NO_3-N AND METOLACHLOR CONCENTRATIONS IN THE SOIL WATER AS AFFECTED BY WATER TABLE DEPTH

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ABSTRACT. *Experiments were conducted in lysimeters to study the effect of shallow water table (WT) depths on the transport of two commonly used agricultural chemicals, nitrate-N and metolachlor, to shallow groundwater. Groundwater samples were collected from 0.20-, 0.40-, and 0.60-m depths using suction tubes during the growing season. The results showed significant reductions in both nitrate-N and metolachlor concentrations in the groundwater by maintaining shallow WT depths. Lowest concentrations of nitrate-N and metolachlor in the groundwater were observed when WT were maintained at 0.15-m depth. Generally, nitrate-N concentrations were increased with the soil depth while metolachlor concentrations decreased with the sampling depth during the growing season. Analysis of drainage outflow data at the end of WT treatment period also provided the evidence of the effectiveness of shallow WTs in reducing chemicals losses to shallow groundwater systems. The results of this study indicated that nitrate-N and metolachlor concentrations in the drainage outflow were 54 and 45%, respectively, lower for the 0.15-m WT treatment than the 0.60-m WT treatment. Regression analysis showed a strong negative linear relationship between metolachlor concentration and days after planting (DAP). Soybean yield was significantly reduced with the rise in WT depth. Average soybean yield obtained for the 0.15-m WT depth was 42% lower than the 0.60-m WT depth. It can be concluded from the overall results of this study that shallow WTs can be used effectively to reduce the nitrate-N and metolachlor losses to the shallow groundwater.*
Keywords. *Agricultural chemicals, Leaching, Nitrate, Groundwater.*

Modern agriculture is heavily dependent on the use of agrichemicals, particularly fertilizers and pesticides. The contamination of surface and groundwater due to the leaching of these chemicals has become a serious threat to human health, wildlife and the environment (Prunty and Montgomery, 1991). Particularly, nitrate and widely used herbicides such as atrazine, cyanazine, alachlor, and metolachlor have become one of the major pollution concerns facing the agriculture today (Hallberg, 1984). In the past two decades, much work has been done to characterize agricultural chemicals losses through drainage systems and the effect of these losses on water quality and crop productivity (Bengtson et al., 1984; Kanwar and Baker, 1991; Schwab et al., 1973; Baker and Johnson, 1976). Hallberg (1986) reported an almost linear increase in groundwater nitrate concentration over the last 20 years. In 1986 the Environmental Protection agency (EPA) reported the presence of 17 pesticides in groundwater in 23 states (Cohen et al., 1986). However, during recent years this figure has gone up, and the reported cases increased to 77 pesticides in the groundwater in 39 states (Williams et al., 1988).

Researchers are investigating the possibility of developing best management practices to protect water resources from chemical pollution while sustaining crop productivity. The agricultural management systems such as crop rotations, chemical management, and water table management (WTM) practices are being considered to reduce the negative effects of the use of agricultural chemicals on groundwater. Water table management systems include subsurface drainage, controlled drainage (CD), and/or subirrigation (SI) and maintains shallow WT depths in the field during certain periods of the growing season (Kalita and Kanwar, 1992). Water table management practices have shown the potential for inducing denitrification and reducing the concentration of nitrate-nitrogen (NO_3-N) reaching water supplies (Skaggs and Gilliam, 1981; Gilliam and Skaggs, 1986; Evans et al., 1989a; Wright et al., 1992; Kalita and Kanwar, 1989; Kanwar and Kalita, 1990; Kalita and Kanwar, 1993). Evans et al. (1989b) presented a compilation of data from North Carolina and supported the use of controlled drainage as best management practice (BMP). Their data showed that controlled drainage decreases both surface and subsurface nitrogen losses as opposed to uncontrolled drainage. They found the average nitrogen loss reduction of 45% resulting from drainage control in North Carolina. They concluded that denitrification accounted for the reduced nitrogen transport from controlled drainage sites in eastern North Carolina, where conditions are conducive to denitrification.

Kalita and Kanwar (1989) found nitrate concentrations in the unsaturated zone to be greater than those in the saturated zone. They also found that by raising the WT depth from 90 cm to 30 cm below the soil surface produced

Article was submitted for publication in January 1996; reviewed and approved for publication by the Soil and Water Div. of ASAE in August 1996.

Journal Paper No. J-16601 of Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 3415. The mention of trade or manufacturer names is for the benefit of readers only and does not imply an endorsement, recommendation, or exclusion by Iowa State University.

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a corresponding decrease in NO_3-N concentrations. At approximately 60 cm below the WT, very low NO_3-N concentrations were found. This finding may be attributed to increased denitrification due to high WT conditions. Evans et al. (1991) summarized results of 10 studies representing approximately 120 site-years of data collected on poorly drained soils in North Carolina. These studies were conducted to evaluate the effects of subsurface drainage, CD and CD-SI on nutrient and pesticide movement to surface and ground water. Fertilizer nutrient losses in conventional drainage effluent typically exceeded 20 kg N and 0.25 kg P ha^{-1} yr^{-1}. Another study in North Carolina was conducted to determine the effects of various artificial drainage treatments on movement of N and P from poorly drained soils in the Coastal Plains (Deal et al., 1986). Computer simulations were used to predict N and P losses over 20 years from six soils. The results showed that both drainage system design and management can significantly affect N and P movement to drainage effluent. Gambrell et al. (1975a) reported that in well-drained soils that were not saturated for extended periods, denitrification was limited. This limitation allowed fertilizer not taken up by the crop to potentially move to shallow aquifers and later to surface water. Baker and Johnson (1976) showed that artificial drainage increases nitrate movement from agricultural sites whether additional fertilizer was applied or not. In a study to evaluate the effect of drainage on the fate of un-utilized fertilizer N in North Carolina, Gambrell et al. (1975a) found smaller loss due to denitrification of residual nitrate in shallow ground water. Skaggs (1987) reported that surface drainage systems tend to have higher runoff rates, with higher concentrations of sediment, phosphorus, and pesticides, than do subsurface drainage systems. However, outflow water from subsurface drainage systems had a higher concentration of mobile compounds such as nitrates. Drainage is an important management practice for improving water quality while sustaining agricultural viability (Fausey et al., 1995).

