INTEGRATED SOIL, CROP AND WATER MANAGEMENT SYSTEM TO ABATE HERBICIDE AND NITRATE CONTAMINATION OF THE GREAT LAKES: HERBICIDES

J.D. Gaynor, C.S. Tan, C.F. Drury and T.W. Welacky
Agriculture & Agri-Food Canada, Harrow Research Centre,
Harrow, Ontario, N0R 1G0

RATIONALE AND OBJECTIVES

Soil and crop management practices have changed dramatically within the Great Lakes basin during the last decades. Livestock-forage based farming has been replaced with monoculture cash-cropping and there has been an accompanying increase in the use of fertilizers, pesticides and large machinery. However, these changes have resulted in soil compaction and structural deterioration and, therefore, increased surface runoff and erosion. Application of more chemical inputs to sustain productivity, in conjunction with increased erosion and runoff has resulted in contamination of surface water by pesticides.

It is increasingly evident that herbicide losses are greatest in runoff events following herbicide application (Gaynor *et al*., 1992). Herbicide losses increase with the amount applied and volume of runoff (Gaynor *et al*., 1992). Current research indicates that conservation tillage alone will not reduce pesticide (Gaynor *et al.,* 1992; Issensee *et al.,* 1990; Sauer and Daniel, 1987)pollution of surface runoff or tile drainage water which eventually discharges into the Great Lakes. Therefore, management strategies that alter the hydrology of runoff or reduce inputs hold the greatest potential to improve water quality and sustain agricultural production. In accordance with our existing knowledge, the integrated management system incorporates controlled drainage, reduced tillage and herbicide input and intercropping as sustainable soil management practices. Banded herbicide application is reintroduced as a management strategy necessitated by the introduction of intercropping for nitrogen management and weed control between the crop rows. Reduced herbicide input associated with banding technology should result in immediate improvement in water quality. Controlled drainage regulates tile discharge to provide storage of rain received after herbicide application. Water which would otherwise have been lost through drain discharge or leached out of the root zone can then be used by the crop later in the growing season. The more moist environment in the root zone with controlled drainage will also aid in dissipation of the herbicide reducing after harvest losses and residue carry over of the herbicide. Therefore, controlled drainage should reduce herbicide concentrations in drainage water. The controlled drainage structures can also be modified to provide for subirrigation during low rainfall periods.

METHODOLOGY

Site characteristics. The experimental site is located at Eugene F. Whelan Experimental Farm (Agriculture Canada, Woodslee, Ontario). The dominant soil series is Brookston clay loam, a poorly drained soil (Typic Argiaquoll). The soil at the experimental field has a 30 cm dark brown, clay loam A_p horizon with 2.5% organic matter. The B horizon has a clay texture and extends to a depth of 1.5 m.

Experimental design. The experiment was initiated in the spring of 1991. A four by two factorial randomized complete block design was used with four crop/tillage management treatments and two water management treatments. The crop/tillage management treatments were moldboard plow tillage (MP), moldboard plow tillage with annual ryegrass (Lolium multiflorum Lam.) intercrop (MP-IC), soil saver (SS) and soil saver with annual ryegrass intercrop (SS-IC). Water management treatments were drainage only and water table control. All experimental plots received the same pesticide and fertilizer application. When a main plot effect was significant without any interactions, a least squares difference test (LSD) was used to determine differences among treatments. Unless otherwise noted, statistical significance is reported at the 0.05 level. Whenever a significant interaction occurred, a least squares means procedure was used to tesawfor differences between preplanned comparisons.

Field layout and installation. The layout of the experimental field, plot size and treatments have been reported (Tan *et al*., 1993). It consists of sixteen plots each 15 m wide by 70 m long with an area of 1068 m^2. Each plot contains two 104 mm diameter tile drains. Drains are installed at 7.5 m spacing and 0.6 m depth with a 0.1% increase in elevation from east to west.

