Special Issue Editorial

We are pleased to present here Vol. 18(3-4) of the International Agricultural Engineering Journal (IAEJ) which features two papers that describe Soil and Water Assessment Tool (SWAT) model applications, which are part of an ongoing Special Issue, as well as four additional papers that describe key findings for several other cutting-edge research topics. The two SWAT papers bring the set of total Special Issue papers to nine, including seven that were previously published in IAEJ Vol. 18(1-2). One additional issue containing Special Issue papers will be published in 2010. The Special Issue was inspired by the first SWAT Southeast Asia (SWAT-SEA) conference that was held in Chiang Mai, Thailand in January of 2009, as described in more detail in the editorial for IAEJ Vol. 18(1-2).

The first Special Issue article, authored by Taheriyoun et al., describes SWAT streamflow, sediment, and phosphorus testing that undergirds a genetic algorithm application for the 930 km^2 Aharchai river watershed located in northwestern Iran. The study describes optimal placement of selected Best Management Practices (BMPs) within different subwatersheds to reduce phosphorus movement to the Satarkhan reservoir, which captures the Aharchai River drainage at the outlet of the watershed. The second Special Issue paper by Jha et al. covers the emerging field of biofuels production and describes SWAT scenarios designed to assess potential expansion of corn or switchgrass production, relative to baseline conditions of corn-soybean production for the 4,800 km^2 Maquoketa River watershed located in northeast Iowa in the U.S. Midwest region. SWAT streamflow and pollutant testing results are also reported for this study as well as an economic analysis of producer costs of converting from traditional row crop production to switchgrass biofuel production. The third paper in this special issue that was authored by Nayak et al. was in fact also presented at the first SWAT Southeast Asia (SWAT-SEA) conference in Chiang Mai in January 2009. This paper highlights the role of nitrogen and phosphorus on eutrophication of lakes and seas from swine manure applications in agricultural watersheds. The other three papers in this special issue are related to water quality issues and give research findings on innovative research topics.

We appreciate your continuing interest in the Special Issue and also the other four papers that have been published in this issue of IAEJ and hope that future IAEJ issues will continue to prove scientifically interesting, relevant, and rewarding to our readers.

Sincerely,

Dr. Philip W. Gassman
Guest Editor, Special Issue IAEJ

Sincerely,

Dr. Rameshwar S. Kanwar
Chief Editor, IAEJ

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OPTIMAL SELECTION AND PLACEMENT OF POINT AND NONPOINT SOURCE POLLUTION CONTROL STRATEGIES USING A GENETIC ALGORITHM

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ABSTRACT

Eutrophication management of reservoirs is highly dependent on the control and reduction of watershed nutrient loads into the reservoir. Designing cost effective best management practices (BMPs) at a watershed scale is an important step in control and management of nutrient loads. In this study, an optimal BMP allocation model is developed by linking the Soil and Water Assessment Tool (SWAT) with a genetic algorithm (GA) to identify the minimum cost design (types and locations) of structural best management practices. The water quality target is derived using Vollenweider model for permissible phosphorous load as the main agent of eutrophication in the reservoir. The allowable phosphorous load input to the reservoir is considered as a constraint of the optimization model. Hydrological and water quality simulations are incorporated through SWAT with combinations of BMPs while the GA searches for the least cost combination. Structural BMPs in this model include detention ponds, field borders, grade stabilization structures and wastewater treatment plants. The case study is the Aharchai river watershed upstream of the Satarkhan reservoir in the Northwestern part of Iran. The optimum solution was obtained after a sensitivity analysis on the GA operating parameter. The cost of optimum BMP combination is U.S. $650 thousand for a 35% reduction in watershed phosphorous load reduction. The results also showed that field border were the most effective BMP and that detention ponds were the least effective BMP for phosphorous load control. The developed model demonstrates a significant value in watershed management practices with the aim of reservoir water quality control.

Keywords: *SWAT model, Best Management Practice (BMP), genetic algorithm, eutrophication.*

1. INTRODUCTION

Eutrophication of lakes and reservoirs is a serious water quality problem in many countries. This phenomenon is caused by excessive nutrient loads from the watershed upstream to the reservoir. Nutrient loads into a reservoir are mainly caused by point sources like municipal or industrial wastewater discharge to surface water and nonpoint sources such as agricultural practices on land. Therefore, the management of nutrient loads into a reservoir requires the knowledge of processes related to nutrient transport and transformation in the watershed.

Best management practices (BMPs) can be effective in reducing or eliminating pollutants before they enter a receiving water body. BMPs include both structural and nonstructural type. Structural BMPs include practices such as detention ponds, field borders, and grass waterways while nonstructural BMPs involve implementation of more efficient fertilizer use, land development restrictions, and similar practices. In this regard, the Soil and Water Assessment Tool (SWAT) model (Arnold and Forher, 2005) has been widely used to design BMPs for reducing nutrient loads at the watershed-scale, as described by Gassman et al. (2007). While evaluation of all BMP combinations are practically intractable, coupling an optimization algorithm with a watershed-scale simulation model (SWAT) can help identify the optimal or near-optimal management practices.

Coupling of genetic algorithms (GAs) with SWAT have been reported for several previous studies. Muleta et al. (2005) developed a decision support system for watershed management which is based on a linkage between a GA and SWAT to identify optimal or near-optimal land use patterns for selection of crop rotation and tillage operations in a watershed. An artificial neural network (ANN) was

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also developed to mimic the SWAT outputs and replace them during the search process. Arabi et al. (2006) used a GA-based optimization framework to evaluate a range of best management practices (BMPs) in a watershed with SWAT to minimize nutrient and sediment loads at minimum cost. Jha et al. (2009) combined the SWAT model with genetic algorithm to develop a trade-off frontier of least cost of achieving nutrient reductions and the corresponding locations of conservation practices. Kaini et al. (2008) coupled the SWAT model with a GA to identify the least cost design (sizes, types, and locations) of structural best management practices (BMPs) while meeting treatment goals at a watershed-scale. The water quality goals were reduction of peak flows and sediment loads at the watershed outlet.

Several previous studies describe SWAT applications that incorporate the effects of reservoirs on stream systems (Bosch et al., 2004; Jones et al., 2008; Prochnow et al., 2007). However, previous studies have not been reported that describe a GA interface with SWAT, that includes an assessment of water quality impacts in a receiving reservoir, reservoir application. The goal of this study is to evaluate reservoir water quality in response to the establishment of watershed management plans. Specifically, the objective of this study is to develop a linked GA- SWAT optimization model that identifies the optimal watershed management practices which can reduce the phosphorous loads into the reservoir at a minimum cost. The permissible load is obtained according to reservoir trophic status criteria. The model is applied to the Aharchai watershed and Satarkhan reservoir, located in northwest Iran.

2. WATERSHED DESCRIPTION

The study area is the 930 km^2 Aharchai river watershed, which is located in northwest Iran in the province of East Azerbaijan (Figure 1) and is a subbasin of the Aras River. The watershed location is between 38° 24' and 38° 41'N and 46° 20' and 46° 55' E and is shown in Figure 1. Land use distribution in the watershed consists of 36.5% dry farming, 27.3% range, 16.6% mixed dry farming and range, 12% bared land, 5.3% mixed irrigated farming and orchard land use, 1.4% irrigated farming, 0.5% urban area, and 0.4% water. The monthly average flow at the outlet of the basin is 2.9 m^3/s. The Satarkhan dam was constructed in 1998 near the watershed outlet (Figure 1) to provide water for drinking, irrigation, mining and industrial use in the region. Therefore, water quality of the reservoir is of great concern which has deteriorated in recent years due to excessive nutrient loads discharged from the river which has resulted in reservoir eutrophication.

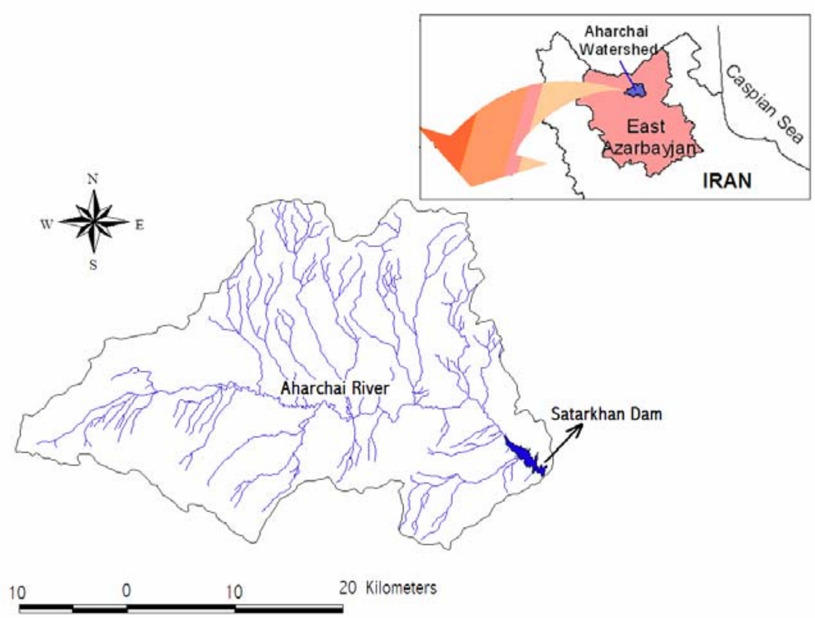

Fig. 1: Aharchai river watershed upstream of the Satarkhan reservoir in east Azerbaijan – North-western Iran

3. METHODOLOGY

The optimization model for this study was developed by coupling SWAT with a GA to design the optimum BMP combination at a watershed scale at a minimum cost. The model is designed to search for the least cost combination of BMPs ensuring that phosphorous load reduction criterion is met. The phosphorous load was selected as the main indicator of the Satarkhan reservoir eutrophication levels in this study. The linkage among various components of the model is illustrated in Fig. 2. This figure shows the steps of the genetic algorithm process to search for the combination of BMPs at a minimum cost. Each component of the model is discussed in more detail below.

4. DESCRIPTION OF SWAT AND DATA INPUTS

SWAT is a physically-based, time continuous simulation model that operates on a daily time step. It is designed to evaluate management effects on water quality, sediment production and yields of agricultural chemicals. The major components of SWAT include hydrology, weather, erosion, pesticide and nutrients (Neitsch et al., 2000). The SWAT model divides the watershed into subbasins to represent the large scale spatial heterogeneity of the study area. Each sub-watershed is parameterized using a series of HRUs (hydrologic response units) which are a particular combination of land cover, soil and management.

In this study, the Aharchai river watershed was subdivided into 81 subbasins and 258 HRUs as shown in Figure 3. The maximum, average and minimum size of the subbasins are 3700, 1150 and 2 ha, respectively, which sum up to 93,000 ha for the total watershed area. The watershed parameterization and the model input were derived using the SWAT Arcview 3.2 (AVSWAT) interface (Di Luzio et al., 2004a; 2004b) and the simulations were performed with SWAT version 2000 (Arnold and Forher, 2005).

The data used for the SWAT simulations included digital elevation model (DEM) with a resolution of 90×90 m , land use and soil maps at a scale of 1:50000, and climatic data, which included daily precipitation and daily maximum and minimum temperatures obtained from two temperature stations and one precipitation station in or near the study region (Figure 4; Tempgages and Raingages) and

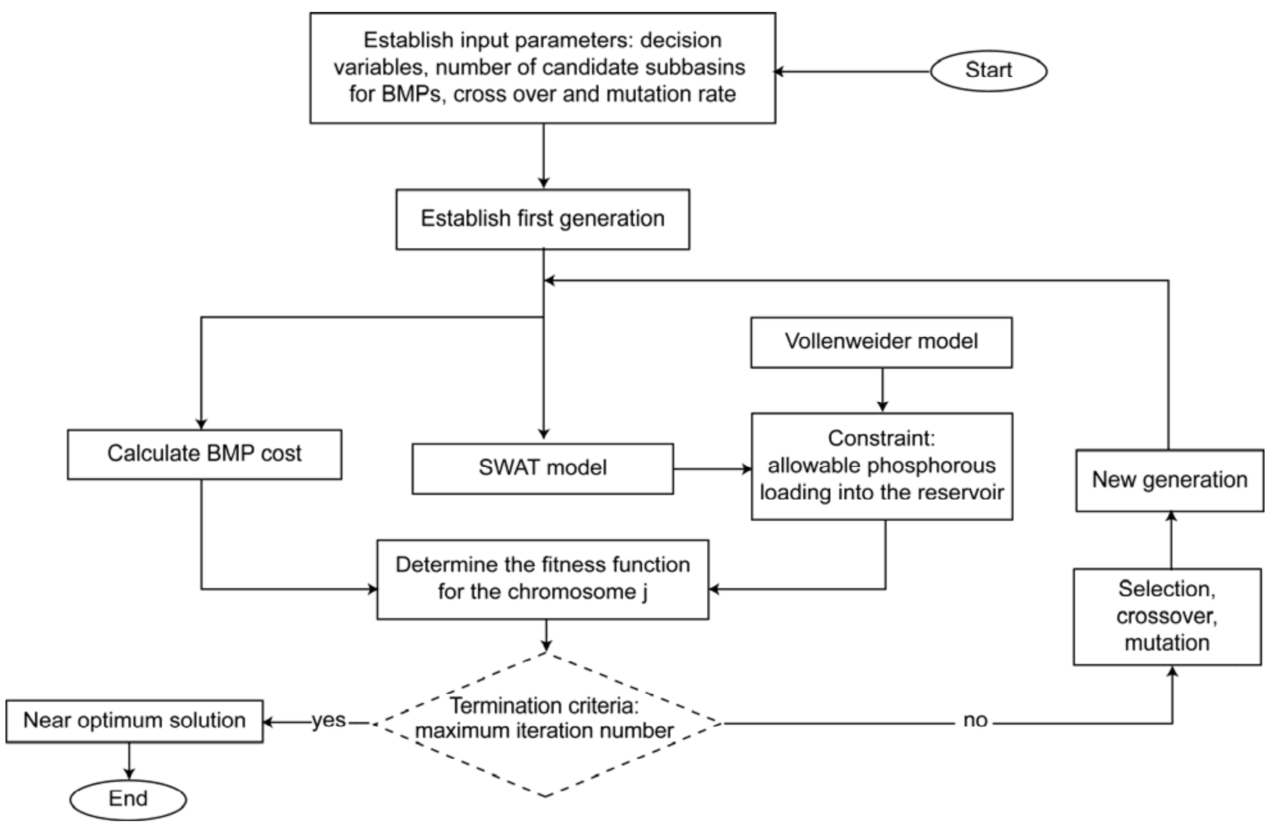

Fig. 2: Flow chart of optimization process used in the GA-SWAT model

solar radiation, wind speed and relative humidity inputs generated internally in SWAT using monthly climate normals available for another station (Figure 4; Weagages). These stations were chosen by the model, among several located in the region, because AVSWAT chooses the climate data that is closest to the geographic centroid of the subwatersheds. The weather data were input to the subwatersheds using the AVSWAT interface. The soil map includes 7 types of soil with 3 to 5 layers which are mostly clay and silt. Point sources of pollution defined for the model were based on the location of villages in the watershed (Fig.3), because there is no industry or urban area in the watershed.

5. MODEL CALIBRATION AND VALIDATION

Gassman et al. (2007) reported more than 100 case studies that describe swat model calibration and validation for flow and pollutants. The majority of the Nash Sutcliffe coefficient values (see Eq. 1 below) exceeded 0.5, indicating that the model was able to replicate a wide range of observed streamflow and in-stream pollutant levels. However, poor results were reported for some studies, especially for daily comparisons.

In this study, the model was manually calibrated and validated for the outlet values of reach 71 which drains directly to the Satarkhan reservoir at the Orang

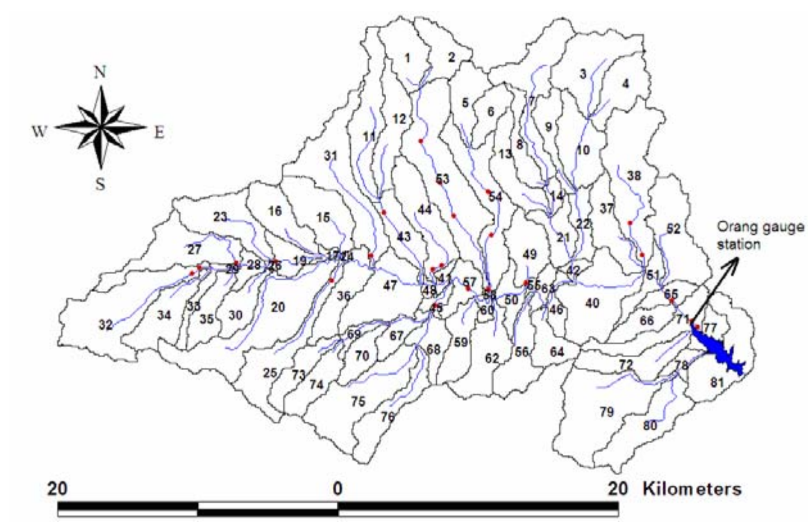

Fig. 3: Aharchai SWAT watershed delineation with 81 subbasins and 258 HRUs; point sources are indicated by the red dots

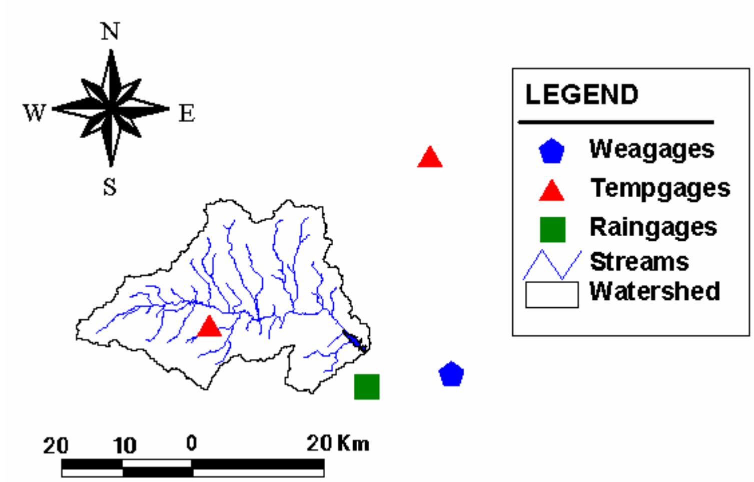

Fig. 4: Location of climate stations that provided temperature, precipitation, and other weather data for the SWAT simulations

gauge station (Figure 3). Monthly flow measurements were available from 1975 to 2005 and sediment and phosphorous were recorded from 2003 to 2005. So calibration and validation was done based on a three-year data series from Jan. 2003 to Dec. 2005, with two years for calibration (2003 to 2004) and one year for validation (2005). The performance of the simulations was evaluated by three criteria: Nash-Sutcliffe efficiency (NSE), Percent bias (PBIAS), and RMSE-observations standard deviation ratio (RSR).

