker *et al.*, 1975) but cumulative losses are greater through drains because of the larger quantity discharged (Culley *et al.*, 1983; Culley and Bolton, 1983). Culley *et al.* (1983) and Calvert (1975) reported a decrease in orthophosphate concentration with drain depth because of the removal of phosphate through adsorption to soil and decreased soil phosphorus content with depth. Seasonal distribution of orthophosphate loss followed that of rainfall distribution and sediment loss (Fig. 28A). Greater than 67% of the orthophosphate loss occurred after harvest in 1988 and 64 to 79% during the growing season in 1989. For the nine month period in 1990, 40 to 66% of the orthophosphate loss occurred during the growing season.

Total Phosphorus and Other Forms

The range and annual mean total soluble P and sediment P concentrations in surface and subsurface runoff from the corn and sod treatments for 1990 are shown in Table 7A. Higher maximum total soluble P and sediment P concentrations were observed in subsurface than surface runoff from all treatments. The mean total soluble P and sediment P concentrations of subsurface runoff were also higher than concentrations in surface runoff.

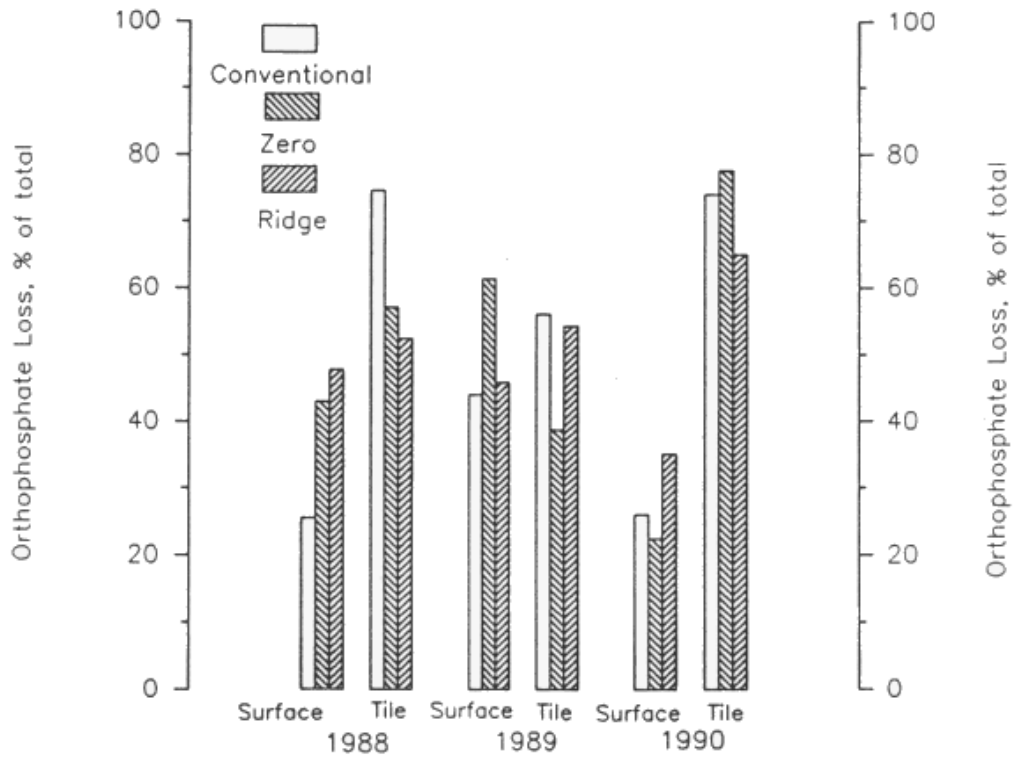


Fig. 27A Surface and tile loss of orthophosphate as a percent of total orthophosphate loss from three tillage practices on Brookston soil.

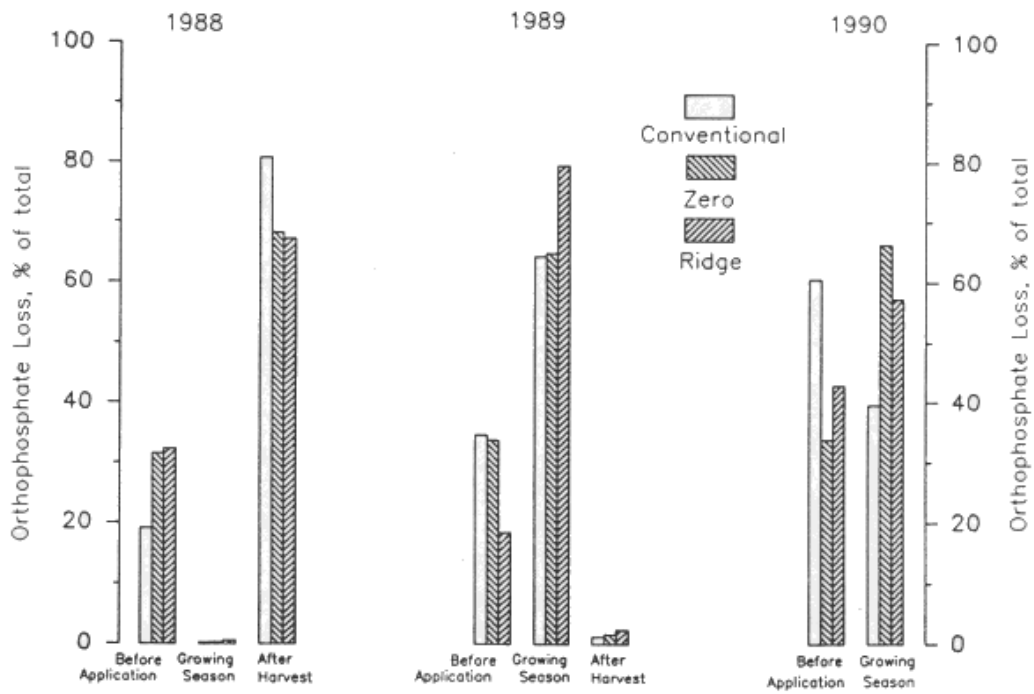


Fig. 28A Seasonal orthophosphate loss as a percent of total orthophosphate loss from three tillage practices on Brookston soil.

The mean total soluble P concentration of surface runoff was 2.5 times higher from the conservation tillage treatments than from conventional tillage. Subsurface runoff from the conservation tillage treatments also contained higher total soluble P concentrations than conventional tillage. Sediment P concentration of surface runoff did not differ among tillage treatments but mean sediment P concentration of subsurface runoff was higher from zero than ridge or conventional tillage.

Table 7A. Range and mean total soluble P and sediment P concentration of surface and subsurface runoff from three tillage practices and a sod treatment for 1990.

Treatment	Range		Mean	
	Surface	Subsurface	Surface	Subsurface
----- Total soluble P, mg/L -----				
Ridge	0.09 - 7.78	0.06 - 9.03	0.89 ± 0.36	0.91 ± 0.17
Zero	0.10 - 5.23	0.07 - 10.00	0.81 ± 0.32	1.20 ± 0.04
Conventional	0.09 - 2.39	0.08 - 6.93	0.32 ± 0.08	0.56 ± 0.04
Sod	0.01 - 2.40	0.09 - 7.48	3.72 ± 1.31	1.35 ± 0.14
----- Sediment P, mg/kg -----				
Ridge	0.01 - 3.94	0.01 - 3.90	0.39 ± 0.01	0.44 ± 0.04
Zero	0.01 - 2.77	0.01 - 5.05	0.33 ± 0.08	0.69 ± 0.07
Conventional	0.02 - 2.86	0.01 - 5.42	0.38 ± 0.05	0.46 ± 0.08
Sod	0.08 - 0.46	0.02 - 4.62	0.25 ± 0.11	0.38 ± 0.09

Sediment phosphorus concentration for 1990 ranged from 0.01 to 3.94 mg/kg in surface runoff. Runoff from ridge tillage had the highest maximum sediment phosphorus concentration whereas runoff from zero and conventional tillage had lower maximum phosphorus concentration (2.77 and 2.86 mg/kg, respectively). Tile discharge had higher maximum phosphorus concentration associated with sediment than surface runoff for all but the ridge tillage treatment. Sediment phosphorus concentration of tile discharge ranged from 0.01 to 5.42 mg/kg with higher maximum concentrations associated with discharge from conventional and zero tillage than from ridge tillage.

Sediment associated phosphorus loss was higher from zero tillage (266±33 g/ha) than conventional (197±43 g/ha) and ridge (199±14 g/ha) tillage (Table 8A). The higher sediment

P loss from zero tillage may reflect soil enrichment. Phosphorus would be mixed with soil from the plowing and disk operations in conventional tillage and reforming of ridges could redistribute soil phosphorus in ridge tillage. Orthophosphate losses were lower from ridge (1178 ± 399 g/ha) compared to zero tillage (1701 ± 374 g/ha) which would support the conclusion that sediment enrichment had occurred from this treatment since orthophosphate concentration of runoff is associated with soil P concentration (Sharpley, 1980a; Sharpley *et al.*, 1981 a and b; Sharpley, 1985; Sharpley and Smith, 1989). Many studies report a relationship between phosphorus loss and sediment loss during the growing season (Culley and Bolton, 1983; Hanway and Laflen and Tabatabai, 1974) but the proportion of orthophosphate increases in fall runoff (Hubbard *et al.*, 1982; Laflen, 1984; Nicholaichuk *et al.*, 1978; Nicholls and MacCrimmon, 1974; Flanagan and Foster, 1989; Culley and Bolton, 1983).

Table 8A. Subsurface and surface loss of various phosphorus forms \pm standard errors from three tillage practices and a sod treatment for 1990.

Treatment	Orthophosphate	Soluble P	Sediment P	Organic P	Total P ^a
	----- g/ha -----				
Ridge	1178 \pm 399	2485 \pm 1304	199 \pm 14	1307 \pm 905	2684 \pm 1318
Zero	1701 \pm 374	2125 \pm 599	266 \pm 33	423 \pm 225	2391 \pm 633
Conventional	587 \pm 42	1046 \pm 123	197 \pm 43	458 \pm 164	1242 \pm 80
Sod	2380 \pm 192	4995 \pm 699	126 \pm 5	2614 \pm 891	5121 \pm 694

^a 18400 g/ha applied to ridge, zero and conventional tillage, 36800 g/ha applied to sod.

Total soluble P and total P (sum of sediment P and total soluble P) transport was 2.0 to 2.5 times higher from the conservation tillage treatments than from conventional tillage (Table 8A). However, the large error associated with the measurements masked treatment effects. Less than 50% of the total soluble P from ridge tillage was identified as orthophosphate with the remainder occurring as other soluble P forms. Thus, the midseason reforming of ridges may aid in decomposition of crop residue in ridge tillage releasing plant associated P. Total P loss was similar between the ridge and zero tillage treatments. Mineralization of phosphorus may be reduced in ridge tillage since total soluble P transported

from ridge and the conventional tillage treatments was 47 to 50% orthophosphate whereas orthophosphate accounted for over 80% of total soluble P transported from zero tillage. Sharpley (1981) determined that orthophosphate is the primary phosphorus form leached from crop residue. However, sediment P was higher from zero than the ridge or conventional tillage treatments. The results suggest tillage may alter nutrient mineralization and sediment enrichment as reported by others (Tracy *et al.*, 1990). Total phosphorus loss amounted to $15 \pm 5\%$ of that applied from ridge, $11 \pm 0.3\%$ from zero and $7 \pm 0.2\%$ from conventional tillage assuming all P originated from fertilizer application. The higher crop residue retained by the conservation tillage treatments in the surface horizon of the soil would result in greater recycling of P which would be available for water transport (Sharpley, 1981). Incorporation of crop residue with soil in conventional tillage would reduce cycling and aqueous availability of soluble P because of adsorption processes (Sharpley *et al.*, 1981b; Sharpley and Smith, 1989).

Sod

Comparison of data from the corn treatments was not made with the sod treatment because the two management practices are not related. Also, the sod treatment received two annual applications of 132 kg/ha 8-32-16 fertilizer since 1987 compared to one annual application for the corn treatments. However, some interesting observations and comparisons can be made between the sod and corn treatments.

Water loss from the sod treatment averaged over the three years was 68% of that from the corn treatments (228 mm). Water loss was similar in 1990 among corn and sod treatments (Table 9A). The root system from the grass and forage growth was very effective in retaining water in the soil or removing it by evapotranspiration when rainfall events were widespread. Runoff amounted to 14% of rainfall in 1988 16% in 1989 and 30% in 1990. Approximately 83 to 97% of the runoff occurred through tile discharge with seasonal distribution similar to that from corn culture (Fig. 4B).

Sediment loss from the sod treatment was less than 129 ± 42 kg/ha (Table 9A) with over 95% of the loss occurring by drain discharge. This loss could be associated with direct entry of soil from around the tile drain or from soil eroded from the face of cracks developed under natural shrinking and swelling processes associated with changes in soil water content. A high proportion of sediment loss from conventional tillage (58 to 68% of total loss) occurred through drain discharge and it was speculated the source was from surface runoff entering the drains by preferential flow through soil cracks. Soil loss through tile drains by preferential flow through soil cracks could be a significant factor in each of the three tillage treatments. For example, assuming all of the sediment loss from the sod plots arises from preferential flow through soil cracking, it was estimated for conventional tillage that the proportion of surface eroded sediment transported by preferential flow could constitute 73 to 90% of the sediment in subsurface runoff. Thus, erosional losses from this soil type may be reduced by a management practice such as subirrigation which would minimize soil cracking. The effect of subirrigation on the overall water budget and hence erosion would need further research. Facilities to study subirrigation effects on water quality are available at Harrow.

Table 9A. Runoff and sediment loss \pm standard error from three tillage practices and a sod treatment for 1990.

Treatment	Runoff, mm	Sediment, kg/ha
Ridge	306 ± 8	429 ± 10
Zero	299 ± 7	353 ± 35
Conventional	256 ± 66	472 ± 64
Sod	258 ± 42	129 ± 87

Orthophosphate loss from sod treatment expressed as a percentage of total phosphorus applied was high in 1990 (6.5%) being similar to that lost from ridge tillage (6.4%) but lower than that lost from zero tillage (9.2%, Table 8A).

The sod treatment lost considerable soluble phosphorus (14% of that applied) in 1990. Total soluble phosphorus accounted for 98% of the total phosphorus loss, of which 48% was orthophosphate. These losses on a percentage bases were similar to those from ridge tillage. Total soluble P accounted for 93% of the total P loss from ridge tillage of which 47% was orthophosphate. Thus much of the total soluble phosphorus from sod and ridge tillage could have originated from decomposed plant material or be a result of organic complexation in soil which was released as dissolved P. Little organic phosphorus was associated with zero tillage presumably because crop residue remained on the soil surface and phosphorus originating from the crop residue was leached as orthophosphate (Sharpley, 1981).

SUMMARY

Tillage did not alter combined surface and subsurface runoff. The proportion of surface runoff was increased in conservation tillage compared to conventional tillage. Conservation tillage reduced soil erosion to 41 to 57% of that from conventional tillage. Orthophosphate loss was higher from conservation than from conventional tillage. Preliminary results for a nine month period in 1990 indicated that total phosphorus, orthophosphate and soluble phosphate loss in runoff water was higher from conservation than from conventional tillage.

IMPLICATIONS OF THE RESULTS

The conservation tillage treatments were effective in reducing soil erosion under environmental conditions conducive to sediment transport. Tillage had little or no effect on total runoff but did result in greater subsurface runoff under conventional tillage. Maximum orthophosphate concentration was higher in surface than subsurface runoff from the

conservation tillage treatments compared to conventional tillage. Over all treatments, the mean orthophosphate concentration of subsurface runoff was higher than that from surface runoff.

Surface and subsurface runoff contribute equally to orthophosphate transport from the conservation tillage treatments but in some years subsurface runoff may be higher than surface runoff. Subsurface runoff is more significant than surface runoff in orthophosphate transport from conventional tillage. Orthophosphate transport was higher from the conservation tillage treatments than conventional tillage because of leaching of orthophosphate from crop residue, altered mineralization and/or reduced retention of mineralized phosphorus forms by soil. Preliminary results suggest higher soluble and total phosphorus losses are associated with the conservation tillage treatments from the Brookston clay loam. Disturbance of the soil surface by ridgeting in the ridge treatments prevented P enrichment of sediment as was observed with zero tillage and altered mineralization of P but did not prevent excessive P transport. Total phosphorus transport from the three tillage treatments occurred primarily by aqueous phase transport with <11 % of total loss associated with the sediment phase. The objective of SWEEP (Soil and Water Environmental Enhancement Program) is to reduce soil and phosphorus impairment of the Great Lakes from agricultural activities. These results suggest that conservation tillage management systems on Brookston clay loam in Essex county will reduce sediment transport but that phosphorus enrichment of surface waters draining to the lakes may be increased. The orthophosphate losses from these tillage treatments in this study are reasonable compared to a total phosphorus loss of 1500 g/ha/yr estimated by Coote *et al.*, (1982) under corn culture from a watershed of similar soil type. Conventional tillage appears to be most effective at managing phosphorus transport, however, further options need to be investigated to reduce sediment and phosphorous transport associated with this management practice. Management systems which enhance nutrient uptake and storage in the crop with crop removal and alter the hydrology of the watershed appear to hold the best promise for phosphorus transport reduction. Also, the introduction of crops with a low fertility requirement

may allow for reduced P rate or the need for P fertilizer. The results of this study suggest phosphorus leached from crop residue and aqueous phase transport are the two most critical factors associated with phosphorus transport from the Brookston clay loam.

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PART B- HERBICIDES

INTRODUCTION

Herbicides are chemical tools employed in crop production to facilitate control of weeds or unwanted vegetation. Their use has resulted in increased yields through control of weeds and a decrease in fuel consumption which may provide higher economic returns. However, their increasing occurrence beyond the site of application has caused concern to both agriculturalists and environmentalists.

Atrazine and metolachlor are widely used herbicides for weed control in corn and soybeans. Extensive research has concentrated on adsorption, mobility, persistence and effect of cultural practices on transport by surface and subsurface runoff. Adsorption, mobility and persistence of a herbicide are related to chemical and physical properties of the herbicide. Generally herbicides of low solubility and stable chemical and biological structure have higher adsorption potential, lower mobility and greater persistence in the soil environment than those which have higher solubility and contain chemical moieties which are easily subject to microbial or chemical cleavage (Wauchope, 1978; Gunther and Gunther, 1970; Erickson and Lee, 1989; Walker, 1987b).

Cultural practices may have an effect on herbicide mobility and transport. Conservation tillage has proven effective in reducing soil erosion but its effect on herbicide transport is more difficult to assess because of the many factors to be considered. Transport of herbicides which have a high affinity for soil constituents may be reduced by conservation tillage whereas those of low adsorption affinity and high water solubility may be unaffected or increased by tillage (Wauchope, 1978; Wu *et al.*, 1983; Baker, 1985). Rainfall intensity and duration, soil texture and aspect greatly affect erosional losses and herbicide transport. Herbicide losses greater than 10% of application rates are typical from fields of slope >3% but losses less than 2% of application are common from low slope fields (Hall, 1974; Klaine *et al.*, 1988; Hall *et al.*, 1989).

Incidence of rainfall event relative to application time, storm intensity, antecedent soil moisture conditions preceding the runoff event or incorporation of the herbicide are all factors which relate to herbicide transport (Triplett *et al.*, 1978; Wauchope, 1978; Hall *et al.*, 1983). Triplett *et al.* (1978) analysed a large body of published data by multiple regression analysis and identified a strong association between the natural logarithm (ln) of "herbicide concentration in the runoff water" and ln of "days after application", and "herbicide rate" and "days between runoff event".

Herbicide transport was also associated with many of these parameters. Tillage practices which alter water use have a more significant effect on herbicide transport than those which have little or no effect on this parameter (Glenn and Angle, 1987). Sauer and Daniel (1987), using simulation techniques compared herbicide runoff losses from three tillage treatments. Tillage had no effect on herbicide runoff, because treatments which reduced water loss were associated with higher herbicide concentrations in the runoff. Under field conditions, runoff transport of alachlor was similar among tillage treatments from soil which had 5 to 12% slopes (Baker *et al.*, 1978).

Most tillage practices were implemented to control soil erosion but herbicide transport occurs primarily in the aqueous phase (Wauchope, 1978). On a silt loam soil with 12-18% slope, 80-90% of the atrazine transported from the application site occurred in the aqueous phase (Baker and Johnson, 1979). Other reports also suggest that aqueous transport of herbicides greatly exceeds sediment transport (Hall 1974; Klaine *et al.*, 1988). Where erosion is severe, sediment transport can account for a significant fraction of herbicide transport. A silty clay loam soil with 14% slope resulted in 50% aqueous and sediment transport (Buttle, 1990, Hall *et al.*, 1983).

Atrazine has moderate water solubility (33 mg/L) and shows limited mobility in soil (Gunther and Gunther, 1970). Low concentrations have been found in soil solution below treated fields (Hall and Hartwig, 1978; Leonard *et al.*, 1988; Smith *et al.*, 1990) but high concentrations have been found in runoff (Wauchope and Leonard, 1980). Typically high

herbicide concentration in the runoff water occur in events nearest application time, on fields with slopes >3% and with high herbicide application rates (Hall *et al.*, 1983; Smith *et al.*, 1990; Hall *et al.*, 1972; Wauchope and Leonard, 1980). Herbicide concentrations are higher in surface runoff water than in the discharge water (Southwick *et al.*, 1990; Bengtson *et al.*, 1990). Tile drainage offers the potential to reduce herbicide transport when compared to no subsurface drainage, however, the quantity of herbicide transported will depend upon the volume of water discharged. Thus, on level plane soils the benefit of lower herbicide concentration in tile discharge water may be offset by a larger volume of water discharged through tile compared to surface runoff.

Conservation tillage treatments usually result in higher crop residue on the soil surface during herbicide application. As a result less herbicide will reach the soil surface during application which could have an effect on herbicide concentration in the runoff water and on transport mechanisms. Herbicide concentration in runoff water from plots containing corn residue was in excess of 900 ppb but concentration rapidly decreased with time (Martin *et al.*, 1978; Kenimer *et al.* 1987). Application of 10 mm of water removed 50-75% of the herbicide residue and 100% was washed off after 35 mm of water was applied (Martin *et al.*, 1978). Herbicide transport losses from corn interseeded with a living mulch were lower than from treatments without the mulch. This occurred because of a reduction in water runoff and an increase in infiltration rate of soil rather than adsorption of the herbicide by the mulch (Hall *et al.*, 1984).

The concentration of herbicide in runoff and tile discharge water is higher than that in receiving streams. Edge of field concentrations may range from 0.05 to 8000 µg/L depending upon herbicide rate, mode of application, incidence of the runoff event relative to application time and source of runoff ie. surface or tile (Triplett *et al.*, 1978; Wauchope and Leonard, 1980). Stream concentrations are typically <40 µg/L because of dilution (Frank *et al.*, 1990; Baker, 1985). Edge of field herbicide concentrations decline rapidly after the third or fourth runoff producing rainfall event because of degradation of the

herbicide in the soil or adsorption to soil particles and organic matter (Triplett *et al.*, 1978; Haith, 1986; Trichell *et al.*, 1968; Smith *et al.*, 1990; Hall *et al.*, 1989; Baker *et al.*, 1978; Roberts *et al.*, 1979; Frank and Sirons, 1979).

A vegetative boarder strip or grassed waterway around the application area has been shown to reduce herbicide transport losses (Asmussen *et al.*, 1977; Hall, 1974). The presence of a grain buffer strip at the base of a corn runoff field reduced atrazine transport to 0.3% of application compared to 3.5% transported in the absence of the buffer strip (Hall *et al.*, 1983). The reduction in transport losses was attributed to the trapping of suspended sediment in the buffer. Atrazine residues in the entrapped sediment were not high enough to be phytotoxic to the grain but the grain strip would have limited effectiveness where erosion was severe enough for the suspended sediment to physically cover the cropped buffer strip. In another study the presence of an oat buffer reduced atrazine transport by 87% compared to that without the buffer (Hall, 1974). However, dicamba and picloram transport was greater from treated sod than from fallow soil (Trichell *et al.*, 1968). When the runoff from the fallow area passed over an untreated sod buffer the quantity of herbicide transported was reduced. Transport of 2,4-D was reduced when the runoff was carried down an untreated grassed waterway (Asmussen *et al.*, 1977).

Soil moisture content is associated with incidence or the onset of water runoff, the magnitude of herbicide transport and herbicide persistence. Soil moisture content and temperature are the two greatest factors affecting herbicide persistence (Walker, 1987a). Atrazine and metolachlor were found to be more persistent in cool soil at low soil moisture content than in warmer soil at higher moisture content (Walker and Zimdahl, 1981; Walker and Brown, 1985). Under comparable temperature and moisture conditions and soil type metolachlor was found to be as persistent as atrazine (Walker and Zimdahl, 1981). Compared to other acetanilide herbicides metolachlor has the longest persistence (Walker and Brown, 1985).