Investigation of the influence of controlled drainage/subirrigation on pesticide transport is just beginning. Several studies are in progress; but, little information is currently available. Munster et al. (1991) observed a 25% increase in aldicarb transport in controlled drainage outflow compared to conventional drainage. It should be noted, however, that recovery of applied aldicarb was very low in both drainage treatments accounting for less than 0.05% of the applied amount. Arjoon et al. (1992) and Kalita and Kanwar (1990) observed lower soil-solution concentrations of Prometryn and Atrazine, respectively, under controlled drainage compared to conventional drainage. They hypothesized that WT control slowed vertical leaching of these pesticides to ground water, but did not report the impact on drainage outflow. They also acknowledged that considerably more data were needed to provide more conclusive results. Bastien et al. (1990) measured pesticide concentrations in tile drainage in the two potato fields where nutrients losses were measured. Metribuzine was detected in the tile flow at concentrations up to 3.47 μg/L. Concentrations in surface runoff samples were higher (33.6 to 47.1 μg/L). Aldicarb, fenvalerate and phorate were not detected in drainage waters.

Nitrate and pesticide leaching from potatoes have been studied in Canada. In a two-year study involving five on-farm sites in New Brunswick, flow-weighted average nitrate concentrations of the subdrain discharge were greater than 10 mg/L (Milburn et al., 1990, as cited by Ritter et al., 1993). Herbicides dinoseb and metribuzine used in potato production were also detected in the drain discharge (95% of positive samples <2 μg/L) both during the year of application and again the following spring, but concentrations were less than detection limits 12 to 18 months after application (Milburn et al., 1991)

Benefits of WT control on water quality have been investigated under different soils, crops, and climatic conditions (Kanwar, 1990; Thomas et al., 1991; Fausey et al., 1991; Skaggs et al., 1991). Few studies have reported on the benefits of WTM practices in reducing water quality degradation (Belcher, 1989; Kalita and Kanwar, 1992; Arjoon et al., 1990). The objective of this study was to evaluate the effects of different WT depths on the movement of metolachlor and residual nitrate-nitrogen to shallow groundwater under soybean production system.

Materials and Methods

To determine the effects of shallow WT depths on the movement of nitrate-N and metolachlor to shallow groundwater, two controlled-environment growth chambers (Conviron PGW36; 247 × 137 × 196 cm) were used to house sixteen lysimeters for this study. The 24-h temperatures were programmed to simulate normal Ames climatic conditions between 01 May and 30 September in the growth chambers. Daily diurnal temperature patterns were based on the 30-year normal maximum and minimum temperatures for the corresponding dates. These temperature values were ramped between hourly set points. For the variable daylight periods, light was provided by 45 incandescent 120-W and 30 fluorescent 115-W light bulbs. During the first hour, only incandescent light was used and for the last hour, only fluorescent light was provided. Relative humidity in these chambers could not be controlled; however, its values were above 50% for most of the growing season.

Construction of the Lysimeters

Lysimeters were made from plastic containers (52 × 42 × 71 cm) for growing soybean plants in the growth chambers. A hole (about 2.50-cm diameter) was made at a height of 5 cm from the bottom of the plastic container with a power saw (fig. 1). This hole was fixed with a bung crossing the container wall on both sides and provided a watertight seal. To raise or lower the water level in the container, a 5-cm diameter, perforated plastic pipe was connected by plastic coupling to the bung. The outside of the bung was fitted with a garden-hose barb, connected to a float system and a water supply reservoir by a transparent polyvinyl tube. The float system consisted of a small bucket-type water reservoir and a float. The system was portable, and was used to change the water level inside the container by changing its height on wooden blocks, which could be adjusted according to the need of the study. A plastic tube 1 m long and 2.54 cm in diameter was installed in each lysimeter to measure water level position inside the lysimeters.