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). The NSE is computed as shown in equation 1:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \quad (1)$$

where, O_{avg} represents the mean of the observed values, S_i and O_i are the simulated and observed values, respectively, and n is the number of values considered. The NSE ranges between $-\infty$ and 1.0, with $NSE = 1$ being the optimal value (Moriasi et al., 2007).

The PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts and is computed as follows:

$$PBLAS = \left[\frac{\sum_{i=1}^{n}(O_i - S_i)\times 100}{\sum_{i=1}^{n}(O_i)}\right] \quad (2)$$

The RSR standardizes the RMSE (Residual Mean Square Error) using the observations of standard deviation. The lower the RSR, the lower the RMSE, and the better the model simulation performance. This criterion is described by equation 3.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(S_i - O_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - O_{avg})^2}} \quad (3)$$

In general, acceptable statistical results for simulation models as suggested by Moriasi et al. (2007) are: $NSE > 0.50$ and $RSR < 0.70$, and $PBIAS < 25\%$, 55%, and 70% for streamflow, sediment, and phosphorus, respectively. The water balance was calibrated first, then the sediment and phosphorous were calibrated.

6. PHOSPHOROUS LOADING MODEL

In order to determine the allowable phosphorous loading input to the reservoir, a Vollenweider loading plot is applied (Vollenweider, 1975; USEPA, 2000). In this method, the eutrophication status is determined through the graph shown in Figure 4 based on reservoir residence time and phosphorous annual load per unit area of the reservoir. The value of the horizontal axis of the graph is calculated based on Eq. (4).

$$\frac{H}{\tau_w} = \frac{HQ}{V} \quad (4)$$

where H represents depth (m), Q is the average annual inflow (m^3/s), V is the volume of the reservoir (m^3), and τ_w refers to the reservoir residence time (s).

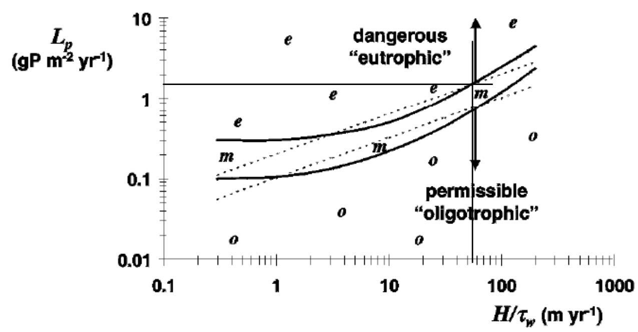

Fig. 5: Vollenweider's loading plot (Vollenweider 1975)

The allowable phosphorous load criterion is obtained from the graph based on the limit between the mesotrophic and trophic status of the reservoir as shown in Figure 5. As the load per unit area of the reservoir is equal to 1.5 $g/m^2.y$, the allowable annual load is calculated 10.8 ton/year. According to the output from base case run of the SWAT model, the annual phosphorus load is equal to 16.7 ton/year. Therefore an overall reduction of about 35% is needed to ensure that trophic status of the reservoir will not exceed mesotrophic conditions. This target can potentially be achieved through structural BMP implementation in the watershed, as discussed in the following section.

7. BMP REPRESENTATION IN SWAT

The structural best management practices that are used in this study include: detention ponds (DP), field borders (FB), grade stabilization structures (GS) and wastewater treatment plants for point source reductions (PR) within the watershed. A detention pond is a permanent pool which reduces the load by retaining flow for certain time. In this study, the infiltration type of detention pond is used with a bottom permeability coefficient (K) of 0.5. A field border is a uniformly graded and densely vegetated area at the border of the field where excessive load due to erosion is likely to occur. A field border is represented by the width of the edge of field border (FILTERW) as described by Neitsch et al. (2002a). A grade stabilization structure is a structure designed to reduce the channel grade in a natural or constructed water course. It reduces or prevents erosion due to higher grade on the channel bed.

The representative parameters for the BMPs are collected from the literature and a manual sensitivity analysis which determined the most effective parameters for BMP representation. Table 1 presents the key parameters used to represent the four BMPs in this study.

The unit costs of BMPs were obtained from the opinions of the experts dealing with the bids and contracts regarding the construction costs in the region. Table 2 shows the cost of BMPs per unit value which are reported in US dollars.

8. OPTIMIZATION COMPONENT

The GA developed by Holland (1975) is based on natural selection of chromosomes from a population for mating, reproduction of offspring by crossover, and mutation to ascertain diversity. Each chromosome string in the population corresponds to a solution for the problem at hand, with each variable being represented by a gene. A GA allows a population composed of many individuals to evolve under specified selection rules to a state that optimizes the cost. After defining optimization parameters and the objective function, potential solutions are randomly generated in the initial generation. Selection, crossover and mutation are the GA operations which generate new solutions. While crossover selects properties from parent solutions to the offspring solutions, mutation ensures that the search will not converge in a local optimum point. The search is stopped based on selected convergence criteria or maximum iteration number. The main steps in genetic algorithms are as follows:

Table 1: BMP types and decision variables used in SWAT

No.	BMP Type	SWAT Parameters	Parameter description	Default	With BMP
1	Grade stabilization structure (GS)	CH_S2	Channel Slope Steepness	0.069	0.03
2	Field border (FB)	FILTERW	Filter width (m)	0	20
3	Point source reduction (PS)	MINPCNST	Mineral Phosphorus load from Point source	Load without treatment	50% load removal
4	Detention pond (DP)	PND_FR	Fraction of HRU draining to pond	0	0.9
		PND_PSA	Surface area of ponds when filled to principal spillway (ha).	0	30
		PND_PVOL	Volume of water stored in ponds when filled to the principal spillway (m^3)	0	20000

Table 2: Unit and total Costs of BMPs

BMP	Unit	Unit Cost ($)	Total Cost ($)
Grade stabilization structure (GS)	Structure	8000	8,000
Field border, (FB)	M width of filter	10	200
Wastewater treatment plants (PS)	Kg/d load of phosphorous	100000	50000 × load*
Detention pond (DP),	m^3 pond volume	1.5	30000

*Assuming 50% of load reduction

1. Encoding of the decision variables and placing them in a chromosome.
2. Setting the probability for mutation and crossover.
3. Creating an initial population (first generation).
4. Determination of fitness for every chromosome in the current population
5. The selection of better chromosomes for matching and running a cross over operator for shuffling the selected chromosomes.
6. Performing mutation for selected chromosomes.
7. Set the new generation.
8. Repeat steps 4–7 to obtain the optimal or near optimal solutions.

The main field of GA applications includes problems with computational complexity due to a high number of decision variables and non-linear behavior. Therefore, the GA is an appropriate optimization technique for spatial allocation of BMPs in the SWAT model, because unlike other optimization methods it does not require linearity, continuity, or differentiability of either the objective or the constraint function. However, one of the disadvantages of the GA is the long time that the algorithm searches for the optimum solution and the other is that its convergence to an optimum cannot be guarantied. However, many previous studies have shown that the GA converges to near optimal solutions for the problem of BMP selection and placement in the SWAT model (Arabi et al., 2006; Muleta et al., 2005; Kaini et al., 2008).

The efficiency of the algorithm depends on the optimization's operating parameters and the initial population. The procedure is less efficient if a higher number of individual evaluations are required for converging to an optimum. The values of the operating parameters are problem-dependent and can be determined by performing a sensitivity analysis. In this study, the GA was employed to optimize spatial allocation of BMPs at a minimum cost. The specification of the optimization model is listed as follows:

1. Objective function: minimize the BMP cost.
2. Constraint: Not violating the permissible phosphorous load and simulation model constraints.
3. Decision variables: representative BMP parameters listed in Table 1.

In the GA, each chromosome corresponds to a specific BMP combination within the watershed. The length of each chromosome corresponds to the total number of genes, which represent individual management actions that are considered in the optimization procedure. Figure 6 shows a schematic of a chromosome for placement of BMPs. In this figure, four genes, corresponding to the four types of BMPs, are implemented as decision variables for each subbasin. A binary coding is considered for the genes referring to the existence of the BMP. Because there are 4 BMP options for each subbasin, the total number of genes for each chromosome is calculated as 81×4=324. A FORTRAN computer code was developed to provide the linkage between the GA and SWAT.

Selection of the population size and the operating parameters is complex and is likely to vary for different problems. Large populations provide the GA with an adequate sampling of the search space. A small population size may cause the GA to become trapped in a local optimum, whereas a population that is too large may be computationally inefficient and take too long to converge. In this study, a sensitivity analysis was performed for the different combinations of operation parameters including population size, generation number, and cross over and mutation rates in order to determine the most optimal GA parameter values. The final GA SWAT runs were performed using just climate year 2004, which was a normal year, to reduce the overall computation time.

9. RESULTS AND DISCUSSION

Figures 7 to 9 illustrate the observed and simulated flow, sediment and phosphorous data for calibration and validation periods. The efficiency for each calibration and validation is shown in the figures.

Fig. 6: Schematic of a chromosome in the genetic algorithm

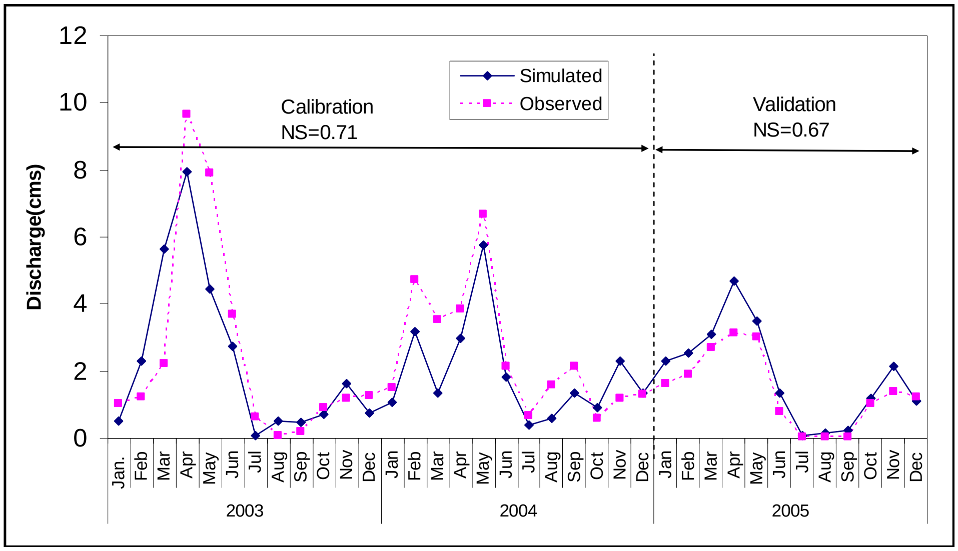

Fig. 7: Model calibration and validation results for monthly discharge data at Orang gauge station inlet to the reservoir from Jan. 2003 to Dec. 2005

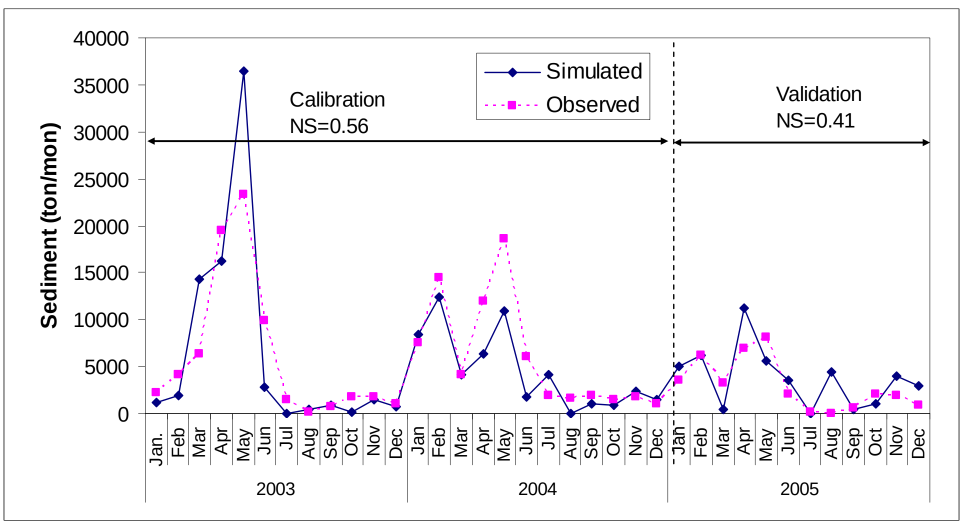

Fig. 8. Model calibration and validation results for monthly sediment data at Orang gauge station inlet to the reservoir from Jan. 2003 to Dec. 2005

Table 3 shows the results of three criteria for discharge, phosphorous and sediment. The NSE is acceptable across all the indicators except for validation of sediment which is less than 0.5. The PBIAS shows the average tendency of the simulated discharge in the validation period is 31% less than the observed values, which is greater than the previously suggested criterion. However, this criterion is in acceptable range for other cases. The RSR for all cases is less than 0.7 and shows satisfactory results both for calibration and validation of the parameters. It shows that the model is best fitted for simulation of sediment.

Table 4 summarizes 6 combinations labeled as setup 1 to 6 for the GA sensitivity study. Figure 10 illustrates the results of the sensitivity analysis through 2000 individual model evaluations. As shown in the figure, setup 3 with the lowest fitness function value was found to be the most efficient. Based on the values of setup 3 a total number of 6400 model evaluations were performed to obtain the optimum solution as depicted in Figure 11. The dots show the solutions that do not satisfy the constraint and a penalty value is added to their cost function. The curve is formed by the minimum values in the iterations.

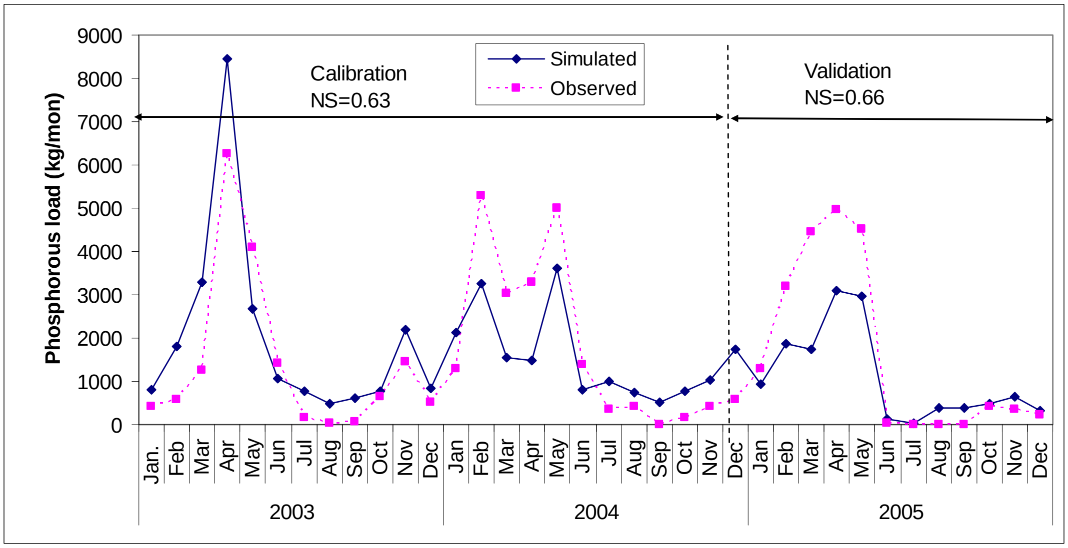

Fig. 9: Model calibration and validation results for monthly phosphorous load data at Orang gauge station inlet to the reservoir from Jan. 2003 to Dec. 2005

Table 3. Results of calibration and validation criteria

Criteria		Discharge	Phosphorus	Sediment
NSE	Calibration	0.71	0.63	0.56
	Validation	0.67	0.66	0.41
PBIAS	Calibration	15.65	-11.02	10.08
	Validation	-31.57	33.15	-16.73
RSR	Calibration	0.58	0.39	0.37
	Validation	0.49	0.42	0.39

Table 4: Various combinations of GA operating parameters in the sensitivity analysis

Setup	Generation	Cross over	Mutation	Population size
Setup 1	150	0.85	0.05	30
Setup 2	100	0.7	0.08	60
Setup 3	80	0.8	0.05	80
Setup 4	120	0.75	0.03	50
Setup 5	100	0.85	0.04	45
Setup 6	150	0.7	0.05	35

The minimum cost for the optimum solution is $650,000. This optimal combination of BMPs can reduce the total watershed phosphorous load to a level of 10.8 ton/yr, which will maintain the trophic level of the Satarkhan Reservoir at the mesotrophic status.