Tillage had little or no effect on persistence of atrazine or metolachlor. Lowder and Weber (1982) reported that soil pH and moisture content had a greater effect on atrazine persistence than tillage. Repeated application of atrazine to corn with zero tillage did not result in accumulation of herbicide residue (Bauman and Ross, 1983). Atrazine was less persistent in soil from zero tillage than from conventional tillage but residues were higher in the soil surface from the zero tillage plots. In another study atrazine persistence was more related to soil acidity than to tillage practice (Ghadiri *et al.*, 1984). In ridge tillage, atrazine was more persistent on ridge tops than in ridge valleys of ridge tillage because of the dryer soil condition of the ridges compared to the more moist environment in the ridge valley (Gaynor *et al.*, 1987).

Atrazine can be dealkylated by microbiological activity or undergo chemical hydrolysis in soil (Walker, 1987b; Erickson and Lee, 1989; Gunther and Gunther, 1980). Adsorption to clay particles may catalyze hydrolysis of the halogen group to form hydroxy atrazine (Armstrong *et al.*, 1967; Armstrong and Chesters, 1968; Skipper *et al.*, 1976; Skipper *et al.*, 1967). Dealkylation of atrazine appears to be more important in atrazine dissipation from southwestern Ontario soils than hydrolysis because of the more alkaline pH of the soils (Sironi *et al.*, 1973).

OBJECTIVES

The research reported herein was developed to provide data on herbicide losses from conventional, zero and ridge tillage practices for corn culture on a poorly drained, level plane soil. Total transport losses, seasonal distribution and the source (surface runoff or tile discharge) of losses were measured for the three tillage practices for atrazine, its dealkylated analog, des-ethylatrazine and metolachlor. The dissipation of these chemicals in the soil was also followed.

MATERIALS AND METHODS

The three tillage practices, and corn seeding and fertilizer rates are described in part A for phosphorus and soil losses. Instrumentation to measure surface runoff and tile discharge have also been reported in the previous section. Sample collection and storage was similar to that for phosphorus and sediment.

Herbicide Application and Sampling

Atrazine (1.8 kg a.i./ha) and metolachlor (2.64 kg a.i./ha) were applied preemergence on May 12, 1988, May 15, 1989 and June 1, 1990. Because of an error in calculation only 2.0 kg a.i. metolachlor/ha instead of 2.64 kg/ha was applied in 1990. Applications were made with a Chelsea[®]sprayer. The 6.0 m boom was equipped with extended range 11004 flat fan nozzles which were set to deliver 150 to 240 L water/ha at 210 to 280 kPa. The volume of water applied and application pressure varied from year to year. The actual herbicide rate applied each year was calculated from gas chromatographic (GC) analysis of residue from petri plates which were placed in the plots perpendicular to the direction of travel of the sprayer. Over the three years of the study, actual atrazine rate ranged from 80 to 98±27% while metolachlor rate ranged from 69 to 121 ±19%. Herbicide application rate within a year was similar for all treatments. Soil samples for herbicide analysis were collected with a 2.5 cm diameter soil sampling tube from the top 10 cm of each plot before and after herbicide application and at six selected dates throughout the growing season. Twenty cores from each plot were composited, air dried and ground to pass through a 2mm sieve and stored at -30°C until extracted for residue analysis by gas chromatography.

Soil and Water Analysis

Forty g of soil was shaken 1 h on a concentric shaker (New Brunswick[®] Model V) with 100mL methanol. The samples were filtered through #1 Whatman filter paper, the volumes reduced to dryness and the residue dissolved in an appropriate volume of 10% ethyl acetate in hexane.

A suitable aliquot from the water samples (125 to 500 mL depending upon expected concentration) was analyzed using solid phase extraction technology. Analyte in the water sample was concentrated onto a preconditioned (1 mL methanol followed by 3 mL water) C-18 solid phase extraction cartridge (Millipore Cat. No. 51910). The cartridge was air dried then eluted with 3 mL acetonitrile and 2 mL methanol. The eluting solvent was removed with an air stream and the residue dissolved in 10% ethyl acetate in hexane for analysis by GC.

Herbicide concentration of the water and soil extracts were determined on a Varian[®] 3400 gas chromatograph equipped with a thermionic nitrogen detector. Analytes were separated on a 1.2 m by 6.4 mm i.d. glass column containing Chromosorb W, HP coated with 10% DC-200 liquid phase. Temperature of the injector was 220°C, column 220°C and detector 250°C. Gas flow rates were 175 mL air/min, 4.5 mL H₂/min and 30 mL He/min. Recovery of analytes from soil and water matrices averaged over 80%. Soil concentrations were corrected for recovery but water concentrations are reported without correction. Triazine results are reported as the sum of atrazine and des-ethyl atrazine.

Data Analysis

Herbicide concentrations in surface and subsurface runoff water are reported as the average of the maximum and minimum concentrations recorded over all events within a year and the annual average of the event concentrations. Herbicide transport for each event was the product of the average herbicide concentration for the event and the total event volume of runoff. Annual transport was calculated as the sum of the event losses for each treatment. Triazine is referred to as the sum of atrazine and des-ethyl atrazine. Soil

residues for the herbicides are in parts per million as shown in the figures. Rainfall, runoff and concentration data in the figures are presented on a logarithmic scale because of the extremes in the values. Total losses of herbicides and water are reported with standard error of sample means and regression analysis, sample means and analysis of variance were performed with ANOVA, MEANS and REG procedures (SAS, 1989).

RESULTS AND DISCUSSION

ATRAZINE

Atrazine and Des-ethyl Atrazine Concentration

The concentration of atrazine and des-ethyl atrazine in surface runoff and tile discharge water along with rainfall and runoff is presented for each treatment and year (Fig. 1-18B). Herbicide concentrations were highest in runoff producing events closest to application then rapidly declined to around 1 µg/L in the fall. The low herbicide concentration in the spring before herbicide application was from the previous years' residue. Atrazine concentration in the tile discharge and surface runoff water was low in 1988 with maximum concentration <23 µg/L (Table 1 B). Average triazine concentration was <3 µg/L and did not differ greatly between surface and subsurface runoff but concentrations were somewhat higher in surface runoff except for the ridge tillage treatment (Table 1 B). The maximum des-ethyl atrazine concentration was lower than that for atrazine (5 vs 23 µg/L) with mean concentrations less than 0.9 µg/L. The low triazine concentrations in 1988 (Fig. 1 to 6B, Table 1 B) are a result of no runoff producing events until late in the year after crop canopy had developed and the herbicide had dissipated in the soil.

Atrazine concentration as high as 715 µg/L was observed in 1989 and higher maximum concentrations were found in surface runoff water from conservation tillage compared to conventional tillage (Fig. 7 to 12B). Atrazine and des-ethyl atrazine

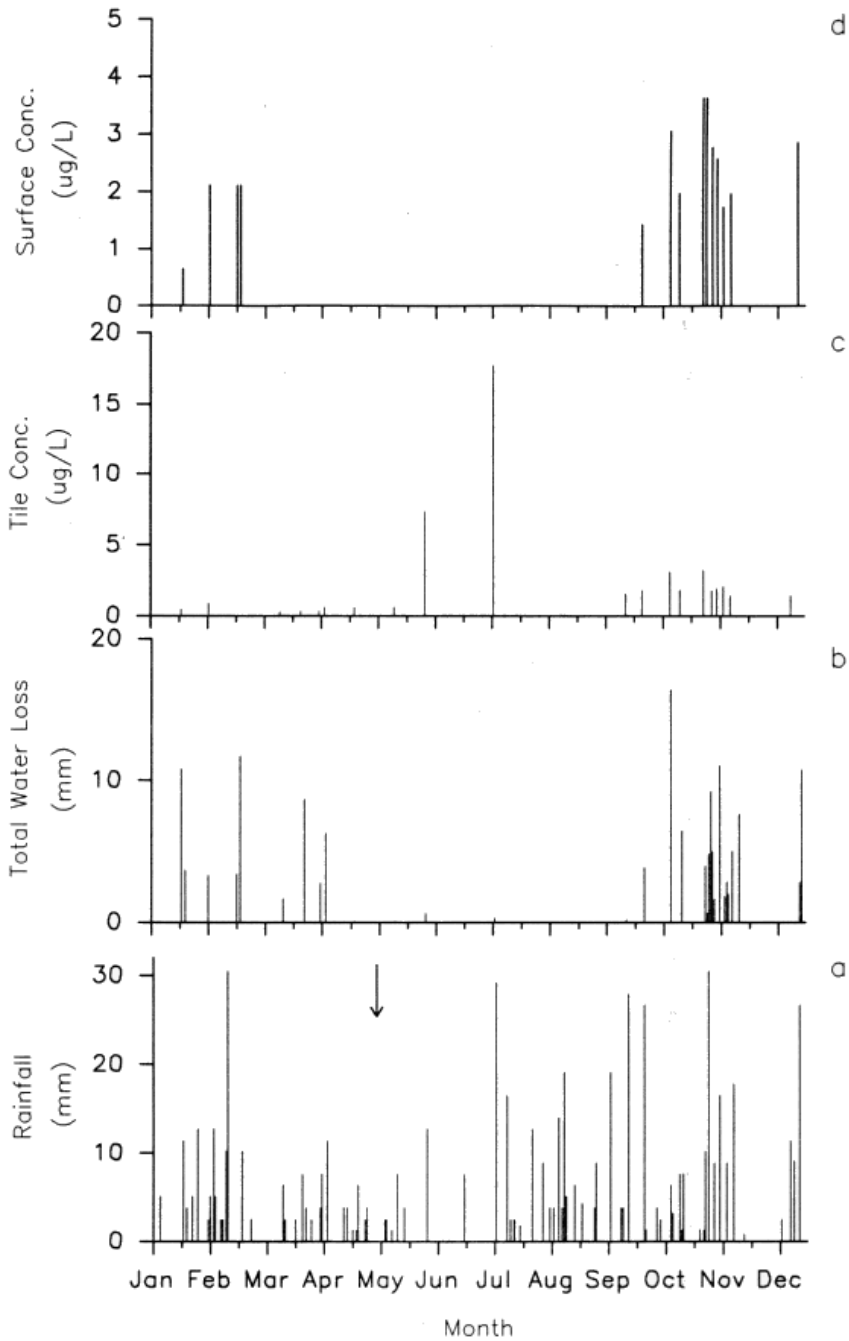


Fig 1B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1988. Arrow denotes planting date on May 11, 1988.

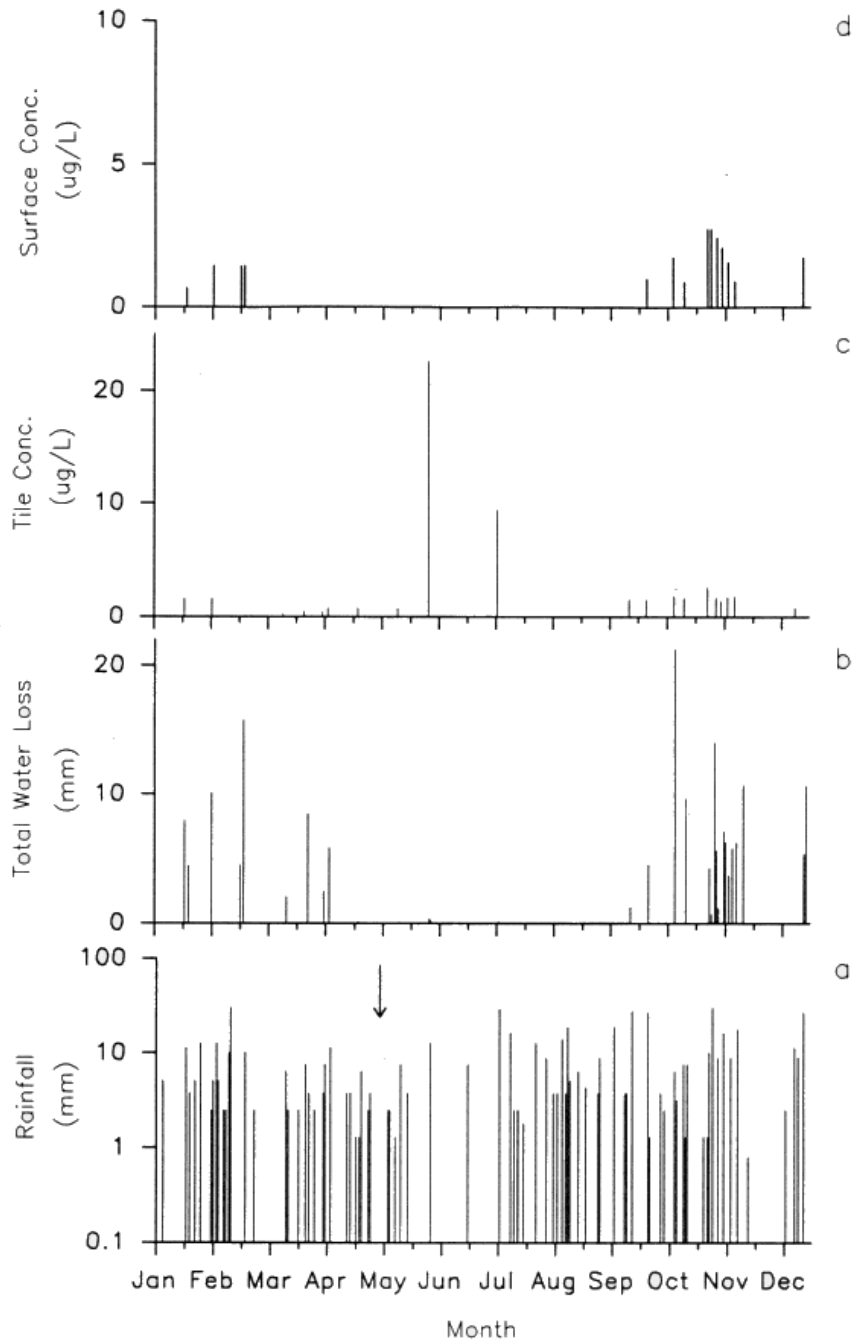


Fig 2B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date on May 11, 1988.

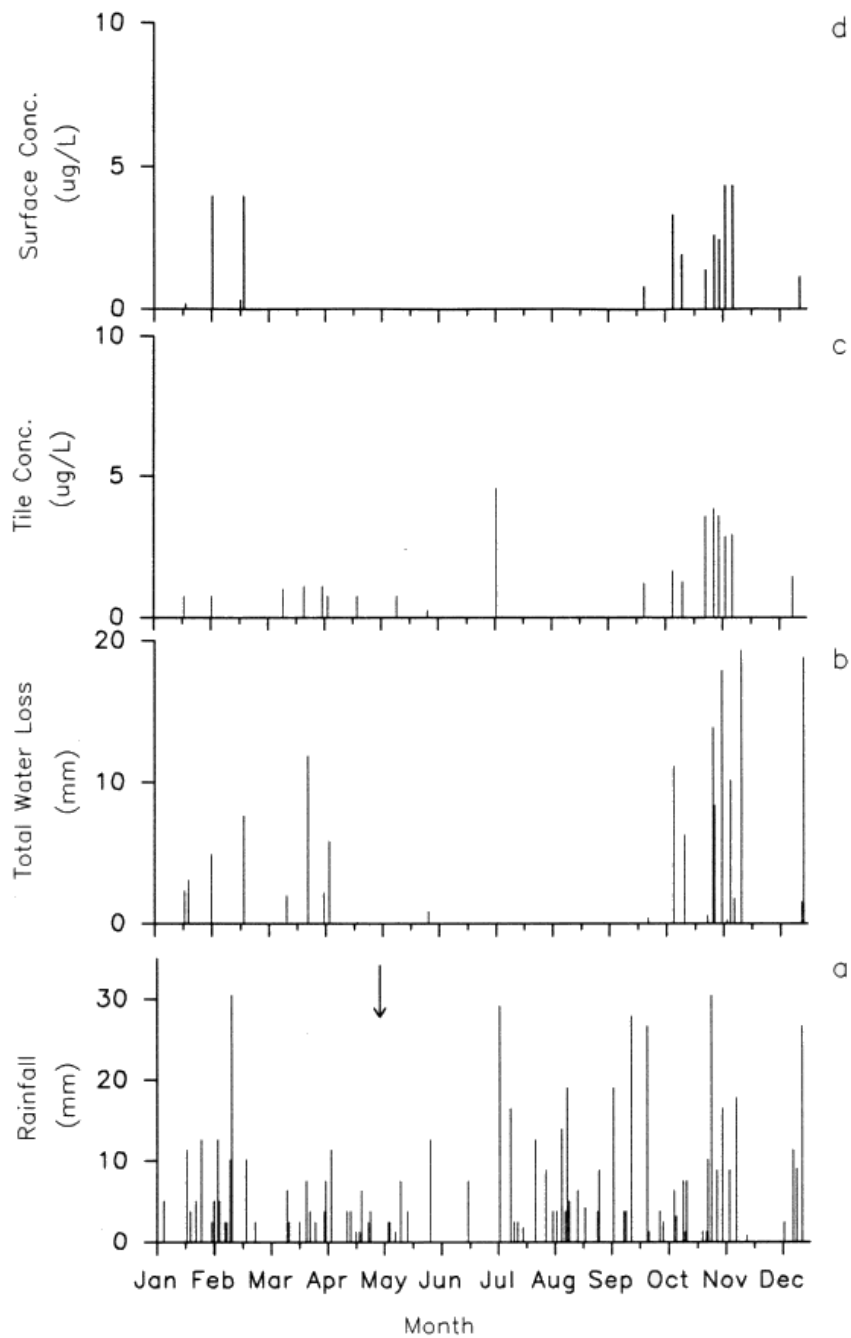


Fig 3B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date on May 11, 1988.

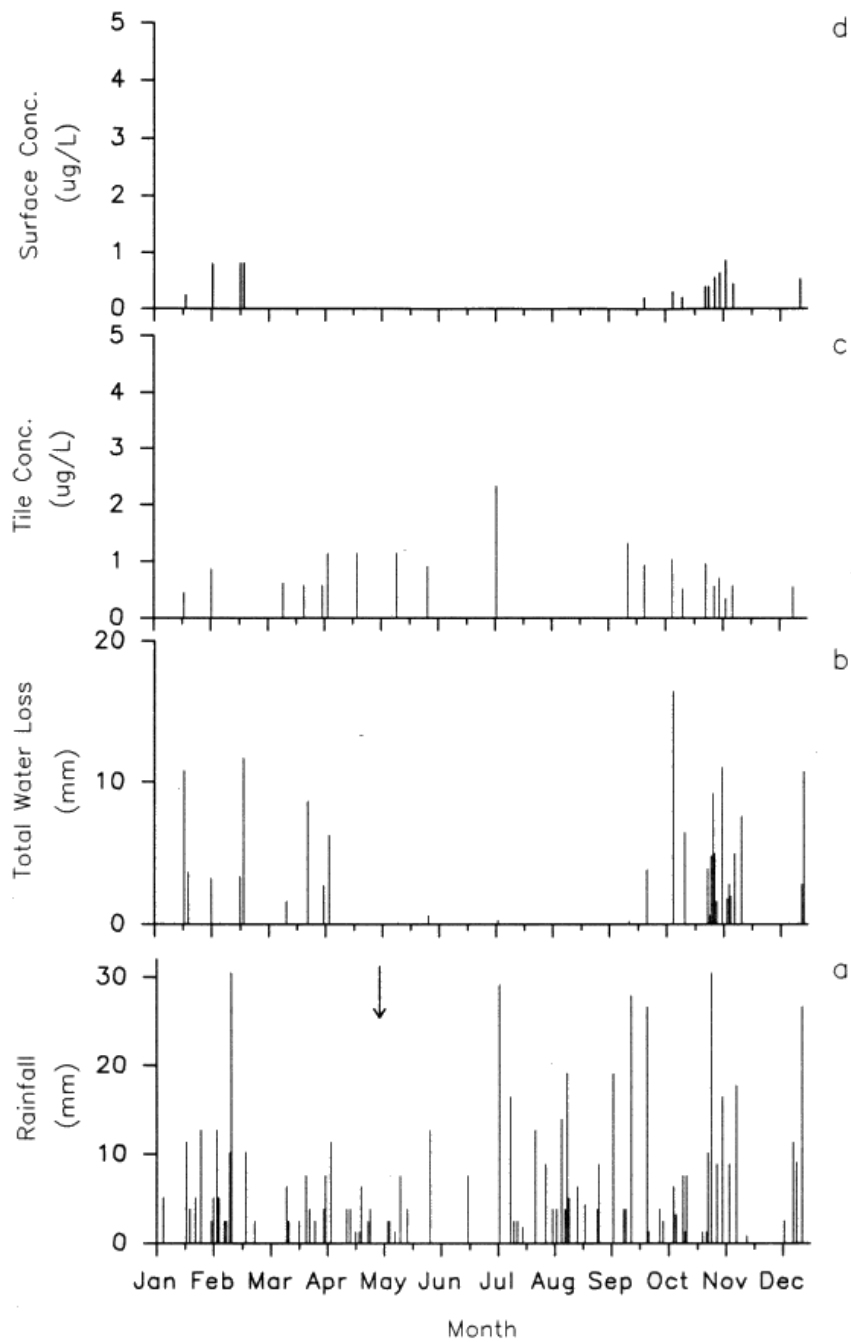


Fig 4B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1988. Arrow denotes planting date on May 11, 1988.

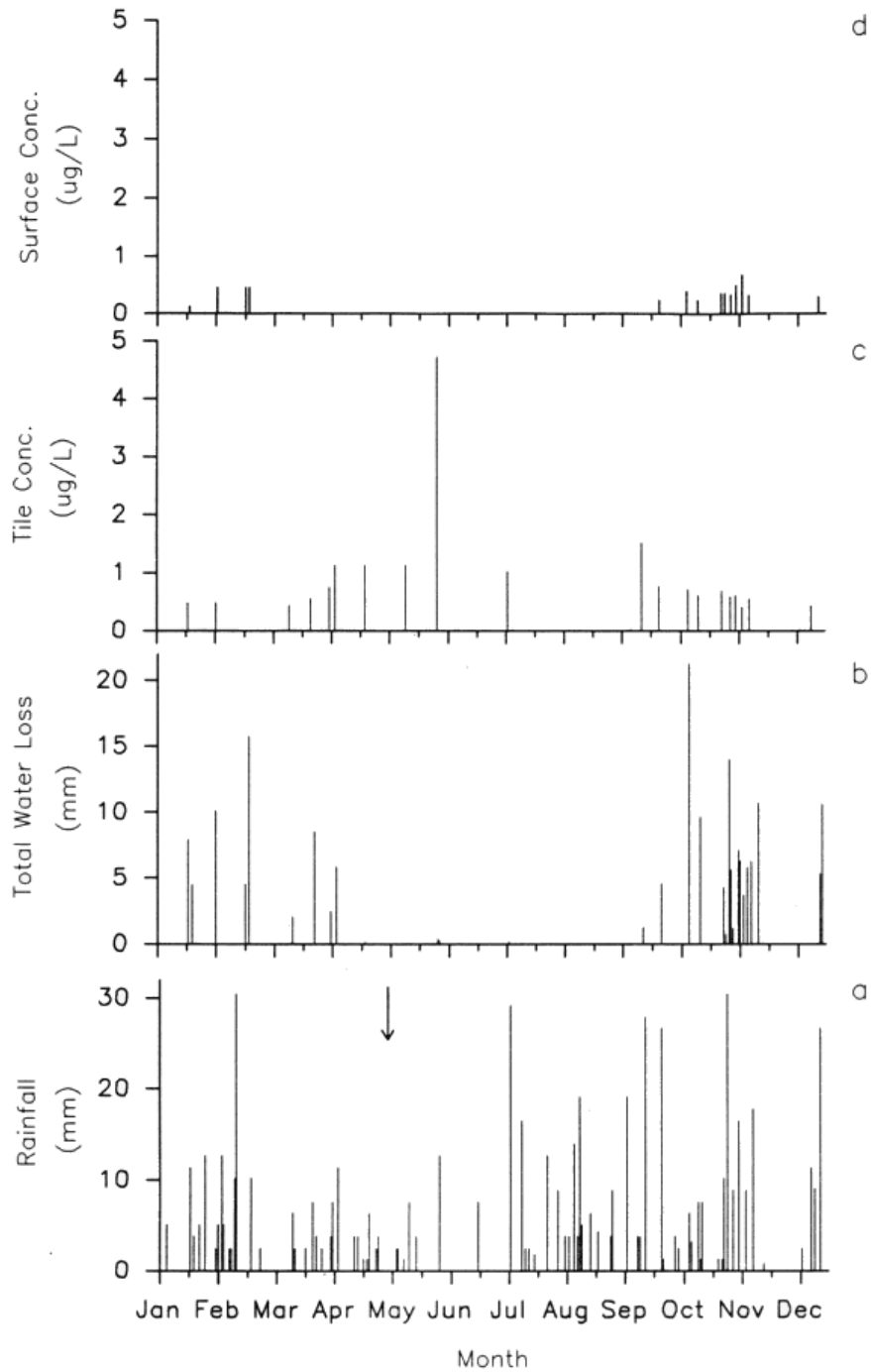


Fig 5B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date on May 11, 1988.