Water table in the irrigated plots is controlled with water level control structures (Tan *et al*., 1993). These structures are built such that, when the bottom drain plug is closed the water rises to desired levels in the structure creating a pressure head which forces the water into the tile drains for subirrigation. When the bottom plug is opened water drains freely from the plots. The water level in these structures can be maintained at a given height by means of a float valve during irrigation. An overflow pipe permits drainage to proceed when the water table rises above the pre-set level. These structures are used for subirrigation and/or controlled drainage during the growing season and controlled drainage during fall, winter and spring.

Tile drains from each individual plot are intercepted at the east border of each plot and routed to a central instrumentation building at the north-east corner of the experimental field via 104 mm corrugated non-perforated drain pipes. Each plot has a 0.5 m diameter surface catch basin at its east boundary to collect the surface runoff. The surface catch basins are also connected to the central instrumentation building through underground non-perforated drain pipes. The 6 m by 8 m instrumentation building is equipped with an electrical circuit breaker panel, heater, fan, telephone line, data acquisition facilities and a backup generator to provide power to the system when electrical failures occur.

Surface and tile flow measurements. Surface and tile drainage water from the sixteen experimental plots, delivered to the instrumentation building are collected in 32 polyethylene sumps (Soultani *et al*., 1993). Each sump is equipped with an electrical, float activated effluent pump. Surface runoff and subsurface drainage from each individual plot flowing into the respective sumps are pumped through water meters to an outlet drain. A multi-channel datalogger utilizes the analog signal of the water meters to monitor, measure and store water volumes on a continuous basis (Soultani *et al*., 1993).

Water quality sampling and frequency. Samples of surface runoff and tile drainage water for herbicide analyses were collected automatically with 32 autosamplers (CALYPSO 2000S, Buhler Gmbh & Co.) stationed in the instrumentation building. Each autosampler contains 24 one-litre bottles. The autosampler is activated by digital signals from the water meter. Sample collection was based on flow volume with collections at 500 to 3000 L depending upon the time of year and expected runoff volumes. The more frequent sampling was done after herbicide application where herbicide concentration would be most dynamic. Water samples were stored in glass bottles at 4EC prior to analyses.

Herbicide analyses. Water samples were analyzed for herbicide concentration within two months of collection. A 500 mL aliquot was filtered under suction through a 0.45 um filter (Gelman Cat GN-6). Herbicide was concentrated from the water on a preconditioned cyclohexyl Sep Pak cartridge (Baker Cat No. 7212-03). After herbicide loading, the cartridge was dried and the herbicide eluted with 1.5 mL methanol. Samples were analyzed by gas chromatography. Analytes were separated on a 15 m DB-5 capillary column temperature programmed from 70 to 210EC. A thermionic sensitive detector operated in N mode was used to detect and quantify the herbicides. Herbicide loss in the water was calculated from the product of the herbicide concentration in the water and the volume of runoff or tile drainage.

Agronomy. Corn (*Zea mays* L., Pioneer 3573) was seeded at a rate of 65,000 seed ha^{-1} in 75 cm wide rows with a Kinze 4 row planter. Fertilizer (8-32-16) was banded beside the seed at a rate of 132 kg ha^{-1}. Urea (46-0-0) was applied with a brush applicator at the 6 leaf stage at a rate based on the average nitrate soil test. Annual ryegrass intercrop was seeded in the interrow with a Brillion seeder.

Herbicide was applied with a Chelsea sprayer equipped with 8004 EVS flat fan nozzles (Teejet) calibrated to deliver 270 L water ha^{-1} in a 38 cm wide band centred over the seeded row. Atrazine (550 g ha^{-1}) was applied at 1.1 kg ha^{-1}, metribuzin (250 g ha^{-1}) at 0.5 kg ha^{-1} and metolachlor (840 g ha^{-1}) at 1.68 kg ha^{-1}.

Climatic measurement. Weather data was collected from a nearby automated weather station. These data include maximum and minimum air temperature, solar radiation, rainfall intensity and amount, wind speed and direction and relative humidity.