The optimum combinations of the BMPs are as follows:

- Grade stabilization structures in 34 subbasins,
- Field borders (FB) in 43 subbasins
- Point source reductions in 35 subbasins
- Detention ponds (DPs) used in 7 subbasins.

The results show that field border is the most cost effective option for phosphorous load reduction. On the other hand, the detention pond is the least-cost effective BMP because this BMP was assigned to the smallest number of subbasins. Figure 12 shows the graphical presentation of optimal spatial allocation of BMPs for the Aharchai watershed.

In order to provide different options for watershed managers in choosing among the best solutions of BMPs in the watershed, a trade-off curve based on the results is developed which is demonstrated in Figure 13. It shows reduction of phosphorous loads estimated for the best solution of the optimization model versus their associated cost. Three marked points on the graph of Figure 13 refers to the optimum solution and its upper and lower limit of 5% tolerance for allowable phosphorous loads.

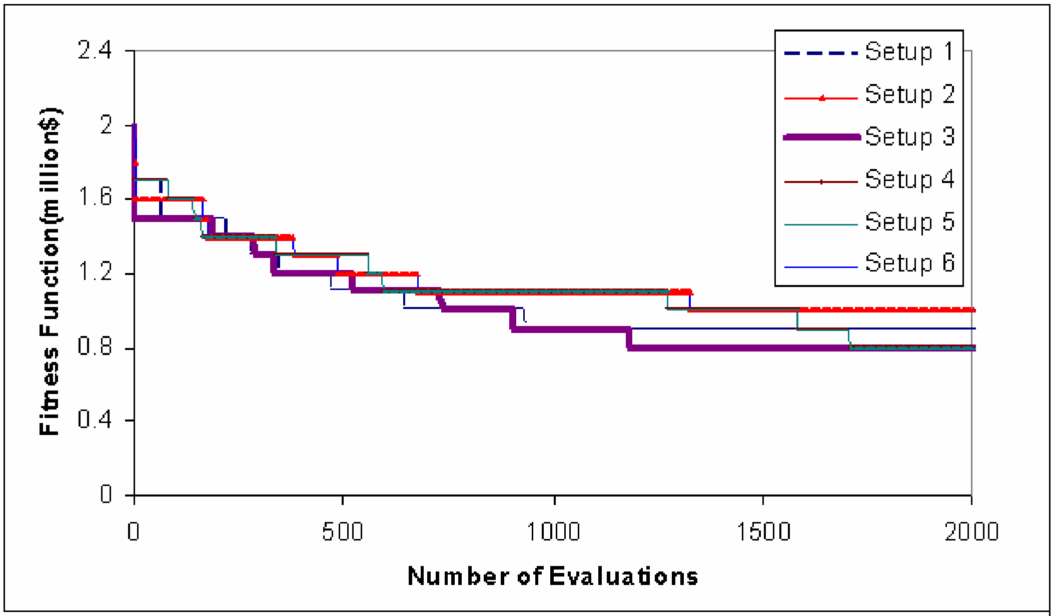

Fig. 10: Sensitivity analysis of the GA operating parameters

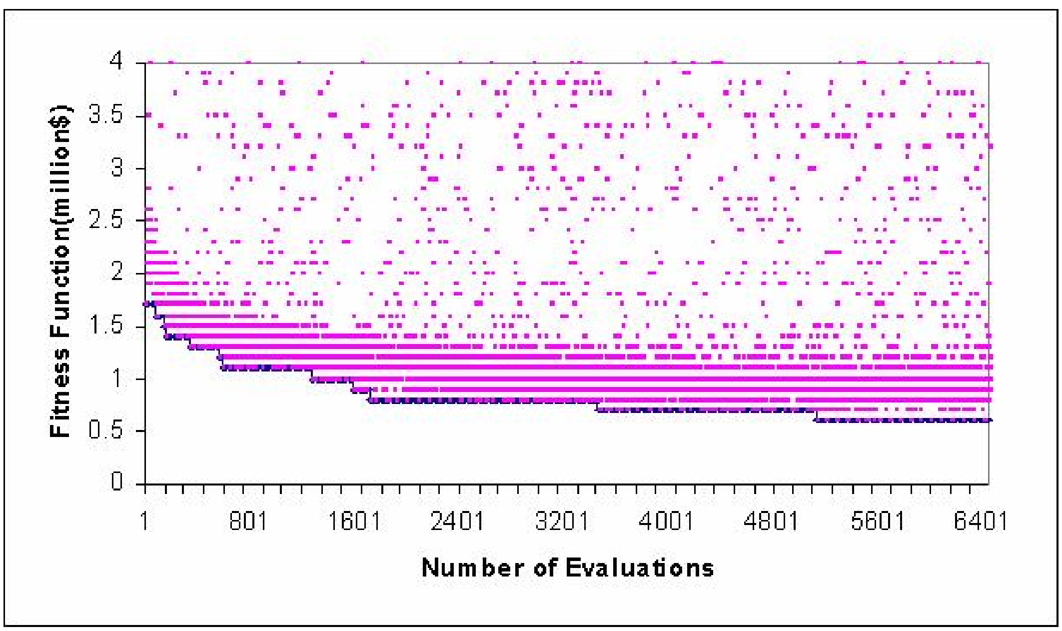

Fig. 11. Optimization outputs for the 6400 evaluation (80 generation)

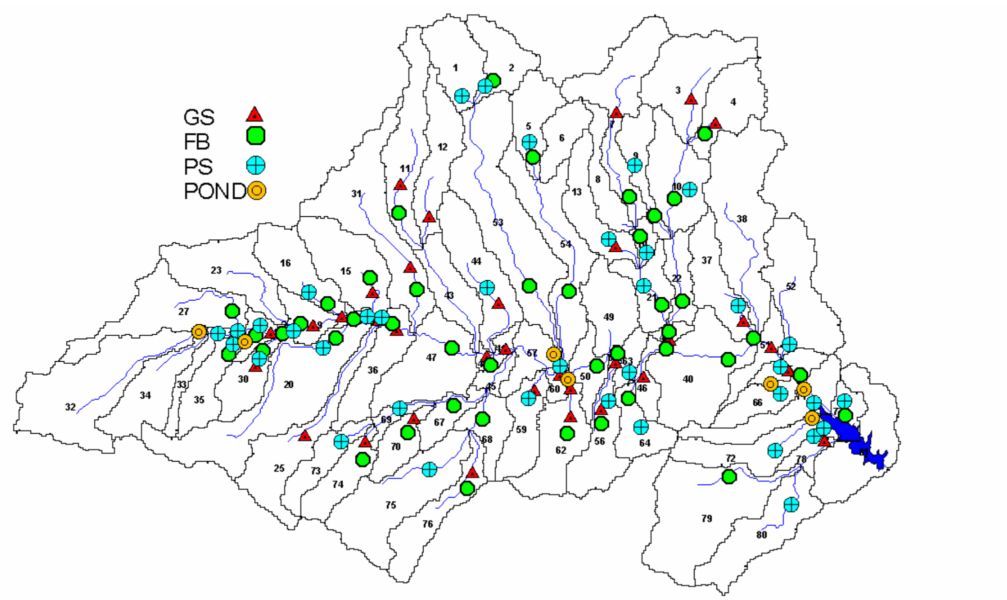

Fig. 12: Optimal spatial allocation of BMPs for the Aharchai watershed

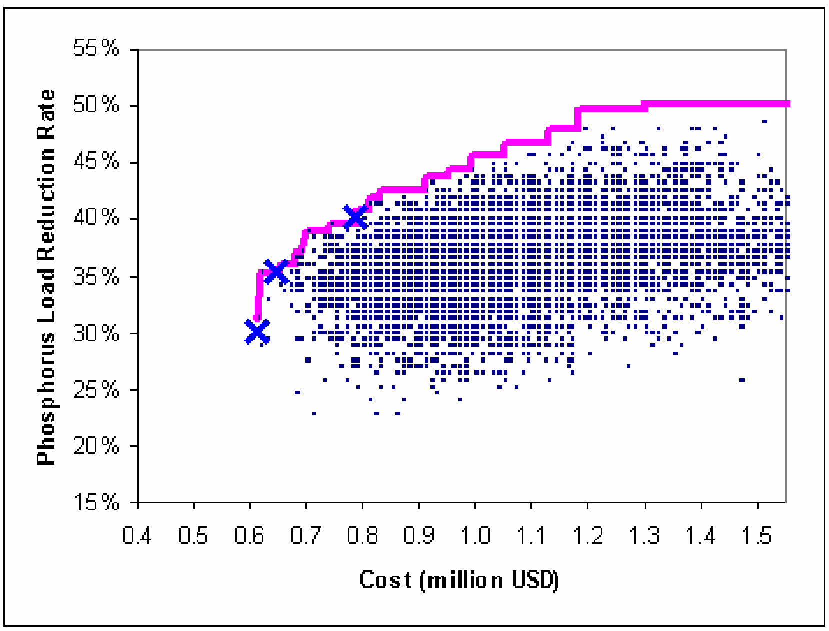

Fig. 13. Trade-off between cost and reduction of phosphorous load

Table 5: Number of BMPs on the best solutions of optimization model

Phosphorus Load(ton/yr)	Reduction Rate (%)	Number of BMP				COST
		GS	FB	PR	DP	Thousands($)
10.8	35%	34	43	35	7	650
10	40%	36	45	37	8	770
11.7	30%	31	42	31	9	610

The three above mentioned BMP combinations with the corresponding cost and percent of load reduction are presented in Table 5. The third row shows that a 6% saving of the BMP cost ($40,000) is achieved by ignoring 5% of the phosphorus load that exceeds the allowable load input to the reservoir (11.7 tons/yr). These results illustrate the capacity of the optimization model to handle the tradeoff between environmental and economic criteria in the objective function. This approach can also be used as a tool by water quality modelers and watershed managers to explore flexible controls of the pollutant loads based on local water quality regulations and standards. In this regard, it is important to analyze the results of the optimization model according to local management considerations, limitations, and engineering judgment.

There are some uncertainties in the results which are needed to be considered in decision making. These uncertainties are due to the assumptions during the modeling procedure. Using a finer resolution of subbasins and HRUs may lead to more precise results. Longer SWAT simulations that incorporate a greater range of climatic inputs, beyond just the typical year of 2004, would also provide better accounting of the impacts of climatic variability. Considering all the possible parameters for representation of the BMPs may be another improvement in the results of this model, such as the SWAT BMP simulation criterion suggested by Arabi et al. (2008). There are also weaknesses in the current SWAT modeling approach for some BMPs such as the FILTERW parameter which is very simplistic representation of filter strips; White and Arnold (2009) have developed an enhanced filter strip method that will allow considerably improved filter strip simulations in future versions of SWAT. Finally, only four BMPs were included in the optimization analysis. Considering more BMPs such as conservation tillage and terraces could improve the reliability of the simulation results.

10. SUMMARY AND CONCLUSIONS

A GA-based optimization procedure was developed for selection and placement of BMPs to control the eutrophication of the reservoir of Satarkhan reservoir. One of the main solutions to eutrophied reservoirs is the reduction of nutrient loads, especially phosphorous, to maintain the trophic status at a maximum allowable level of mesotrophic condition. The effect of structural BMPs can be simulated by the SWAT model and the coupled GA-SWAT model is able to search for the minimum cost combination of BMPs in order to achieve the nutrient reduction criteria used in this study. The best operating parameters of the genetic algorithm was selected through a sensitivity analysis. The optimum solution was also evaluated through a trade-off curve which consists of load reduction versus BMP cost. The results showed the field border as the most cost effective measure for phosphorous load reduction due to its efficiency and the low cost. On the contrary, detention pond was rarely used because of the high construction cost and insufficient efficiency in comparison with the other BMPs. The watershed-scale optimization model used in this study is well suited to establish relationships between structural BMPs and reservoir water quality, thus satisfying environmental policy objectives. Regardless of the existing limitations and uncertainties of the developed optimization model such as BMP type and subbasin resolution, the algorithm shows promise for developing watershed restoration and management plans.

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ECONOMIC AND ENVIRONMENTAL IMPACTS OF ALTERNATIVE ENERGY CROPS

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ABSTRACT

This paper provides estimates of the cost associated with inducing substantial conversion of land from production of traditional crops to switchgrass and its potential environmental consequences. Higher traditional crop prices due to increased demand for corn from the ethanol industry has increased the relative advantage that row crops have over switchgrass. Results indicate that farmers will convert to switchgrass production only with significant conversion subsidies. Potential environmental consequences of this conversion were analyzed using three stylized landscape usage scenarios, one with an entire conversion of a watershed to switchgrass production, a second with the entire watershed planted to continuous corn, and a third scenario that places switchgrass on the most erodible land in the watershed and places continuous corn on the least erodible. The Soil and Water Assessment Tool (SWAT) watershed-scale water quality model was applied to the Maquoketa River Watershed, which drains approximately 4,800 km^2 of heavily cropped area in eastern Iowa. The modeling set up was well-calibrated for streamflow, sediment yield, and nutrient loadings including nitrogen and phosphorus, as evident by R^2 and model efficiency (E) values greater than 0.7. Conversion of all existing croplands to switchgrass reduced sediment yield substantially by 84% and nitrate and phosphorus loads by 44 and 83% respectively, whereas converting everything to cropland increased all three by 23, 147, and 138% respectively. This study presents initial steps in identifying the economic as well as environmental consequences of a large-scale move to the bioeconomy.

Keywords: *Switchgrass, energy crops, land use, SWAT, water quality.*

1. INTRODUCTION

Biofuels are a renewable energy source that can be produced domestically from a wide variety of plant materials and wastes. Because plants absorb CO_2 during growth and may increase stores of soil organic carbon, biofuels may reduce greenhouse gas emissions relative to petroleum-derived fuels. It has been suggested that biomass energy crops such as switchgrass and miscanthus could be used for the increased production of bioenergy in the Midwest USA while still preserving, or even improving, environmental quality in the region (Heaton et al., 2008; Schmer et al., 2008; Simpson et al., 2008). Numerous studies at the field scale provide indications concerning the yield and energy potential associated with growing switchgrass and other bioenergy crops (e.g., Parrish and Fike, 2008), but there is a dearth of information concerning the landscape effects, particularly in terms of water quality, that might be associated with large-scale changes in cropping systems. Such changes might take very different forms, that is, toward more intensive cropping of continuous corn with large-scale residue removal versus significant planting of perennial crops such as switchgrass, depending on economic conditions and the design of farm program payments.

The purpose of this study is to provide a starting point for discussion of these issues at the landscape level. To do so, we provide general estimates of the costs associated with inducing substantial conversion of crop land to switchgrass production; such large-scale conversions of cropland into switchgrass production have not occurred previously in Iowa or the upper U.S. Midwest region. We then quantify the environmental impacts of large-scale conversions of agricultural landscapes into either expanded corn and/or switchgrass production, to provide insight into the potential impacts of introducing increased levels of potential biofuel crops. The environmental impacts were determined using the Soil and Water Assessment Tool (SWAT) water quality model (Arnold et al.,

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1998; Arnold and Fohrer, 2005), which was applied for several biofuel scenarios for the Maquoketa River watershed in northeast Iowa that is characterized by a high percentage of agricultural land use and is a major source of sediment and nutrient exports to the Mississippi River.

The specific objectives of the study were to: (1) provide an overview of economic factors that must be considered when introducing switchgrass as a biofuel crop, (2) calibrate and validate SWAT for streamflow, sediment yield, nitrate, total nitrogen (Total N) and total phosphorus (Total P), and (3) use the calibrated model to evaluate the effect of three stylized landscape usage scenarios on sediment and nutrient loadings in the watershed that included entire conversion of the watershed to switchgrass production, entire conversion to continuous corn, and switchgrass placed on the most erodible land and continuous corn planted on the least erodible in the watershed.

2. ECONOMIC ANALYSIS OF SWITCHGRASS CONVERSION

Midwestern farmers will move acreage toward production of switchgrass only when the returns from growing switchgrass can compete with the returns from growing prevailing corn and soybean crops. Currently, the returns over variable costs of production from growing corn and soybeans in either a corn-soybean rotation or a continuous corn rotation are projected to be approximately $250 per acre. This suggests that the returns over variable costs and annualized establishment costs to switchgrass production will need to approach this level before farmers will consider changing to switchgrass.

Duffy and Nanhou (2001) provide estimates of the annual cost of producing switchgrass and the annualized cost of establishing a stand of switchgrass. With a yield of four tons per acre, the cost is approximately $187/acre. A yield of six tons per acre raises the cost to $241 because of increased harvest cost. These costs include the cost of baling the switchgrass into large bales but do not include transporting the bales to an ethanol plant. While it is uncertain that switchgrass yields could increase substantially above these levels, it is not likely that significantly increased yields will be common during the next 5 to 10 years without major research breakthroughs.

Adding these cost estimates to the projected returns from corn and soybeans gives the amount of revenue per acre that will be required to induce farmers to switch a significant number of acres to switchgrass. The break-even revenue level for switchgrass with a yield of four tons, a variable cost of $187, and a required return over costs of $250 is $437 or almost $110 per ton. The break-even revenue rises to $491 per acre with a yield of 6 tons per acre because of the higher production costs. The higher yield reduces the per-ton break-even price to about $82 per ton.

Without subsidy, a producer of cellulosic ethanol must be willing to pay a farmer at least this amount at the farmgate to induce a corn and soybean farmer to switch acres. The ability of the ethanol producer to pay for biomass depends on a number of factors including: (1) the cost of transporting the harvested production from the farm to the plant, (2) the variable cost of converting the biomass to ethanol, and (3) the price of ethanol.

Transportation costs will depend on a number of factors, including distance traveled, fuel prices, and labor prices. A reasonable estimate for the total cost of delivering bales to a processing facility is $8.00 per ton.