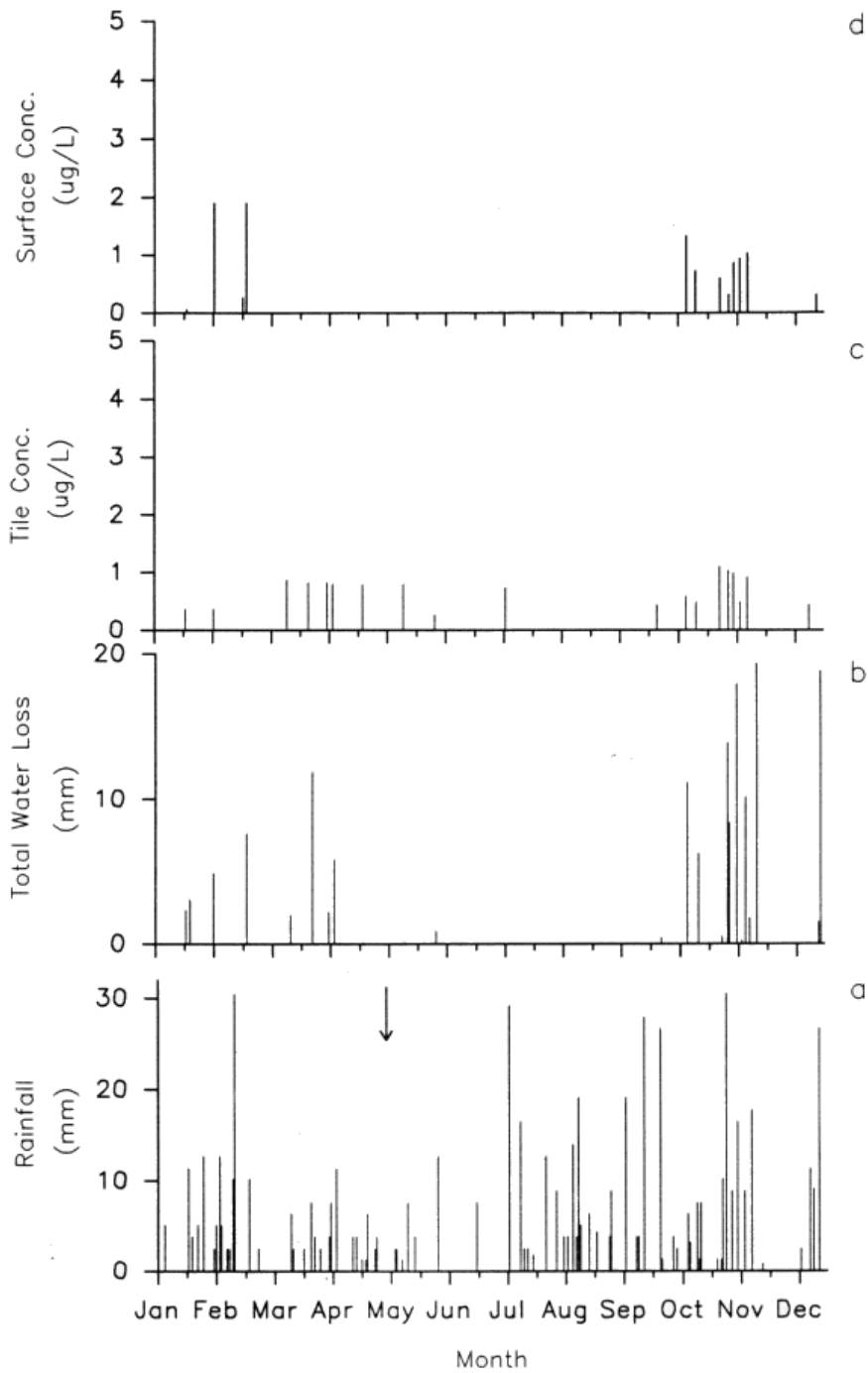


Fig. 6B. Precipitation(a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date on May 11, 1988.

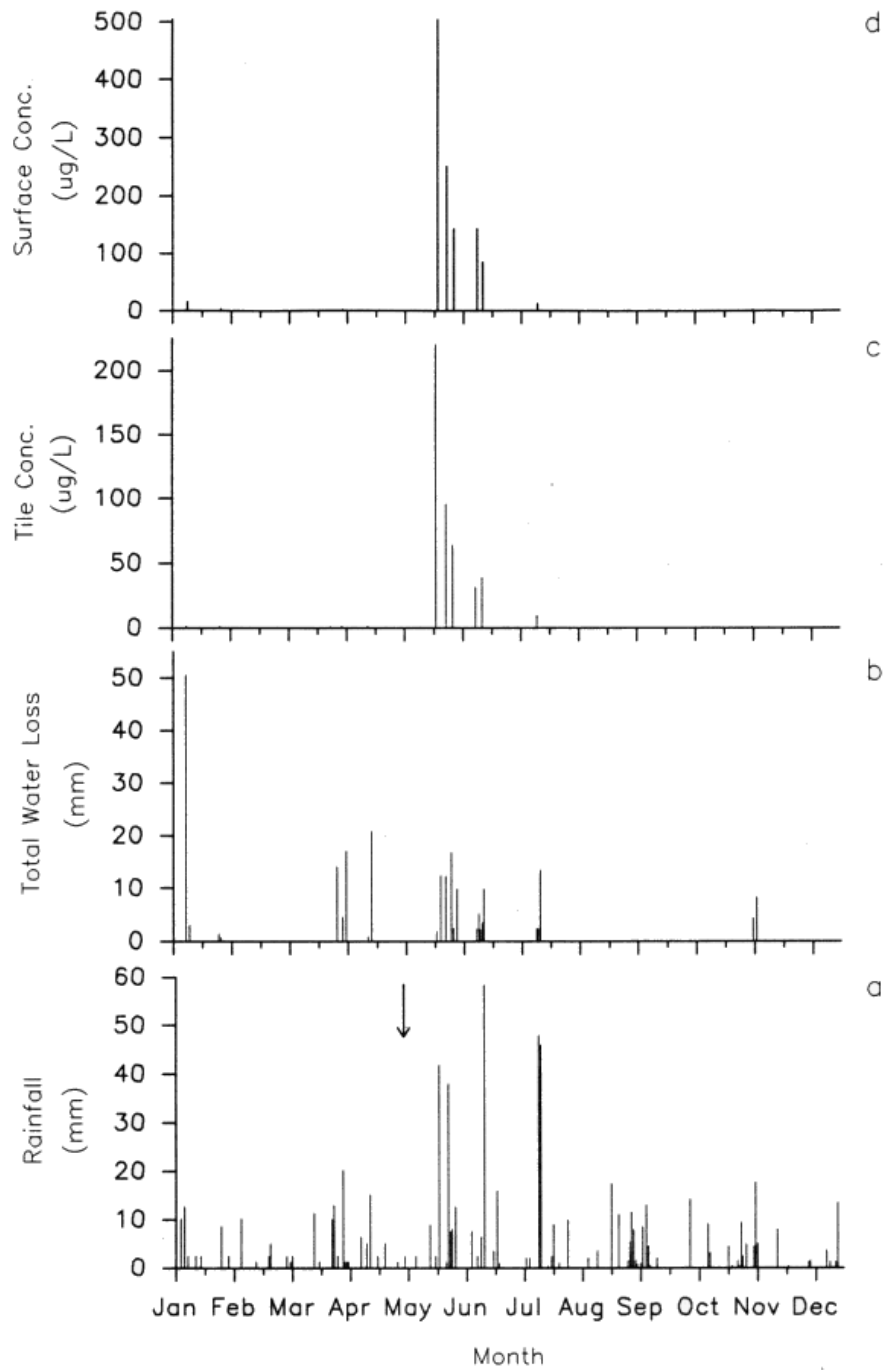


Fig 7B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1989. Arrow denotes planting date on May 10, 1989.

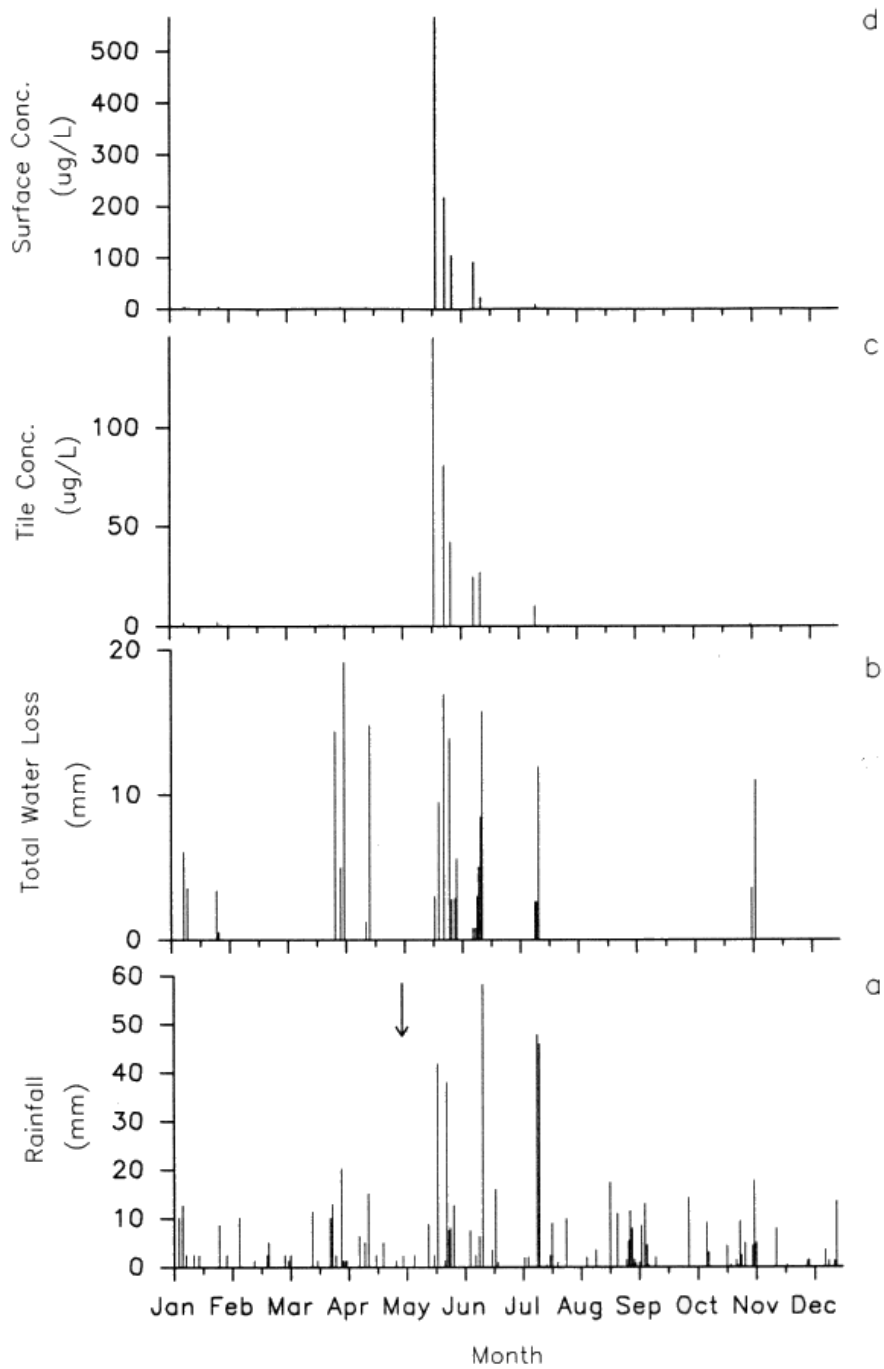


Fig 8B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date on May 10, 1989.

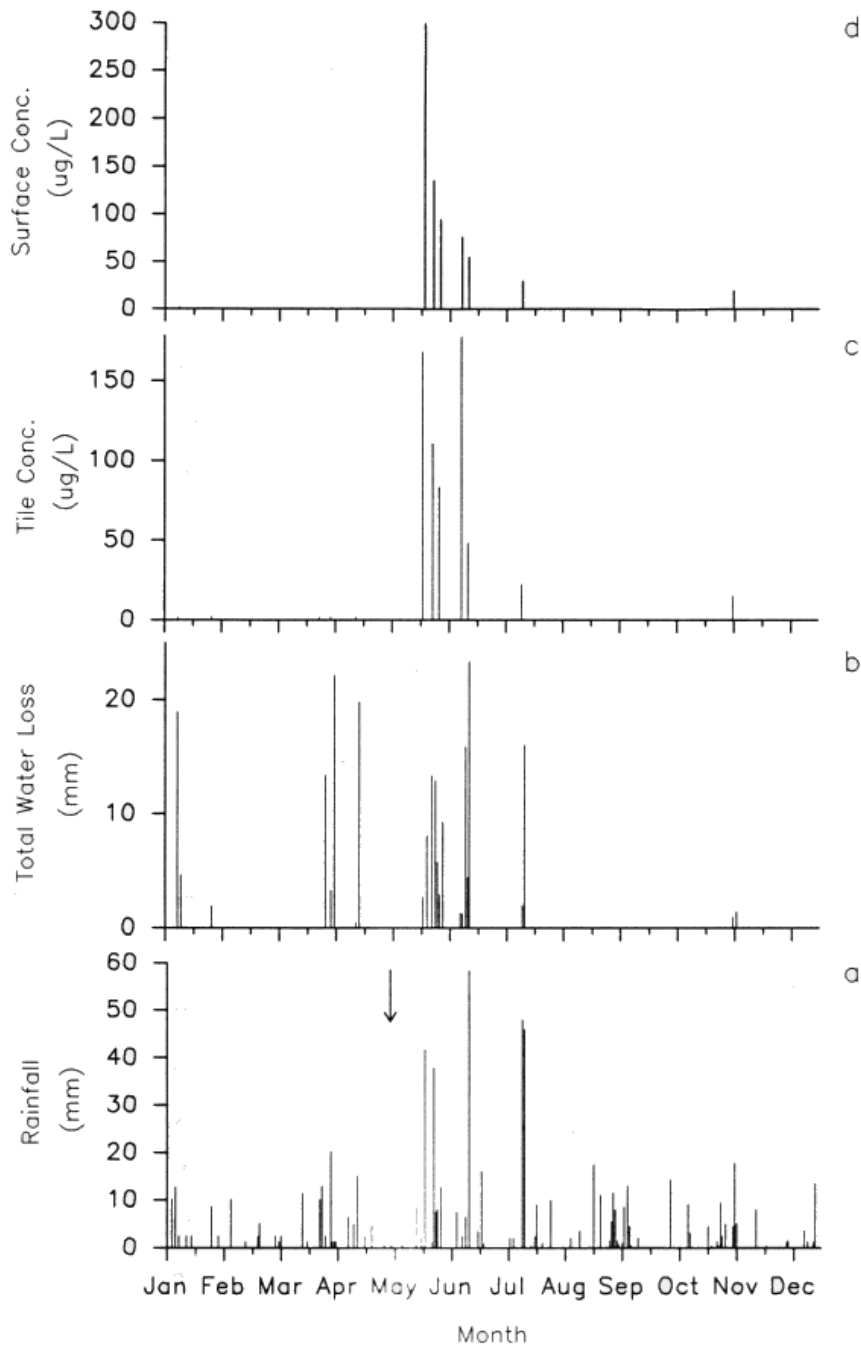


Fig 9B Precipitation (a) total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d) from conventional till for 1989. Arrow denotes planting date on May 10, 1989.

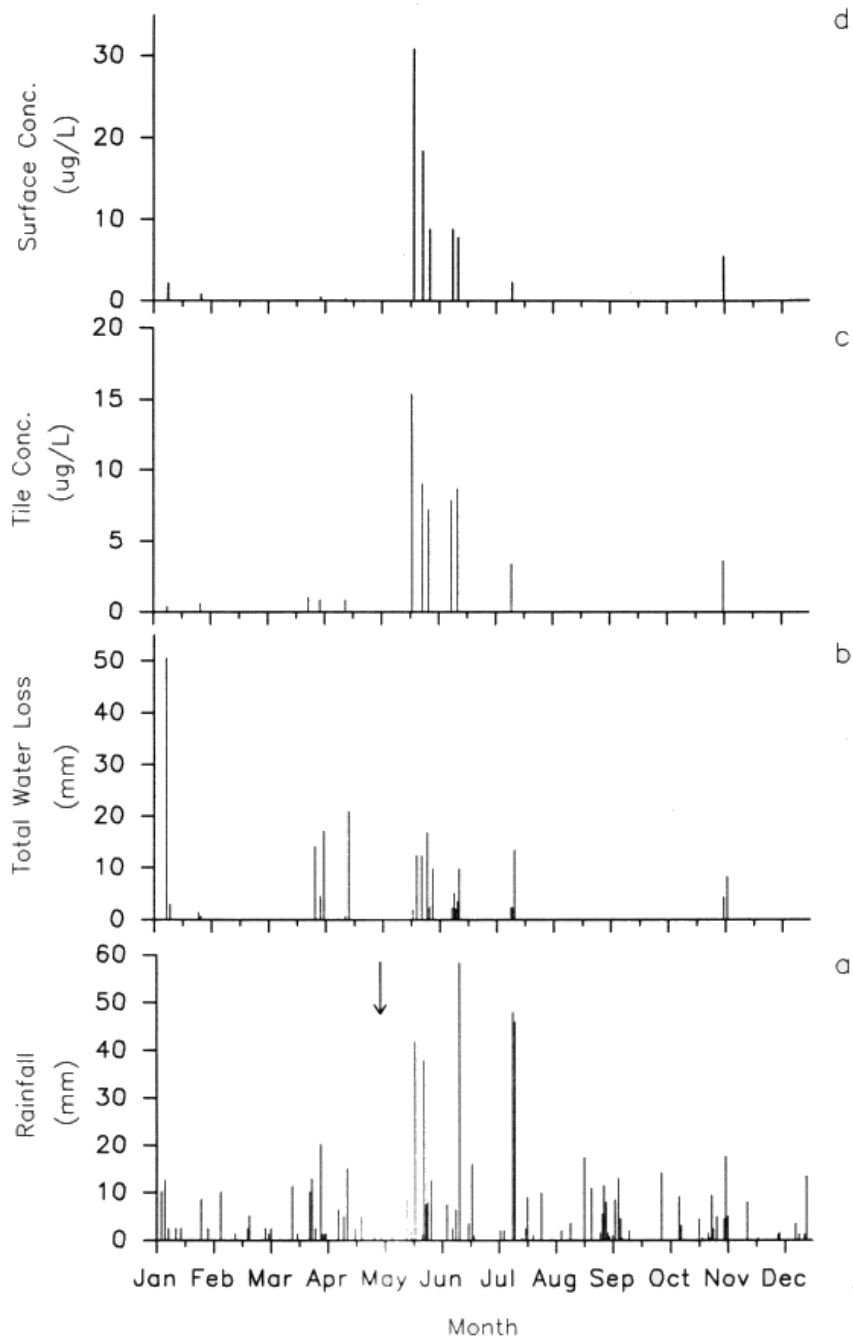


Fig. 10B. Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1989. Arrow denotes planting date on May 10, 1989.

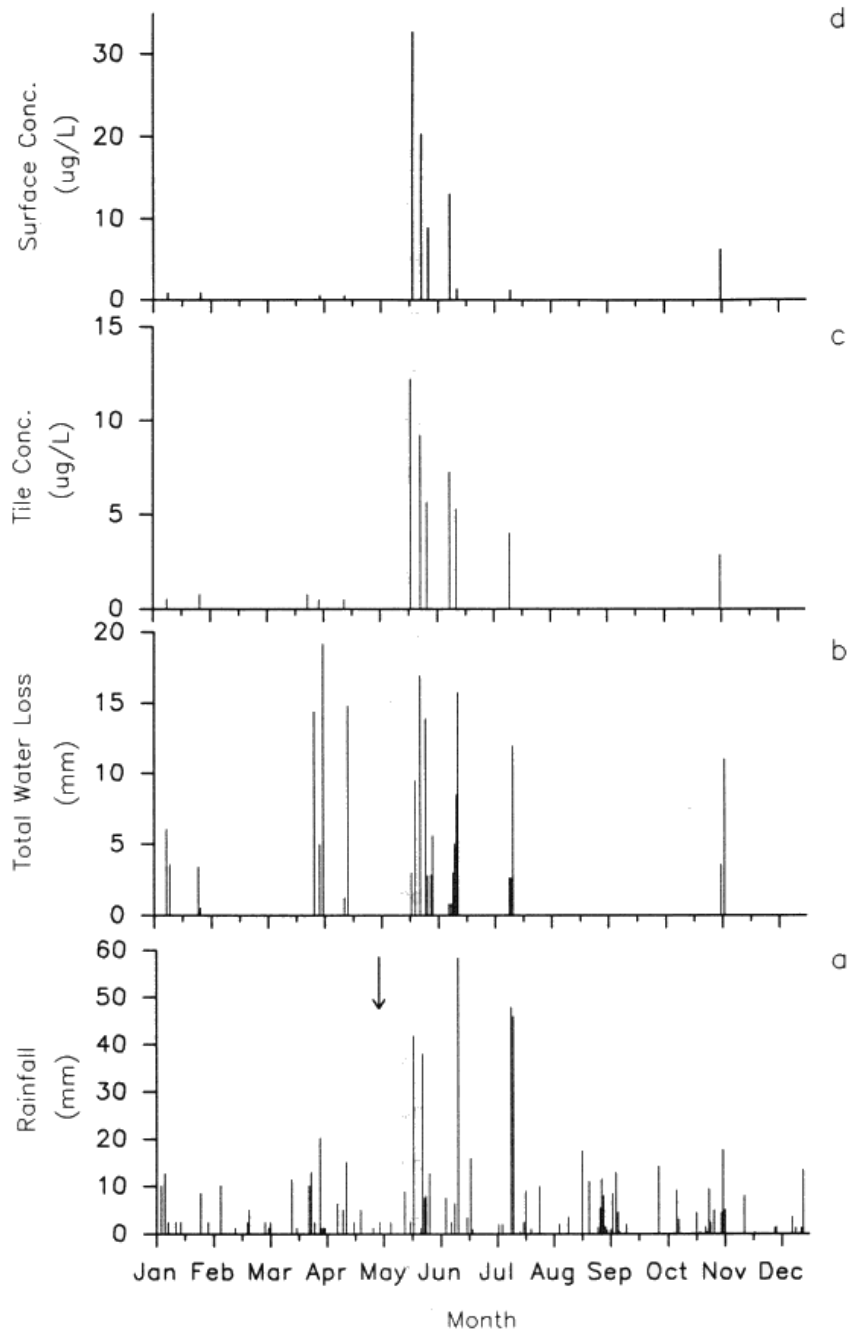


Fig 11B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date on May 10, 1989.

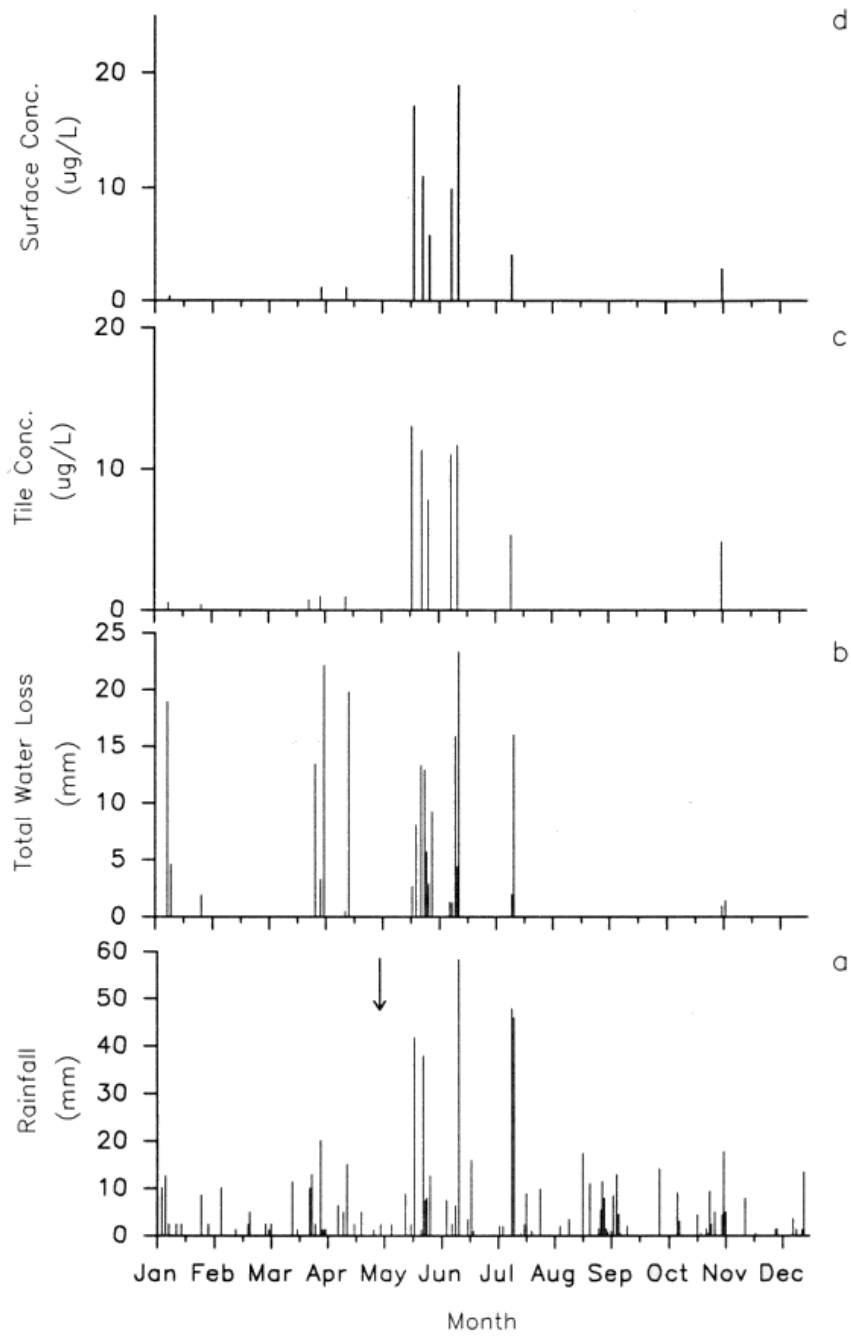


Fig 12B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date on May 10, 1989.