FINDINGS

Herbicide Concentration. Herbicide concentrations in 1992 ranged from 0.01 to 68.6 ug/l in surface runoff and 0.01 to 125.1 ug/l in tile discharge (Table 1). Metolachlor concentration was larger than that for atrazine partly because of its higher rate of application. Concentrations of the three herbicides were larger in tile drainage than in surface runoff events because two small drainage events occurred within 25 d after herbicide application. The small rain events leached the herbicides into the soil which reduced availability for surface transport. This was manifest by the maximal deethylatrazine concentration in surface runoff and tile drainage soon after herbicide application. Atrazine is dealkylated by soil microorganisms (Skipper *et al*., 1967; Skipper and Volk, 1972) and maximal concentrations of the metabolite were measured in tile drainage and surface runoff 39 and 68 d after herbicide application, respectively in 1992 compared to 171 and 205 d after application, respectively in 1993. In 1993 larger herbicide concentrations were found in surface runoff (maximum 307 ug/l) than in tile drainage (maximum 107 ug/l). Intensity and duration of the rain affects the movement of the herbicides into the soil and transport mechanisms. Both a surface runoff and tile drainage event occurred 22 d after herbicide application in 1993. Maximal herbicide concentration appeared in the tile drainage events but maximal concentration was not seen in surface runoff events until 52 d after application of the herbicides. This indicates that rain intensity 22 d after herbicide application allowed greater vertical than horizontal movement of the herbicides. In both years herbicide concentrations were greatest in events right after herbicide application then decreased in subsequent runoff events during the growing season reflecting biological degradation of the herbicide and binding to the soil. The decrease in herbicide concentration with time after application was greater for metribuzin than for atrazine or metolachlor because of the shorter persistence of this herbicide in soil.

The U.S. EPA has established a maximum contaminant level for atrazine of 3 ug/l in surface waters servicing drinking supplies. Herbicide concentrations reported in this study were measured at the edge of the field which are usually orders of magnitude greater than in surface waters servicing domestic drinking supplies (Wauchope, 1978; Frank *et al*., 1990). Applying the EPA quideline to our results, 44% of the surface runoff and 25% of the tile drainage events exceeded the guideline for atrazine in drinking water in 1992 (Table 2). In 1993, 62 and 39% of the event samples exceeded the drinking water guideline for atrazine. Although deethylatrazine was not included in the EPA quideline with atrazine, a similar number of event samples were greater than the 3 ug/l limit for this metabolite.

A health advisory level of 100 ug/l has been set by the U.S. EPA for metolachlor. This guideline was exceeded in 22 and 17% of the surface runoff events in 1992 and 1993, respectively and in only 1% of the tile drainage samples in 1993 (Table 2). The health advisory level was not exceeded in any of the tile drainage events sampled in 1992.

Concentration of herbicide in the water may have more adverse effect on water quality than the amount of herbicide transported. Metolachlor was lethal to 50% of selected vertebrates at a concentration of 5 ug/l in a 96 h bioassay (Kent *et al*., 1991). Low, sustained concentrations may have an adverse effect if the herbicide has a tendency to bioaccumulate in the food chain. Current research has shown no propensity for these herbicides to bioaccumulate but the effect of the high maximal concentrations in events immediately following herbicide application on aquatic vegetation and biota is unknown. Also, the transport mechanisms for herbicides from the edge of field to receiving streams, rivers and lakes is poorly understood.

Herbicide Loss with Tillage and Intercrop. Treatment and controlled drainage main effects for herbicide loss in surface runoff, tile drainage and total runoff were detected in 1992. Herbicide loss was unaffected by treatments in 1993. No treatment by controlled drainage interaction was identified in 1992 or 1993. The effect of controlled drainage on herbicide loss was similar in 1992 and 1993. Therefore, herbicide loss from the tillage/intercrop treatments within years was averaged over controlled drainage (Figure 1) and controlled drainage effects were summed for 1992 and 1993 and averaged over treatments (Table 3).