Because there are no commercial-scale cellulosic ethanol plants in operation, it is quite difficult to determine what will be the variable cost of converting switchgrass to ethanol. English et al. (2006) assume that conversion costs decrease from $1.40 per gallon in 2006 to $0.73 per gallon in 2015. The average conversion cost for the farm bill period of 2008 to 2012 is $1.10 per gallon.

What ethanol prices will be in the future cannot be known. Ethanol futures are trading at about $1.75 per gallon, but the contracts extend out only one year. Most observers believe that ethanol prices could drop precipitously as total ethanol production approaches 13 to 14 billion gallons per year because this level of production will saturate the 10 percent blend market. To show the effects of lower prices, we calculate ability to pay for switchgrass at a price of $1.25 per gallon and a price of $1.75 per gallon.

The first step in this calculation is to convert everything to a per-ton basis. Using an ethanol yield of 70 gallons per ton of switchgrass yields a cost of $77 per ton of converting switchgrass to ethanol. Adding in the $8.00 transportation cost gives a total cost of $85 per ton. Revenue per ton of switchgrass is found by multiplying the price of ethanol by the ethanol yield per ton, which is $87.5 per ton at an ethanol price of $1.25 per gallon and $122.5 per ton at an ethanol price of $1.75 per gallon.

The maximum amount a processor will pay per ton of switchgrass equals the difference between revenue and cost. At the $1.25 per gallon price, this amount is $2.50 per ton. At the $1.75 per gallon, this amount is $37.50 per ton. Because both of these maximum prices are less than the per-ton break-even farmgate prices, no market for switchgrass will emerge without some sort of public support. The minimum amount of per-ton support needed equals the difference between the farmgate break-even price and the maximum willingness to pay of the ethanol producer. Table 1 reports these amounts. The required price subsidies range from $44.33 per ton to $106.75 per ton depending on switchgrass yields and the price of ethanol. Converting these per-ton subsidies into per-acre payments can be done simply by multiplying these per-ton subsidies by the yield per acre. The resulting per-acre payments range from a low of $265.98 per acre to $475.98 per acre.

Given the assumptions behind this analysis, the conclusion that can be drawn here is that the level of required payments will be quite high unless the price of ethanol unexpectedly increases or the cost of converting cellulose to ethanol drops significantly. Of course, on land where the returns to corn and soybeans are less than $250 per acre, then the required payments will also decrease. But high corn and soybean prices have dramatically increased returns to these crops, so much of the Iowa farmland is expected to have returns of these magnitudes over the farm bill period.

The most straightforward policy mechanism available to make these payments would be to have farmers enroll their land into some sort of biomass reserve program whereby in exchange for per-acre payments farmers will dedicate their land to biomass production. If the economic returns from converting cellulose to ethanol do not improve significantly above the levels previously identified, then farmers would not be required to actually harvest and sell their biomass crop to an ethanol producer. This would allow farmers and scientists to fine-tune biomass crop production techniques on a commercial scale without artificially forcing farmers to incur harvest costs and without having the ethanol producer actually have to transport the harvested biomass to a plant and convert it into ethanol unless the economic returns dictate that it makes sense. In this way, the maximum payment that would be required would equal the opportunity cost of land, which is $250 per acre.

Table 1: Price subsidies needed to make switchgrass competitive with corn

Switchgrass Yield (tons per acre)	*Price of Ethanol ($/gal)*	
	1.25	1.75
	Subsidies Needed $/ton	
4	106.75	71.75
6	79.33	44.33

In addition, it would make sense to have an additional alternative payment scheme for farmers willing to participate in field-scale trials of biomass crops and biomass systems (for example, intercropping, new crops, innovative collection and transportation approaches) other than straight switchgrass in order to learn more about other alternatives for energy production.

In short, a two-pronged policy approach might be implemented, one prong focused on getting a large amount of biomass crops in production to provide adequate feedstock in the future in anticipation of the development of technology that makes large-scale production economically viable (this could be thought of as a biomass reserve component) and the second prong focused on developing innovative alternatives that might eventually solve the current technological problems (a biomass innovation program).

The biomass reserve program could be quite similar to the current U.S. Conservation Reserve Program (CRP), which is described by USDA-FSA (2009), with one important difference. While farmers could offer to plant their land to biomass crops in exchange for per acre payments (ideally through an efficient bidding mechanism), they would retain the option of selling the biomass. This latter feature differs from the current CRP but would have the important benefit of providing an incentive to both farmers and processors to identify ways to solve the transport and conversion issues currently preventing economic viability of switchgrass production. The biomass innovation program might be modeled after the Conservation Innovation Grants program or possibly woven into a revised Conservation Securities Program.

3. ENVIRONMENTAL IMPACT ASSESSMENT USING SWAT

3.1 Description of SWAT

SWAT is a long-term, continuous, watershed-based model and operates on a daily time step. It was developed to predict the impact of land management practices on the hydrology and water quality responses for a watershed. Major model components are hydrology, weather, soil temperature, crop growth, sediment, nutrients, pesticides, bacteria, and land management. In the SWAT modeling approach, a watershed is first divided into multiple subwatersheds and then the subwatersheds are further subdivided into smaller lumped units called hydrologic response units

(HRUs). HRUs are unique combinations of land use, soil, and management practices. Water balance and nutrient dynamics are computed at the HRU level and the resulting loadings are summed at the subwatershed level. Total loadings at the subwatershed level are then routed through streams and reservoirs to the watershed outlet. The model has been extensively used worldwide and has proven to be a very successful and useful tool in simulating hydrology and water quality response at the watershed level, as evidenced by over 200 SWAT-related peer-reviewed publications reviewed by Gassman et al. (2007). Routing of water and pollutants are simulated in the model from the HRUs to the subwatershed level, and then through the stream network to the watershed outlet. Complete documentation is provided by Neitsch et al. (2005) for SWAT2005, which is the version of the model that was used in this study.

3.2 Description of Study Area

The Maquoketa River watershed is located in Northeast Iowa (see Figure 1) and drains an area of approximately 4,800 km^2 before entering the Mississippi River. The Maquoketa River is a major source of sediment and nutrients to the Mississippi River stream system. Land use in the watershed is primarily agricultural, about 55% cropland (mostly corn and soybeans), 32% grassland (primarily pasture), 10% forest, and 3% urban area based on a periodic survey conducted by the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) in its National Resources Inventory (NRI) (Nusser and Goebel, 1997). Extensive use of chemical fertilizers on cropland is the major source of nutrient loadings from this watershed.

3.3 Simulation Framework and Calibration/ Validation Methodology

The Maquoketa River watershed was divided into a total of 10 subwatersheds (Figure 1) that coincided with the boundaries of standard 10-digit hydrologic units used by U.S. federal agencies (USGS, 2009a). Key soil, topographic, and land cover data were obtained from the NRI database. Precipitation and temperature data required for the SWAT simulations was provided by the Iowa Environmental Mesonet (ISU, 2009). Distribution of tile drainage across the watershed was estimated using algorithms developed by Miller (2007) and Jaynes (2007).

The SWAT calibration process was performed by adjusting key hydrologic, sediment, and nutrient related parameters within accepted ranges and comparing the simulated output with corresponding measured data collected at the U.S. Geological Survey (USGS) gauge located near Maquoketa, Iowa (Figure 1). The model was calibrated and validated for streamflow, and calibrated for sediment yield, nitrate load, and Total P load; validation was not performed for the predicted pollutant losses due to limited available observed data. Daily streamflow data and bi-weekly or monthly pollutant grab sample data were obtained (USGS, 2009b) in order to perform the comparisons between simulated and measured streamflows and pollutant losses.

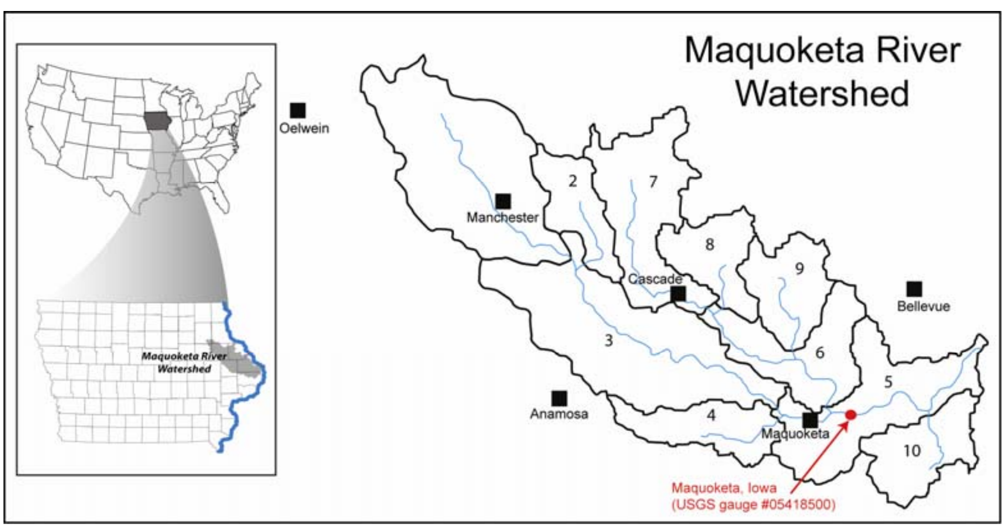

Fig. 1: Locations of Iowa within the United States and the Maquoketa River Watershed within in Iowa, and the delineation of subwatersheds, location of climate stations (black squares), and location of the USGS monitoring gauge within the Maquoketa River watershed for SWAT model application

The first phase of the calibration process involved an annual water balance assessment for 1986 to 2005, which included determining how much of the overall streamflow should be partitioned between surface runoff and subsurface flow. Annual and monthly predicted streamflows were then calibrated for the period 1986 to 1995, followed by streamflow validation during 1996 to 2005 based on comparisons between predicted and measured streamflows. Several model parameters were adjusted for the streamflow calibration process including curve number, soil available water capacity, soil evaporation compensation factors, and groundwater components. Sediment, nitrate, and total P testing were then performed for a 2000 to 2005 calibration period as a function of calibrated streamflows and additional calibrated parameters including in-stream sediment routing components and nutrient-related parameters. The pollutant comparisons were performed on the basis of loads, which required the conversion of measured pollutant concentrations into "measured loads" using the USGS Load Estimator (LOADEST) regression model (Runkel et al., 2004).

Statistical evaluation of the simulated results was assessed using two performance criteria: coefficient of determination (R^2) and Nash-Sutcliffe's coefficient (E) (Nash and Sutcliffe, 1970). The accuracy of the statistics was judged based on criteria proposed by Moriasi et al. (2007), who developed multiple statistical standards based on a synthesis of previous modeling studies and other relevant information. They suggest that E values computed for simulated hydrologic and pollutant loss assessments on a monthly time step should exceed 0.5 in order for model results to be judged as satisfactory (and that appropriate relaxing and tightening of the standard be performed for daily and annual time step evaluations, respectively). We assume here that this criterion is applicable for both the E and r^2 values computed in this study.

3.4 Land Use Scenarios

Three land use scenarios were developed in SWAT to assess the water quality impacts of introducing more corn or switchgrass production in the Maquoketa River watershed that could be harvested for bioenergy purposes. The effect of each scenario was determined by comparing the results with the baseline. A summary of each scenario including management assumptions used follows.

Scenario 1. In Scenario 1, we convert all cropland, including land that are already taken out of production in the existing baseline, to plant perennial warm-season grasses, such as switchgrass. A key assumption in simulating this land use pattern was that no tillage of the soil was undertaken and spring fertilizer applications of 110 lb/ac of nitrogen fertilizer and 60 lb/ac of phosphorus fertilizer were applied.

Scenario 2. In Scenario 2, we convert all cropland, including lands that are already taken out of production in the existing baseline, to continuous corn. The management for this scenario assumes a mulch-tillage operation and regular fertilizer application, including spring application (nitrogen - 60 lb/ac and phosphorus - 45 lb/ac) and fall application (nitrogen – 120 lb/ac and phosphorus - 90 lb/ac).

Scenario 3. In Scenario 3, we convert all cropland, including land that was already taken out of production in the existing baseline, to a combination of switchgrass and continuous corn based on the designation of highly erodible land (HEL). Cropland is considered to meet the HEL designation if the Erosion Index (EI), as reported in the NRI (USDA-NRCS, 2009), exceeds a value of 8. For this scenario, continuous corn is placed on land that has an EI of less than 8 (land that is not considered highly erodible) and switchgrass is selected if HEL is equal to or greater than 8. This criterion allocates 53% to switchgrass and 47% to continuous corn of the total available land. Both land use types were assumed to have the same management assumptions as those described in scenarios 1 and 2.

4. RESULTS AND DISCUSSION

4.1 Calibration and Validation Results

Table 2 lists the R^2 and E statistical results for the calibrated and validated annual and monthly streamflows, and for the calibrated sediment, nitrate, and total P loads. Generally strong statistics were predicted for all of the simulated streamflows and pollutant loads, and all of the computed statistics satisfied the criteria suggested by Moriasi et al. (2007). Graphical comparisons between the simulated and measured monthly streamflows across both the 1986 to 1995 calibration and 1996 to 2005 validation periods, and annual simulated and measured sediment, nitrate, and total P loads for the 2001 to 2005 calibration period, are also shown in Figures 2 to 5. The graphical results further confirmed that SWAT accurately replicated the measured streamflows and pollutant loads.

4.2 The Land Use Scenarios and Water Quality Projections

Table 3 lists the streamflow, sediment, nitrate, total N, and total P losses for the baseline and the three alternative landuse scenarios. The baseline represents the current cropping mix and other land use conditions in the Maquoketa River watershed and provides a basis of comparison for assessing the effects of the alternative land use scenarios.

Table 2: Calibration and validation for SWAT streamflow and pollutant predictions near the watershed outlet of the Maquoketa River watershed

Indicator	Calibration or validation	Time Period	Annual		Monthly	
			R^2	E	R^2	E
Streamflow	calibration	1986-1995	0.91	0.89	0.83	0.73
	validation	1996-2005	0.79	0.79	0.77	0.76
Sediment	calibration	2000-2005	0.96	0.91	0.82	0.74
Nitrate	calibration	2000-2005	0.81	0.67	0.75	0.72
Total P	calibration	2000-2005	0.94	0.91	0.87	0.82

Table 3: Average annual values at the watershed outlet over a period of 20 years (1986-2005)

Description	Streamflow (mm)	Sediment Yield (Tons)	Nitrate (Tons)	Total N (Tons)	Total P (Tons)
Baseline	250	146,652	8,380	10,030	360
All switchgrass (scenario 1)	255	22,780	4,673	4,697	65
Continuous corn (scenario 2)	257	180,054	20,738	25,067	857
Switchgrass or continuous corn (scenario 3)	254	119,135	12,382	13,201	206

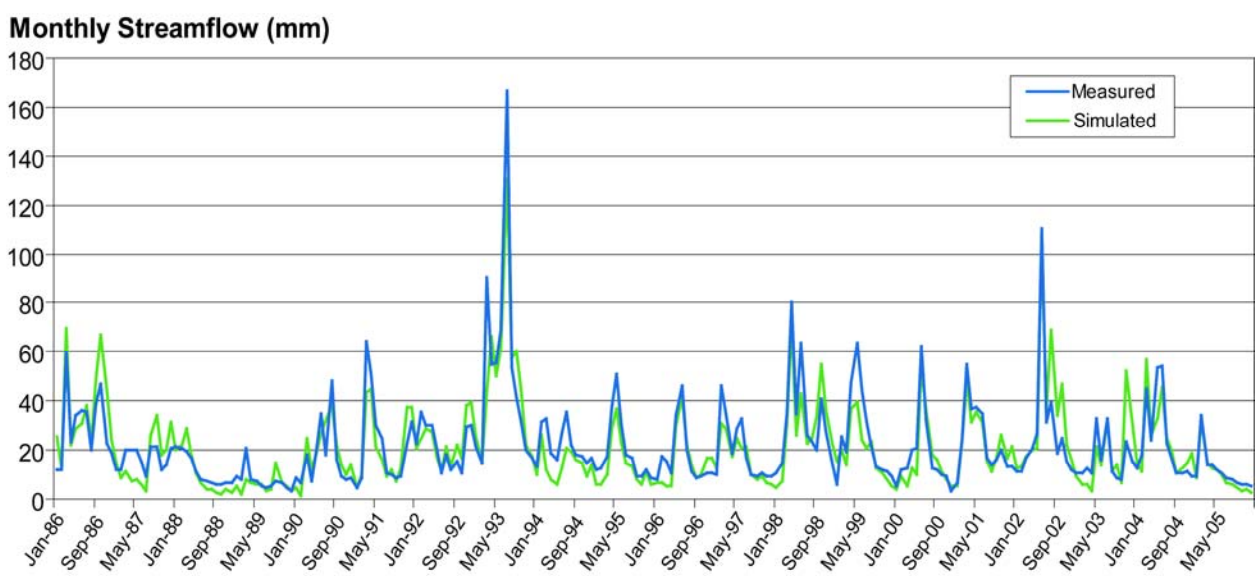

Fig. 2: Time-series comparison between simulated and measured monthly streamflows at the USGS gauge shown in Figure 1

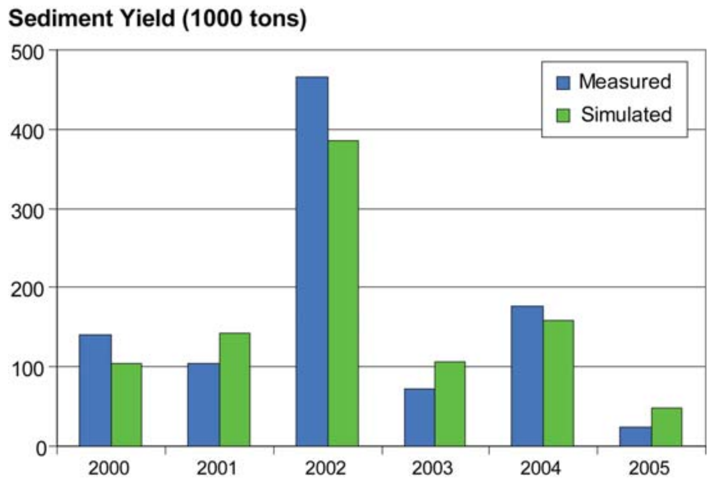

Fig. 3: Comparison between simulated and measured annual sediment loads at the USGS gauge shown Figure 1