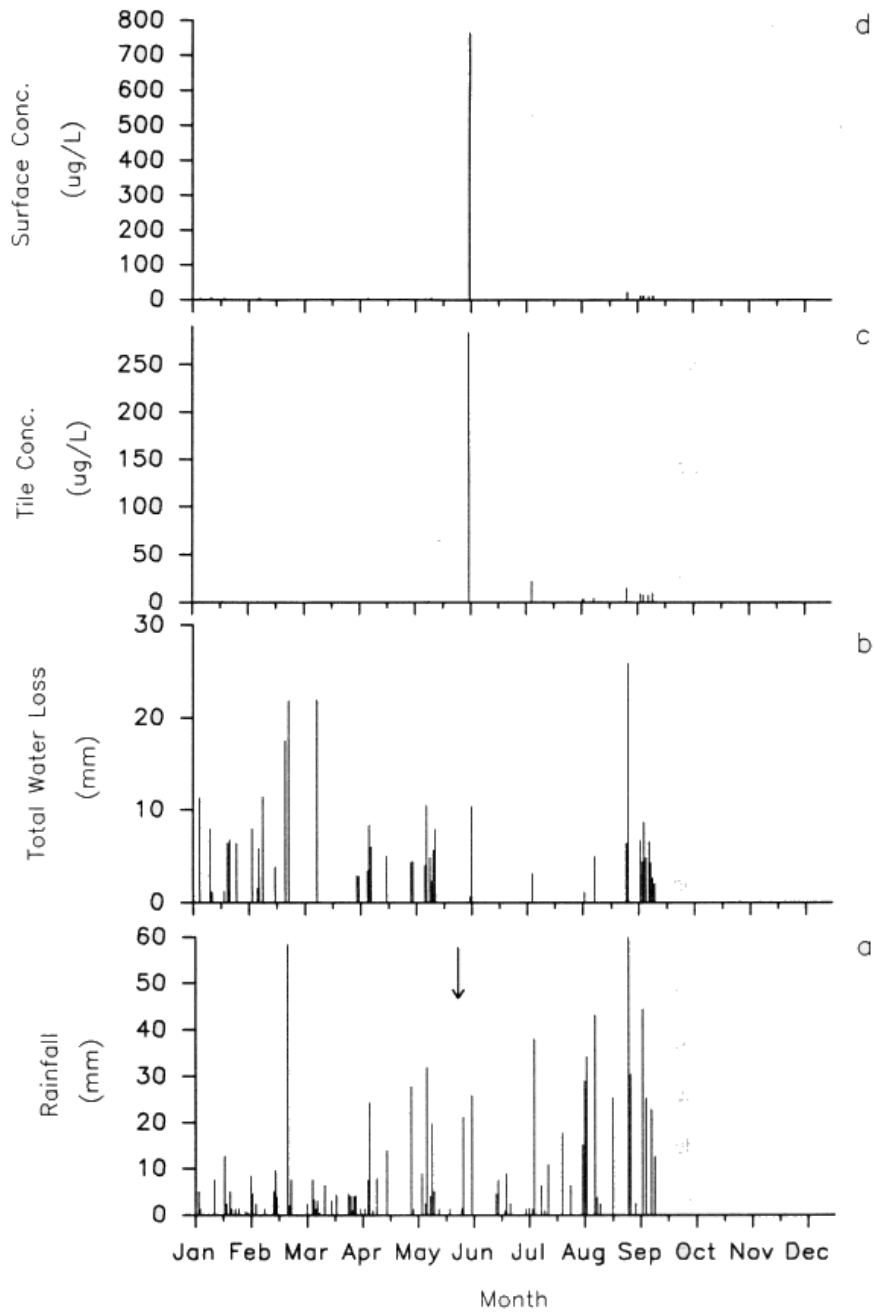


Fig 13B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

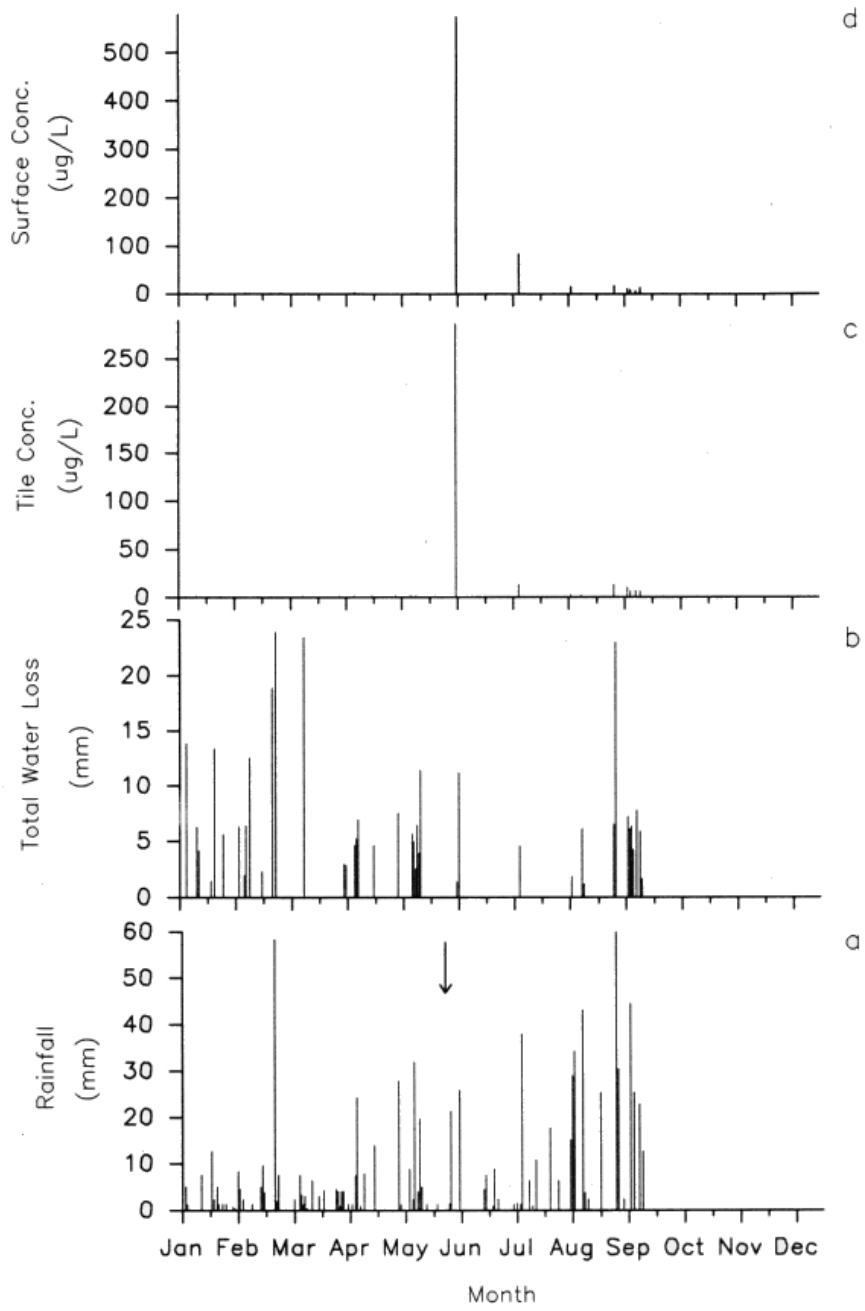


Fig 14B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

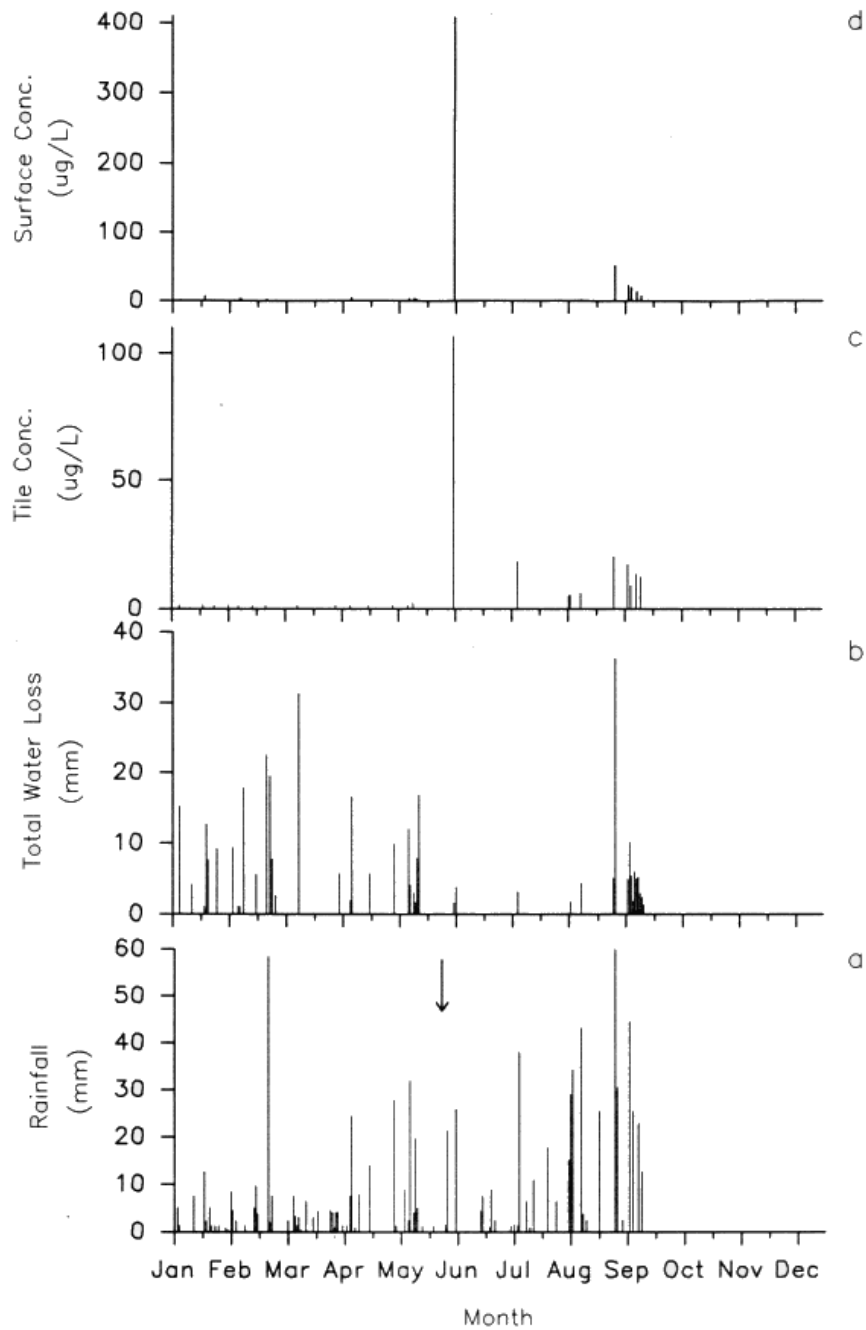


Fig 15B Precipitation (a), total runoff (surface and tile) (b), and atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

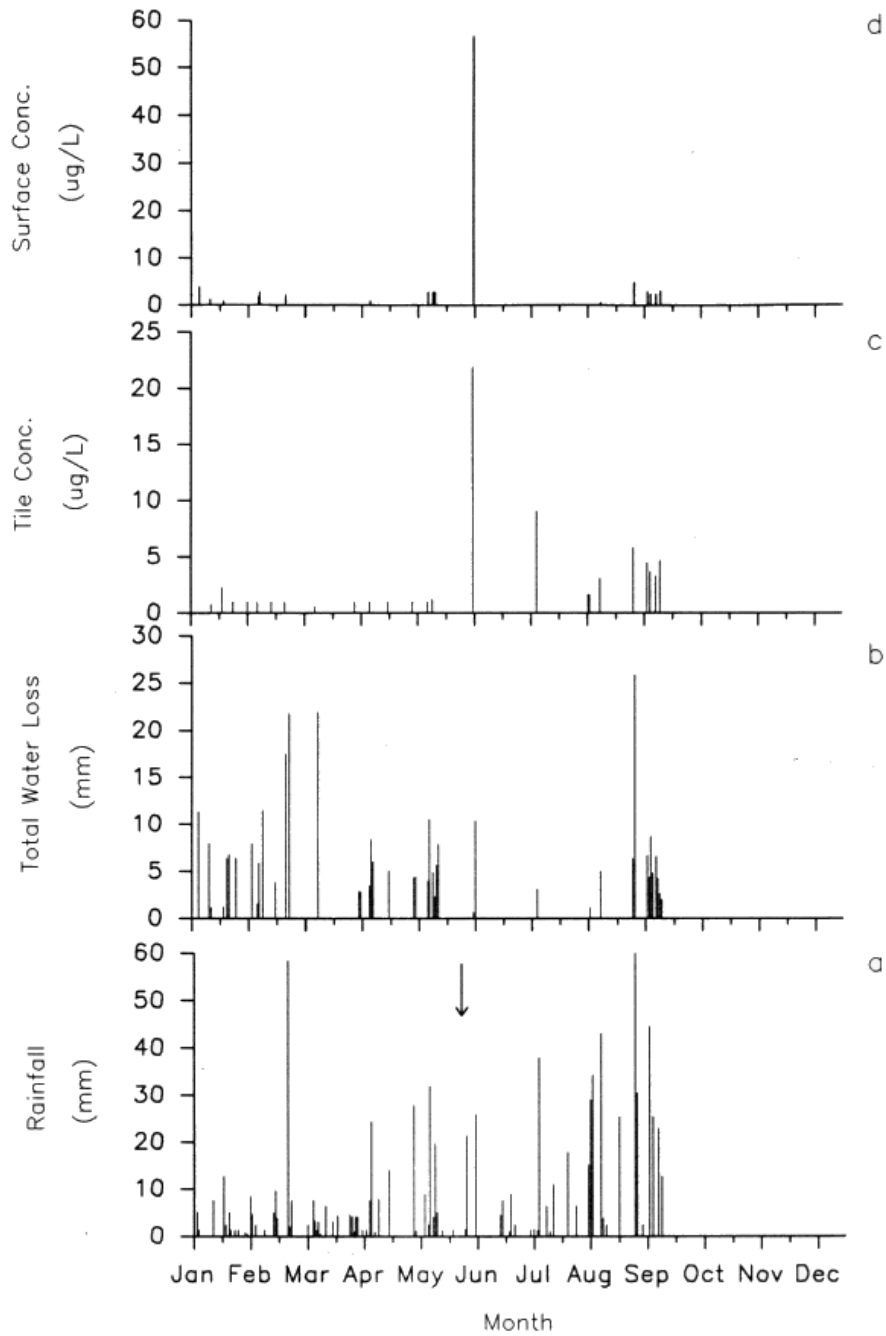


Fig 16B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

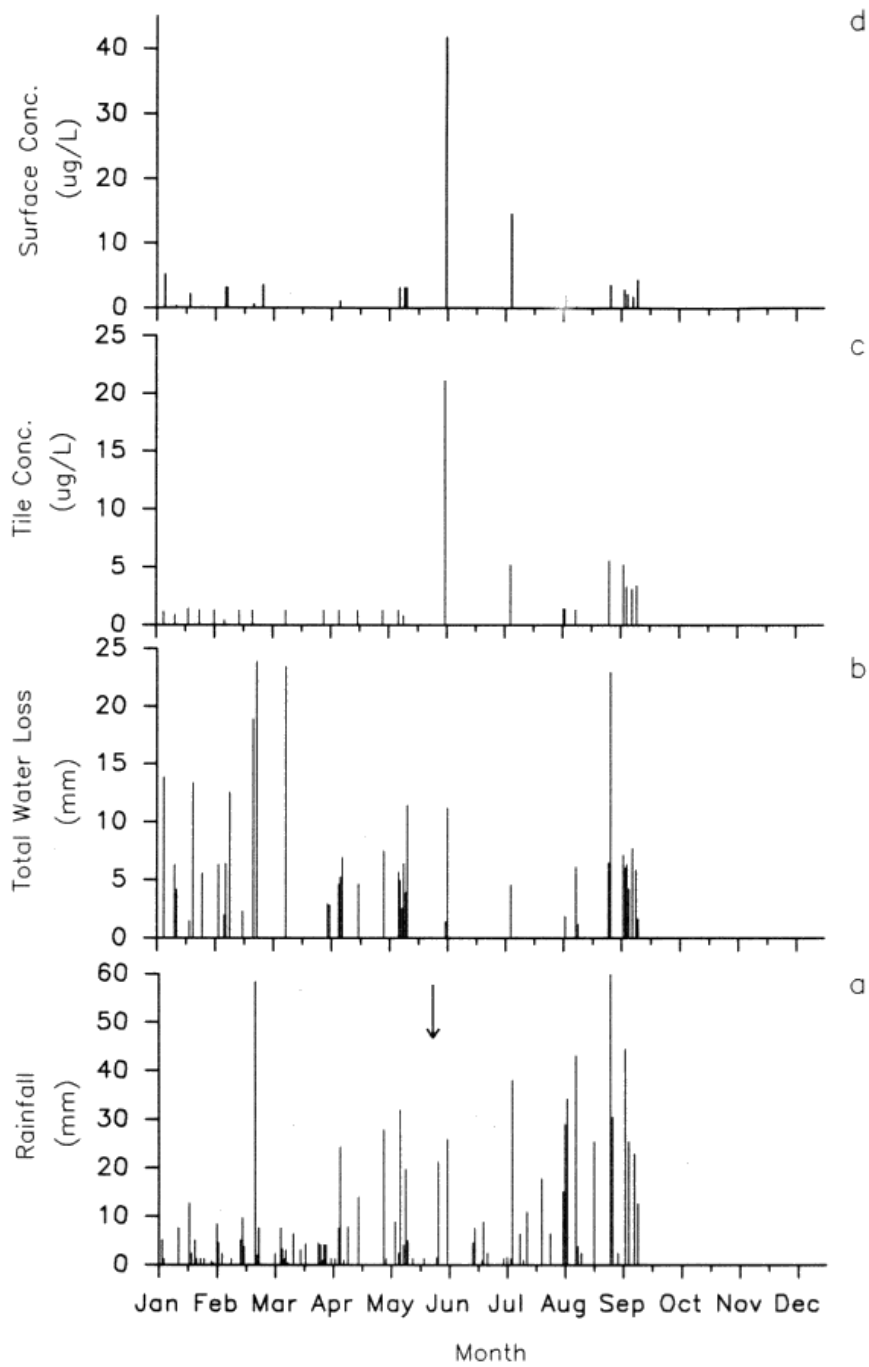


Fig 17B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

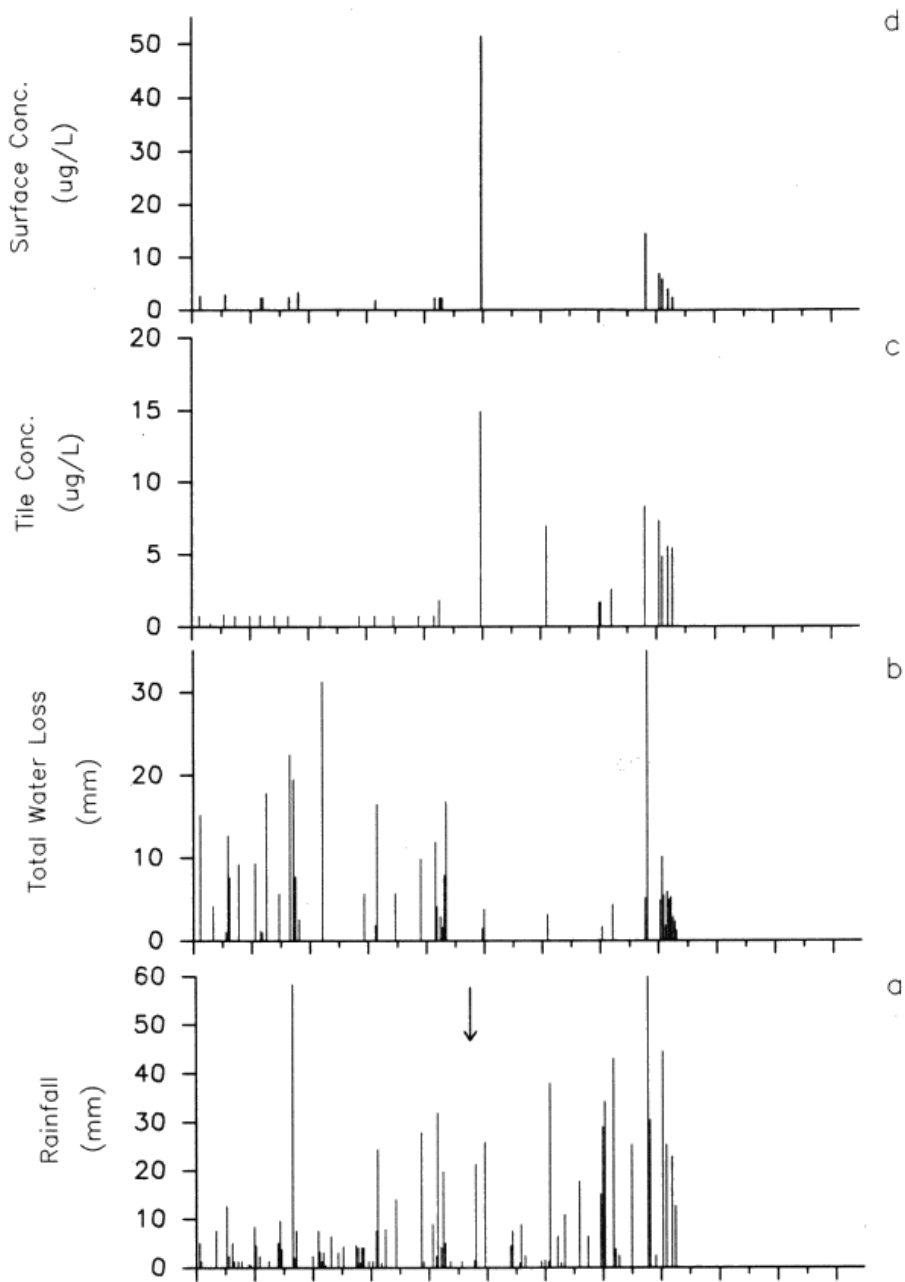


Fig 18B Precipitation (a), total runoff (surface and tile) (b), and des—ethyl atrazine concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

Table 1 B. Range and average atrazine and des-ethyl atrazine concentration of surface and subsurface runoff water from three tillage treatments for 1988. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Tillage	Source	Range	Mean	Range	Mean
		Atrazine conc, $\mu\text{g/L}$		Des-ethyl atrazine conc, $\mu\text{g/L}$	
Ridge	Surface	0.37 - 3.84	1.79 ± 0.13	0.03 - 1.19	0.38 ± 0.06
	Tile	0.12 - 22.62	2.27 ± 0.11	0.12 - 4.73	0.79 ± 0.22
Zero	Surface	0.65 - 5.14	2.61 ± 0.06	0.08 - 1.38	0.49 ± 0.01
	Tile	0.25 - 17.68	2.58 ± 0.05	0.21 - 2.33	0.85 ± 0.02
Conventional	Surface	0.17 - 6.58	2.91 ± 0.38	0.05 - 2.68	0.94 ± 0.33
	Tile	0.24 - 7.01	2.27 ± 0.62	0.16 - 3.39	0.75 ± 0.26

concentration in the runoff decreased progressively with each runoff event after herbicide application. The mean atrazine concentration of the tile discharge water was lower than that in surface runoff water and did not vary greatly among tillage practices (Table 2B).

Table 2B. Range and average atrazine and des-ethyl atrazine concentration of surface and subsurface runoff water from three tillage treatments for 1989. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Tillage	Source	Range	Mean	Range	Mean
		Atrazine conc, $\mu\text{g/L}$		Des-ethyl atrazine conc, $\mu\text{g/L}$	
Zero	Surface	0.99 - 715	176 ± 32	0.44 - 41	15 ± 3
	Tile	0.44 - 282	59 ± 5	0.41 - 22	7 ± 2
	Surface	0.11 - 624	187 ± 19	0.42 - 41	13 ± 1
	Tile	1.01 - 354	77 ± 1	0.40 - 24	8 ± 1
Conventional	Surface	6.36 - 360	121 ± 5	1.55 - 34	12 ± 2
	Tile	1.62 - 412	93 ± 12	1.11 - 25	9 ± 2

The high concentrations of atrazine in the runoff is attributed to runoff producing events within ten days of herbicide application. Herbicide washoff from crop residue is associated with the higher average and maximum atrazine concentrations from the

conservation tillage treatments compared to conventional tillage. Martin *et al.*, (1978) found that atrazine was readily washed from corn residue with a simulated rainfall over 35 mm. Des-ethyl atrazine concentrations were lower than atrazine concentrations (41 µg des-ethyl atrazine/L vs 715 µg atrazine/L maximum) and followed trends similar to that of atrazine.