Approximately 60 to 80% of the herbicide loss occurred within 75 days of herbicide application in 1992 and 55 days of application in 1993. In both years herbicide loss was greatest for atrazine (9.0 and 13.7 g/ha in 1992 and 1993, respectively) followed by metolachlor (7.6 and 13.6 g/ha, respectively) and metribuzin (2.5 and 6.2 g/ha, respectively, Figure 1). The rate of metolachlor application was 53% greater than that for atrazine (1.1 kg/ha) but loss was less relative to atrazine probably because of greater adsorption to soil. Metolachlor and atrazine had similar soil persistence (Figure 2). Metribuzin was applied at 45% the rate of atrazine and its loss by water transport relative to atrazine was in proportion to its' rate of application.

Environmental factors were more important in the quantity of herbicide lost in surface runoff and tile drainage than tillage, intercrop and controlled drainage. The sum of herbicide lost in surface runoff and tile drainage was 16% less in the presence of the ryegrass intercrop than with the nonintercropped treatment (Figure 1). This trend was consistent in 1992 and 1993. The reduction in herbicide loss due to intercrop occurred in surface runoff not tile drainage (Figure 1). Tillage had an inconsistent effect on herbicide loss. Soil saver had 34% less herbicide loss in 1992 than moldboard plow tillage but 15% greater loss in 1993. This result was consistent with previous studies where tillage effects on herbicide loss depended on environmental factors (Gaynor *et al*., 1992). The reduction in herbicide loss from tillage in 1992 occurred in surface runoff (Figure 1). In 1992, the first two runoff events produced tile drainage but no surface runoff. Thus herbicide was leached into the soil, reducing its potential for surface transport. Furthermore, herbicide loss in the tile drainage from these two events was less than 1 g/ha. Both surface runoff and tile drainage occurred in the first runoff event of 1993 which produced large herbicide loss (8 to 14 g/ha).

Controlled Drainage and Herbicide Loss. The purpose of the controlled drainage treatment was to reduce tile drainage losses after herbicide application, where losses are greatest, by retaining the water in the soil. The retained water could be utilized by the crop to enhance yield and make more efficient use of the fertilizer. Controlled drainage decreased tile discharge 32% and increased surface runoff 100% compared to the free drained treatment but total runoff remained unchanged (Table 3). Similarly, herbicide loss increased in surface runoff and decreased in tile drainage but the combined herbicide loss remained unchanged compared to the non-controlled drainage treatment (Table 3). This effect was consistent in 1992 and 1993. Therefore, controlled drainage did not reduce total herbicide loss but did have a beneficial effect on fertilizer use efficiency as demonstrated for nitrogen. The failure to alter total runoff in the controlled drainage treatment may be related to weather conditions in 1992 or unknown characteristics of the soil type making it dificult to maximize water storage in 1993. Rain in 1992 was adequate for crop growth and no moisture deficit occurred in any of the treatments.

Soil Residues. Tillage and intercrop had no effect on the rate of herbicide dissipation in soil. The three herbicides had longer persistence in 1991 than in 1992 and 1993 because of the lack of rain (Figure 2). Herbicide was recovered at all sampling depths to 20 cm in 1992 and 1993 as reperesented by the data for atrazine (Figure 3). Greater vertical movement occurred in 1992 than in 1993. Little herbicide was recovered at greater than 15 cm depth in 1991 (Data not shown). Controlled drainage enchanced herbicide dissipation in soil in 1993 but not 1992. Atrazine concentration in the soil after harvest in 1993 was 34% less in controlled drainage than in drained (29 ug/kg) treatments. Metolachlor concentration was 15% less in controlled drainage than drained (78 ug/kg) treatments. Controlled drainage did not alter herbicide residue in the soil in 1992 because of the high seasonal rain. Therefore, controlled drainage holds potential to reduce herbicide carry over to the next cropping season.

Banded Herbicide Application. Banded herbicide application over the seeded row reduced the quantity of herbicide applied to the land by 50%. In a rain simulation study, herbicide loss in surface runoff was reduced in direct proportion to the amount applied (Figure 4). Thus, herbicide applied in a band to 50% of the area reduced herbicide loss in runoff water and tile drainage 50% compared to that applied broadcast. This result would be independent of environmental factors unlike the other cultural practices studied.