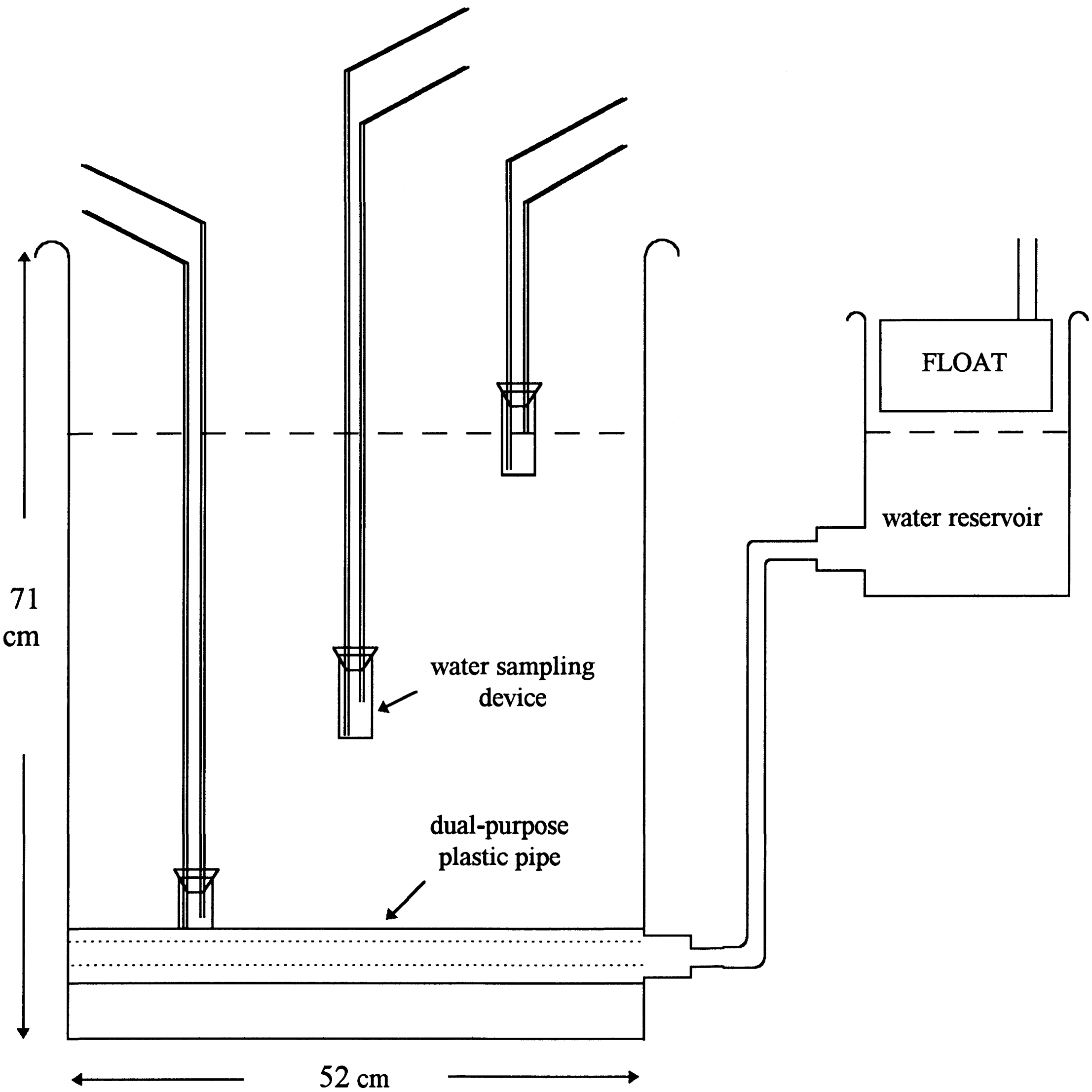

Figure 1–Schematic sketch of a lysimeter.

Placement of Soil in the Lysimeters

The soil used for this study was Nicollet loam soil from the Clarion-Nicollet-Webster Association. A small area (8 m × 4 m) in the field was selected, crop residues were removed, and the area was then divided into 16 smaller areas (2 m × 1 m), one for each lysimeter. The soil profile of each smaller area was excavated in 0.15 m layers, to a depth of about 0.75 m. The soil was dried, ground, and sieved before being placed in the lysimeters. To match the original vertical soil profile and bulk density, soil was packed into the lysimeters in the same order of layers. Surplus soil, if any, was saved for later use of lysimeters in the event soil settling occurred in the lysimeters. Soil-filled lysimeters were then brought to the Agronomy Department of ISU and placed in the growth chambers. Eight lysimeters could be placed in one growth chamber at a time. To allow the soil to settle, water was raised slowly (about 10 cm in 4 h) from the bottom of the lysimeters to the soil surface of each lysimeter and was kept there for three days. Soil in almost all the lysimeters settled during this flooding event. The lysimeters were then refilled with the surplus soil to bring the depth of the soil in the lysimeters to the depth of the original soil excavation. The same soil was used in both the growth chambers.

Planting

In the center of each lysimeter, a groove was made about 20 cm from the walls. Eighteen soybean (Hobbit 87) seeds were planted in each lysimeter. After germination these plants were thinned to six plants per lysimeter. The procedure was repeated in both growth chambers. Before planting, soil samples were taken from all lysimeters to determine soil fertilizer needs. The results of soil analysis showed high amounts of phosphorus and potassium already present in the soil; therefore, no fertilizers were applied. Herbicide metolachlor (trade name dual) was applied at a rate of 2.2 kg/ha in all lysimeter to monitor the transport of metolachlor through the lysimeters' soil profile. Some properties of metolachlor are presented in table 1.

Irrigation

To determine the amount of water required for each surface irrigation during the growing season, 30 years (1965-1994) of rainfall data were obtained, and weekly

Table 1. Selected properties of metolachlor

Soil adsorption, K*	4
Solubility (mg/L)	530
Half life (days)	90
Vapor pressure† (Lasso = 1)	2.2
Health advisory level (µg/L)	100
Rating‡	
Leaching	Large
Runoff adsorbed	Medium
Runoff solubility	Large
Old runoff	Medium

* K - concentration in soil/concentration in water, for soil with 2% organic carbon.

† Vapor pressure relative to that of Lasso (arbitrary chosen as reference point).

‡ SCS (1991).

averages were calculated from 01 May through 30 September. To simulate field conditions, rainfall water was applied on a weekly basis (equal to 30 years average weekly rainfall) in the form of irrigation because rainfall intensities in the controlled environment growth chambers could not be obtained. This kind of irrigation schedule was needed to match climatic conditions for soybeans grown in the humid midwest.

Water Sampling Devices

Different devices were used to collect water samples from unsaturated and saturated soils. The water sampling device for unsaturated soil consisted of a porous ceramic cup (a clay vessel closed at one end, about 7.5 cm long, with 3-cm outer and 2.5-cm inner diameter, two transparent tygon tubes (3.5 mm), a two-hole rubber stopper (size 4), two plastic clamps, and 4- and 6-cm lengths of 4-mm outer diameter glass tubing. The two glass tubes were placed in the holes of rubber stopper. One of the glass tubes reached the bottom of the cup, and the other, reached the top of the cup and acted as an air vent when the water sample was removed. The two polyethylene tubes were inserted on to the glass tubes and sealed with a sealant. A 60 cc syringe was used to create suction inside the porous cup one day before collecting water samples for chemical analysis.

For collecting water samples from saturated soil, a device was constructed in a similar way. The only difference was that instead of a porous ceramic cup, a perforated, transparent, plastic pipe (9.0 cm long, with 3-cm inside diameter) was used. The top and bottom this pipe were closed with a two-hole and a solid rubber stopper (size 3), respectively. After construction, this pipe was covered with a fiber glass matting to prevent the possible clogging of perforations in the pipe. These devices were installed at depths of 0.20, 0.40, and 0.60 cm below the surface in each lysimeter.

Water Analysis Methods

Several methods are available for water quality analysis and choice depends on the substance to be measured and the degree of accuracy required. Cost and time limitations must also be considered when selecting the method of analysis. More than one method are often utilized in order to verify results. The following sections provide a brief description of the methods used for the analysis of nitrate-N and metolachlor in this study.

Automated Cadmium Reduction Method for NO_3-N Analysis. The cadmium reduction method actually measures the sum of both NO_3-N and NO_2-N. In groundwater, however, NO_2-N levels are generally negligible in comparison to NO_3-N concentrations and results from this method are usually reported in mg/L of NO_3-N.

In the cadmium reduction method of NO_3-N analysis, water samples pass through a column of cadmium (Cd) granules coated with copper (Cu). In the presence of cadmium, NO_3-N reduces to NO_2-N. After reduction, the sample is diazotized with sulfanilamide and coupled with N-(1-naphthyl)-ethylenediamine to form a highly colored azo dye which is measured colorimetrically (APHA, 1985). If significant levels of NO_2-N exist in the original sample, an adjustment may be made by analyzing the sample without the reduction step and subtracting the amount of NO_2-N from the sum of NO_3-N plus NO_2-N.