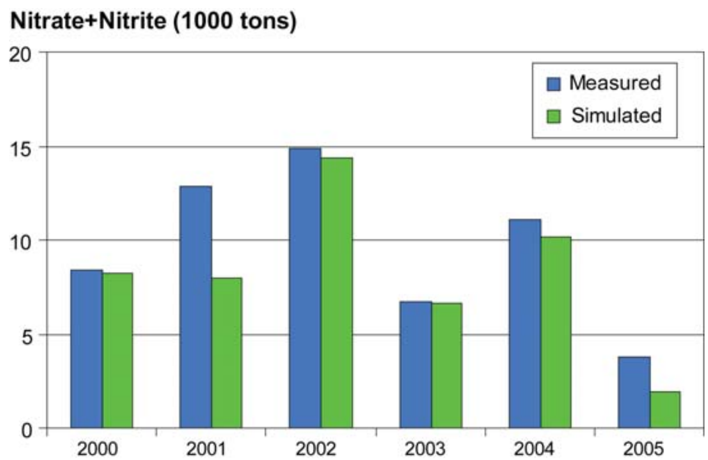

Fig. 4: Comparison between simulated and measured annual nitrate loads at the USGS gauge shown in Figure 1

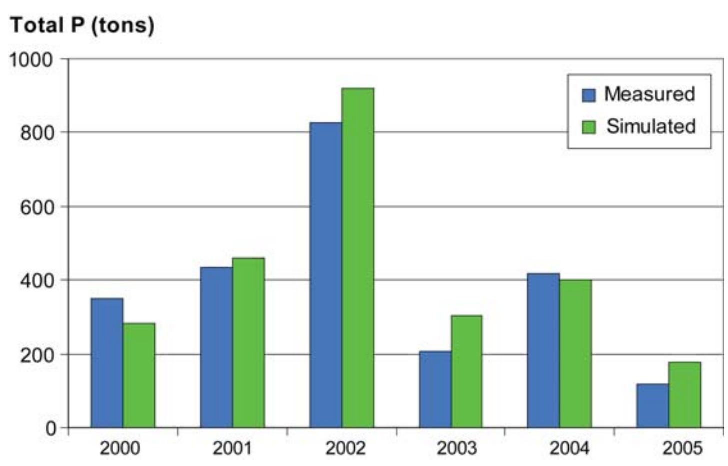

Fig. 5: Comparison between simulated and measured annual total P loads at the USGS gauge shown in Figure 1

Scenario 1, conversion of cropland to switchgrass, was predicted by the model to reduce sediment at the outlet of the watershed substantially by 84%. Large reductions in nitrate (44%), total N (53%) and total P (83%) were also predicted. The second scenario, which involved total conversion of cropland to continuous corn, was estimated to increase sediment yield by 23% relative to the baseline, nitrate by 147%, total N by 150%, and total P by 138% on an average annual basis. This is due primarily to the different tillage operation assumed and the higher fertilizer application compared to the baseline (57,441 vs. 35,972 tons of N fertilizer and 7,440 vs. 4,660 tons of P fertilizer). As expected, this scenario produced mixed results, with a reduction in sediment yield of 19% and a reduction in total P of 43% compared to the baseline. However, nitrate and total N in Scenario 3 increased by 48% and 32%, respectively. The increase in nitrogen load compared to baseline may be attributed to the fertilizer application rates in switchgrass production and similarly, the decrease in sediment and phosphorus load may be due to the fact that switchgrass conversion controls surface runoff (lower curve number for modeling), higher evapotranspiration and hence lower surface runoff, and no tillage operation.

Some further research is needed regarding the overall hydrologic balance and streamflow estimates obtained for the scenarios in this study. Total streamflow was predicted to increase with the conversion of part or all of the cropland to switchgrass, which is not consistent with the results reported by Schilling et al. (2008). This likely points to the need to revise some of the switchgrass crop parameters and/or operations for this study. However, the overall results reported in Table 3 are still very consistent with expectations regarding greatly improved water quality conditions resulting from increased use of switchgrass in the Maquoketa River watershed.

5. CONCLUSIONS

Conversion of land from annual row crop production to perennial switchgrass production could significantly reduce off-farm environmental impacts while simultaneously increasing the net greenhouse gas reduction from biofuels consumption. However, farmers will not begin to convert their land unless the financial returns from switchgrass production equal the returns from traditional crop production. Conditions that would increase the ability of cellulosic ethanol producers to pay for switchgrass include lower cellulose-to-ethanol conversion costs or higher ethanol prices. However, only lower conversion costs would reduce the relative disadvantage of switchgrass because higher ethanol prices would result in higher corn prices.

A SWAT modeling setup for the Maquoketa River watershed, located in northeast Iowa, was used to examine the potential consequences of converting land use for bioenergy crop production. A significant environmental advantage was predicted for expanded switchgrass production. Conversion of all existing cropland to switchgrass reduced sediment yield substantially by 84% and nitrate and phosphorus loads by 44 and 83% respectively, whereas converting everything to cropland increased all three by 23, 147, and 138% respectively.

It is important to recognize that the model and results presented here are exploratory in nature. A great deal is unknown about how large-scale switchgrass production would occur, how technology would evolve over time, how markets would develop and react to these changes, as well as a host of other variables. Additionally, the models employed here have not been extensively tested for the alternative energy crops we consider and there is need to perform additional model testing for both water balance and pollutant loss estimates. Thus, the results should be viewed not as a final answer but as one of many first steps in identifying both the benefits and costs that a large-scale move to the bioeconomy may bring.

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PHOSPHORUS LEACHING TO SUBSURFACE DRAIN WATER AND SOIL P BUILDUP IN A LONG-TERM SWINE MANURE APPLIED CORN- SOYBEAN ROTATION SYSTEM

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ABSTRACT

Organic forms of nitrogen (N) and phosphorus (P) from animal manure can reduce oxygen levels in surface water resources and further enrich the supply of nutrients causing nuisance aquatic plant growth. The PO_4-P at levels as low as 0.05 mg/L can promote the growth of algae and speed up the process of eutrophication in lakes, reservoirs, rivers, and the sea. Therefore, monitoring of dissolved reactive phosphorus (DRP) leaching losses from subsurface drained fields under manured and non-manured soils can help us understand DRP leaching processes through the soil profile to shallow groundwater and develop strategies for water quality mitigation. A field study was conducted from 2001 through 2006 to investigate effects of swine manure application on phosphorus (P) losses to subsurface drainage water urea in comparison to ammonium nitrate (UAN) application in the corn-soybean production system Swine manure application significantly (P=0.05) increased DRP concentration in the subsurface drainage water in comparison to UAN application. Growing season precipitation and cycles of wet and dry years primarily controlled DRP transport and concentration in the subsurface drain water. Continuous application of swine manure for six years resulted in an increased soil test P in the surface soil by two to six times over the agronomic optimum range. The results of this study clearly indicated that DRP concentrations in subsurface drain water increased with the increase in the agronomic soil test P values when the pooled data from manure and UAN applied plots were analyzed together. In swine manure applied soils, P leaching did not increase with the increase in soil test P.

Keywords: *Subsurface drainage water, dissolved reactive phosphorus (DRP), Bray-P (BP), Mehlich extractable P (M3P) and liquid swine manure.*

1. INTRODUCTION

Nutrient enrichment (in particular nitrogen and phosphorus) in water bodies causes Eutrophication. The eutrophication from phosphorus enrichment in water could be substantial as aquatic organisms, like cyanobacteria, can proliferate at P concentration of as low as 0.01 mg l^{-1} (Goltermann and de Ouede, 1991). The P applied to agricultural soil from commercial fertilizers or animal manure is transported to river or lake waters primarily by surface runoff (overland flow) through diffused P transport processes (Haygarth and Sharpley, 2000). However P loading to subsurface flow from P saturated soils can be significant in the presence of rapid non equilibrium water movement through macropores, roots and earthworm channels, natural soil cracks and fractures, which surpasses the buffering capacity of the sub surface horizon ((Jarvis 1994; Andreu et al. 1996; Lennartz et al. 1999; Djodjic et al. 2004). The "preferential flow" has been implicated as efficient mechanism of transport of P to subsurface drainage water and accounts frequently for observed relationships between the P concentration in subsurface drainage water and the P contents in the upper soil horizon (Heckrath et al. 1995; Ule´n, 1999).

Several studies have been conducted to determine relationships between soil P status and P losses to surface water and groundwater. These studies indicated that P losses to water bodies increased significantly as the soil test P values increased beyond agronomical optimum ranges (Sims et al., 2000 Sharpley et al., 1999). Working in an agricultural watershed in Pennsylvania, Sharpley et al. (1999) reported that 52% of soil samples had concentrations of soil P above the levels needed for obtaining optimum crop yields**.** In some soils, where preferential flow was the dominant

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water transport pathway, higher P losses occurred bypassing the high P sorption capacity of the subsoil. Conversely, P leaching losses from some soils were low in spite of higher P applications due to high P sorption capacity in the subsoil. Therefore, site-specific factors may serve as indicators for P leaching losses to surface and subsurface waters (Djodjic et al. 2004).

Nutrient management practices such as fertilizer and manure application and crop rotations can influence P loadings to subsurface drainage flow. Phosphorus applied from animal manures to soils can increase the labile P and P mobility in soil in comparison to P applied from inorganic fertilizer sources (Brookes et al. 1997; Chardon et al. 1997; McDowell and Sharpley,2004) by reducing the P sorption in soils (Delgado et al. 2002a). Subsurface flow is an important mechanism of P transport in manured artificially drained soils (Kleinman et al.2003; van Es et al. 2004). As high as 18,200 µg L^{-1} and 36.8 kg ha^{-1} of dissolved ortho-P concentration and loss, respectively were reported in subsurface drainage water in an organic soil by Miller (1979).

Manure from swine production facilities in different states of USA are used as source of N and P for crop production. The excessive application of swine manure can have serious impacts on the quality of surface and ground water resources. Past research has identified a relationship between soil P test and possible P loss to subsurface drainage water. A comprehensive evaluation of wide range of soils for P test for predicting P leaching to subsurface drainage water from swine manured soils has not yet been conducted. Lucero et al. (1998) showed that Bray-P (BP) and Mehlich extractable P (M3P) tests were similar in evaluating soil P contents after poultry litter application. In soils that received some kind of manure application, acid bound extractant, such as BP and M3P soil test, may over estimate P availability for crops (Sharpley and Smith, 1995; Sharpley, 1996). These investigators also found a strong co-relation between NaHCO3-extractable P fraction and increase in Ca bound P fraction after manure application. Mallarino (1997) showed that BP test extracts gave lower P values compared to OP and M3P test vales in calcareous and high pH soil.

The overall objective of this study was to investigate the relationship between the soil –P, extracted by various agronomic soil-P test, and P loss to subsurface drain water under swine manure application for the corn and soybean production system.

2. MATERIALS AND METHODS

The field experiments were conducted at Iowa State University's Nashua Water Quality Research Site from 2001to 2006.The soils at this site is Kenyon silty clay loam derived from glacial till classified as Clarion loam and is derived from calcareous, loamy, glacial till material. The soils at this site had an average soil pH ranging from 6.6 to 7.0; organic matter ranging from 30 to 40 g kg^{-1} and belong to the Kenyon–Clyde–Floyd soil association (Bakhsh et al., 2007).

The research site has a total of 36 experimental plots laid out in a complete randomized block design with different tillage and crop rotation treatments. Each plot is 58.5 m by 67 m in size, with fully documented tillage and cropping records for the past 28 years. Out of 36 experimental plots, 18 were used in this study with chisel plow tillage practice under UAN and manure management treatments for corn-soybean rotation. The experimental treatments are described as different systems in the following paragraphs:

System I

CN: corn after soybean – spring preplant application of UAN to corn@ 170 kg –N/ha in rotation with soybean

SN: soybean after corn – No N or P application to soybean in rotation with corn (CN)

System II

CN: corn after soybean – fall application of liquid swine manure to corn@ 170 kg-N/ha rotated with SN

SN: soybean after corn – No N or P application to SN rotated with CN

System III

CN: corn after soybean – fall application of liquid swine manure to corn @ 170 kg-N/ha rotated with SN

SN: soybean after corn – fall application of liquid swine manure to so0ybean @ 226 kg-N/ha rotated with CN. This treatment was designed where both corn and soybean plots received application of swine manure to meet N-uptake needs of corn and soybeans.

Each treatment was replicated three times in a complete randomized block design. The details of experimental treatments are given in table 1.

Table 1: Experimental treatments for the Nashua site for the manure management study

System	# of plots per treatment	Application timings and source of N	Crop	Treatment symbol	Application method	Application rate, kg-N/ha	
						N-based rate	P-based rate
I	3	Spring (UAN)	Corn	CNI	Incorporated	170	As needed
	3	-	Soybean	SNI	-	-	As needed
II	3	Fall (manure)	Corn	CNII	Inject	170	-
	3	-	Soybean	SNII	-	-	As needed
III	3	Fall (manure)	Corn	CNIII	Inject	170(manure+UAN)	P-based (corn uptake)**
	3	Fall (Manure)	Soybean	SNIII	Inject	226 (soybean removed)	P-based (soybean uptake)***

*As needed: application rate of P from fertilizer based on soil P test needed to meet P-uptake of corn

** P-based: application rate of P from swine manure on the basis of P removal by corn

*** P-based: application rate of P from swine manure on the basis of P removal by soybean

2.1 Manure and UAN Fertilizer Application

Liquid swine manure was obtained from a nearby swine farm with a one year manure storage capacity in pit. The manure was agitated in the manure pit at the farm for few days before hauled for application in the experimental plots. Liquid swine manure was sampled before application and analyzed for nutrient contents (N, P, K) by the Iowa Soil Testing Laboratory (table 2). A manure injector was used to inject the liquid swine manure to the field at depth of 100 to 150 mm in the spring immediately before planting. Nutrient management system I (CNI and SNI) and system II (CNII and SNII) were designed to compare the effects of N application rates of 168 kg-N/ha from liquid UAN fertilizer and liquid swine manure on subsurface drain water quality. Nutrient management system III (CNIII and SNIII) was designed to apply manure at application rates based on P needs for both corn and soybean (with supplemental application of N from UAN if needed to meet corn N-uptake needs). These rates were chosen to supply the maize N and P requirements from fall manure applications.

Table 2: Average swine manure characteristics applied to corn and soybean

Chracteristics	Value
Total solids (%)	6
TKN content (%)	0.55
Ammonia-N content (%)	0.43
Phosphorous content (%)	0.15
Potassium content (%)	0.35

2.2 Subsurface Drainage System and Data Collection Procedures

At experimental site, the subsurface tile drains were installed in centre of each plot at a depth of 1.2 m with a drain spacing of 28.5 m. Separate tile lines were installed on the north and south borders of each of the plots to check cross contamination from subsurface flow and further isolating of plots was made on the eastern and western borders with berms to check the cross contamination from surface runoff (Kanwar, Bjorneberg, and Baker, 1999). The tile lines passing through the middle of each plot were intercepted at the end of the plot and were connected to individual sumps for measuring subsurface drainage effluent and collecting composite water samples for chemical analysis. The sumps are equipped with a 110-V effluent pump, water flow meter, and an orifice tube to collect water samples. Data loggers were connected to water flow meters for continuous recording of data on tile flow as a function of time. Composite water samples were collected for DRP (dissolved reactive P) analysis using an orifice tube installed on the outlet pipe before subsurface drain water from the sump is pumped to the drainage outlet. Approximately 0.2% of the water pumped from the sump flowed through a 5-mm diameter polyethylene orifice tube to the water sampling bottle located in the underground collection sump, each time the sump pump operated to discharge subsurface drainage water collected in the sump. Cumulative subsurface drain flows were monitored and sampling bottles were removed three times per week or whenever got filled beginning from mid-March to the beginning of December during the entire study period.

No data were on subsurface drain flows were recorded between December and mid-March because of the soil frozen conditions. A more detailed description of the automated subsurface drainage system installed at the site can be found in Kanwar et al. (1999).

2.3 Soil and Water Analyses

A) Soil Analysis

All soil analyses were done in duplicate and analyzed for Bray-P (BP) every year. At the end of 6^{th} year the soils were analyzed for both BP and Mehlich extractable P (M3P, Mehlich, 1984). For the BP extraction from soil samples, one gram of soil was mixed and shaken for five minutes with solution of 10 ml of 0.03 *M* NH4F and 0.025 *M* HCl. For the M3P, gram of soil was extracted with 10 mL of 0.2 *M* CH3COOH, 0.25 *M* NH4NO3, 0.015 *M* NH4F, 0.013 *M* HNO3, and 0.001 *M* EDTA, again for shaking for five minutes. All extracts were filtered through a Whatman No. 42 filter paper and P was determined calorimetrically by the Murphy and Riley (1962) method.

B) Water Analysis

Drainage water was analyzed for dissolved reactive P (DRP). Dissolved forms were assumed to be those determined in water samples that could pass through a 0.45 lm pore size membrane filter. Dissolved reactive P (DRP, largely orthophosphate, measured in an undigested, filtered sample) was determined according to Murphy and Riley (1962) using a Lachat Quickchem 8000 Automated Ion Analyzer system (APHA 1985).