STUDY CONCLUSIONS:

The integrated crop management, controlled drainage/subirrigation project provided individual and collective assessment of each of the components of the agricultural practices on water quality. Following this approach allows producers to adopt part or all of the management practice dependent upon economic considerations and expected improvements in water quality.

Control of herbicide inputs and runoff volume are essential components of the management strategy to improve water quality. Herbicide loss is the product of runoff volume and herbicide concentration of the runoff. Large runoff volumes of small herbicide concentration or small runoff volumes of large herbicide concentrations could result in large herbicide losses. Herbicide applied in a band over the seeded row reduces herbicide use and improves water quality in direct proportion to the area treated. Applying herbicide to 50% of the area will reduce herbicide loss and improve water quality 50%. Intercrop and tillage hold potential to improve water quality greater than that achieved by banded herbicide application alone but the extent of improvement will depend upon environmental factors such as the incidence and intensity of rainfall after herbicide application and intercrop establishment. Water quality was improved 16% with the intercrop and 30% with conservation tillage. The combined tillage and intercrop practice improved water quality 46% compared to conventional tillage with banded herbicide application. A conservative estimate indicates water quality was improved greater than 70% had these losses been compared to a conventional treatment with broadcast herbicide application. Controlled drainage increased aqueous transport by surface runoff but decreased loss through tile drainage so that total loss remained unchanged.

NEW TECHNOLOGIES AND BENEFITS

New Technology. The introduction of an integrated management system which incorporates controlled drainage/subirrigation, conservation tillage and intercrop as sustainable production management practices.

Benefits. All or part of the integrated management system can be adopted depending upon farmer acceptance and cost. The extent of adoption will determine the extent of improvement on water quality. Banding of herbicide is immediately adoptable which will provide the greatest benefit with respect to herbicide loss independent of weather factors.

The integrated management system should result in improved water quality (ie. reduce herbicide loss), increased crop yields (ie. improve soil water regimes by controlled drainage/ subirrigation) and lower input costs (ie. reduce herbicide input 50%). Therefore, the integrated management system developed at Harrow addresses both environmental quality and agricultural production issues in a balanced way.

IMPLICATIONS FOR GREAT LAKES ECOSYSTEM

The integrated management system developed at Harrow provides technology to reduce non-point contributions of herbicide to the Great Lakes ultimately improving the lakes' ecosystem. Also, reduced herbicide input will decrease potential for leaching to the groundwater.

TECHNOLOGY TRANSFER POTENTIAL

Components of the integrated management system:

- (a) banded herbicide application
- (b) conservation tillage
- (c) intercrop
- (d) controlled drainage/subirrigation

The integrated management system is based on existing farming structures (ie. tile drains). The existing drainage structures with minor modification can be converted to a controlled drainage/subirrigation system for better management of water and nutrients. Furthermore, the controlled drainage/subirrigation system incorporated with intercrop dramatically reduces herbicide losses because of alterations in runoff volume and increased herbicide dissipation rate.

Part or all of the integrated management system can be easily adopted and implemented as a sustainable agricultural management practice to minimize use and transport of agricultural chemicals.

GAPS NEEDING FUTURE RESEARCH

(1) Determine the effectiveness of controlled drainage/subirrigation and intercrop on herbicide losses from other soils, crops and crop rotation systems.

(2) The emphasis of the GLWQ project centred on surface and subsurface runoff water quality. The ground water quality and the migration and dissipation of herbicide in soil from the integrated management system needs to be studied further.

(3) Determine the relative contributions of drainage outflow over tile and between tile area in the integrated management system using a non-reactive tracer (results could impact management practices by changing fertilizer/herbicide placements, use of intercrop over tiles or direction of planting etc.; results should also provide a useful database for model calibration).

(4) Utilize our field and climatic data to verify and/or develop models for estimating herbicide transport (ie. surface runoff, subsurface drainage, leaching and dissipation).

(5) Identify transport mechanisms from farm gate to lake system.

(6) Insect and disease incidence with the integrated management practice needs investigation.