Atrazine and des-ethyl atrazine concentration in runoff for 1990 followed similar patterns to that for 1989 (Fig. 13 to 18B). Herbicide concentration was highest in events nearest application time and progressively decreased in subsequent events to concentrations <10 µg/L. Sampling of runoff was discontinued after September 30, 1990 because of the end of the field sampling phase. Herbicide concentrations were low in September samples and subsequent runoff losses would be low as well.

Antecedent soil moisture content and other factors are important in the occurrence of a runoff producing event as manifest in the 1990 data. A runoff event occurred seven days after herbicide application which caused surface and tile runoff from the conventional tillage treatment but the intensity and duration of the event was not sufficient to produce surface runoff from both replicates of the conservation tillage treatments. Consequently the maximum atrazine concentration of the replicate for which a surface runoff event occurred was 871 µg/L (Fig. 13 and 14B) similar to that observed in 1989 (Fig. 7 and 8B) whereas that from the corresponding replicate which had a smaller insignificant runoff was 19 µg/L. The variation between replicates is not observed in figures 13 and 14B because the high concentration is presented for this event rather than the average. Average concentration is reported in Table 3B thus, the reason for the large standard error of the mean associated with average concentration. This variation in maximum atrazine concentration was not observed in the tile discharge water (Table 3B) which had concentrations similar to those recorded in 1989 (Table 2B) because the soil was saturated in both replicates of each treatment. Higher maximum atrazine concentrations were found in tile discharge water from

the conservation tillage treatments than from conventional tillage in 1990 (Table 3B). Runoff producing events which occur later in the season after the herbicide

Table 3B. Range and average atrazine and des-ethyl atrazine concentration of surface and subsurface runoff water for three tillage practices from January to September 30, 1990. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Tillage	Source	Range	Mean	Range	Mean
		Atrazine conc, µg/L		Des-ethyl atrazine conc, µg/L	
Ridge	Surface	0.22 - 341	24 ± 19	0.07 - 27	4.0 ± 1.0
	Tile	0.80 - 337	22 ± 3	0.33 - 31	3.8 ± 0.6
Zero	Surface	0.68 - 445	31 ± 25	0.53 - 40	4.42 ± 1.3
	Tile	0.53 - 322	23 ± 4	0.56 - 29	4.09 ± 0.6
Conventional	Surface	0.18 - 409	33 ± 6	0.83 - 52	7.4 ± 1.3
	Tile	0.36 - 157	14 ± 1	0.24 - 21	4.0 ± 0.7

had equilibrated in the soil and undergone dissipation (1988) or the occurrence of runoff producing events that greatly exceed soil infiltration rate (1989), have more uniform herbicide concentration and as will be shown later, less variation between replicates in herbicide transport.

As observed in previous years, des-ethyl atrazine concentration of surface runoff and tile discharge water was considerably less than atrazine concentration. Concentrations of this metabolite never exceeded 52 µg/L (Table 1B to 3B). Similar concentrations among treatments were found in tile discharge and surface runoff water. Generally higher concentrations of the metabolite were found later in the season (Fig. 4 to 6B, 10 to 12B, 16 to 18B) after dissipation of the herbicide or coincided with the rate of degradation of atrazine in the soil. As observed with atrazine, des-ethyl atrazine concentrations of tile discharge water were less variable than concentrations in surface runoff water (lower more uniform standard error).

Triazine Transport

Total quantities of triazine (atrazine+ des-ethyl atrazine) transported from the treatments in the aqueous phase varied for each of the years monitored. Triazine losses were lowest in 1988 (<0.3% of applied) and highest in 1989 (6.1 to 7.6% of applied). There were no differences among tillage practices on triazine transport (Fig. 19B). This was not unexpected since tillage had no effect on water removal (Fig. 2A) and herbicide transport primarily occurs in the aqueous phase (Wauchope, 1978). Triazine transport averaged over three years from each treatment was 58 ± 1 g/ha from ridge tillage, 63 ± 3 g/ha from zero tillage and 62 ± 13 g/ha from conventional tillage. The high standard error associated with the transport losses for conventional and zero tillage masked tillage effects.

Des-ethyl atrazine is the primary, phytotoxic degradation product of atrazine. The proportion of total triazine transport composed of the dissipation product increased with time after application or coincided with the dissipation of the herbicide in the soil. In 1988 triazine transport occurred late in the season and 25% of total triazine was transported as the dissipation product (Fig. 20B). Des-ethyl atrazine has a higher affinity for soil than atrazine (Brouwer et al., 1990) which would reduce its concentration in the runoff and lower transport losses. Triazine losses were greatest in 1989 (109 to 137 g/ha) but <10% of that transported was des-ethyl atrazine. This was because most of the loss occurred soon after application before the herbicide had dissipated in the soil. Total triazine transport for the nine month period in 1990 was less than that in 1989 and 18-26% of that transported was the metabolite indicating a suitable environment for rapid dissipation of the parent herbicide in the soil. Although triazine loss was not measured for the last three months of 1990, it was estimated that loss was less than 1 g/ha from any of the treatments. This estimate was based on the assumption that 37% of the rainfall (279 mm) would appear as runoff

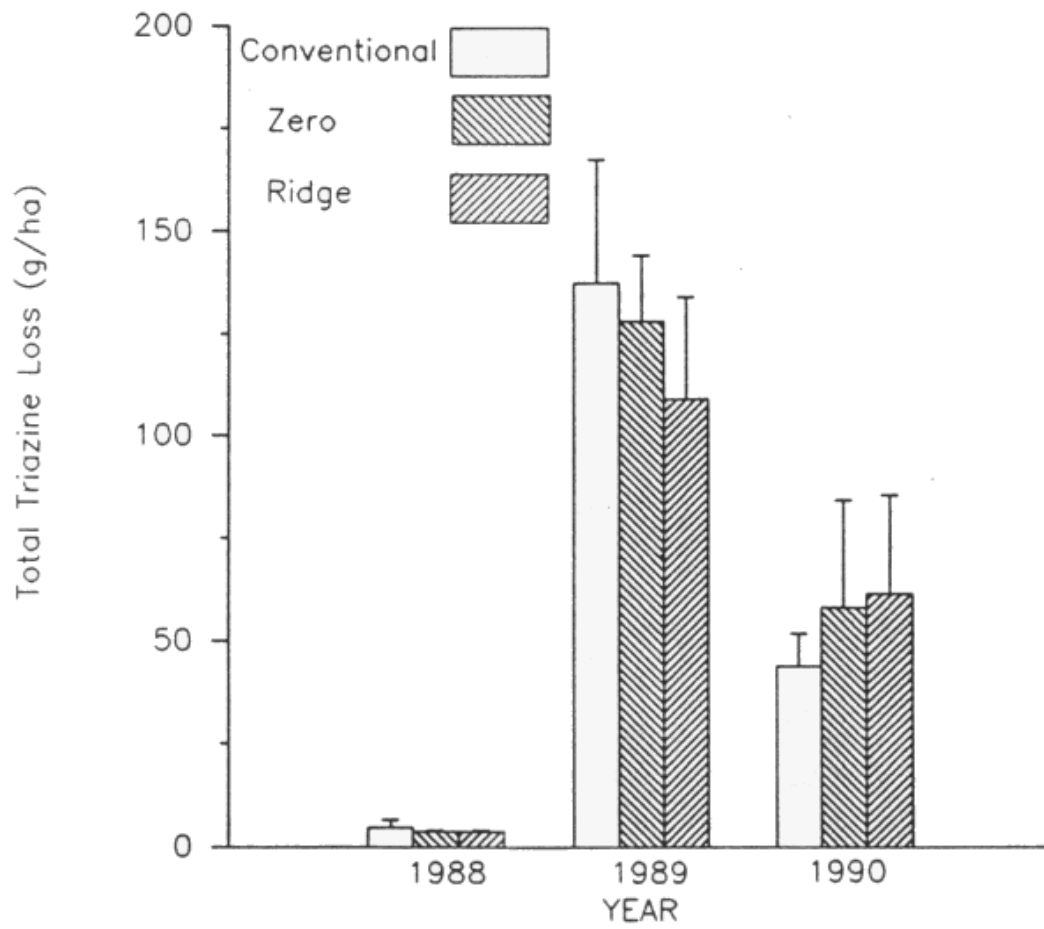


Fig. 19B Total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.

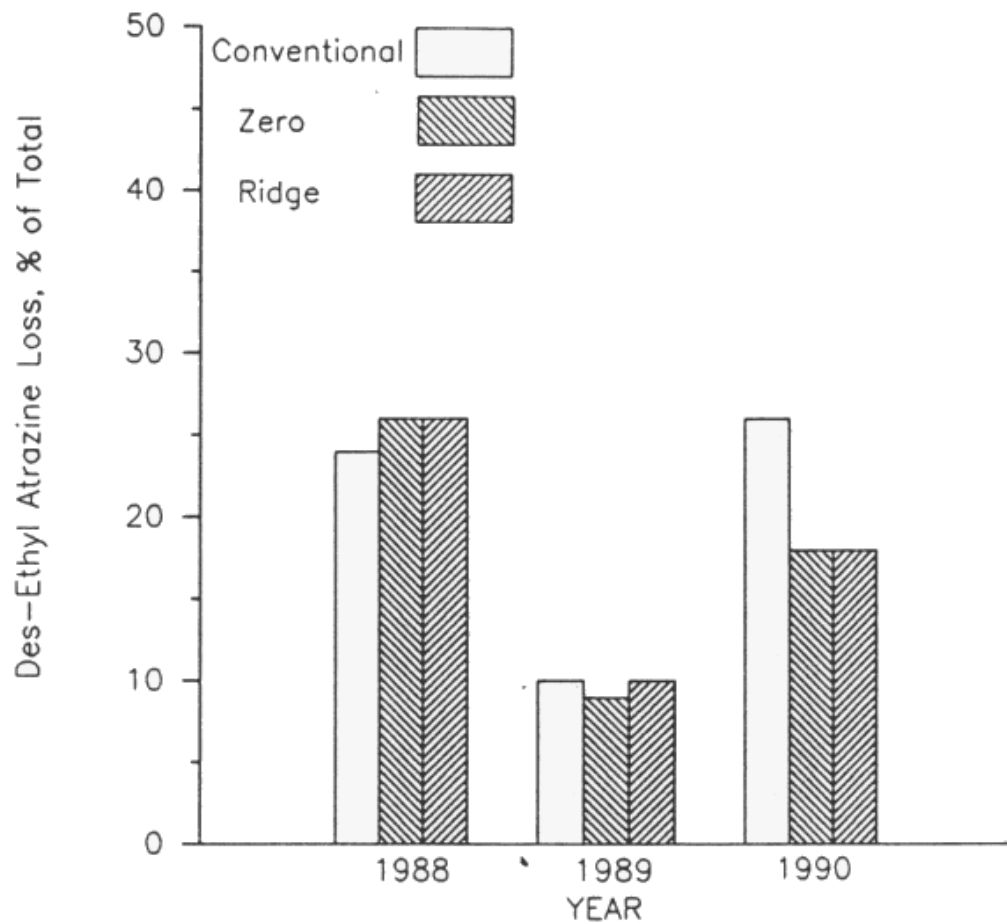


Fig. 20B Des-ethyl atrazine loss as a percent of total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil.

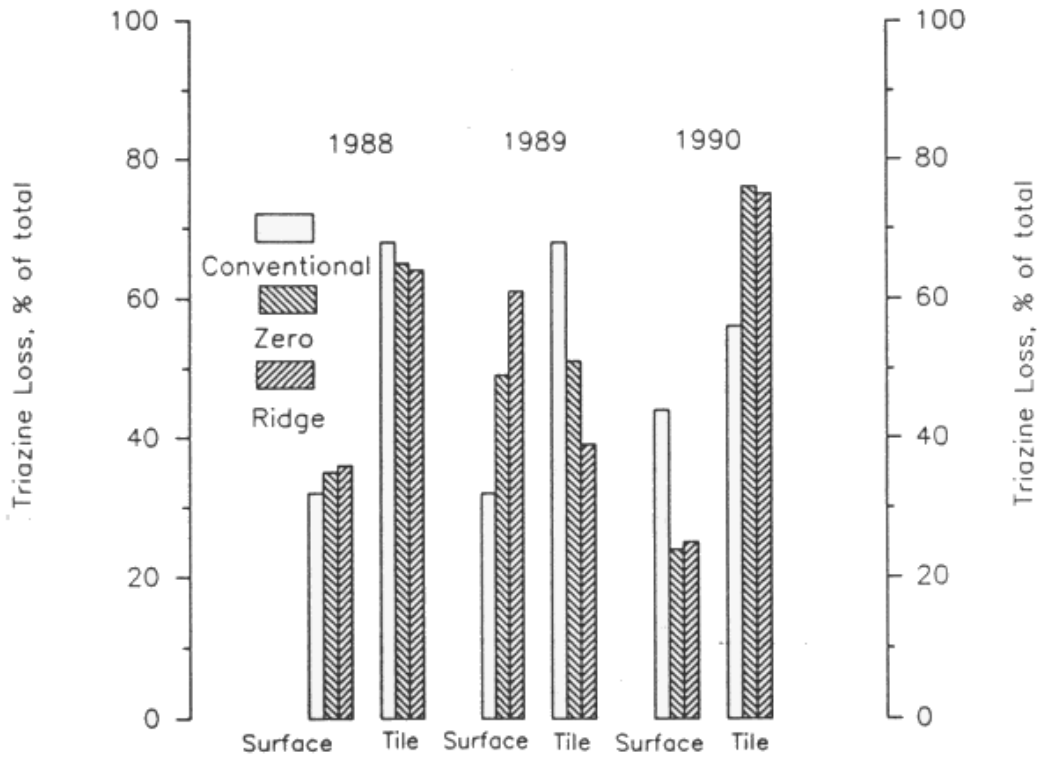


Fig. 21B Surface and tile loss of triazine as a percent of total triazine (atrazine and des-ethyl atrazine) loss from three tillage practices on Brookston soil.

(62% tile discharge and 38% surface runoff) and that the concentration of the runoff was similar to that of the last sampling event in September.

The proportion of triazine transported by surface and subsurface runoff varied from year to year and by tillage treatment (Fig. 21 B). Tile discharge accounted for 64 to 76% of the triazine transported in 1988 and 1990. Tillage had little effect on the proportion of triazine in tile discharge or surface runoff in 1988. Triazine transported in subsurface runoff amounted to 64 to 68% of the total load from the three tillage practices and 32 to 36% was transported in surface runoff. The transport pattern of triazine was influenced by tillage in 1989 and 1990. The proportion of triazine transported in tile discharge water in 1990 was greater from the conservation tillage treatments (75 to 76% of that transported) than from conventional tillage (56%). In 1989, more triazine was transported from conventional tillage through tile discharge (68%) than from surface runoff, ridge tillage had a larger proportion transported through surface runoff (61 %) and zero tillage had equal amounts (49 or 51 %) transported through surface and subsurface runoff. In all years subsurface runoff exceeded surface runoff for water loss with few differences among treatments (Fig. 3A reproduced as Fig. 22B for convenience) but triazine transport did not follow this pattern in all years.

The seasonal transport of triazine herbicide followed seasonal distribution of water loss for 1988 and 1989 but not for 1990 (Fig. 23B and 24B). A larger proportion of water loss occurred (Fig. 24B) before herbicide application in 1990 when atrazine and des-ethyl atrazine concentration was near detection limit (Fig. 13 to 18B). Herbicide transport is more related to incidence of application than to seasonal distribution of rainfall. In 1988 most rainfall and runoff producing events occurred after harvest (Fig. 24B) hence all of the small (<0.3% of applied) amount of herbicide transport occurred after harvest (Fig. 23B). Runoff producing events occurred shortly after herbicide application in 1989 and 1990 which accounted for 84 to 98% of herbicide transport. Other studies have also shown that runoff producing events shortly after herbicide application account for most of the herbicide

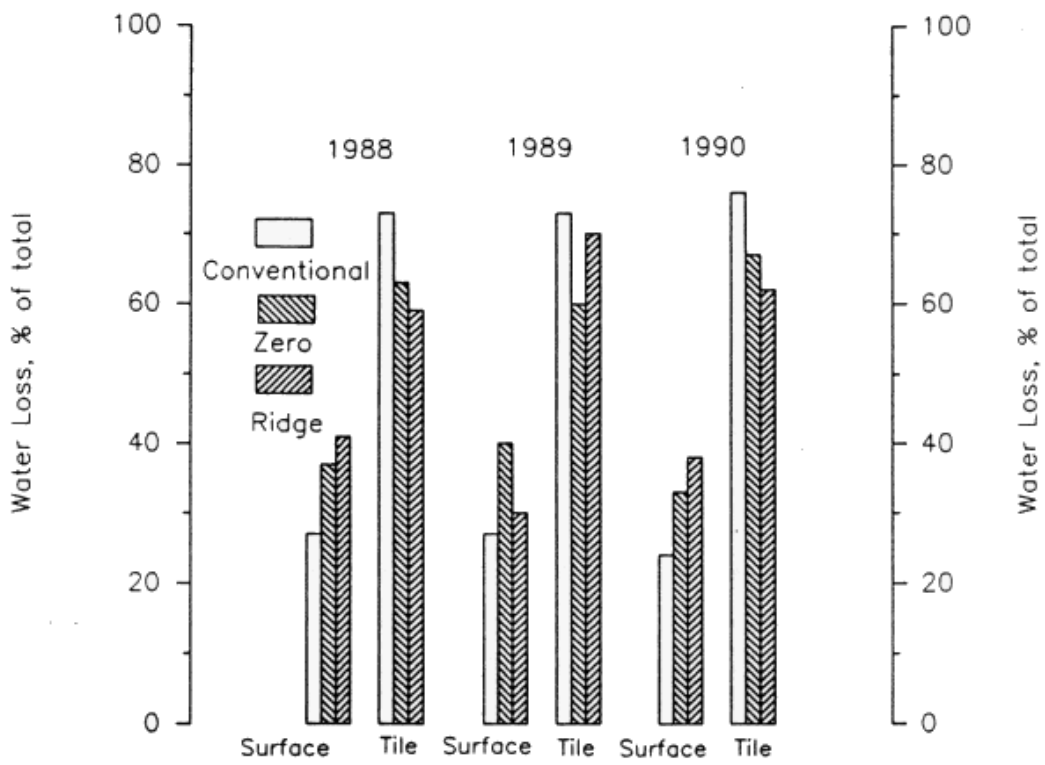


Fig. 22B Surface and tile loss of water as a percent of total water loss from three tillage systems on Brookston soil.

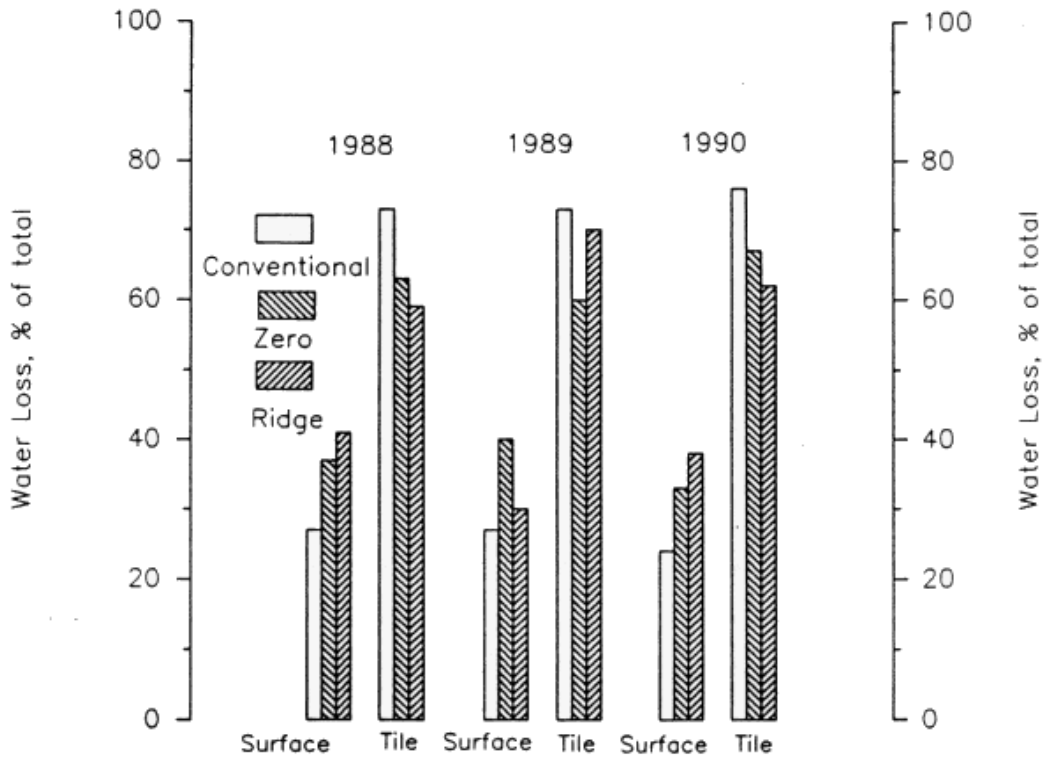


Fig. 23B Seasonal triazine loss as a percent of total triazine (atrazine and des-ethylatrazine) loss from three tillage practices on Brookston soil.

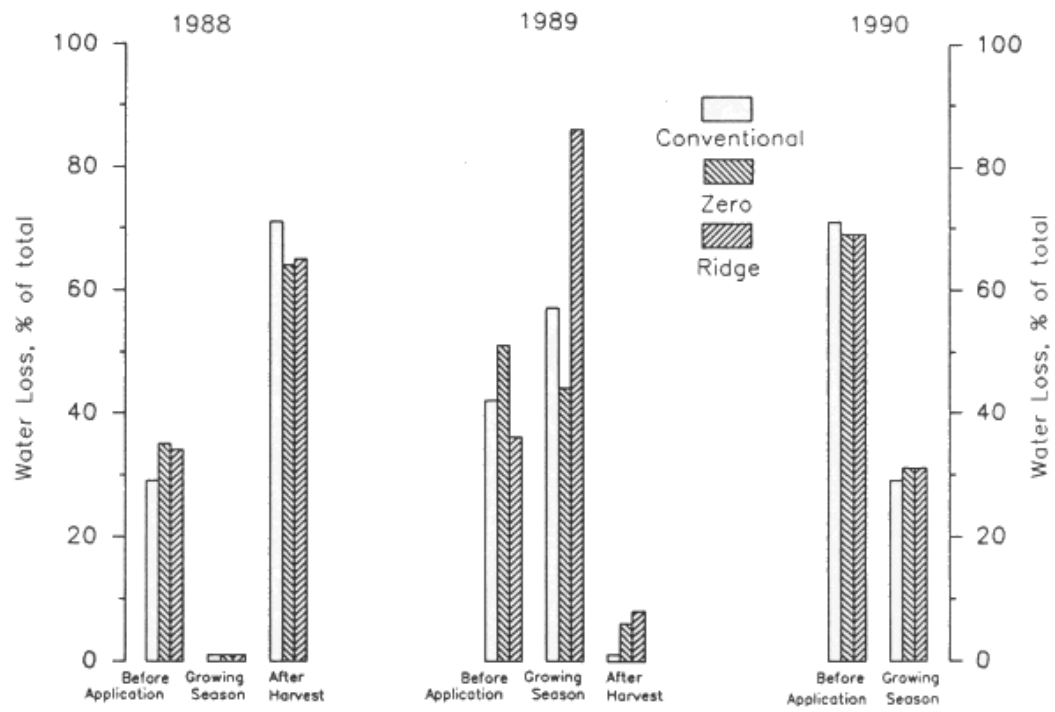


Fig. 24B Seasonal water loss as a percent of total water loss from three tillage practices on Brookston soil.

transport (Hall *et al.*, 1972; Triplett *et al.* 1978; Baker and Johnson, 1979; Haith, 1986). In years where herbicide transport occurs late in the season as in 1988, herbicide transport will follow the water pattern but quantities will be low. The proportion of triazine transport as des-ethyl atrazine was greater after harvest and before application reflecting the dissipation of atrazine in the soil in all treatments.

Triazine transport by sediment was not determined since other studies on this soil have suggested sediment phase transport compared to aqueous phase transport was insignificant (VonStryk and Bolton, 1977). In this study, assuming soil residue of 0.5 mg/kg (Fig. 25B) because loss occurred late in 1988, sediment phase transport would amount to <0.7 g/ha. Assuming soil residue of one mg/kg for 1989 and 1990 (Fig. 26 and 27B) because runoff occurred near application, sediment phase transport would account for <0.2% of total transport.

Soil Persistence

Soil samples collected from the top 10 cm of each treatment were analysed for triazine (atrazine + des-ethyl atrazine) residues. Soil was collected before herbicide application to determine residue carryover from the previous application, at application and at selected times throughout the growing season.