Nitrate-nitrogen concentrations in groundwater range from near zero to several times the Maximum Contamination Level (MCL) of 10 ppm. Water samples with NO_3-N levels above that of the highest calibration standard can be diluted by the appropriate factor to bring the concentration within the range of calibration curve. Automated equipment allow rapid analysis of water samples for NO_3-N.

Enzyme-linked Immunosorbent Assay Method for Metolachlor Analysis. The enzyme-liked immunosorbent assay or ELISA method of pesticide analysis is used in many areas of work including drug testing, infectious and non-infectious disease diagnosis, and in agricultural applications such as analysis of food and water for pesticide residues. ELISA methods have gained popularity in recent years because of simplicity, relatively low cost, and rapid results.

While there are several types of ELISA methods, all use the same fundamental principles. The ELISA method make use of the biological relationship between antibodies and the antigen, which in the case of groundwater analysis is pesticide. The antibodies are obtained from the tissues of animals, such as rabbits, which have been exposed to the particular pesticide. The pesticide specific antibodies are separated from the animal tissues and maintained in a buffer solution for use in the ELISA test. The ELISA procedure for metolachlor analysis requires several steps:

Step 1 – A prepared solution containing the metolachlor conjugated with an enzyme is combined with 200 µL of the sample water to be analyzed.

Step 2 – The metolachlor antibody coupled paramagnetic particles solution is mixed with the sample and the enzyme conjugate pesticide and incubated at room temperature for 30 min. During incubation of the mixture, any pesticide present in the sample will compete with the enzyme-labeled pesticide for binding sites on the antibodies.

Step 3 – After the incubation period, the antibodies, which now have the labeled and possibly unlabeled pesticides bound on them, must be separated from the rest of the solution. Several methods have been used to achieve isolation of the antibodies after reaction with antigen. One method uses antibodies covalently bound to paramagnetic particles. After incubation with the antigen the test tubes containing the mixture are placed in a magnetic rack which holds the paramagnetic particles, and likewise the antibodies and bound antigen, to the test tube wall while the remaining solution is decanted. The paramagnetic particles combination is then washed with deionized distilled water and decanted again. The washing procedure is performed twice to ensure complete removal of any unbound labeled and unlabeled antigen.

Step 4 – A color reagent added to the test tube reacts with any enzyme which may have attached to the antibody via the labeled antigen producing a colored product. More enzyme in the solution causes more color development. After another incubation period of 20 min, the reaction is stopped with sulfuric acid and the absorbence is read with a spectrophotometer. Maximum color development occurs when the water sample contains no unlabeled pesticide specific to the antibody, because the enzyme labeled pesticides then need not to compete for the antibody binding sites. Sample concentration is therefore inversely proportional to the light absorbence of the final colored solution. Inclusion of samples with known concentrations allows development of a calibration curve to which samples of unknown concentration can be compared. The lower and upper limits are 0.05 ppb and 5.0 ppb, respectively, for atrazine, alachlor, and metolachlor for kits produced by Ohmicron.

Ohmicron manufactures a 60-tube magnetic rack in which as many as 50 samples may be analyzed. The remaining 10 spaces are required for the calibration and control samples. Duplication of each sample is recommended leaving 25 distinct sample analyses that can be completed in about 2 h. Only one analyte can be tested at a time.

Although relatively inexpensive and rapid, ELISA methods of pesticide analysis have important limitations. ELISA test results can vary by as much as 20% of the true analyte concentration. Consistency of results depends largely on the pipetting skills of the individual preparing the assay. Environmental conditions in the lab, i.e. temperature, may also affect results. Greatest variation of ELISA results occur when comparing results from separately calibrated runs. Within a given calibrated set of samples, however, results are more consistent and subtle differences in pesticide concentrations are more evident.

Cross-reactivity of the ELISA antibodies with compounds other than the intended analyte presents the greatest disadvantage of this method of pesticide analysis. The presence of cross-reactive substances in the water samples can cause false positive detection's or indicate much higher concentrations than actually exist. Cross-reactivity is major consideration in groundwater quality research because pesticides often co-exist with one or more of their metabolites and/or with other pesticides of similar structure which are likely to be cross-reactive (Baker et al., 1993).

Manufacturers of ELISA kits provide limited data on cross-reactivity. Ohmicron indicates several compounds which may affect the accuracy of their ELISA test results and provides corresponding least detectable doses (LDD) with each kit. The LDD is defined by Ohmicron as " the lowest level . . . which can be reliably distinguished from zero" (Ohmicron, 1991). While positive detection's by the ELISA method of pesticide analysis can provide misleading information, negative results are an accurate indication of concentrations below the detection limit of the intended analyte. Confirmation of positive ELISA detection's by a more compound specific method is recommended.

Experimental Design and Layout

The experimental treatments consisted of constant WT levels maintained at 0.15, 0.30, 0.45, and 0.60 m below the soil surface (these treatments started on 37 DAP and ended on 107 DAP). These treatments were arranged in a randomized complete block design with four replications. There were two replicates in each growth chamber. Lysimeters were arranged in the growth chambers in such a way that each lysimeter received similar light levels.

Water samples for nitrate-N and metolachlor analysis were taken at 0.20-, 0.40-, and 0.60-m depths below the soil surface. These samples were collected on 50, 71, 92, and 113 DAP. The amount of samples collected on 50 DAP was not enough to make the analysis of nitrate-N possible for this date. Therefore, for nitrate-N, data on 71, 92, and 113 DAP has been reported. For metolachlor, only 200 µL of sample (using ELISA method) was needed to make the analysis possible, that is why data for all sampling dates has been reported.

Statistical Analysis

The statistical analysis was performed on each parameter using the GLM procedures of the SAS Institute (1990). Data were analyzed for each week of measurements separately. The overall effects of treatments on different parameters were determined by using the data for all weeks. This technique helped investigate the variation between WT treatments during the growing season and also the overall effects. The regression analyses on different parameters were performed by using Microsoft Excel (Ver. 5a, Microsoft Corp.). This program had the capability to conduct trend analysis directly on scatter diagrams of each parameter and to give model equation suitable for the data set.