Total phosphorus leaching loss (P load) through soil was determined by multiplying the P concentration in the subsurface drain water with its corresponding measured subsurface drain flow for each tile drain for each time increment. The integral of this product over time during the drainage season was calculated to be the total P load during the growing season. Cumulative drainage and P load for each individual plot were calculated for each year. Soluble P losses for each sampling period were summed up to give the total annual P leaching losses with subsurface drain water. Mass load for each plot was calculated in grams per hectare (g ha^{-1}).by dividing the soluble P load by the area of the plot.

2.4 Statistical Analysis

Data on subsurface drainage flow, DRP leaching loss, and flow weighted average DRP concentrations, and corn and soybean grain yields were collected and analyzed using PROC GLM procedure in SAS version 9.1 for Windows (SAS, 2003). Separate analysis of variance (ANOVA) tables were constructed for corn and soybean yields. Least significant difference (LSD0.05) test was used to study treatment effects on water quality (P concentration and P load) and crop yields at 5% probability values. Linear regression analysis was performed between each soil test and DRP in tile drains across all replications for each treatment with data analysis tool pack in Excel 2000 (Microsoft, 2000).

3. RESULTS AND DISCUSSION

3.1 Precipitation and Drain Flow

Data monthly precipitation and subsurface drain flow are given in Figures 1 and 2, respectively.

Both figures show that subsurface drain flow exhibited different patterns in different years but subsurface drain flow events were closely related to the rain events. Subsurface drain flow events were longer in duration and the fraction of rain water that became part of subsurface drain flow was higher at the beginning of the growing season in comparison to the end of the growing season. This is due to the fact of lower evapotranspiration rates in the early part of the growing season in comparison to later parts of the growing season resulting in lower subsurface drain flows in summer and later part of the growing season. The Another observation was quite evident that average subsurface drain flows for all the management system, were significantly higher under the soybean production in comparison to corn production system because of its different rooting pattern, biomass production, and water uptake pattern characteristics for corn and soybeans (Bakksh et al. 2005).

3.2 Subsurface Drain Water DRP Concentration and P Loss

Treatment effects on flow weighted subsurface drain flow DRP concentrations were significant for all the years. The cycles of wet and dry weather patterns during years showed significant effects on DRP concentrations and leaching losses with subsurface drainage water. Swine manure application to corn only in the corn-soybean production system (System II) and to both the corn and soybean in the corn-soybean production system (System III) resulted in higher DRP concentration (p=0.05) in comparison with the UAN application corn only in the corn-soybean production system. (System I) (Figure3). The volume-weighted concentrations of DRP in subsurface drain water did not show any clear or consistent pattern when comparing between different swine manure application treatment systems such as system I and System III. There was no evidence that with increasing P input from swine manure resulting in the increase of soil P contents may have resulted in the increase flow weighted P concentrations in subsurface drain water (Figure 3). In other words, the swine manure applied soil P leaching did not increase with the increase in soil P test.

Under the nutrient management system II, the corn phase of production system resulted in higher DRP concentration in the subsurface drain water in corn six year flow weighted average DRP concentration in drain water varied from 5.2 µg l^{-1} to 13.2 µg l^{-1} resulting in an average loss of 2.5 g P ha^{-1} to 12.2 g P ha^{-1} (Table 3).

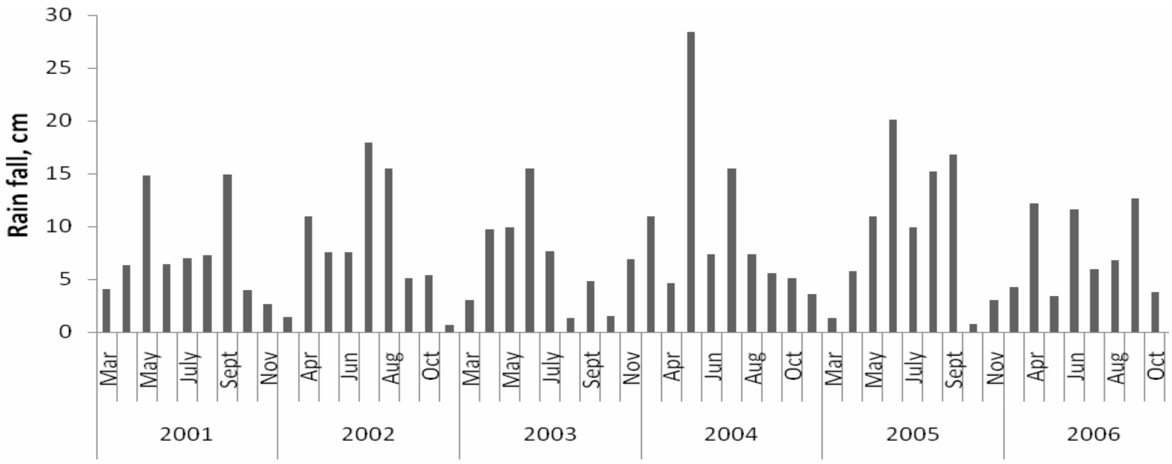

Fig. 1: Month-wise rainfall distribution in the study area

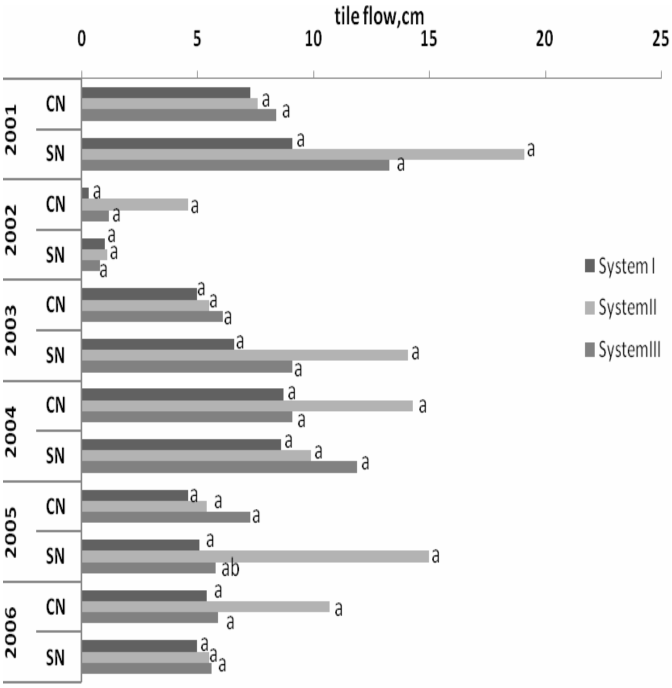

Fig. 2: Annual subsurface tile flow (cm) for urea ammonium nitrate (UAN, system I), swine manure applied to corn phase of production and swine manure applied to both corn and soybean phase of production (Bars at each crop labeled with different letters are significantly different $P \leq 0.05$ by the Turkey,s test)

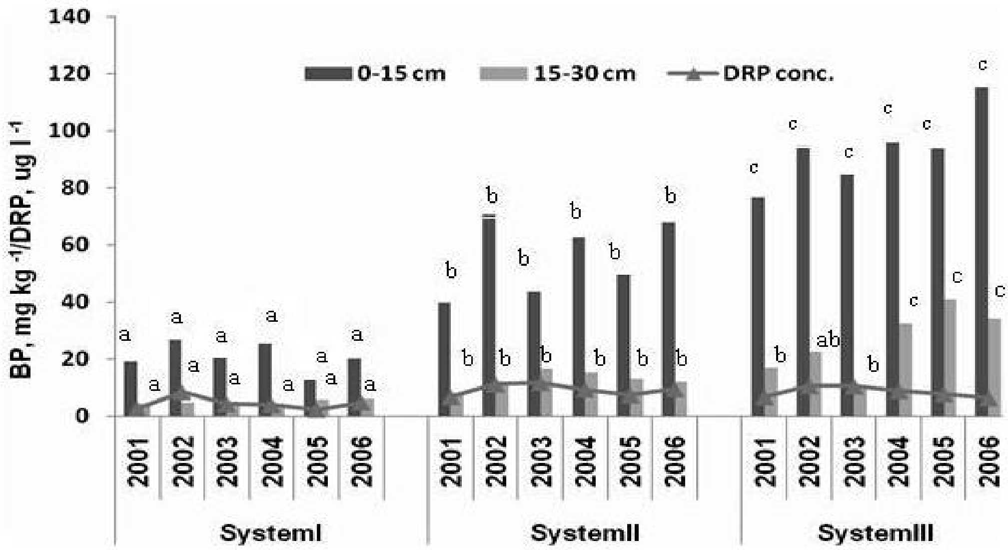

Fig. 3: Anuual BP (mg kg-1) at 0-15 cm and 15-30 cm soil depth and the DRP (ug l-1) for urea ammonium nitrate (UAN, system I), swine manure applied to corn phase of production and swine manure applied to both corn and soybean phase of production

(Bars at each crop labeled with different letters are significantly different P $\leq$ 0.05 by the Turkey,s test test)

Table 3: Six year mean for the field site production and P analysis in surface soil (0-15 cm) in 2006.

(At same crop under different swine manure and UAN treatments (system I, system II an System II) labeled with different letters are significantly different P $\leq$ 0.05 by the Turkey,s test)

System	Treatment	Tile water flow,cm	Yield t ha^{-1}	Bray- P mg kg^{-1}	M3P mg kg^{-1}	P in tile drain	
						Conc µg l^{-1}	loss g ha^{-1}
I	CN	5.2b	11.6a	30.3c	31.3c	5.6b	2.0b
	SN	5.9b	3.6a	21.5c	19.7c	5.2a	2.5b
II	CN	8.0a	11.7a	68.12b	75.2b	13.1a	9.4a
	SN	10.8a	3.7a	35.5b	36.0b	7.1a	5.0ab
III	CN	6.3ab	11.9a	115.3a	124.8a	6.3a	3.5ab
	SN	7.9ab	3.8a	79.9a	84.7a	13.2a	12.2a

Experimental plots treated with swine manure accumulated greater quantities of P in the soil \in comparison to plots not treated with swine manure (Figure 3). Similarly swine manure applied to both the corn and soybean phases of corn-soybean production system resulted in higher BP over all the years as compared to the system where the swine manure was applied to the corn phase of production system only. The BP soil test value in the surface soil (0-15 cm) at the end of six years of the experiments in the soils applied with swine manure both to the corn and soybean phase of production (system III) was 115.5 mg kg^{-1} for corn and 79.9 mg kg^{-1} for soybean (table 3). Similarly, the M3P values were 124.8 mg kg^{-1} and 84.7 mg kg^{-1} for corn and soybean plots, respectively. The soils applied with UAN showed a BP soil test values of 30.3 mg kg^{-1} and 21.5 mg kg^{-1} for corn and soybean, respectively. For the same soil, the M3P values were 31.3 mg kg^{-1} and 19.7 mg kg^{-1}, respectively. For the soils applied with swine manure for corn and soybean phase of production, the M3P test extracted higher P compared with the BP test. The magnitude of difference in the agronomic soil test P between manured and nonmanured soils were less at soil depth of 15-30 cm, below this depth, there was no significant difference among the treatments. These values were 2-4 times for system II and 4-5 times for system III higher than optimum agronomic soil test for Iowa soils. The results of this study confirmed that there low probability of corn and soybean yield response at soil test P levels higher than 16 ppm. This level is in the lower range (16 to 20 ppm) in comparison to the current optimum soil-test P interpretation class given in Iowa State University recommendations for most Iowa soils which are used for making fertilizer recommendations (Mallarino et al, 2004). Swine manure is applied at rates that match crop N needs, P applications usually exceed crop P removal by 300 to 500%. This residual P would raise soil Bray P1 levels by approximately 8 mg P/kg per year (Vitosh et al., 1973) under an almost ideal N-based manure management scenario.

The paired t test between the agronomic soil P test for corn and soybean phase of production indicated corn accumulate higher soil P over the soybean, this may be due to non application of fertilizer to soybean phase of production Nevertheless, rotating the corn with soybean could be an option for the soil P management.

3.3 Agronomic Soil Tests P and DRP in Tile Drains

A statistical relationship between BP and DRP concentrations in the subsurface drain water and Mehlich-3 P and DRP in tile drain water at the end of the sixth year of the experiment in 2006 can describe the changing pattern of P loss with the agronomic soil P (Figure 4). In the regression relationship between the tile drain water DRP and each of the agronomic soil tests, a rapid increase in DRP concentration in the tile drain water was observed beyond certain point of soil P concentrations (Figure 4). Similar trend was observed in both relationships between BP and DRP, and M3P and DRP. This was due to a higher correlation between the BP and M3P values. There was no clear threshold for identifying sharp increases or decreases in P loss that could be established across all conditions. However, P concentration in tile drainage water was low and unrelated to soil-test P until BP test values exceeded 60 to 70 ppm and M3P value exceeds 80yo 100ppm. At these high soil test levels also, the annual amount of P loss to tile drainage water has been observed to be very low. At these soil test values which is 4 to 5 times the agronomic optimum range of this soil, annual loss to the tile drain water remained low (12to 13 g ha^{-1}). This indicates that the soil has a higher buffering capacity and P loss through the preferential flow is low.

3.4 Corn and Soybean Yields

Annual yield data shown in the figure 5 indicated that swine manure applications produced higher corn and soybean yields in comparison with UAN application at 170 kg N ha^{-1}. The six year data on average yields of corn presented in the table 3 showed that there was no significant difference in the corn yield between the manured and UAN treatments and yields ranged from 11.6 t ha^{-1} in the UAN treatment (System I) to 11.9 t ha^{-1} in the swine manure treatment applied to both corn and soybean phase of production (system III). Similarly the six years \average soybean yields were 3.6 t ha^{-1} and 3.8 t ha-1, respectively, for the system I and system III. In a corn and soybean production system, application of 170kg N ha-1 from swine manure to corn phase of production is sufficient for optimum corn and soybean yields as well as for soil agronomic P test and for maintaining subsurface drain water quality.

4. CONCLUSION

Swine manure application at rates that match crop N uptake needs could result in building high soil P levels without resulting comparative yield advantages for corn in the corn-soybean production system in comparison with similar rates of N applications from urea ammonium nitrate (UAN). A six year study was conducted (2001 to 2006) to investigate effects of swine manure application and urea ammonium nitrate (UAN) on soil P build up and phosphorus (P) losses to subsurface drainage water urea in the corn-soybean production system. The results of this study indicated that six years of continuous application of swine manure to both corn and soybean years in the corn-soybean production system resulted in increasing soil test P to levels between five to six times the optimum levels needed for soils without increasing P losses to subsurface drain water or shallow groundwater from agricultural fields. The results of this study also indicated that sustainable corn and soybean yields can be obtained sustained at swine manure application rates giving a total of 170 kg-N ha-1 to the corn phase of production without adversely affecting subsurface

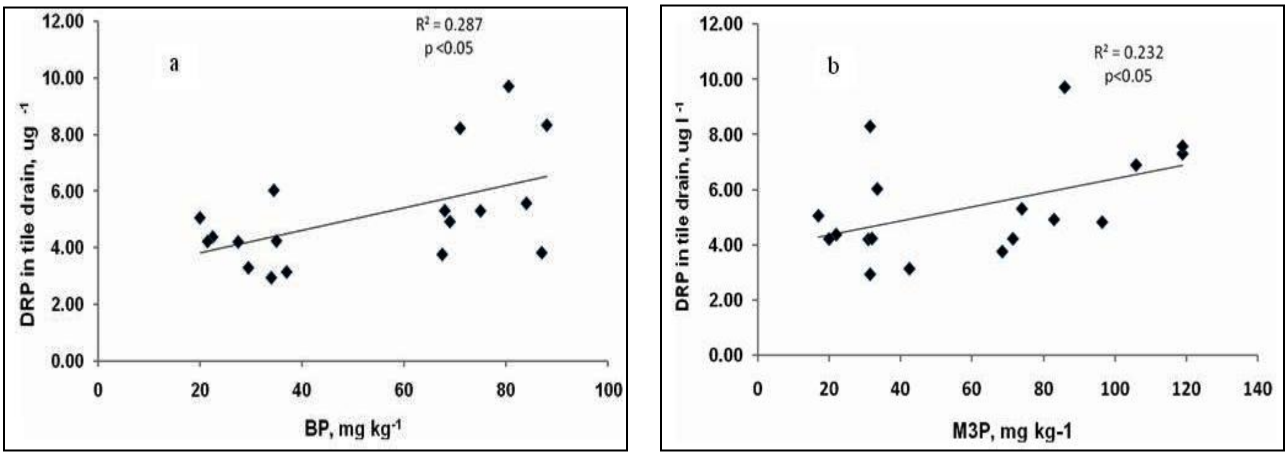

Fig. 4: Comparison of the concentration of dissolved reactive phosphorus (DRP) in the year 2006 drainage and the agronomic soil tests (*a*) BP, (*b*) M3P

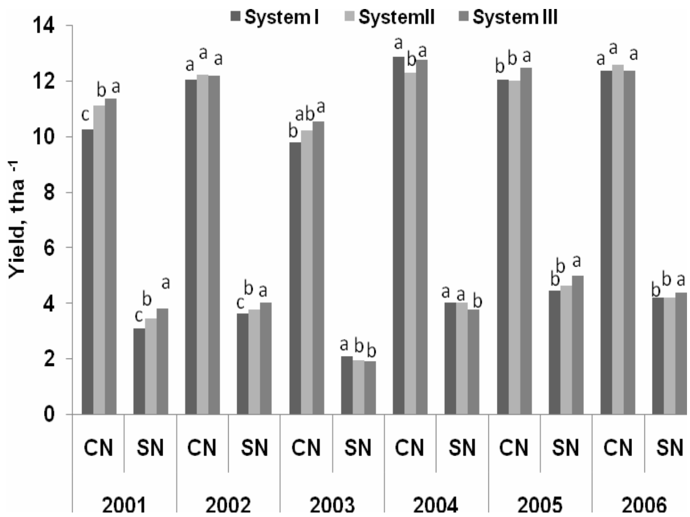

Fig. 5: Annual corn and soybean yield for urea ammonium nitrate (UAN, system I), swine manure applied to corn phse of production and swine manure applied to both corn and soybean phase of production (Bars at each crop labeled with different letters are significantly different P ≤ 0.05 by the Turkey,s test)

drain water quality. Further this study indicated that two of the most important factors affecting the release of soil P to subsurface drain water are the capacity of the subsoil to adsorb or release P and the water transport mechanisms through the soil matrix.