REFERENCES

Frank, R., B.S. Clegg, C. Sherman and N.D. Chapman. 1990. Triazine and chloroacetamide herbicides in Sydenham river water and municipal drinking water, Dresden, Ontario, Canada, 1981-1987. Arch. Environ. contam. Toxicol. 19:319-324.

Gaynor, J.D., D.C. MacTavish and W.I. Findlay. 1992. Surface and subsurface transport of atrazine and alachlor from a Brookston clay loam under continuous corn production. Arch. Environ. Contam. Toxicol. 23:240-245.

Issensee, A.R., R.G. Nash and C.S. Helling. 1990. Effect of conventional vs. no-tillage on pesticide leaching to shallow groundwater. J. Environ. Qual. 19:434-440.

Kent, R.A., B.D. Pauli, D.M. Trotter and J. Gareau. 1991. Canadian water qulaity guidelines for metolachlor. Scientific Series No. 184. Inland Waters Directorate, Water Quality Branch, Ottawa, Ontario.

Sauer, T.J. and T.C. Daniel. 1987. Effect of tillage system on runoff losses of surface-applied pesticides. Soil Sci. Soc. Amer. J. 51:410-415.

Skipper, H.D. and V.V. Volk, 1972. Biological and chemical degradation of atrazine in three Oregon soils. Weed Sci. 20:344-347.

Skipper, H.D., C.M. Gilmore and W.T. Furtick. 1967. Microbial versus chemical degradation of atrazine in soils. Soil Sci. Soc. Am. J. 31:653-656.

Soultani, M., C.S. Tan, J.D. Gaynor, R. Neveu and C.F. Drury. 1993. A simple automated system to sample and measure volume of surface runoff and subsurface drainage. Applied Engineering in Agriculture 9(5):447-450.

Tan, C.S., C.F. Drury, J.D. Gaynor and T.W. Welacky. 1993. Integrated soil, crop and water management system to abate herbicide and nitrate contamination of the Great Lakes. Wat. Sci. Tech. 28:497-507.

Wauchope, R.D. 1978. The pesticide content of surface water draining from agricultural fields -a review. J. Environ. Qual. 7:459-472.

PUBLICATIONS

(a) Refereed Journals

1. Soultani, M., C.S. Tan, J.D. Gaynor, R. Neveu and C.F. Drury. 1993. Measuring and sampling surface runoff and subsurface drain outflow volume. Applied Engineering in Agriculture 9(5):447-450.

2. Tan, C.S., C.F. Drury, J.D. Gaynor and T.W. Welacky. 1993. Integrated soil, crop and water management system to abate herbicide and nitrate contamination of the Great Lakes. Wat. Sci. Tech. 28:497-507.

(b) Conference Proceedings

1. Tan, C.S., C.F. Drury, M. Soultani, T. Oloya, J.D. Gaynor and T.W. Welacky. 1992. Evaluation of an integrated soil, crop and water management system to abate nitrate

loss. Workshop proceeding on Agricultural Nitrate and Impacts on Water Quality in Ontario (in press).

(c) Other

1. Soultani, M., C.S. Tan, J.D. Gaynor, C.F. Drury and T.W. Welacky. 1991. Integrated management system for abatement of herbicide and nitrogen loss. ASAE No. 91-2584.

2. Soultani, M., C.S. Tan, J.D. Gaynor and C.F. Drury. 1993. An automated system for runoff measurement and water quality assessment. ASAE No. 93-2136.

3. Tan, C.S., J.D. Gaynor, C.F. Drury and T.W. Welacky. 1993. Tillage and water table management to abate herbicide and nitrate loss in surface runoff and tile drainage water. ASAE No. 93-2081.

4. Drury, C.F., C.S. Tan, J.D. Gaynor and T.W. Welacky. 1994. Influence of control drainage/subirrigation on nitrate loss from Brookston clay soil. ASAE No. 94-2068.

(d) Abstracts

1. Soultani, M., C.S. Tan, J.D. Gaynor, C.F. Drury and T.W. Welacky. 1991. Integrated management system for abatement of herbicide and nitrogen loss. Paper presented at ASAE Winter Meeting.