Results and Discussion

Nitrate-N Concentration in Water Samples

The average nitrate-nitrogen (NO_3-N) concentration in groundwater at sampling depths of 0.20, 0.40, and 0.60 m as a function of WT depths and DAP are presented in figure 2. The analysis of variance results show lower concentrations of NO_3-N at a depth of 0.20 m compared with the deeper depths. The average nitrate-N concentration, on 71 DAP, at a depth of 0.20 m, for the 0.15-m WT treatment was 50% lower compared with the 0.60-m WT treatment. The highest nitrate-N concentration of 3.79 mg/L was observed at a depth of 0.40 m for the 0.45-m WT treatment. The lowest nitrate-N concentration of 0.14 mg/L was observed at a depth of 0.20 m under the 0.15-m WT treatment.

The nitrate-N concentrations on 92 DAP for the 0.15-, 0.30-, 0.45-, and 0.60-m WT treatments were 25, 88, 92, and 71%, respectively, lower (average of three sampling depths). The results showed significantly lower nitrate-N concentrations at shallow WT depths when compared with deeper WT depths. The highest nitrate-N concentration, on 92 DAP, was observed at a depth of 0.40 m for the 0.45-m WT treatment. The lowest nitrate-N concentration, on 92 DAP, was also observed at a sampling depth of 0.40 m for the 0.15-m WT treatment. The results indicate that the nitrate-N concentrations for the 0.15-m WT treatment was 36% lower than the 0.60-m WT treatment. This provides

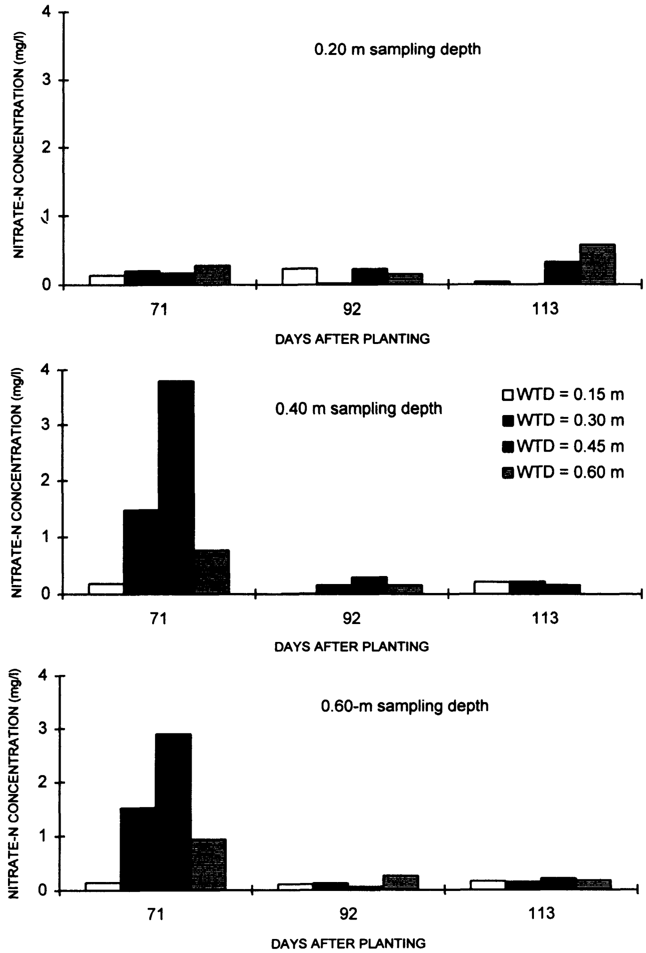

Figure 2–Residual nitrate concentration (mg/L) as a function of DAP.

the evidence of the effectiveness of shallow WT in reducing nitrate-N leaching to deeper depths.

On 113 DAP, the highest nitrate-N concentration of 0.57 mg/L was observed for the 0.60-m WT treatment at a depth of 0.20 m and the lowest nitrate-N concentrations of 0.04 mg/L was observed for the 0.15-m WT treatment at the same depth. On the average, the nitrate-N concentrations for the 0.15-m WT treatment were 55% lower than the 0.60-m WT treatment. The nitrate-N concentration observed at a depth of 0.20 m was 58% higher compared with the 0.60-m sampling depth.

The analysis was conducted on the entire data to investigate the overall effect of WT treatments on nitrate-N concentration. These results showed that nitrate-N concentration for the 0.15 m WT was 81% lower compared with the 0.45-m WT treatment, although, the results was statistically insignificant. The nitrate-N concentrations values for the 0.60-m WT treatment were lower than the 0.45-m WT treatment. This could be due to lower nitrate-N concentrations at a sampling depth of 0.60 m (the results on the overall nitrate-N concentrations at various depths showed that nitrate-N concentration at a depth of 0.60 m was 32% lower compared with the 0.40-m depth).

The nitrate-N concentrations observed under this study are lower than those reported in the literature. This may be due to the fact that no nitrogen fertilizer was applied for this study. The nitrate-N concentrations observed in water sample are the residual nitrate-N concentrations of the soil profile. Some of the nitrate-N in the soil profile might have lost during the initial flooding and draining event before the start of experiment (see method and material section) which was done to let the soil moisture content in all the lysimeter to come to field capacity.

Nitrate-N Concentration in Drainage Outflow

Table 2 presents data on nitrate-N concentration in the drainage water for different WT treatments. The results showed that nitrate-N loss to groundwater was significantly reduced by maintaining high WT depths. The lowest nitrate-N concentration of 0.23 mg/L was observed under the 0.15-m WT treatment which provides the evidence that shallow WT did reduce the nitrate-N loss to the deeper depths. The overall nitrate-N concentrations for the 0.15- and 0.30-m WT treatments were about 54 and 36%, respectively, lower compared with the 0.45 m WT treatment. The nitrate-N concentration for the 0.60-m WT treatment was 16% lower than those for the 0.45-m WT treatment (these trends are similar to those observed for water samples). Average nitrate-N concentration obtained from the drainage water was 0.36 mg/L.

Nitrate reduction by controlled drainage have been reported in the literature. Water table management (WTM) techniques, specifically, drainage-subirrigation (CD-SI) and controlled drainage (CD), have been identified as beneficial practices for reducing nitrate loss from the soil matrix by increasing denitrification (Gilliam et al., 1979; Skaggs and Gilliam, 1981; Gilliam and Skaggs, 1986; Gambrell et al., 1975a, b; Kalita and Kanwar, 1989). Gilliam et al (1979) observed 50% reduction in nitrate loss from fields by controlled drainage. Evans et al. (1989b) found the average nitrogen loss reduction of 45% resulting from drainage control in North Carolina. Bengtson (1993) found that subsurface drainage was effective in reducing nitrogen loss from fields by 17%. These reductions has been attributed to higher rates of denitrification thought to be associated with high water tables.