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INFLUENCE OF COMPOST AMENDMENTS ON LEACHING OF PHOSPHORUS IN A CALCAREOUS SOIL OF SOUTH FLORIDA

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ABSTRACT

The retention and movement of water and phosphorus (P) was investigated in a calcareous soil (Krome) amended with three types of compost: 1) Bedminster (BDM)- a mixture containing 75 % clean municipal solid waste and 25 % biosolids, 2) Biosolids (BSD) and 3) Clean organic waste (COW). The study demonstrated that 55(no-compost)-163(BSD) % of more than applied P was leached, which included native soil P, during simulated rain. Phosphorus leached out at a slower rate (BSD-9 %, COW-12 %, BDM-38 % less) from the compost amended soil during initial rainfall. Soil amended with BDM showed lowest water movement and P leaching rate compared to soil amended with other composts. BDM had the highest P adsorption among different composts. A higher P adsorption was observed in Krome soil than that in BSD and COW composts. An equivalent of 93 % of applied P to different treatments was leached from the control showing a high presence of soluble native P. This study showed that adding 134 t ha^{-1} of BDM compost to the calcareous soil increased soil water-holding capacity, reduced water movement and had the least leaching potential for P.

***Keywords*:** *Compost, calcareous, Phosphorus, leaching, sorption.*

1. INTRODUCTION

The agricultural area of South Miami-Dade County, Florida, is bounded by urban development to the north, Biscayne Bay and Biscayne National Park to the east, Everglades National Park (ENP) to the west and Florida Bay to the south (Fig. 1). The warm climate (mean: 23 °C), high humidity (mean: 62 %) and ample rainfall (mean annual: 165 cm) are appropriate for the production of tropical and subtropical fruits year around and traditional vegetable crops for eight months of the year.

The three main agricultural soil series in southern Miami-Dade County (Krome, Chekika and Perrine) are calcareous (> 40 % $CaCO_3$) and cover about 85 % of the county's agricultural area. These soils overlay bedrock of porous limestone containing the shallow Biscayne Aquifer. The soils have low water-holding capacity and high permeability (Savabi, 2001). Therefore, large quantity of water, fertilizers and pesticides applied to crops during a growing season has potential to leach into the aquifer.

In 1996, the United States Environmental Protection Agency published an interim report on the South Florida Ecosystem Assessment documenting that nutrient loading from agricultural and urban areas had significantly increased nutrient concentrations, particularly phosphorus (P) in the ENP. The report further indicated that discharging P at the current control target of 50 µg L^1 would continue to allow eutrophication of over 95 % of the Everglades marshes (USEPA, 1996).

Several studies and reports documented P loading, enrichment and eutrophication problems in the Everglades (DeBusk et al., 2001; Noe et al., 2001; Sharpley et al., 2003). Agricultural soils in Miami-Dade County of south Florida are mainly composed of crushed limestone, which has a low water and chemical retention capacity, with a shallow depth (Savabi, 2001). Poor retention of water, nutrients and pesticides by these soils prompted this investigation into the use of compost as a soil amendment. Phosphorus adsorption and leaching in the soils of Frog Pond area (Fig. 1) needs to be understood because of environmental concerns due to its close proximity to ENP as no study

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has investigated this before. Several studies demonstrated that amending soil with compost improves the soil's physical and chemical properties, microbial population density, enzyme activity, nutrient retention and crop yields (Hargreaves et al., 2008; McDowell and Sharpley, 2004; Pinamonti et al., 1997). Little information is available on P leaching for calcareous soils (with high levels of carbonates) amended with composts especially when subject to high seasonal rainfall and heavy storm events. The objective of this study was to investigate the effects of different types of compost amendments on the movement of water and leaching of P in a calcareous soil of south Florida.

2. MATERIALS AND METHODS

2.1 Soil and Compost Material

Krome soil (*loamy-skeletal, carbonatic, hyperthermic, Lithic udorthent*) from the Frog Pond area (Fig. 1) with an average depth of 20 cm was used for this study. The <2 mm soil particle size distribution showed 60 % sand, 28 % silt, 12 % clay and overall 25 % rocks (mainly $CaCO_3$), by weight. Three composts; 1) Bedminster (BDM)- a mixture containing 75 % municipal solid wastes and 25 % biosolids, 2) Biosolids (BSD) and 3) Clean Organic Waste (COW), commonly used composts in south Florida, were selected for this investigation. Two other treatments included were: 1) No compost amendment (NOC) and 2) Control (CTL) - no compost amendment and no P application. The chemical properties of the composts and soil are provided in Table 1.

2.2 Soil Phosphorus Sorption Study

The distribution coefficient (K_d) for sorption of P was measured with a batch equilibration method (Graetz and Nair, 2009). A 20 mL of P solution with concentrations of 0, 100, 300, 500 and 700 mg L^{-1} in 0.1 M KCL solution was added to 1 g of air-dried soil and compost material with particles <2 mm in diameter. Triplicate samples were equilibrated for 24 h and P concentrations in clear supernatant solution were analyzed by IC detection method. The sorption coefficient for P was determined by the Freundlich linear relationship (Travis and Etnier, 1981) given as:

$$S = K_d C \qquad (1)$$

where S (mg g^{-1}) is the amount of P adsorbed by the soil or composts at equilibrium, C (mg mL^{-1}) is the amount of P in solution at equilibrium, K_d (mL g^{-1}) is the sorption coefficient.

2.3 Phosphorus and Bromide Leaching Study

A portable rainfall simulator, placed 2.5 m above the soil columns, was used to simulate a uniform rainfall rate of 13 cm h^{-1}, highest storm rainfall intensity for south Florida based on 100 year return period. Rain gauges were used during the rainfall simulation to ensure uniform distribution over the entire series of columns. Grids constructed with 2"x4" wooden planks were lined under the rainfall simulator. Each grid contained one PVC (polyvinyl chloride) pipe column, 57.2 cm in total height and 30.5 cm in diameter. Thirty cm of soil was packed over 25 cm of gravel in each column. Different composts were incorporated in the top 15 cm of soil in the columns at the common application rate of 1.1 kg $column^{-1}$ (based on field rate of 134 t ha^{-1}) on an air-dry weight basis. All columns were saturated upward from below and then allowed to drain for two hours prior to starting the leaching experiment. Five storm events were simulated during 4 consecutive days for a total of 13 hours with events of 2, 3, 2, 3 and 3 h durations. These multiple storm events were used to measure potential of P leaching in such an extreme scenario.

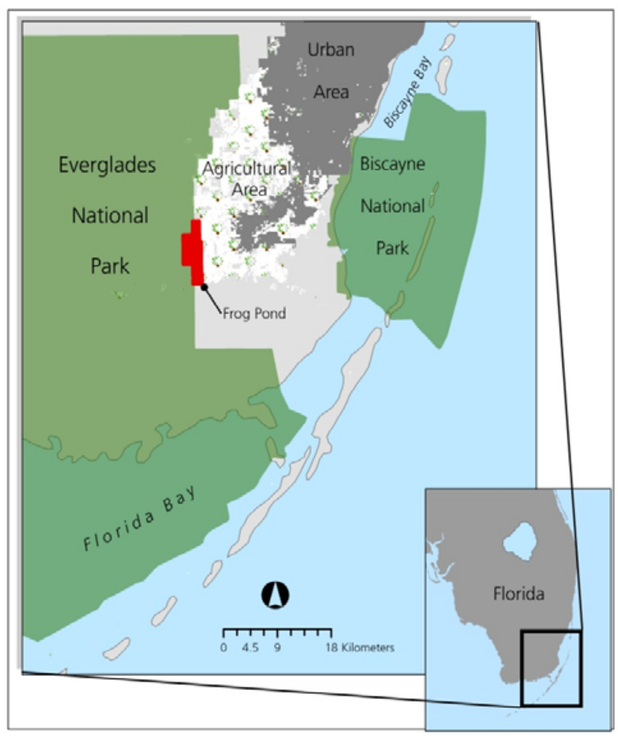

Fig. 1: Map showing the location of Frog Pond area and Everglades National Park, FL USA

Table 1: [‡]Chemical properties (dry weight basis) of the composts: Bedminster (BDM), Biosolids (BSD), Clean Organic Waste (COW) and Frog Pond soil (FPS)

Properties	Unit	BDM	BSD	COW	FPS
Organic Carbon	%	26	28	16	3
Total Nitrogen	g kg^{-1}	18.20	40.84	12.17	2.84
Total Phosphorus	g kg^{-1}	7.17	45.20	2.94	3.57
Calcium	g kg^{-1}	36.8	72.1	123.7	359.5
pH	–	6.7	5.8	7.1	7.3
Cation Exchange Capacity (NH_4Sat)	C mol_c kg^{-1}	22.8	33.7	19.0	6.1
Saturated Hydraulic Conductivity	mm h^{-1}	39	32	34	42
Water Content at Saturation	%	55	53	58	50
Water Holding Capacity @ 1/3 Bar	%	77	75	33	25
Water Holding Capacity @ 15 Bar	%	45	57	31	8

[‡]Analyses performed by A & L Southern Agricultural Laboratories, Inc., Pompano Beach, FL.

Table 2: Relative magnitude of chemical properties for composts and the Frog Pond soil (FPS)

Parameter	Relative Magnitude						
	1		2		3		4
k_d	COW 1.0	<	BSD 1.7	<	FPS 2.2	<	BDM 3.3
Native P	COW 1.0	<	FPS 1.2	<	BDM 2.4	<	BSD 15.3
Al	COW 1.0	<	FPS 2.0	<	BDM 4.5	<	BSD 5.8
Fe	FPS 1.0	<	COW 1.1	<	BSD 2.9	<	BDM 4.7
pH	BSD 1.0	<	BDM 1.16	<	COW 1.22	<	FPS 1.26
CEC	FPS 1.0	<	COW 3.1	<	BDM 3.7	<	BSD 5.5
OC	FPS 1.0	<	COW 5.3	<	BDM 8.5	<	BSD 9.0

In addition to P, bromide (Br) was employed as a non-adsorbent, conservative tracer to investigate the hydrodynamic character of the soil-compost medium. At the surface of each column, 676 mg of P (equivalent to 100 kg ha^{-1}) and 200 mg of Br was applied as spray in 1 L of solution. Effluent for P and Br breakthrough curves (BTCs) was collected for 5 sec. at every 10 min. interval. The effluent concentration of P and Br were measured by IC detection and ion selective electrode, respectively.

At the end of the experiment the columns were divided into three sections; top, middle and bottom, each 10 cm in depth and about 500 g soil was collected from each section. The samples were air-dried, ground and sieved through a 2 mm sieve for P extraction. The total P was determined by digesting 0.05 g of sample following the method of Jackson (1957). Phosphorus concentration in the solution was measured by IC detection.

2.4 Statistical Analysis

A completely randomized design was used for the column experiment (four treatments with three replications) and the data was analyzed using SPSS version 11.0.1 (SPSS, Inc., Chicago IL) performing a two-way analysis of variance (ANOVA).

3. RESULTS AND DISCUSSION

3.1 Sorption Isotherms for Phosphorus

Data from the sorption isotherms for P are shown in Fig. 2. The values of K_d (Eqn. 1) for the composts and the soil followed the order: BDM>FPS>BSD>COW. A higher P adsorption was observed in Frog Pond soil than that in BSD and COW composts. The ranking (Table 2) of native P in the soil and compost material followed the order BSD>BDM>FPS>COW. The high K_d for BDM (Fig. 2) is likely due to a high Fe + Al, organic carbon (OC) content and relatively lower pH in this compost. Fe and Al are more available in soil solution at acidic pH. BDM had the highest Fe + Al and second highest OC content of any material used in this study (Table 1). Yuan and Lavkulich (1994) found significant correlations between P sorption and oxalate-extractable Al and Fe in spodosols. Similar positive relationships between P sorption and oxalate-extractable Al and Fe have been reported by several other researchers (Borggaard et al., 1990; Singh and Gilkes, 1991). In general, COW had lowest amount (Table 2) of native P, Al + Fe, second lowest OC and second highest pH (Table 1) that are reflected in its lowest sorption capacity for P.

BSD on the contrary showed second lowest sorption capacity (Fig. 2), which may be due to highest native P content (Table1), despite having a higher Al + Fe content. The BSD material had more than double the amount of native P than that of any other material studied. Agbenin and Tiessen (1994) concluded that soils with relatively high concentrations of initial P had low K_d values because most of their reactive sites were saturated with P.

3.2 Break Through Curves (BTCs) for Bromide and Phosphorus

The BTCs obtained (data not shown) from displacement of bromide solutions in the three compost amendments showed that the order of the Br peak appearance was COW> BSD> NOC> BDM, with respect to pore volume (PV). This finding suggests that the percolation rate was higher in columns with COW application. As a whole, there was little difference in water movement characteristics among the three compost amendments and the non-amended Frog Pond soil (Table 1); however, BTCs indicated that bromide tended to leach slowest in BDM and fastest in the COW treatment. Note that BDM holds more water and COW least water (Table 1). Almost all bromide applied was leached out from the columns.

The BTCs for P (data not shown) were asymmetrical with multiple peaks in all cases. The cause of asymmetry is attributed to sorption kinetics during leaching (Nkedi-Kizza et al., 1989). The multiple peaks in the BTCs represented different storm events and were due to the diffusive flow of native P into the soil solution between the storm events. Ideally, the peak concentration of the effluent would be expected to decrease as the sorption coefficient (K_d) of P increases. However, in this experiment we observed a contrary effect due to a high native content of P in some composts (Tables 1 and 2), that released the native soluble P in the effluent. The order of initial peak arrival during the first storm event of experiment was NOC>BDM>COW>BSD>CTL. Even with the lowest native P content (Table 2), COW showed high peaks releasing more native P than expected in the effluent, probably due to low Fe + Al content and lowest sorption coefficient (Tables 1 and 2). Although less P is adsorbed in BSD and COW compared to Frog Pond soil (Table 2), their peaks appeared later. These data suggest that for the same amount of rainfall, P leaching will be higher in soil amended with BSD and lower in soil amended with COW and BDM.

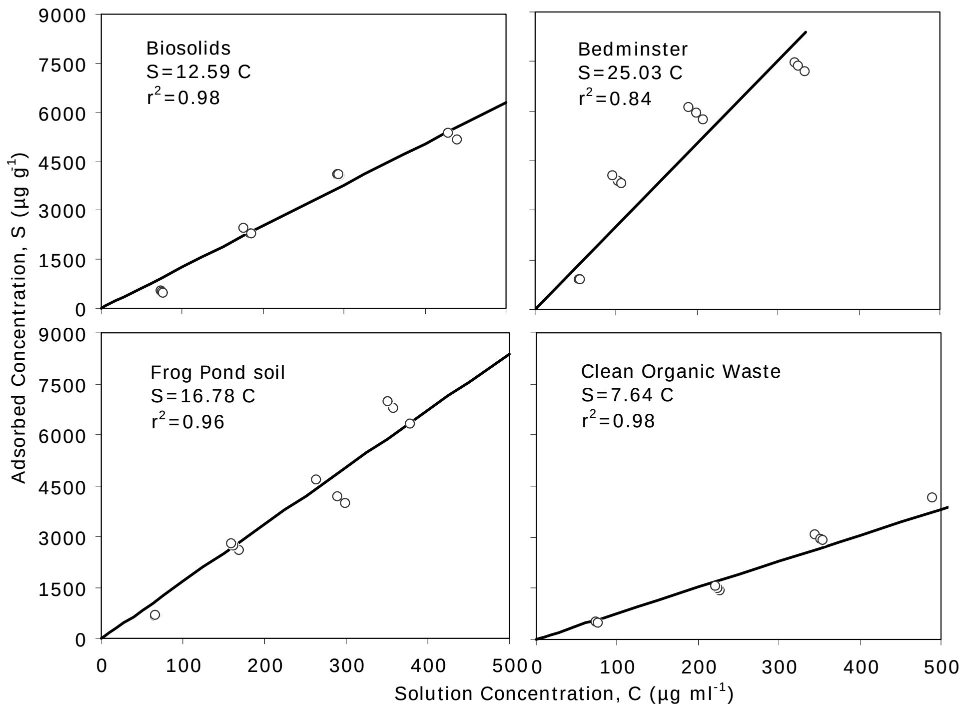

Fig. 2: Phosphorus adsorption isotherms for Frog Pond soil and other composts

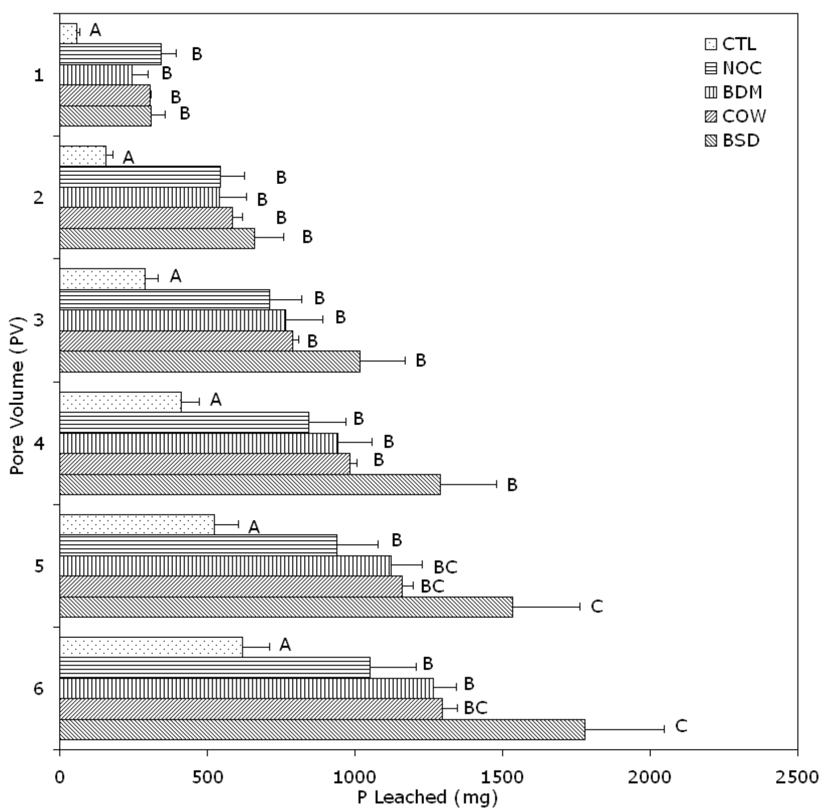

Fig. 3: Cumulative leaching of P recovered at different pore volumes of leachate from treatments, which received 676 mg of P each. The error bars represent the standard deviation of the mean. At each reported PV, values with the same letter do not differ significantly (Fisher's LSD, $\alpha<0.05$)

3.3 Cumulative Leaching of Phosphorus

The cumulative amount of P leached at different PV was used for statistical analysis (Fig. 3). Phosphorus leaching from CTL was significantly different from all other treatments during the whole experiment. There were no significant differences in the means among NOC, COW, BDM and BSD up to 4 PV of effluent. Thereafter, at 5 PV BSD leached significantly more than NOC and later at 6 PV also more than BDM. Lower leaching of P in composts amended soil as compared to that in NOC was observed initially at 1 PV. Most of the applied P was initially adsorbed in composts soon after application, which resulted in reduced P leaching compared to NOC. Higher desorption of P in NOC could be a result of lower Al + Fe, CEC and OC content (Tables 1 and 2). Villapando and Graetz (2001) found that regardless of the amount of newly adsorbed P, desorption was highest for low-Al soils.