Triazine residues from the previous years' application amounted to <10% of that applied (Fig. 25 to 27B). At application, herbicide residues in soil were highest on conventional tillage. The lower residues recovered from the conservation tillage treatments was from herbicide deposited on the crop residue which was not sampled. All treatments received the same rate of herbicide as determined from analysis of residue from petri plates placed in the field before application. Subsequent analysis of soil following rainfall indicated that the herbicide was readily washed to soil from the crop residue in accordance with data published by Kenimer *et al.* (1987) and Martin *et al.* (1978).

Soil samples taken from conventional and ridge tillage after midseason cultivation or reforming the ridges had higher residues than those from the previous sampling (Fig. 25 to 27B).

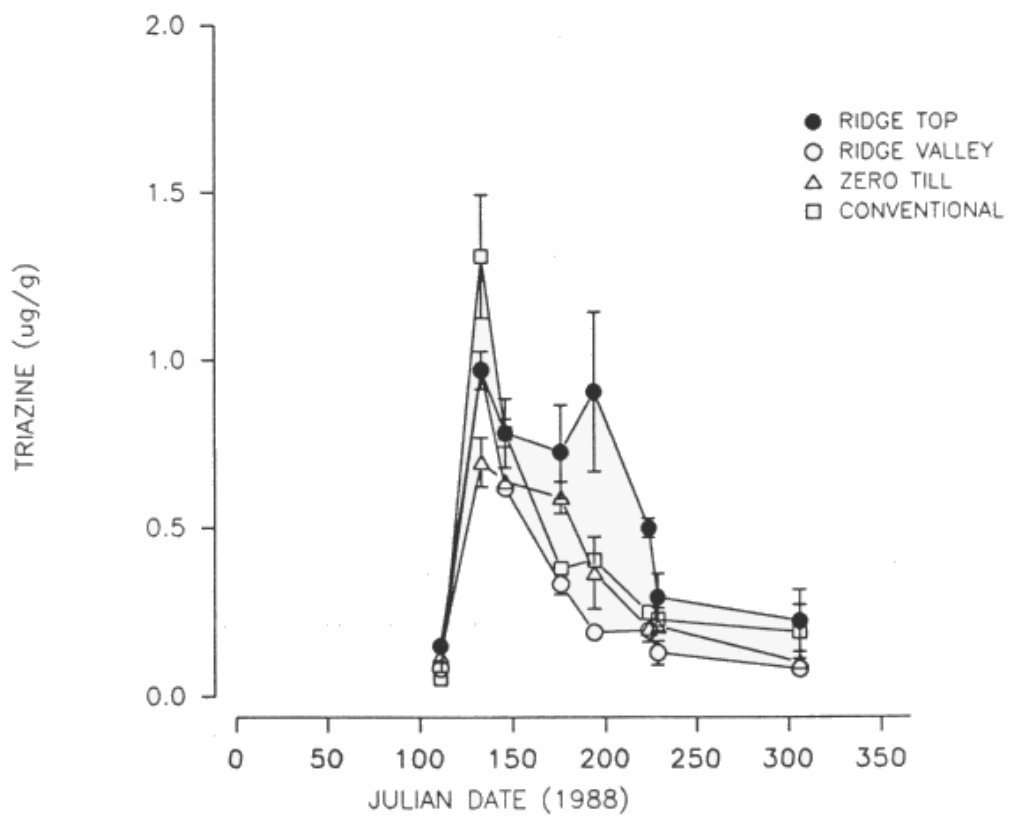


Fig. 25B Triazine (atrazine and des-ethyl atrazine) soil residues in Brookston soil from three tillage practices, in 1988. Vertical bars are standard error of sample means.

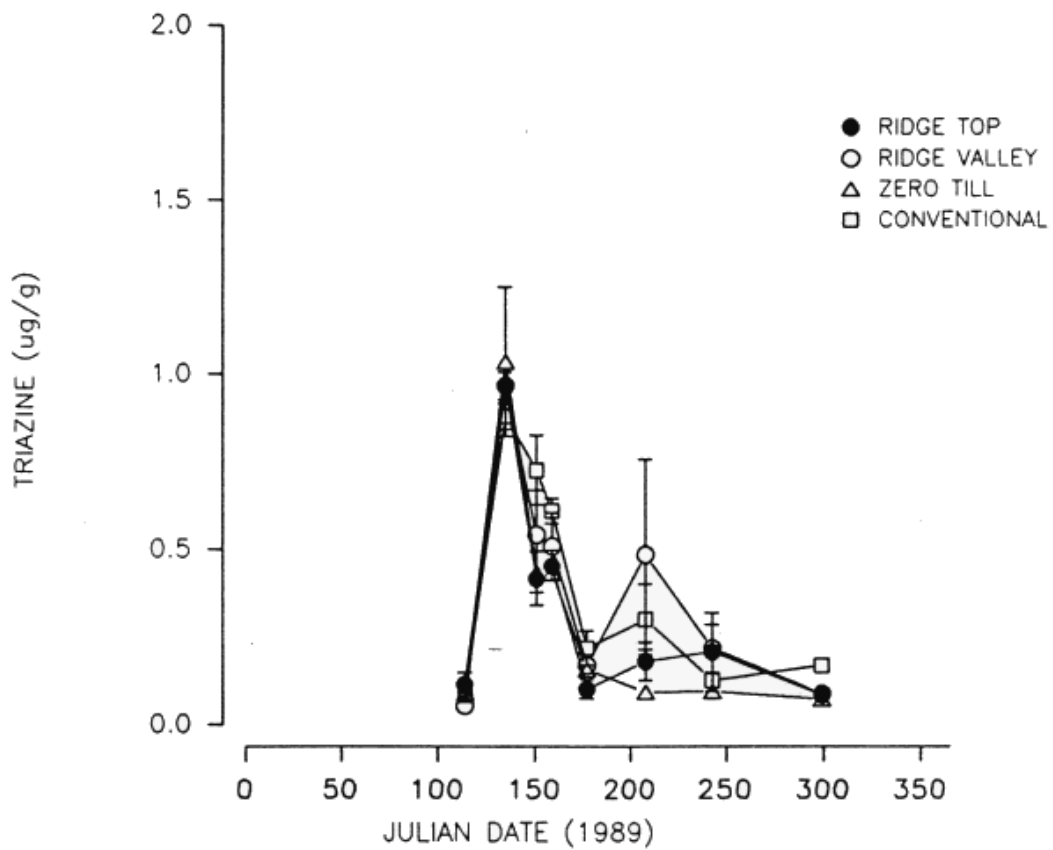


Fig. 26B Triazine (atrazine and des-ethyl atrazine) soil residues in Brookston soil from three tillage practices, in 1989. Vertical bars are standard error of sample means.

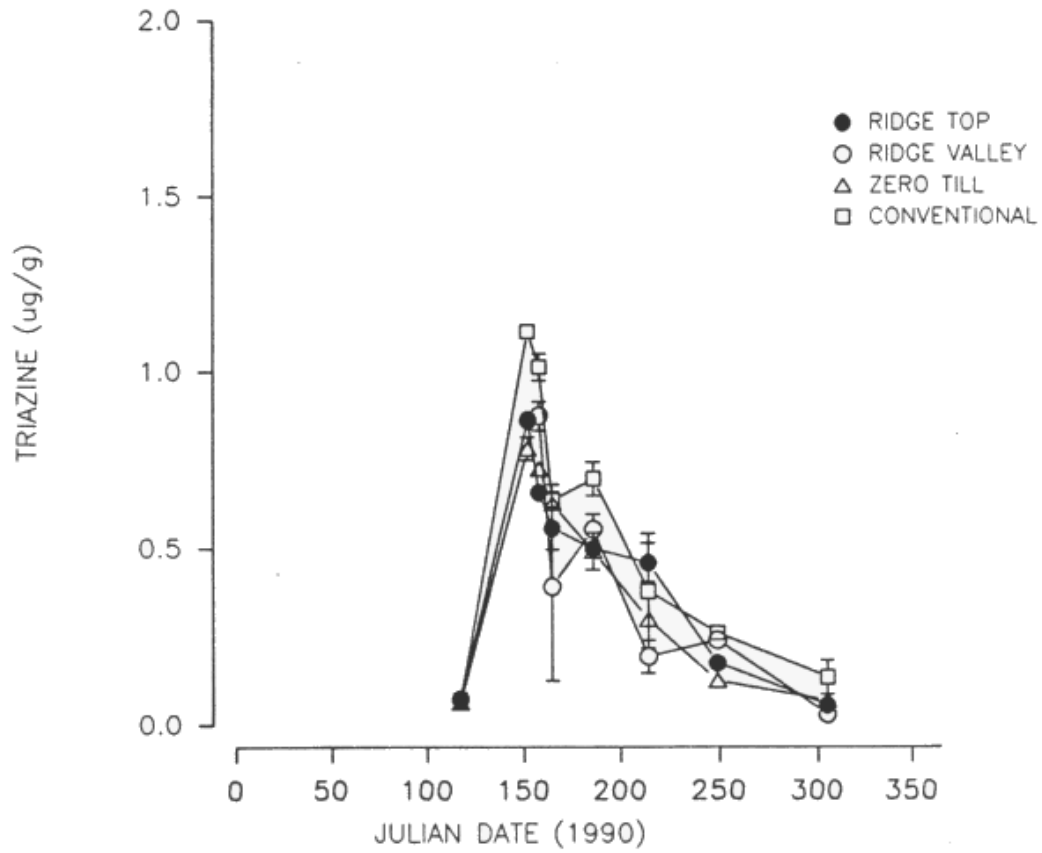


Fig. 27B Triazine (atrazine and des-ethyl atrazine) soil residues in Brookston soil from three tillage practices, in 1990. Vertical bars are standard error for sample means.

This was consistent for the three years of the study. Soil samples analyzed from zero tillage showed a steady decline in triazine residue for each of the sampling dates after application. The increase in midseason residue concentration observed in conventional tillage could be related to changes in soil bulk density following cultivation and in ridge tillage to redistribution of surface soil by ridding. Generally triazine residue was higher on ridge tops than in the valley of ridge tillage and in accordance with this, a greater proportion of metabolite was recovered from the valley. The ridge reforming operation would remove the top two cm of soil containing high residues from the valley and deposit it on the ridge thus elevating the residue concentration of the ridge top. Studies have shown that herbicide residues decrease with depth and that the highest concentration is in the top 5 cm of soil (Bauman and Ross, 1983; Huang and Frink, 1989). The metabolite accounted for 4 to 32% of the total residue with the larger proportion of metabolite associated with later samplings.

Soil moisture content and temperature are the two most important parameter related to herbicide persistence (Walker, 1987b). Atrazine is both chemically and biologically degraded in soil (Skipper *et al.*, 1967; Skipper *et al.*, 1976) but in calcareous soil, dealkylation, rather than hydrolysis predominates (Sheets, 1970; Weber, 1970; Kaufman and Kearney, 1970; Sirons *et al.*, 1973). Herbicide persistence can be described by the first order rate equation, $\ln(\text{conc}) = -kt + \ln(\text{conc at } t=0)$ where 'k' is the first order rate constant, 't' is time after application and 'ln' is the natural logarithm (Walker, 1987a and b). Half life (the time for herbicide residue to degrade to half the initial concentration) can be calculated from the first order rate constant by the equation $t = \ln(0.5)/k$. First order rate constants and half life were calculated from the persistence curves using regression analysis (Table 4B). Determination coefficients were significant ($P < 0.05$) for all persistence curves. Residues in ridge and conventional tillage treatments had poorest fit to the first order rate equation in all years because of an increase in soil concentration when ridges were reformed and cultivation in June as discussed previously. No increase in soil residue concentration was

observed with zero tillage treatments (Fig. 25 to 27B) and residue data was well described by the rate equation ($R^2=0.71$ in 1989, 0.91 in 1988 and 0.96 in 1990, Table 4B).

Table 4B. Adjusted coefficient of determination (R^2), slope and half life of triazine in Brookston clay loam from three tillage treatments.

Year	Treatment	Coeff. of Determin., R^2	Slope, K	Half Life, days
1988	Conventional	0.75	-0.0111	62
	Ridge Top	0.69	-0.0095	73
	Ridge Valley	0.85	-0.0141	49
	Zero	0.91	-0.0122	57
1989	Conventional	0.64	-0.0111	62
	Ridge Top	0.50	-0.0120	58
	Ridge Valley	0.61	-0.0121	57
	Zero	0.71	-0.0152	46
1990	Conventional	0.84	-0.0136	51
	Ridge Top	0.93	-0.0164	42
	Ridge Valley	0.67	-0.0185	37
	Zero	0.96	-0.0167	42

Triazine half life differed between years and treatments and was related to rainfall. Less rainfall was received after application in 1988 (Fig. 1B) compared to 1989 (Fig. 7B) and 1990 (Fig. 13B) hence soil moisture content would be lower in 1988 resulting in greater persistence (longer half life). Triazine was less persistent in ridge valleys and on zero tillage treatments than on conventional tillage in all years. Triazine was more persistent on ridge tops than on zero tillage in all years but only in 1988 was persistence greater on ridge tops than conventional tillage. Stone *et al.* (1989) recorded lower moisture content in the seed zone of ridge tillage treatments compared to mold board plow and zero tillage. Mean early season temperatures did not differ among tillage treatments in their studies. Their discussion indicated ridge valleys had higher moisture content because of reduced evaporation by residue cover. The presence of crop residue and higher moisture content

in ridge valleys would result in lower soil temperatures (Potter et al., 1985), but the overall net effect would provide an environment conducive to shorter triazine persistence in ridge valleys compared to ridge tops. As indicated previously triazine residues were highest and the proportion of des-ethyl atrazine residue lowest on ridge tops compared to ridge valleys.

SUMMARY

Atrazine is considered to be a moderately persistent herbicide. Because of its persistence it has the potential to be of environmental concern. Conservation tillage was introduced because it reduces soil deterioration by erosion (Unger, 1990). Herbicide transport occurs primarily in the aqueous phase therefore conservation tillage would not be expected to have a large impact on reducing herbicide losses by water.

The data presented here suggest atrazine transport is not affected by conservation tillage. Environmental factors such as the incidence of a runoff event to herbicide application or antecedent soil moisture conditions preceding a runoff event are more important in controlling herbicide transport than tillage. Triazine (atrazine + des-ethyl atrazine) transport did not differ among tillage treatments but year effects were significant. Up to 8% of applied atrazine was transported from the treatments when runoff events occurred within a week of application. Transport losses are greatly reduced (0.3 to 3.0% of applied) when runoff events occurred later in the season because of degradation and binding of the herbicide to soil particles. The results indicate that tile discharge is important in late season runoff, but that both tile discharge and surface runoff contribute significantly to triazine transport when a runoff producing event occurs close to herbicide application time.

Tillage had little or no effect on atrazine persistence in soil. Triazine persistence was most affected by soil temperature and moisture, higher soil moisture and/or higher soil

temperatures result in shorter atrazine persistence. In some years, triazine persistence was longer on ridge tops than in ridge valleys in the ridge tillage treatment because of higher moisture content of the soil in the valley but residues were not high enough in ridge tops to affect growth or yield of sensitive crops. Des-ethyl atrazine accumulated to <18% of total triazine with no evidence of accumulation throughout the year. Concentration in the water and transport of the metabolite increased with time after herbicide application.

METOLACHLOR

The soil and environmental factors affecting triazine transport and persistence as discussed previously also apply to metolachlor. Metolachlor has greater water solubility than atrazine (580 mg/L vs 33 mg/L) therefore a greater potential exists for aqueous transport. However, mobility of metolachlor is more related to soil adsorption rather than to water solubility (LeBaron *et al.*, 1988).

Concentration in Runoff

The relationship between application time and metolachlor concentration in surface and subsurface runoff is shown in Fig. 28 to 36B along with runoff and rainfall amounts. As seen from the figures, metolachlor concentration in the water declines to <10 µg/L after the first six runoff producing events. Maximum concentration of metolachlor in surface water ranged from 4 to 900 µg/L (Table 5 to 7B) depending upon proximity of the runoff event to application (Fig. 28 to 36B). Maximum metolachlor concentrations in surface runoff water were lowest in 1988 when runoff occurred late in the season (Fig. 28 to 30B) and highest in 1989 and 1990 (Fig. 31 to 36B) when runoff occurred near application. Maximum metolachlor concentration was higher in surface than in subsurface runoff water in 1989 and 1990. The consistently high concentration of metolachlor in surface runoff relates to

its higher solubility relative to atrazine and its low retention by crop residue (Crutchfield et al., 1985). Mean concentration of metolachlor was higher in surface runoff from the conservation tillage treatments than from conventional tillage in all years.

Table 5B. Range and average metolachlor concentration of surface and subsurface runoff water from three tillage treatments for 1988. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Treatment	Source	Range	Mean
		Metolachlor conc $\mu\text{g/L}$	
Ridge	Surface	0.28 - 6.40	2.55 \pm 0.35
	Tile	0.05 - 10.41	1.67 \pm 0.18
Zero	Surface	0.35 - 7.80	3.92 \pm 0.34
	Tile	4.05 - 16.67	2.83 \pm 0.05
Conventional	Surface	0.37 - 4.33	1.93 \pm 0.66
	Tile	0.05 - 6.13	1.72 \pm 0.33

Table 6B. Range and average metolachlor concentration of surface and subsurface runoff water from three tillage treatments for 1989. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Treatment	Source	Range	Mean
		Metolachlor conc $\mu\text{g/L}$	
Ridge	Surface	0.81 -914	217 \pm 33
	Tile	0.21 -274	55 \pm 4
Zero	Surface	2.02 -747	211 \pm 19
	Tile	0.55 -318	67 \pm 1
Conventional	Surface	10.5 -519	167 \pm 8
	Tile	13.4 -473	94 \pm 10

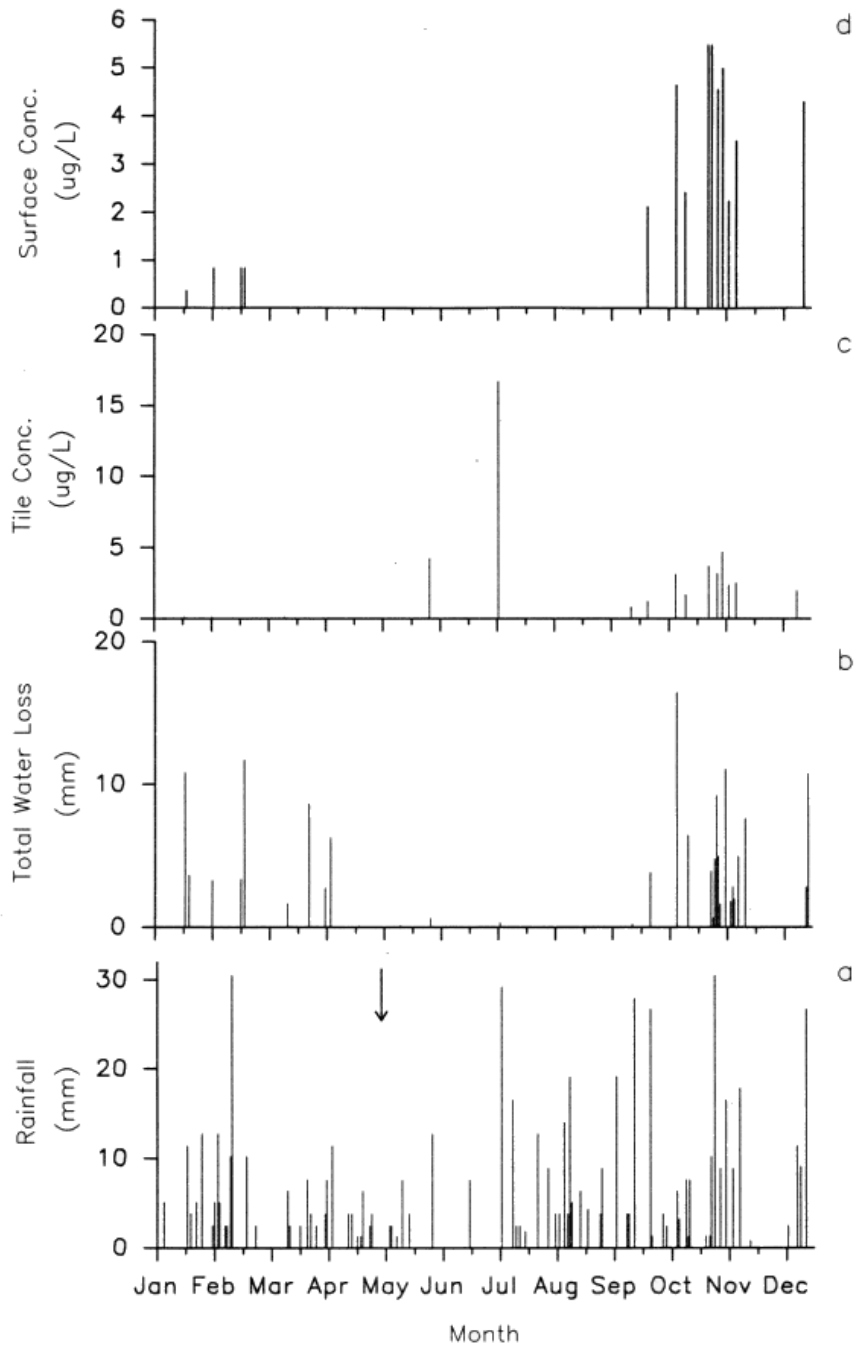


Fig 28B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1988. Arrow denotes planting date on May 11, 1988.

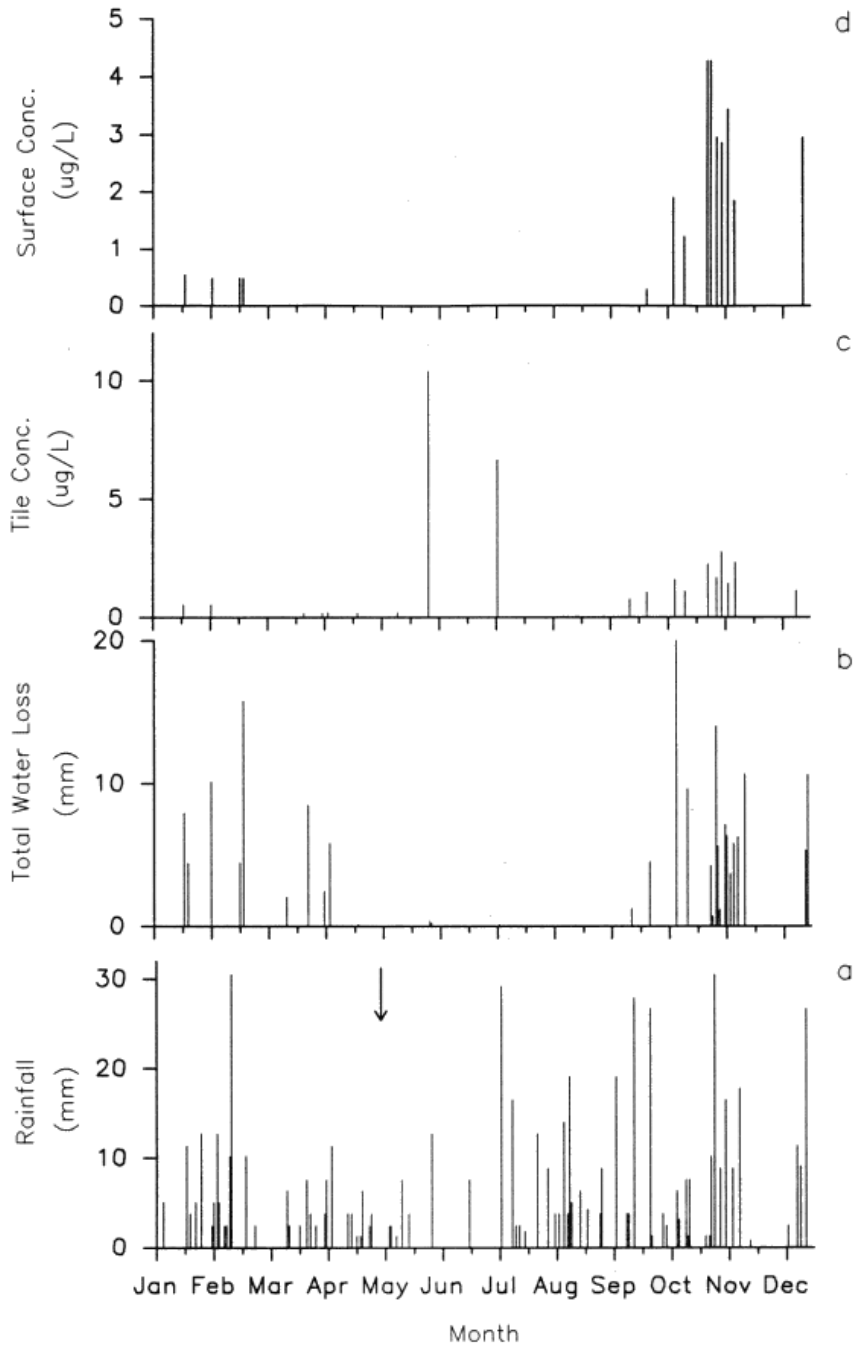


Fig 29B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1988. Arrow denotes planting date on May 11, 1988.