Metolachlor Concentration in Water Samples

Data on metolachlor concentration at various water table (WT) depths as a function of soil depths and time is presented in figure 3. First water sampling was done on 50 DAP. The results indicate that highest metolachlor concentration of 2.79 ppb was found under the 0.15-m WT treatment 0.20 m below the surface and the lowest metolachlor concentration of 0.66 ppb was found under the 0.30-m WT treatment at a depth of 0.60 m. At a depth of 0.20 m, on 50 DAP, the metolachlor concentration generally increased with the rise in WT depth. Different results were observed for the other two sampling depths.

Table 2. Mean Nitrate-N concentration (mg/L) in drainage outflow under different water table treatments

	Water Table Depth (m)				
	0.15	0.30	0.45	0.60	Pr > F
Chamber	(mg/l)				
1	0.21a*	0.26a	0.48a	0.32a	0.4500
2	0.26a	0.38a	0.51a	0.51a	0.2208
Overall avg.	0.23c	0.32bc	0.50a	0.42ab	0.0475

* Means in rows followed by the same letter are not significantly different at the 0.05 probability level.

The metolachlor concentrations, at a sampling depth of 0.40 and 0.60 m, were highest for the 0.60-m WT treatment. The results (using the average of all WT treatments) showed that metolachlor at a depth of 0.20 m was 63% higher than the 0.60-m sampling depth.

As compare to 50 DAP, the average metolachlor concentrations (average of all sampling depths) for the 0.15, 0.30, 0.45, and 0.60 m WT were 38, 19, 11, and 16% less. The analysis of variance showed that metolachlor concentration was significantly lower at deeper depths compared with shallow depths. Average metolachlor concentration at a sampling depth of 0.60 m was 48% lower than the 0.20-m sampling depth. The highest metolachlor concentration of 2.31 ppb was found 0.40 m below the surface under the 0.60-m WT treatment and the lowest metolachlor concentration of 0.50 ppb was found 0.60 m below the surface under the 0.30-m WT treatment. The results were not consistent for the 0.20-m depth, however, generally the metolachlor concentration decreased with the rise in WT depth. The analysis using the average of three depths showed that the metolachlor concentration was significantly decreased with the rise in WT depth. The metolachlor concentration found under the 0.15-m WT treatment was, on the average, 32% lower compared with the 0.60-m WT treatment.

Average metolachlor concentration, on 92 DAP, for the 0.15-m WT treatment was 46% lower than the 0.60-m WT treatment. The highest metolachlor concentration of 1.99 ppb was found 0.20 m below the surface under the 0.60-m WT treatment and the lowest metolachlor concentration of 0.43 ppb was observed 0.60 m below the surface under the 0.30-m WT treatment. The analysis of variance by using the average of all WT treatments showed that metolachlor concentration was significantly lower at deeper depths. Average metolachlor concentration at a sampling depth of 0.60 m was 42% lower than the 0.20-m sampling depth.

On 113 DAP, the metolachlor concentration under the 0.60-m WT treatment was significantly higher compared with the shallow WT depths. The metolachlor concentration under the 0.30-m WT treatment was 43% lower than the 0.60-m WT treatment. The highest metolachlor concentration of 1.23 ppb was found 0.20 m below the surface under the 0.60-m WT treatment and the lowest metolachlor concentration of 0.33 ppb was observed 0.60 m below the surface under the 0.45-m WT treatment. The analysis of variance using the average of all WT depths showed that metolachlor concentration was significantly decreased with the increase in sampling depth. On the average, the metolachlor concentration at a sampling depth of 0.60 m was 25% lower than the 0.20-m sampling depth.

The analysis of variance was conducted to investigate the overall effect of WT treatments on metolachlor concentration. The results showed that metolachlor concentration was significantly decreased with the rise in WT depth. On the average, the metolachlor concentration found under the 0.15-m WT treatment was 30% lower than the 0.60-m WT treatment. The difference between the 0.15- and 0.30-m WT depths were not significant. The results also showed that the average metolachlor concentration was significantly decreased at deeper sampling depths. Average metolachlor concentration at a depth of 0.20 m was 54% lower than the 0.60-m sampling depth.