2. Gaynor, J.D., C.S. Tan, C.F. Drury, T.W. Welacky and A.S. Hamill. 1992. Integrated soil, crop and water management system to abate herbicide and nitrate contamination of the Great Lakes. Paper presented at Weed Science Society of America Annual Meeting, Denver, Co. Feb. 8-11, 1993.

3. Gaynor, J.D., C.S. Tan, C.F. Drury and T.W. Welacky. 1993. Assessment of water quality employing intercrop, water table control and tillage management for corn production with band application of atrazine, metribuzin and metolachlor. Paper presented at 206th American Chemical Society Annual Meeting, Chicago, Ill. Aug. 22-27, 1993.

4. Tan, C.S., C.F. Drury, J.D. Gaynor and T.W. Welacky. 1993. Integrated soil, crop and water management system to abate herbicide and nitrate contamination of the Great Lakes. Paper presented at the International Workshop on sustainable Land Management for the 21st Century.

5. Tan, C.S., C.F. Drury, J.D. Gaynor and T.W. Welacky. 1993. Tillage and water management system to abate herbicide and nitrate contamination of the Great Lakes. Paper presented at 1st International Conference on Diffuse (Nonpoint) Pollution: Sources, Prevention, Impact and Abatement.

6. Soultani, M., C.S. Tan, J.D. Gaynor and C.F. Drury. 1993. An automated system for runoff measurement and water quality assessment. Paper presented at ASAE International Summer Meeting.

7. Tan, C.S., J.D. Gaynor, C.F. Drury and T.W. Welacky. 1993. Tillage and water table management to abate herbicide and nitrate loss in surface runoff and tile drainage water. Paper presented at ASAE International Summer Meeting.

8. Drury, C.F., C.S. Tan, T.O. Oloya, J.D. Gaynor and T.W. Welacky. 1993. Influence of subirrigation/controlled drainage and intercropping systems on nitrate loss through surface runoff and tile drainage. Paper presented at American Society of Agronomy Annual Meeting.

9. Gaynor, J.D., C.S. Tan, C.F. Drury, I.J. Van Wesenbeeck and T.W. Welacky. 1994. Atrazine concentration and losses in subsurface runoff as affected by tillage, band application, intercrop and water table control. Paper presented at 29th Canadian Symposium on Water Pollution Research, Burlington, Ont. Feb. 9-10, 1994.

10. Gaynor, J.D., C.S. Tan, C.F. Drury, T.W. Welacky and I. van Wesenbeeck. 1994. Herbicide loss in surface runoff from corn plots: Effects of tillage, water table control, intercrop and banding. Presented at 207th American Chemical Society Meeting, San Diego, Ca. Mar. 13-18, 1994.

11. Tan, C.S., C.F. Drury, J.D. Gaynor and T.W. Welacky. 1994. Influence of control drainage/subirrigation on nitrate loss from Brookston clay soil. Paper presented at ASAE Meeting, Kansas City, Mo. June 19-23, 1994

12. Tan, C.S., J.D. Gaynor, C.F. Drury and T.W. Welacky. 1994. Tillage, corn cropping practices and controlled drainage/subirrigation systems on water quality. I. Field design and automated runoff measurement. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994 and International Great Lakes Research Conference Windsor, Ont., June 6-9, 1994.

13. Gaynor, J.D., C.S. Tan, C.F. Drury and T.W. Welacky. 1994. Tillage, corn cropping practices and controlled drainage/subirrigation on water quality. II. Herbicide loss. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994 and International Great Lakes Research Conference Windsor, Ont., June 6-9, 1994.

14. Drury, C.F., C.S. Tan, J.D. Gaynor, T.W. Welacky and T.O. Oloya. 1994. Tillage, corn cropping practices and controlled drainage/subirrigation systems on water quality. III. Nitrate loss. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994 and International Great Lakes Research Conference Windsor, Ont., June 6-9, 1994.

15. Welacky, T.W., C.F. Drury, C.S. Tan and J.D. Gaynor. 1994. Tillage, corn cropping practices and controlled drainage/subirrigation systems on water quality. IV. Crop performance and yield. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994 and International Great Lakes Research Conference Windsor, Ont., June 6-9, 1994.