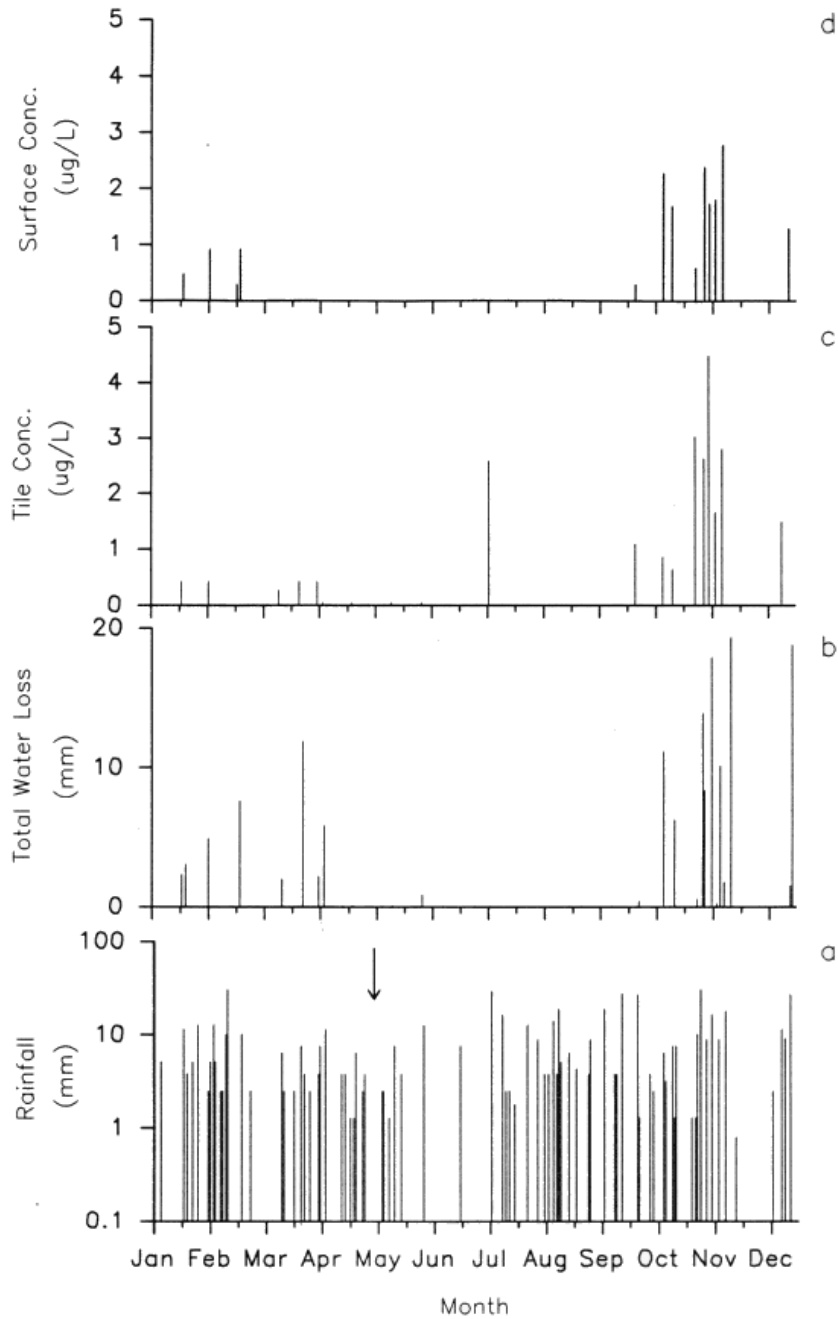


Fig 30B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1988. Arrow denotes planting date on May 11, 1988.

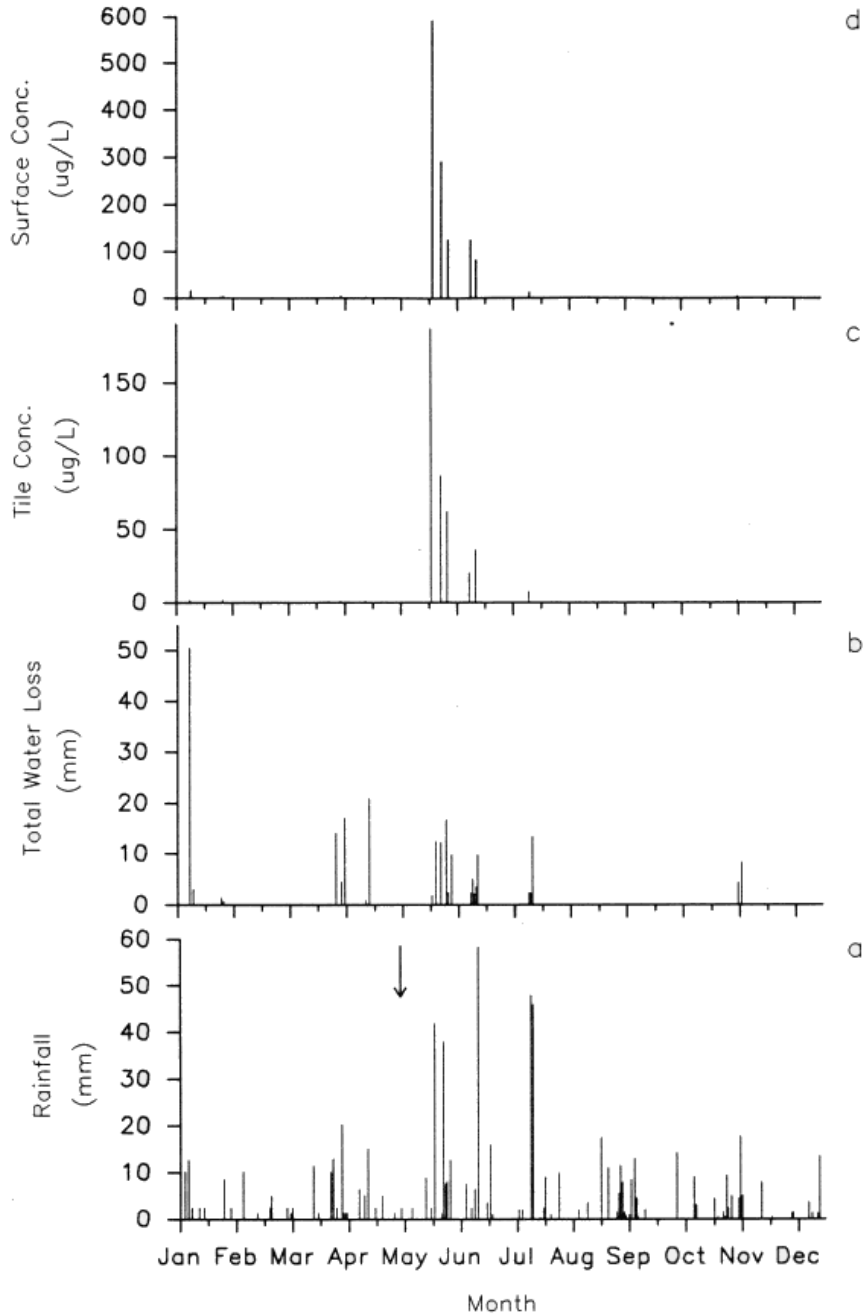


Fig 31B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from zero till for 1989. Arrow denotes planting date on May 10, 1989.

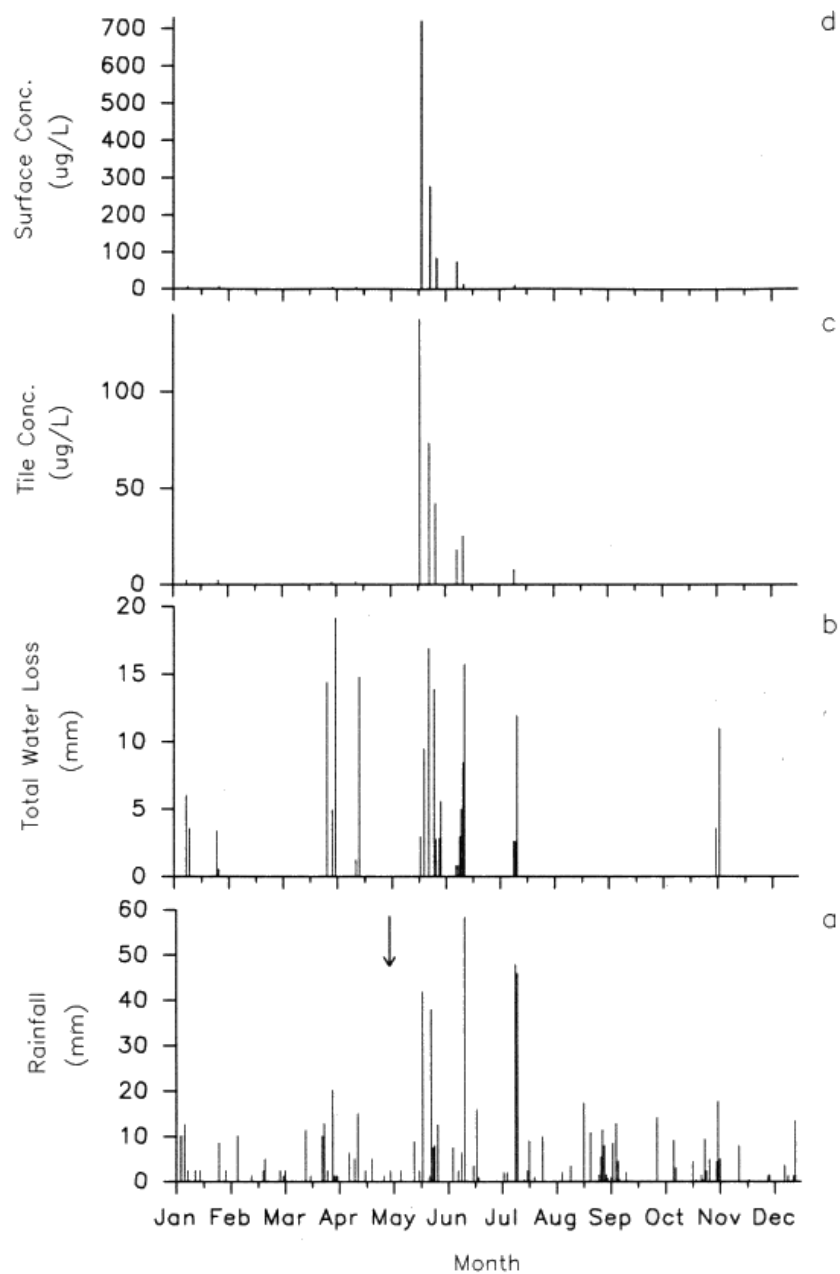


Fig 32B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till for 1989. Arrow denotes planting date on May 10, 1989.

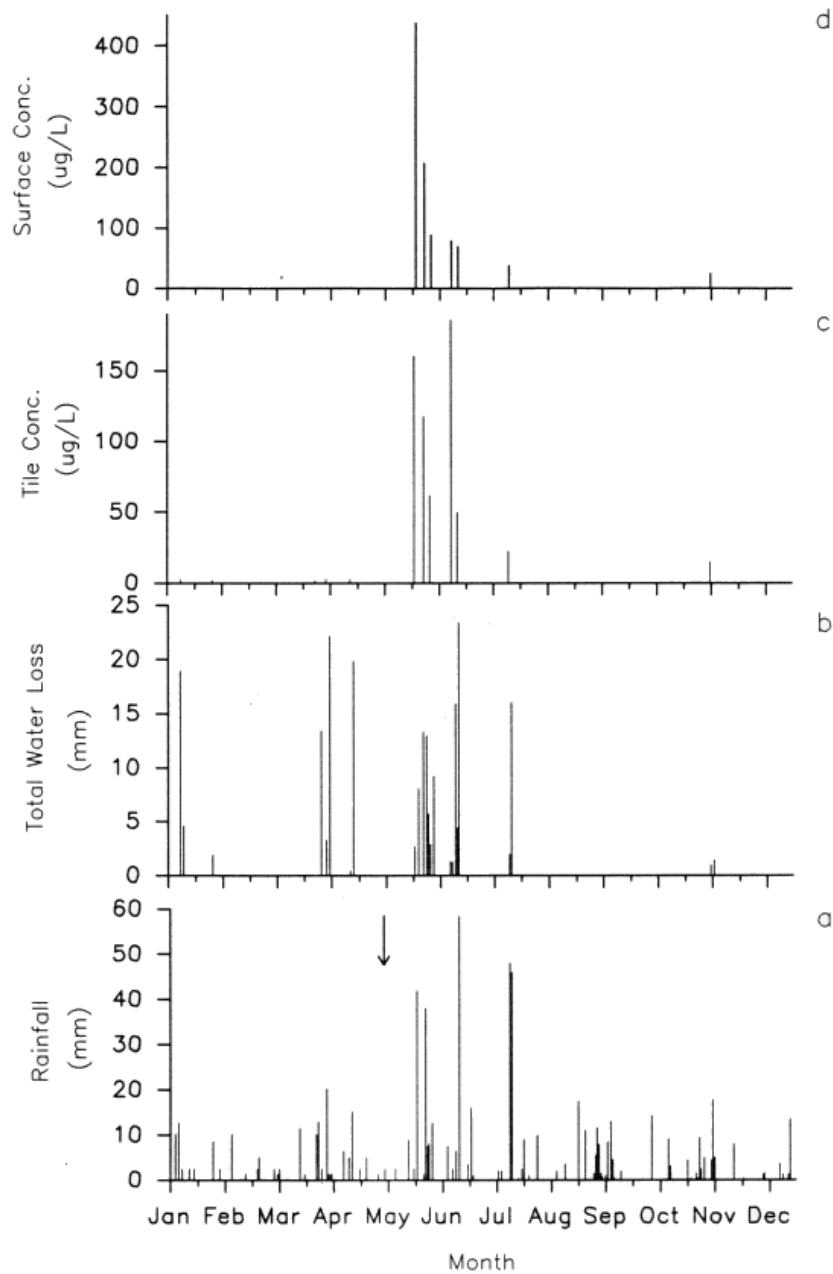


Fig 33B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till for 1989. Arrow denotes planting date on May 10, 1989.

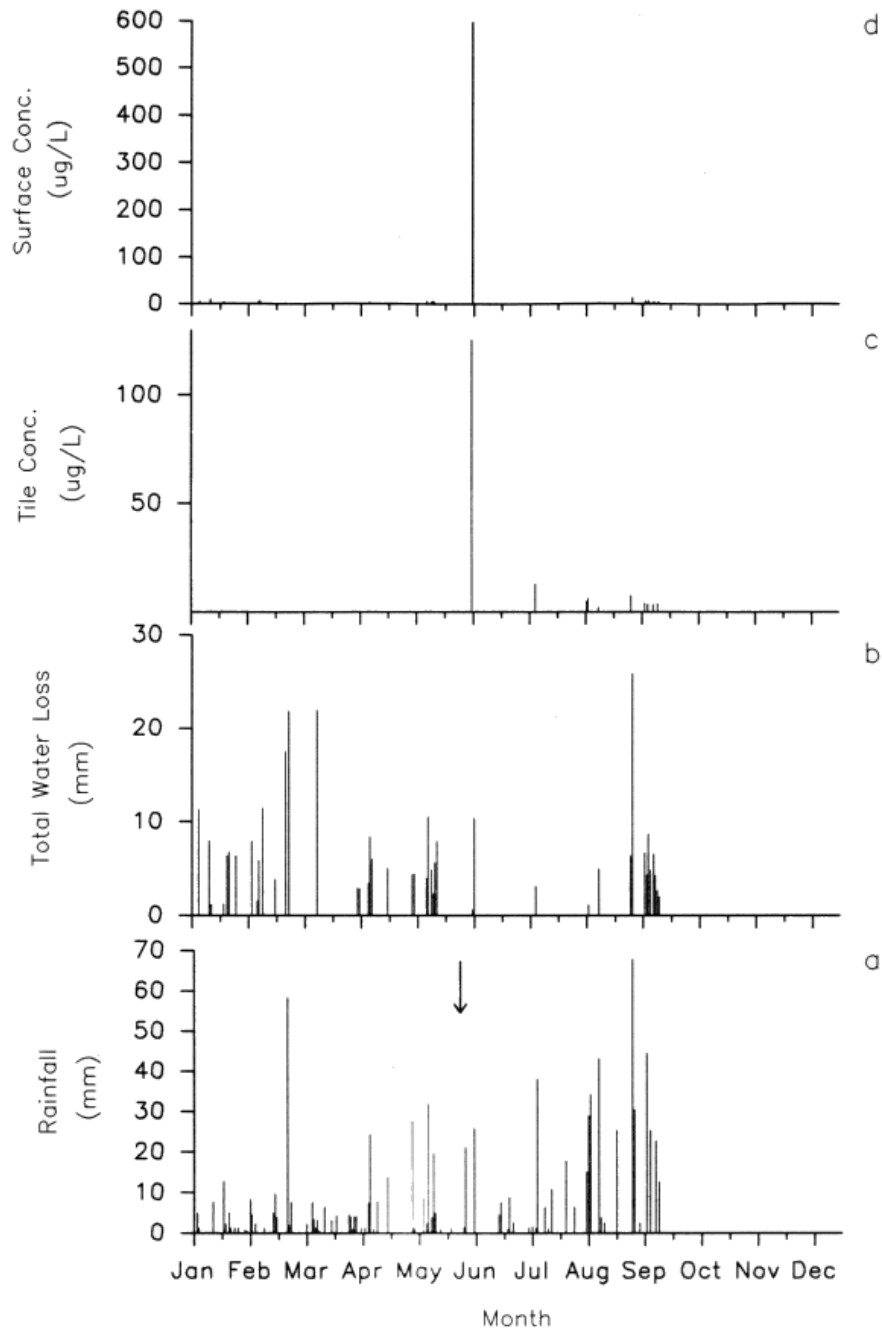


Fig 34B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (1)) from zero till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

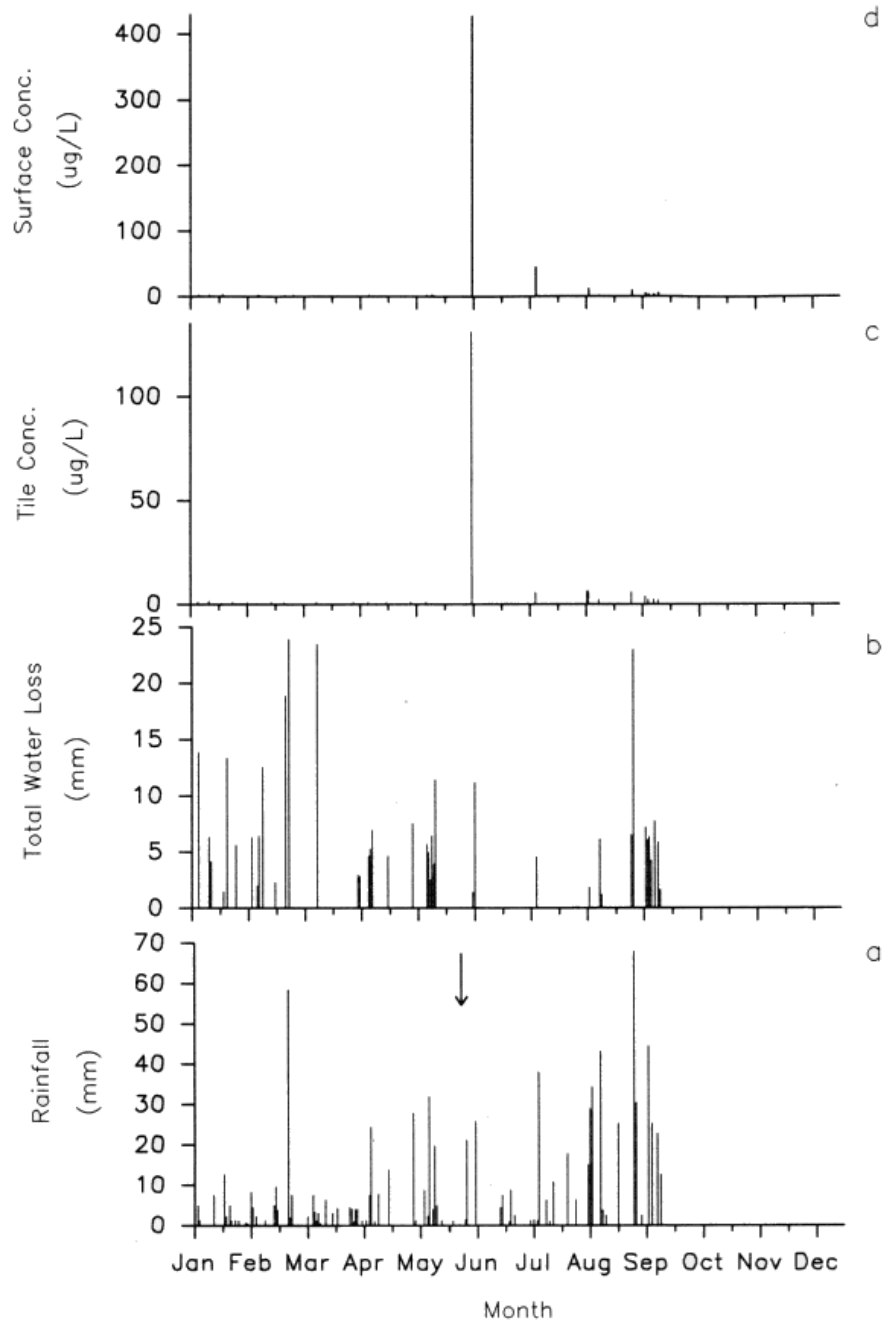


Fig 35B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from ridge till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

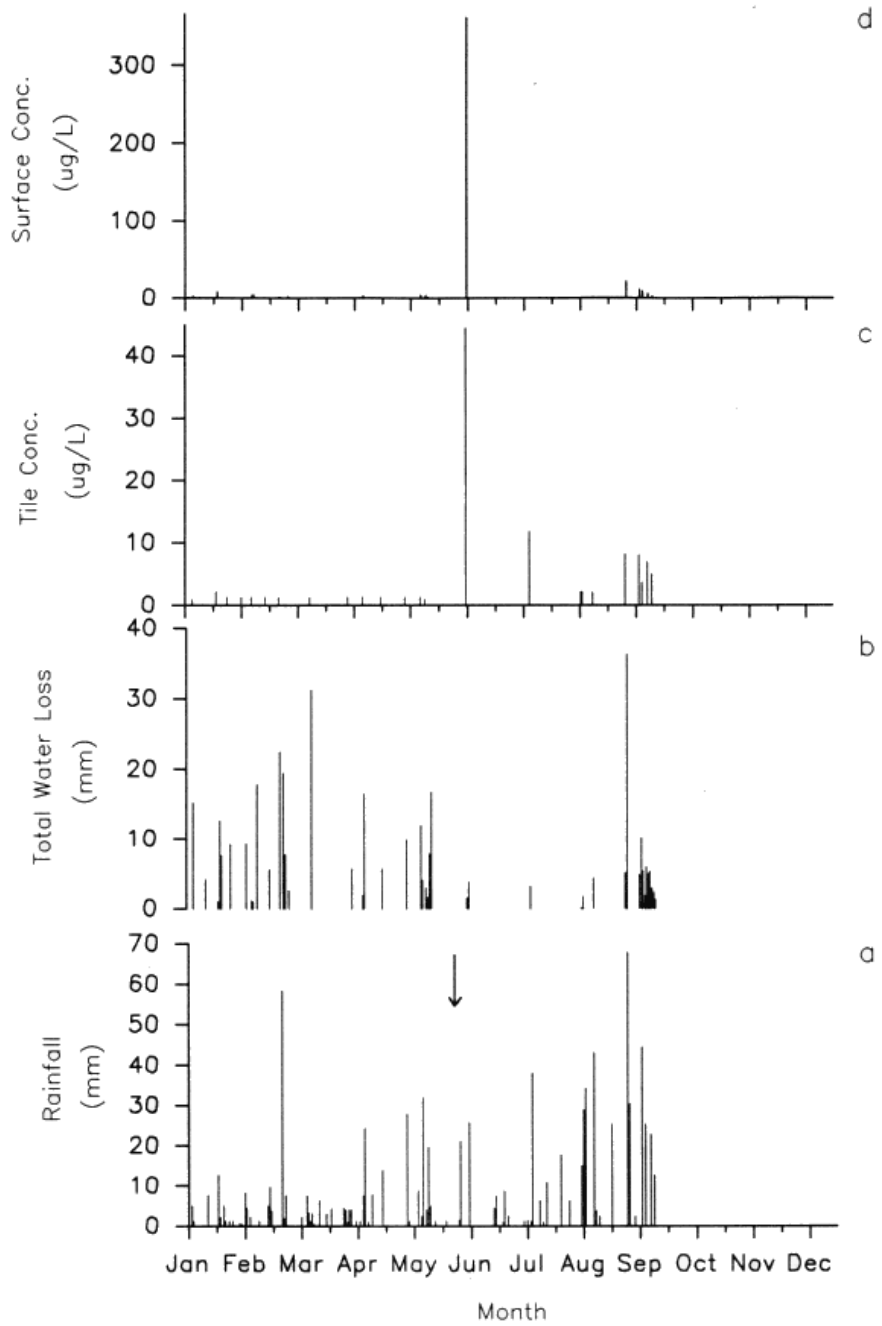


Fig 36B Precipitation (a), total runoff (surface and tile) (b), and metolachlor concentration in the runoff (tile discharge (c) and surface runoff (d)) from conventional till from January 1 to September 30, 1990. Arrow denotes planting date on June 1, 1990.