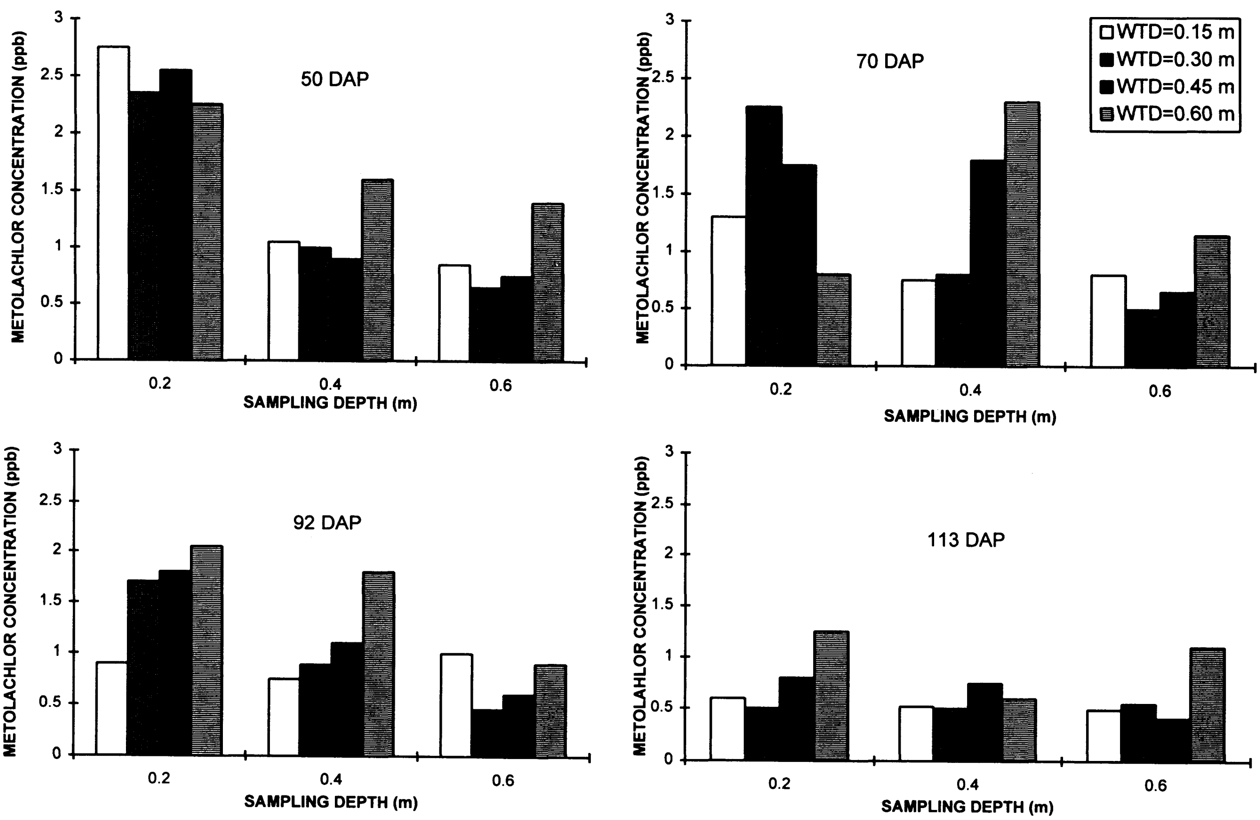

Figure 3–Metolachlor concentration at different depths below the soil surface for various water table treatments on different DAPs.

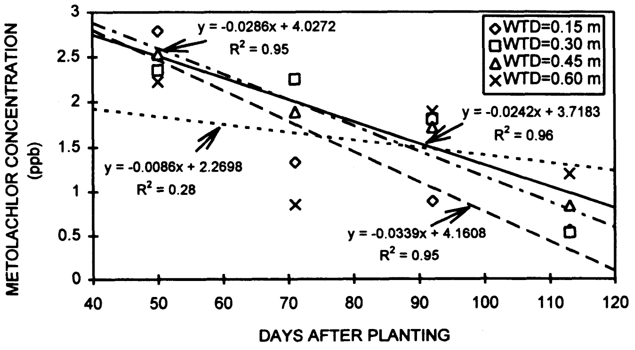

Figure 4–Metolachlor concentration at 0.20-m soil depth as a function of days after planting.

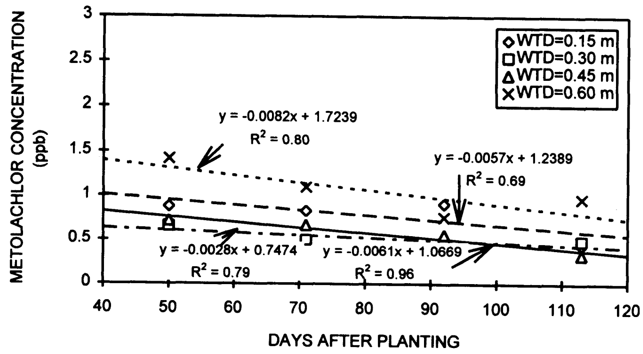

Figure 6–Metolachlor concentration at 0.60-m soil depth as a function of days after planting.

The metolachlor concentrations found in this study are considerably lower than those observed under field conditions (Southwick et al., 1990; Bengtson et al., 1990; Bowman, 1988). The reason could be the faster degradation or increased adsorption in the lysimeters.

Relation Between Metolachlor Concentration and Days after Planting (DAP)

Figure 4 shows relation between metolachlor concentration and DAP at a depth of 0.20 m. The results showed that metolachlor concentration was significantly decreased with time. Highest metolachlor concentration, at a depth of 0.20 m, was found on 50 DAP under the 0.15-m WT treatment. The lowest metolachlor concentration, at a depth of 0.20 m, was found on 113 DAP, under the 0.15-m WT treatment. Relationships were developed between the metolachlor concentration in groundwater under different WT treatments and DAP. The result showed that metolachlor concentration was negatively correlated to DAP. The determination coefficients (R^2) for the 0.15-, 0.30-, 0.45-, and 0.60-m WT treatments were 0.95, 0.95, 0.96, and 0.28, respectively.

Figure 5 presents the relation between metolachlor concentrations and DAP at a sampling depth of 0.40 m. This figure shows a decrease in metolachlor concentrations with time for all WT depths. The highest metolachlor concentration of 2.31 ppb, at a depth of 0.40 m, was found for the 0.60-m WT treatment on 71 DAP. The lowest metolachlor concentration of 0.47 ppb, at a depth of 0.40 m was found for the 0.30-m WT treatment on 114 DAP. Regression analysis showed that a strong negative linear relationship exists between metolachlor concentration and DAP.

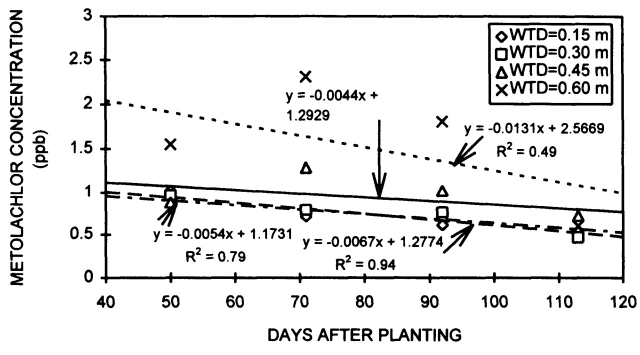

Figure 5–Metolachlor concentration at 0.40-m soil depth as a function of days after planting.

Figure 6 shows the relation between metolachlor concentrations and DAP at a sampling depth of 0.60 m. This figure also shows a progressive decrease in metolachlor concentration with time. Highest metolachlor concentration of 1.42 ppb, at a depth of 0.60 m, was found under the 0.60-m WT treatment on 50 DAP and the lowest metolachlor concentration of 0.33 ppb was observed under the 0.45-m WT treatment on 114 DAP. The regression analysis showed that metolachlor concentration could be predicted from DAP. The regression coefficient for the 0.15-, 0.30, 0.45-, and 0.60-m WT treatments were 0.69, 0.79, 0.96, and 0.80, respectively.

Metolachlor Concentration in Drainage Outflow

Data on metolachlor concentration in drainage water is presented in table 3. The analysis of variance shows that there was about 45% reduction in metolachlor loss to deeper soil depths by maintaining WT at a depth of 0.15 m below the surface. Highest metolachlor concentration of 0.86 ppb was observed under the 0.60-m WT treatment. The metolachlor concentrations for the 0.30- and 0.45-m WT treatments were 23 and 40%, respectively, lower compared with the 0.60-m WT treatment, although, the results were statistically insignificant.