16. Tan, C.S., C.F. Drury, J.D. Gaynor and I. Van Wesenbeeck. 1994. Water table control and N-supply effects on water quality in undisturbed soil columns. I. Plant growth and

water use. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994.

17. Drury, C.F., C.S. Tan, J.D. Gaynor and I. Van Wesenbeeck. 1994. Water table control and N-supply effects on water quality in undisturbed soil columns. II. Nitrate. Paper presented at the Northeast AG/BIO Engineering Conference.

18. Gaynor, J.D., C.S. Tan, C.F. Drury and I. Van Wesenbeeck. 1994. Water table control and N-supply effects on water quality in undisturbed soil columns. III. Herbicide. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994.

19. Van Wesenbeeck, I., C.S. Tan, J.D. Gaynor and C.F. Drury. 1994. Comparison of DRAINMOD simulation of a tile drainage and controlled drainage/subirrigation system with field data in S.W. Ontario. Paper presented at the Northeast AG/BIO Engineering Conference Guelph, Ont. July 24-29, 1994.

20. Drury, C. F., C. S. Tan, T. O. Oloya, J. D. Gaynor and T. W. Welacky. 1994. The influence of water table management on surface and tile nitrate loss from corn production. Paper to be presented at American Society of Agronomy Annual Meeting.

Table 1. Flow weighted maximal and minimal concentration (Fg/L) of herbicide in surface runoff and tile drainage events for 1992 and 1993. Days after herbicide application in parentheses.

Date Herbicide Applied	Source	Attribute	Deethylatrazine	Atrazine	Metribuzin	Metolachlor
May 14, 1992	Surface	maximum	16.5 (68)	59.4 (68)	29.9 (68)	68.6 (39)
		minimum	0.01 (308)	0.11 (175)	0.01 (308)	0.04 (187)
	Tile	maximum	18.8 (39)	83.0 (25)	41.5 (39)	125.1 (25)
		minimum	0.03 (314)	0.13 (323)	0.01 (264)	0.01 (264)
May 17, 1993	Surface	maximum	28.0 (205)	272.0 (52)	147.4 (52)	307.1 (52)
		minimum	0.06 (205)	0.25 (205)	0.01 (205)	0.73 (136)
	Tile	maximum	16.2 (171)	107.0 (22)	50.1 (22)	100.4 (22)
		minimum	0.18 (205)	0.11 (205)	0.09 (136)	0.02 (205)

Table 2. Number of surface runoff and tile drainage events where concentration exceeded US EPA maximum contaminant level for atrazine (3 Fg/L) and US EPA health advisory level for metolachlor (100 Fg/L) in 1992 and 1993.

Year	Source	Deethylatrazine	Atrazine	Metolachlor
1992	Surface	17(36)	16(36)	8(36)
	Tile	9(71)	18(71)	0(71)
1993	Surface	29(52)	32(52)	9(52)
	Tile	17(87)	34(87)	1(87)

Total number of events in parenthesis

Table 3. Cumulative herbicide loss in surface runoff, tile drainage and combined runoff from controlled drainage/subirrigation and no drainage control treatments from May 14, 1992 to Dec. 8, 1993. Averaged over tillage/cropping treatment. Herbicide applied May 14, 1992 and May 17, 1993.

Source/Drainage control	Volume	Deethylatrazine	Atrazine	Metribuzin	Metolachlor
	mm	-------------------------------	g/ha	-------------------------------	
Surface runoff					
Drained	123***	1.22***	9.89**	3.83**	10.15*
Controlled drainage	247	2.99	17.47	6.68	17.25
Tile drainage					
Drained	388**	2.85*	13.18	5.14	11.47*
Controlled drainage	267	1.72	7.97	3.05	6.36
Total Runoff					
Drained	512	4.08	23.07	8.97	21.62
Controlled drainage	514	4.71	25.44	9.74	23.61

*,**,*** = P<0.05, P<0.01, P<0.001