Table 7B. Range and average metolachlor concentration of surface and subsurface runoff water for three tillage treatments from January to September 30, 1990. Range is the average of maximum and minimum concentration of two replicates, mean is the annual average concentration of two replicates with accompanying standard error.

Treatment	Source	Range	Mean
		Metolachlor conc	µg/L
Ridge	Surface	0.08 - 234	17 ± 14
	Tile	0.26 - 236	11 ± 1
Zero	Surface	0.48 - 391	24 ± 19
	Tile	0.19 - 173	10 ± 2
Conventional	Surface	0.33 - 362	22 ± 1
	Tile	0.10 - 73	7 ± 1

Amounts Lost

The total quantity of metolachlor transported from the three tillage practices is presented in Fig. 37B. Metolachlor losses were lowest in 1988 (0.1% of applied) and highest in 1989 (<5.2% of applied). Although metolachlor is more soluble in water than atrazine and the rate of application was 47% higher than that for atrazine, the unit area quantity losses were less for metolachlor than those for atrazine. This was possibly because of metolachlor's short soil persistence (Walker and Zimdahl, 1981), low mobility in soil (Bowman, 1988; 1989) and high soil adsorption (Kozak *et al.*, 1983; Obrigawitch *et al.*, 1981; Peter and Weber, 1985; Weber and Peter, 1982). Metolachlor losses averaged over three years for the three treatments were 46±3 g/ha from ridge tillage, 48±1 g/ha from zero tillage and 53±6 g/ha from conventional tillage. As with atrazine, tillage had no effect on metolachlor transport.

The proportion of metolachlor transported by surface or subsurface runoff (Fig. 38B) was similar to that for triazine (Fig. 21 B). Runoff producing events later in the season (1988) or small surface runoff events near application (1990) resulted in tile discharge dominating as the major transport mechanism. Large surface producing runoff events

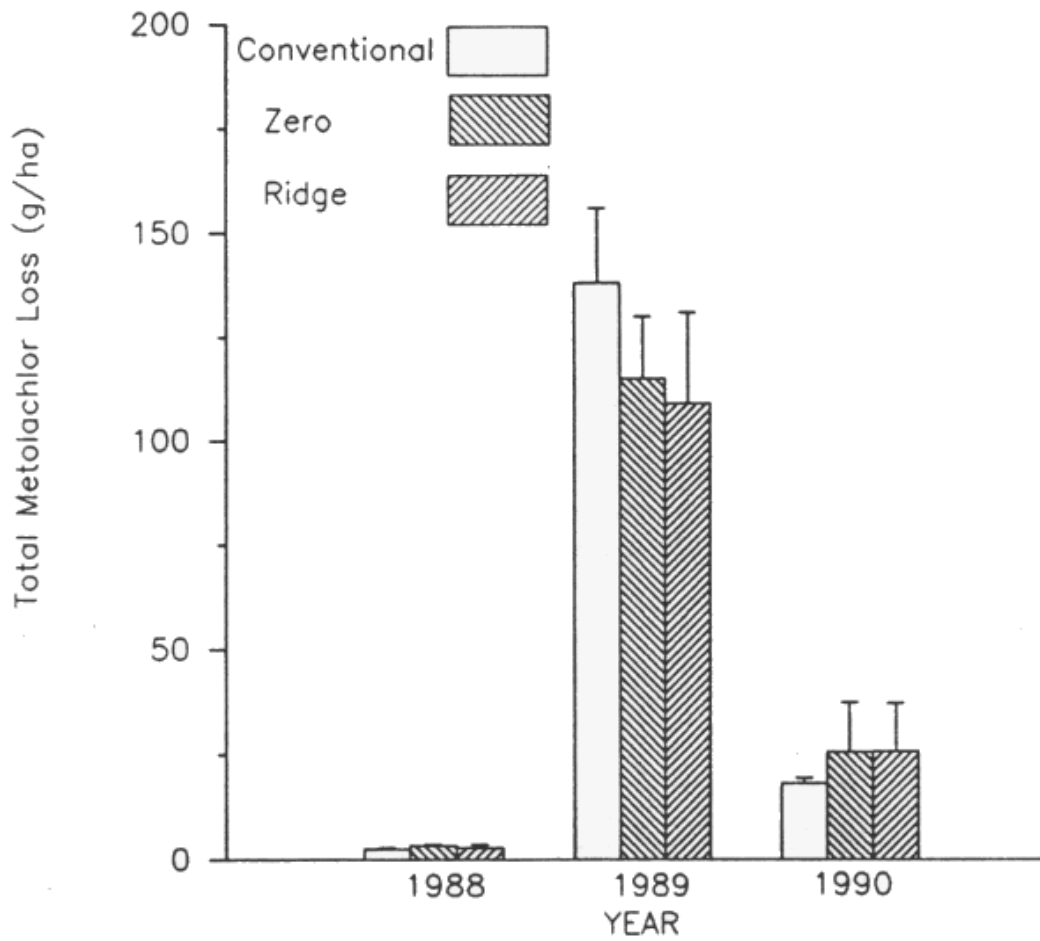


Fig. 37B Total Metolachlor loss from three tillage practices on Brookston soil. Vertical bars are standard error of sample means.

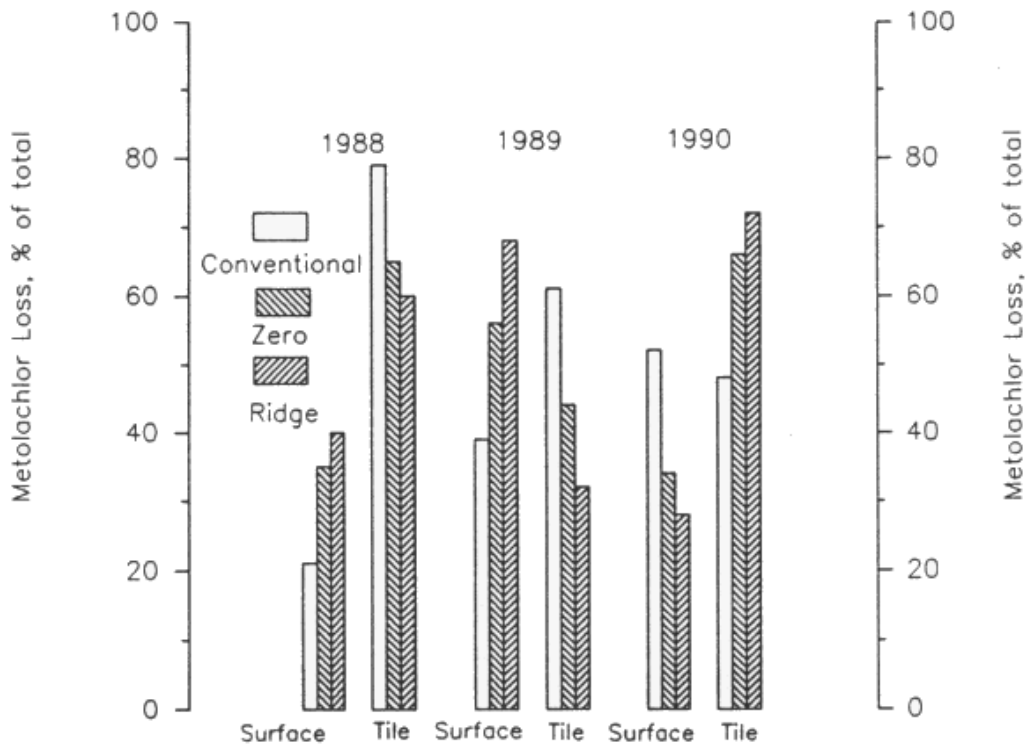


Fig. 38B Surface and tile loss of Metolachlor as a percent of total Metolachlor loss from three tillage practices on Brookston soil.

near application (1989) increased the proportion of metolachlor transported in surface runoff water. Metolachlor transport from the conservation tillage treatments followed a similar pattern which differed from conventional tillage. An equal proportion of metolachlor was transported from conventional tillage in tile discharge and surface runoff in 1990, but tile discharge dominated in 1988 and 1989.

Metolachlor transport was related to proximity of runoff producing events to application time. Large proportions (81 to 99%) of metolachlor were transported in the growing season in 1989 and 1990 (Fig. 39B) because of large runoff producing events close to application time. In 1988 a small amount of metolachlor (0.1 g/ha) was transported from the treatments. Eighty-eight to 91 % of the transport occurred after harvest. Other studies report results similar to these suggesting that highest herbicide transport occurred in the first runoff producing event closest to time of herbicide application. These reports also suggest that transport losses are greatly reduced as the length of time between herbicide application and runoff producing events increases. The estimated metolachlor loss for the last three months of 1990 for which measurements were not made would be less than 0.3 g/ha.

Sediment phase transport was not followed because preliminary studies indicated it was insignificant compared to aqueous phase transport. Assuming soil concentration of 2 mg/kg (application concentration, Fig. 40B to 42B) and maximum annual soil loss of 1000 kg/ha, sediment phase transport would amount to <2% of metolachlor loss in 1989, the year of greatest loss.

Soil Persistence

Metolachlor persistence in the soil was unaffected by tillage treatment except for ridge tillage. Here, residues in 1988 and 1990 were highest on ridge tops compared to the ridge valley (Fig. 40 to 42B). Metolachlor's persistence was longer in all tillage treatments

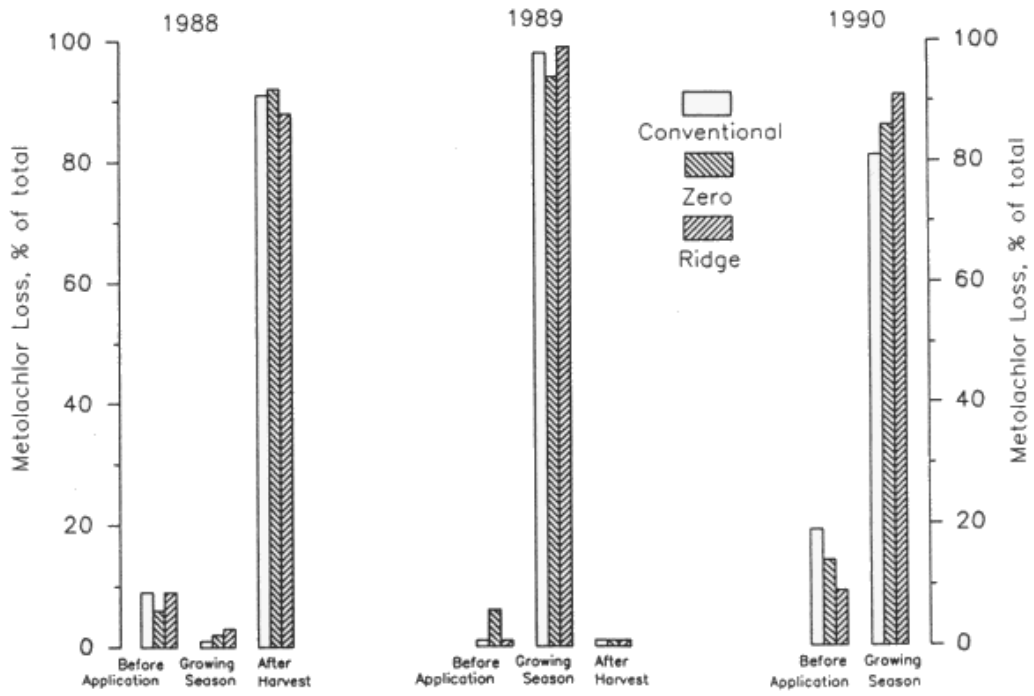


Fig. 39B Seasonal metolachlor loss as a percent of total metolachlor loss from three tillage practices on Brookston soil.

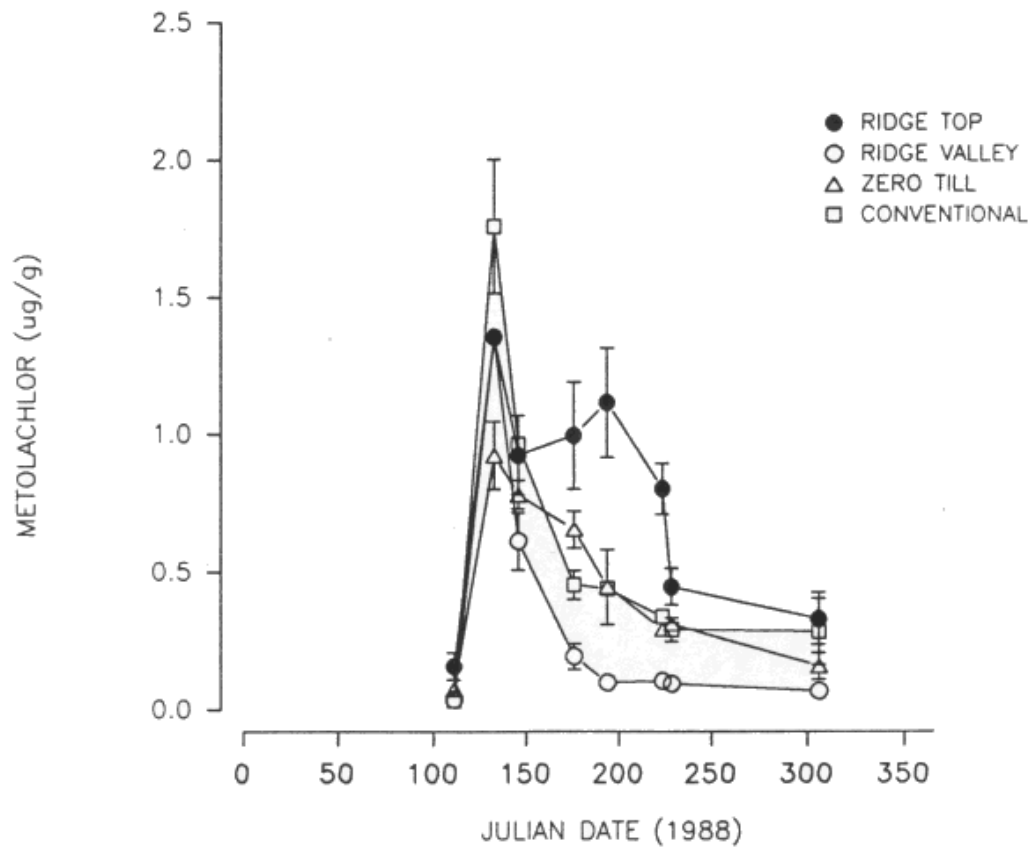


Fig. 40B Metolachlor soil residues in Brookston soil from three tillage practices, in 1988. Vertical bars are standard error of sample means.

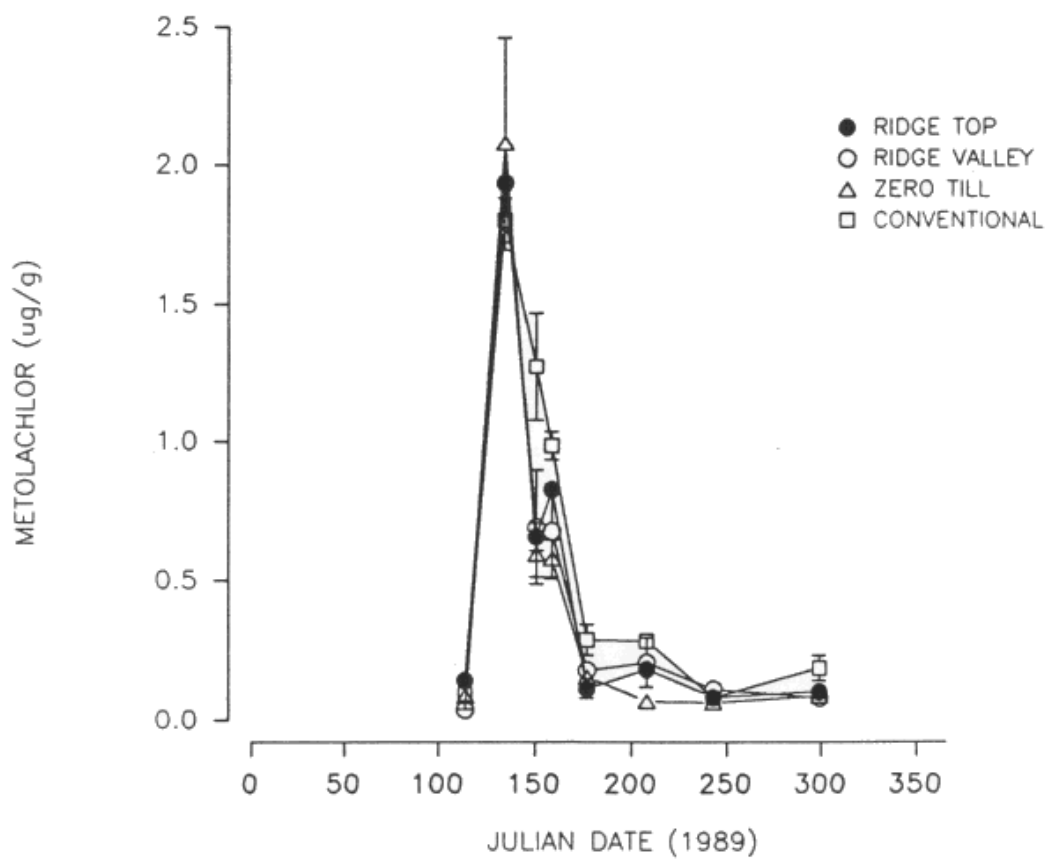


Fig. 41B Metolachlor soil residues in Brookston soil from three tillage practices, in 1989. Vertical bars are standard error of sample means.

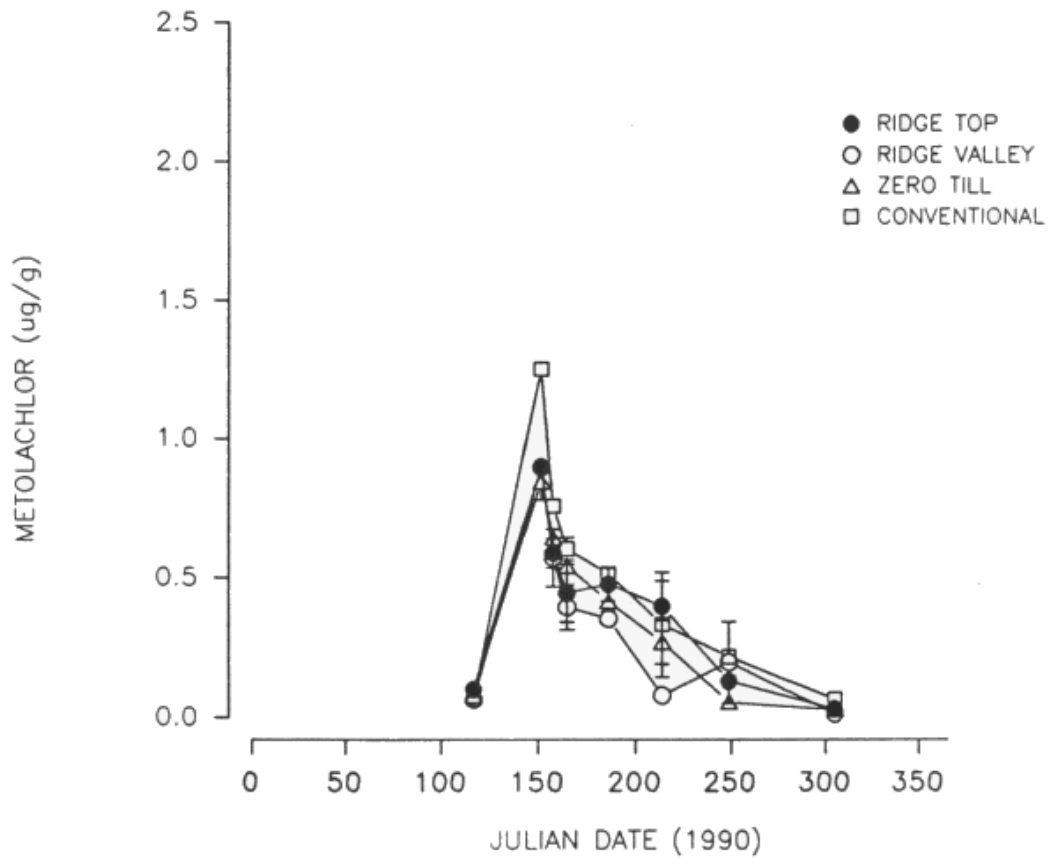


Fig. 42B Metolachlor soil residues in Brookston soil from three tillage practices, in 1990. Vertical bars are standard error of sample means.

in 1988 (Table 8B) relative to 1989 and 1990 because of the lack of rainfall during the growing season and absence of runoff producing events (Fig. 28B). The differences in soil concentration among treatments at application is likely due to interception of the metolachlor by crop residue which was not sampled during soil collection. The same amount of metolachlor was applied to each of the treatments as determined from analysis of residue deposited in petri plates during application. The increase in soil residues after the initial application in the ridge and conventional tillage treatments occurred because of midseason cultivation or ridge reforming as discussed for atrazine.

Table 8B. Adjusted coefficient of determination (R^2), slope and half life of metolachlor in Brookston clay loam from three tillage treatments.

Year	Treatment	Coeff. of Determin., R^2	Slope, K	Half Life, days
1988	Conventional	0.66	-0.0102	68
	Ridge Top	0.68	-0.0080	87
	Ridge Valley	0.68	-0.0164	42
	Zero	0.88	-0.0107	65
1989	Conventional	0.65	-0.0161	43
	Ridge Top	0.59	-0.0169	41
	Ridge Valley	0.72	-0.0175	40
	Zero	0.62	-0.0186	37
1990	Conventional	0.87	-0.0173	40
	Ridge Top	0.89	-0.0196	35
	Ridge Valley	0.80	-0.0248	28
	Zero	0.93	-0.0234	30

Herbicide residues generally declined with time according to the first order rate equation as presented in the atrazine section. Half life for metolachlor was calculated from residue data by the method of least squares (Table 8B). Tillage or ridge restructuring in conventional and ridge tillage caused an increase in residue concentration over that from the previous sampling.

This reduced the degree of fit to the first order rate equation (lower R^2) thereby providing a poorer estimate of half life in these treatments relative to zero tillage. Half life of metolachlor was longer in conventional tillage when compared to the conservation tillage treatments in all years except 1988. In ridge tillage, ridge tops had longer half life than ridge valleys because of the reasons discussed previously respecting atrazine persistence. Generally half life for metolachlor was shorter than atrazine's half life. Walker and Zimdahl (1981) reported similar half life between these two herbicides under controlled environmental conditions but atrazine was more persistent than metolachlor in a Plainfield sand (Bowman, 1989).

SUMMARY

Metolachlor transport did not differ among tillage treatments. Higher losses were calculated in those years where runoff producing events occurred closest to herbicide application. Surface and subsurface transport of metolachlor were equally important when runoff producing events occurred close to herbicide application time. Later in the season a greater proportion of metolachlor transport occurred by subsurface runoff.

Metolachlor dissipated rapidly in soil when moisture and temperature were optimum for dissipation. Dissipation was slow in 1988, a very dry year.

IMPLICATIONS OF THE RESULTS

Zero, ridge and conventional tillage had no effect on atrazine and metolachlor transport. Over the three years of the study, annual and cumulative transport was similar for the three tillage treatments. Highest transport was observed when runoff producing events occurred shortly after herbicide application. Tillage altered the source of transport loss. Transport by surface runoff was low from conventional tillage, but tile discharge transported substantial amounts of the herbicide. Herbicide transport from the conservation

tillage treatments was observed by both surface and subsurface runoff depending upon rainfall intensity, duration and antecedent soil moisture content. Surface runoff transport can exceed subsurface runoff from the conservation tillage treatments because of washoff from crop residue. Rainfall intensities below or near infiltration rate of the soil, insufficient to produce surface runoff, may leach herbicide from crop residue to soil increasing transport by tile discharge.

Herbicide transport is greatest when runoff producing events occur close to application time. Therefore, control measures to reduce aqueous transport around application time will be most successful to retain herbicide on the site. Thus, preventing contamination of receiving waters. Excessive crop residue could result in greater transport losses if a runoff producing event occurred close to application. Crop residues appear to have little affinity to retain herbicide residues. Tillage alone and crop residue appear to have little effect on herbicide retention.

Herbicide transport losses increase with increased rate of application. Practices which band herbicide over the seed row and rely on cultivation or intercropping to control weeds between rows could reduce the quantity of herbicide transported from the site of application since less herbicide would be applied to the site. Between row cultivation or the presence of an intercrop may reduce surface runoff. This would further reduce the quantity of herbicide transported. The intercrop could increase water retention of the soil or reduce soil water content by evapotranspiration, thereby reducing surface and subsurface runoff. In turn, this would reduce aqueous transport of the herbicide.

Cultural practices which utilize non-persistent, post emergent herbicides may cause less impairment of water quality, however, further research is required to identify those parameters which will achieve the greatest transport reduction. Preplant incorporation treatments would reduce surface transport but subsurface and sediment phase transport would become more significant.

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