These trends are in agreement with the studies recently reported in the literature. Kalita and Kanwar (1990) found significant reductions in atrazine and alachlor by maintaining shallow WTs. Arjoon et al. (1992) observed lower soil-solution concentrations of Prometryn, under controlled drainage compared to conventional drainage. Mirjat (1994) observed reductions in average atrazine and alachlor concentrations by maintaining shallow WT depths between 0.30 and 0.60 m. Munster et al. (1991) found 25%

Table 3. Mean metolachlor concentration (ppb) in drainage outflow under different water table treatments

	Water Table Depth (m)				
	0.15	0.30	0.45	0.60	
Chamber	----------------(ppb)				Pr > F
1	0.62a†	0.81a	0.58a	0.85a	0.7693
2	0.33a	0.51a	0.47a	0.88a	0.3558
Overall avg.	0.47b	0.66ab	0.52ab	0.86a	0.1156

* DAP - days after planting.

† Means in rows followed by the same letter are not significantly different at the 0.05 probability level.

increase in aldicarb transport in controlled drainage outflow compared to conventional drainage. Bengtson et al. (1993) found that the losses of atrazine and metolachlor from the plots with subsurface drainage were 55 and 51% less than those from plots with subsurface drainage only.

Effect of Water Table Depths on Soybean Yield

Crop yield data for the two, growth chamber experiments are presented in table 4. In both experiments, the highest crop yields were obtained for the 0.60-m WT treatment and the lowest was for the 0.15-m WT treatment. The analysis was performed using SAS procedures to determine the difference between yield means under four WT treatments for individual chamber. The results from growth chamber 1 showed that the average yield from the 0.15-m WT treatment was significantly lower than the other three WT treatments. The yield differences between the 0.30-, 0.45-, and 0.60-m WT treatments were insignificant, though yields were always greater at the lower WT depths. Similar trends were obtained from growth chamber 2 but the values of mean yield for the 0.15-, 0.30-, and 0.45-m WT treatments were greater than chamber 1. Combined analysis of the two growth chambers improved the results, and the yields for the 0.60-m WT treatment were significantly greater than for the 0.15-, 0.30-, and 0.45-m WT treatments. The average soybean yield obtained for the 0.15-m WT treatment was 20, 28, and 42% lower than the mean yield for the 0.30-, 0.45-, and 0.60-m WT treatments, respectively. The yield values for the 0.30-m WT treatment were 10 and 28% lower than the yield for the 0.45- and 0.60-m WT treatments, respectively. The overall mean yield for the 0.45-m WT treatment was about 20% lower than the 0.60-m WT treatment but only 10% higher than the mean yield for the 0.30-m WT treatment. The differences between the 0.30- and 0.45-m WT treatments were always found to be insignificant.

The soybean yield for different WT treatments obtained from this experiment are greater than those obtained in field experiments (Cooper et al., 1991, 1992; Oosterhuis et al., 1990). The reason for these greater yields could be the effect of a controlled environment that removed stresses like very dry or very wet climatic conditions.

The regression analysis was performed to determine the relationship between yield and WT depths (fig. 7). These results showed a linear increase in soybean yield with the increase in WT depth. Similar results were obtained by Madramootoo et al. (1993); however, these results are in contrast with the results obtained under field conditions (Cooper et al., 1991, 1992; Nathanson et al 1984). Pookpankdi et al (1989) found that average soybean yield was higher under saturated soil culture (SSC) than the conventional irrigation (CI). Soybeans developed a transitory chlorosis and shoot growth was slowed following exposure to high water tables (Hunter et al., 1980; Lawn 1985; Nathanson et al., 1984; Troedson et al., 1983). After an acclimatization period of two to four weeks, plants regained a healthy green color and rapid shoot growth resumed (Stanley et al 1980). Cooper et al. (1992) found the greatest yield of soybean at a 0.41-m WT depth when grown on a silt loam soil with a subirrigation/drainage water management system.

Table 4. Mean soybean yield (kg/ha) under different water table treatments

	Water Table Depth (m)						
	0.15	0.30	0.45	0.60			
Chamber	(kg/ha)				Mean	$LSD_{(0.05)}$*	Pr > F
1	4649b†	5962ab	6149ab	8324a	6271a	2670	0.0779
2	4930b	6005ab	7206ab	8273a	6604a	2328	0.0621
Mean	4789c	5984b	6677b	8298a	6437	1131	0.0042

* $LSD_{(0.05)}$ - least significant difference at the 0.05 probability level.
† Means in rows followed by the same letter are not significantly different at the 0.05 probability level.

Conclusions

The effect of WT depths on the movement of nitrate-N and metolachlor was studied in lysimeters. Nitrate-N and metolachlor concentrations in water samples were determined during the growing season at three sampling depths using suction tubes. After the removal of WT treatments, drainage outflow samples were also collected. Both nitrate-N and metolachlor concentrations were significantly reduced for shallow WT depths compared with deeper WT depths. Higher nitrate-N concentrations were observed at deeper soil depths while the metolachlor concentrations were higher at shallow soil depths. Generally, the nitrate-N and metolachlor concentrations decreased with the increase in time after planting. The results from the drainage outflow analysis also supported the fact that shallow WT depth can reduce the leaching of these chemicals to groundwater. Soybean yield was significantly reduced with the rise in WT depth. The results of this study indicate that, on the average, about 42% increase in soybean yield is possible by maintaining WT at a depth of 0.60 m below the surface.

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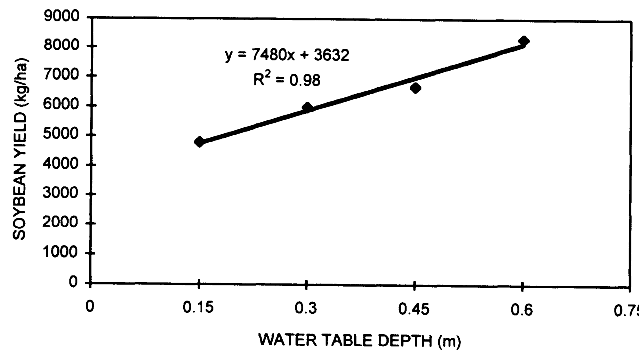

Figure 7–Soybean yield as a function of water table depth.

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