However, once the subsequent slow phase ended, P leaching in BSD was higher than the other composts. Note that BSD had relatively high amount of soluble native P (Table 2) that was released in the effluent. At the end of the experiment, total cumulative amounts were considerably higher than the applied P (676 mg). Fig. 3 shows that 155(NOC) - 263(BSD) % of more than applied P to the treatments was leached. The data imply that the P leached through the columns was not only from the applied P, but also included contributions from water soluble native P contained initially in the soil (see CTL, Fig. 3) and the compost materials. The control treatment (CTL) with no P application leached an equivalent of 93 % applied P to other treatments reflecting a high presence of soluble native P.

Highest P leaching in BSD may have resulted from the high amount of native P initially present in the adsorbed phase and influence of biosolids (Tables 1 and 2). Sui and Thompson (2000) reported that addition of biosolids to the soil decreased the ability of the soil to adsorb the applied P. Over all BDM showed the highest capacity for P sorption (Fig. 2) and least potential for P leaching (Fig. 3) when compared to BSD and COW amendments. In a review of the use of composted municipal solid waste (CMSW) in agriculture, Hargreaves et al. (2008) suggested that low mineralization rates of P from CMSW immediately after application resulted initially in P retention by soils; however, repeated application of CMSW decreased the soil P retention.

4. CONCLUSIONS

Bedminster compost was most suitable in terms of a lower potential for P leaching. The sorption study indicated that BDM would enhance P sorption of the amended soil. Bromide data revealed little difference in water movement between soil amendments. Therefore P leaching was more affected by sorption on soil amendments.

This study demonstrated that amending soil with composts reduced leaching of P into the groundwater at the beginning of rainfall, exhibiting a significant impact on common agrichemical P leaching below the rooting zone. However, caution should be exercised that the compost material itself contains an enormous amount of P that could eventually transport into the groundwater. During the year of compost application, regular P fertilization can be minimized due to high native P contents of these composts.

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IN-FIELD WIRELESS SENSOR NETWORK (WSN) FOR ESTIMATING EVAPOTRANSPIRATION AND LEAF WETNESS

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ABSTRACT

Grapes cultivation in India is limited due to high recurring cost of cultivation. Controlling infield variability in yield and quality of grapes is a challenge for wineries. Vine soil-water status constitutes one of the main driving factors which affect plant vegetative growth, yield and wine quality. Providing the methods and tools for continuous measurement of soil and crop parameters to characterize the variability of soil water status will be of great help to the grape growers. To ensure the accurate estimation of irrigation and disease, their variability, management and evaluation in space-time over a grape field, inexpensive sensors and communication technology involving sensors for ambient temperature, wind velocity, ambient humidity, soil moisture and leaf wetness were deployed in an intensely cultivated commercial grape farm. The measured and recorded values of parameters in real time over a period of 3 months permitted the calculation of Evapotranspiration (ET) and 'Leaf Wetness'. Data collected from the sensors were sent via General Packet Radio Service (GPRS) to a server 200 km away from the fields. The water requirement of 110 days of grape cultivation in the field ranges between 500 to 1200 mm and the values computed through the sensed parameters in this work ranged from 550-1500 mm. The ET in grape fields was three times higher than the ET of okra. Further results showed that wireless sensor network enabled distributed measurements, spreading sensors all over the field. The real time information from the fields such as, soil water content, temperature and plant characteristics provided a good base for making decisions such as irrigation (i.e. when and how much water to apply) and application of pesticides by computing Infection Index.

Keywords: Evapotranspiration, grapes-agriculture, precision farming, wireless sensor network.

1. INTRODUCTION

1.1 Precision Agriculture

The indications of food-grain shortages are noticed in India, which is one of the resource wealthy nations. The fact that the forecasted needs for the Indian food grain requirement to reach 480 million tones/yr targets by the year 2050 calls for adoption of modern technology in Indian agriculture (Mondal et al. 2004). With these targets in mind, the sustainable agriculture practices that provide acceptable production efficiency and engage appropriate technology for maintaining the environmental balance are being searched. Precision agriculture is an agricultural system that can contribute to the sustainable agriculture concepts. Agricultural systems are inherently characterized by spatial and temporal variability making yield maximization with minimal inputs a complex task. Precision farming meaningfully employs information-based and technology-driven agricultural system which is designed to improve the agricultural processes by precisely monitoring each step to ensure maximum agricultural production with minimized environmental impact. The advent of inexpensive sensors and communication technology can be meaningfully deployed to enhance precision in operations such as irrigation, disease forecasting and related rational use. Furthermore, because of developments in the field of wireless sensor networks and growing interest in automated data acquisition and information processing, precision agriculture is going to form another milestone towards improved farm management (Shibusawa, 2001). The success in precision agriculture depends on the accurate assessment of the variability in crop production; its management and evaluation in space-time coordinates. The potential for economic, environmental and social benefits of precision agriculture is largely unrealized because the space-

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time continuum of crop production has not been adequately addressed (Patil et al. 2004). By exploiting in-field variability, it is possible to manage crop production inputs (water, fertilizer, pesticides, etc.) on a site-specific basis to increase profits, reduce waste and maintain environmental quality.

Grapes are one of the intensely cultivated commercial crops in India. Literature indicates (Shikhamany, 2000) that area under grapes in India is 34,000 ha. This can be considerably increased if the recurring cost of cultivation can be reduced. Precision agriculture has always been mainly focused on high value crops like grapes.

1.2 Estimation of ET and Disease Forecasting as Components of Precision Agriculture of Grapevine Fields

Irrigating farms backed-up by estimated water-requirements is one of the essential components of precision irrigated agriculture to reduce water wastage. Given the limited water resources of the region, optimizing irrigation efficiency is essential. In addition, the optimum soil moisture content is dependent on local conditions i.e. soil and weather characteristics. The soil moisture governs the amount of stress that is put on the grapevine which, in turn governs the size of the grape, which is normally kept smaller for wine grapes than the size of table grapes. In the case of wine grapes, the stress also affects the wine taste. Great amount of money is spent on pesticide spray to prevent disease such as Downey Mildew of grapes. The consequences are not only the added cost but also the unacceptable levels of harmful chemicals. Environmental data such as temperature, relative humidity, and leaf wetness are typically needed to run disease prediction models. In particular, leaf-surface wetness is one of the most significant meteorological pest-promoting factor that triggers fungal and bacterial plant diseases and activities of insects. Specific leaf surface conditions, i.e. certain leaf temperature and a film of water on the plant surface, favor spores to germinate. Increase in severity of disease is directly related to the length of time the leaves are wet (i.e. wetness duration). The longer the leaf surface is wet, the greater the risk of infection and the greater the number of infections per leaf. The severity of some plant disease increases as the length of leaf wetness increases above 9 hours and minimal infection of this disease occurs when the duration of leaf wetness is below 6 hours (Thomas et al. 1994).

Wireless weather station (WWS) enables measurement and communication of both weather and crop parameters. However, there is constraint on the number of sensors (and hence sampling points) and their connectivity in WWS within agriculture. Wireless sensor network (WSN), on the other hand, provides distinct advantages in terms of multiple numbers of sensor points representing the spatial variability and ease of operation as explained in section 1.3.

1.3 How Wireless Sensor Network (WSN) can Help Precision Farming of Grape Fields

There is significant variability in the quality of grapes over the years and also within the field. Grapes are a perennial crop and the economic life of vines is about 15 years. Irrigation requirements are currently estimated from winter/summer season as well as berry forming stages. Assessing the yield and quality (both temporal and spatial) is a big challenge for wineries. Vine soil-water status constitutes one of the main driving factors which affect plant vegetative growth, yield and wine quality. Providing the methods and tools for continuous measurement of soil and crop parameters to characterize the variability of soil water status will be of great help to the grape growers.

A wireless sensor network can facilitate creation of a real-time networked database. This database can be used to design the planting layout, irrigation and fertilization system layout, so as to maximize the crop yield and minimize its susceptibility to various pests and diseases. The real time information from the fields such as soil water content, temperature, and plant characteristics provided a good base for making decisions such as irrigation (i.e. when and how much water to apply) and application of pesticides. Within agricultural ecosystems, the interaction between crop and surroundings is quite complicated. Work presented here explored how to utilize the actual crop growth monitoring in a commercial vineyard near Nashik (India) farm enabling to test the deploybility of the WSN concepts. Thus the objective of the study presented here was twofold:

1) To relate irrigation requirement through ET calculation from measured parameters; and

2) To estimate the infection index through leaf wetness values thereby allowing the relevant forecasting as to when the crop is at risk, which in turn is useful in taking action on application of pesticide when it is absolutely needed.

2. MATERIALS AND METHODS

This section describes the agricultural experiments conducted in the field which concentrated on monitoring different parameters relating to crop, soil and climate by deploying the wireless sensors so as to establish a correlation between sensors output and agricultural requirement in terms of water and pest management. Initial deployment of sensors with a wireless sensor network (WSN) in a greenhouse at IIT Bombay (6 X 9 m) provided a pilot scale crop-monitoring environment. It was used for testing the ruggedness of WSN for crops grown under controlled conditions in a greenhouse, using sensors embedded in soil and surrounding which was later extended to a larger scale in Sula vineyard at Nashik (India).

2.1 Sensors

The WSN system deployed at a greenhouse, IIT Bombay and Vineyard, Sula, Nashik, India, consisted of the battery-powered nodes equipped with sensors for continuously monitoring agricultural parameters consisting of air temperature, air relative humidity, soil temperature, soil water content and leaf wetness. Fig. 1 shows the schematics of agricultural environment sensors deployed in the field. Each node was able to transmit/receive packets to/from other nodes every minute over a transmission range of 30 m. The soil moisture was measured using ECH_20 probes (Decagon, US) that measured the dielectric constant of the soil, to find its volumetric water content with resolution of ± 2%. ECH0 Temp sensors had temperature sensitivity of ± 0.1 ^{0}C. Data collected by the sensors were wirelessly transferred in a multi-hop manner to a base station node (about 700 m away from the mote) connected with embedded gateway for data logging and correlation. The leaf wetness sensor detects the presence of leaf surface moisture and calculates the duration of wetness. It is an artificial-leaf electrical-resistance type and consists of a sensing grid, low-voltage bi-polar excitation circuit, and conductivity-sensing circuit. The attached console measures the conductivity across the grid and displays the result as a moisture level, scaled from 0 (completely dry) to 15 (fully saturated). The user may select the threshold level at and above which moisture-hour totals are accumulated. The sensor is positioned at a 45° angle to simulate a typical leaf position and to permit runoff of excess moisture.

SHT1x is a single chip relative humidity and temperature sensor. The device includes a capacitive polymer sensing element for measuring relative humidity and temperature. Data were further transferred from a base station to a server, via GPRS connection established at an embedded gateway.

2.2 Wireless Sensor Network (WSN)

The closed loop self organizing WSN used in the study comprised of the following:

- The battery powered nodes with embedded sensors for registering the air temperature and relative humidity were deployed at grid of 30 X 30 m.
- Networked sensors that measure, and record into an electronics data base, several variables of interest such as soil moisture, soil temperature, pH, ambient relative humidity and ambient temperature. Such automated monitoring systems also provide the crop experts with a large amount of raw data in electronic formats.

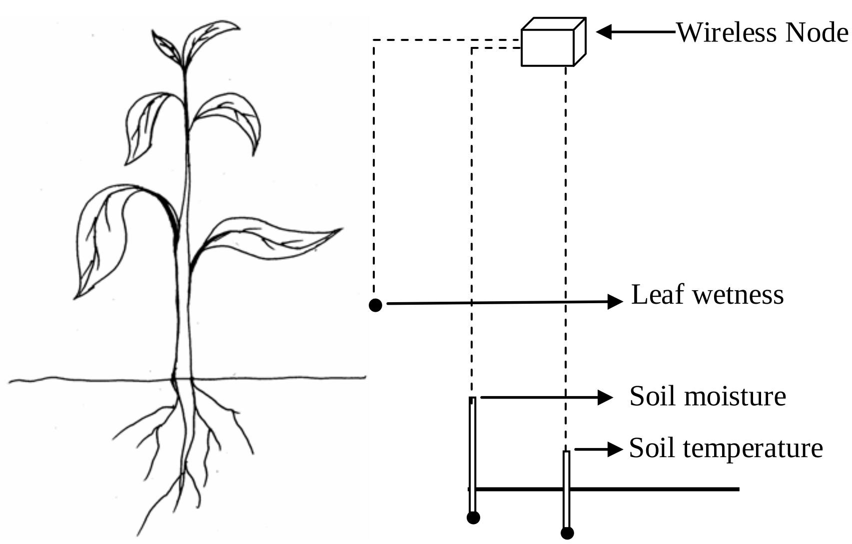

Fig. 1: Schematics of agricultural environment sensors deployed in field

- Each node is able to transmit/receive packets to other nodes inside a well-defined transmission range varying between 30 to 1000 m. A single node can transmit the temperature and relative humidity every minute.
- In a wireless sensor network, when the transmission range of a sensor node is not sufficient, it uses multi-hop communication to reach the destination node or sink node. For example a node communicates data collected, to a nearby node which in turn transmits to another nearby node in the direction of the sink node (see Fig. 2). This data forwarding mechanism continues till the sink node is reached. Multi-hop communication extends the transmission range of a sensor node and also prevents it from draining too soon.
- Signal processing and data processing algorithms that extract useful information out of massive amounts of raw data which is then used to generate alerts that are used to alter sampling frequencies and activate actuators.
- Secure web portal that allows users at different locations to access and share their agri-data.
- Solar cell Polycrystalline solar modules (6 V and 500 mA) were used for charging lead acid battery.

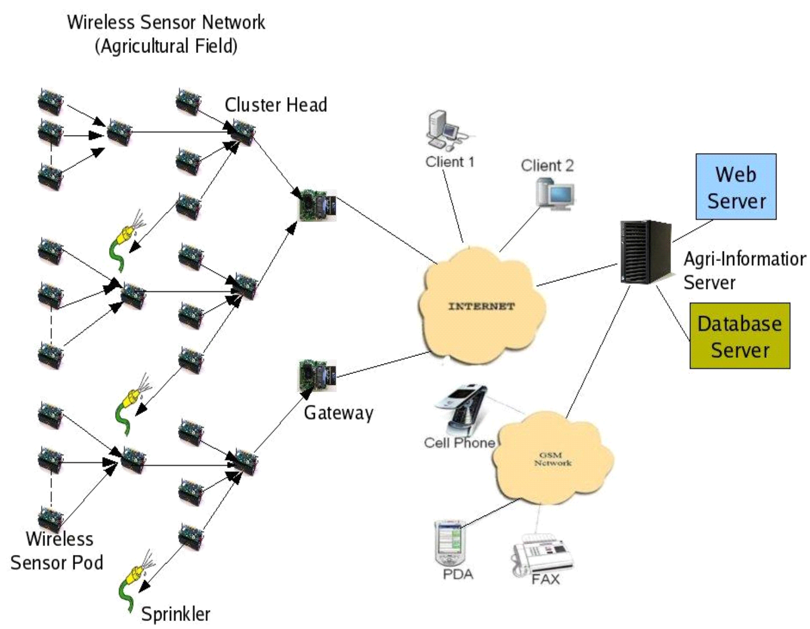

Fig. 2: Different components of Agrisense system

Fig. 3: Wireless sensor network (WSN) deployment in vineyard Nashik, MS, India

2.3 Experimental Setup at Greenhouse, IIT Bombay and Vineyard at Nashik

In the greenhouse (6 X 9 m) at IIT Bombay, the okra plants were planted in nine plots (1.5 X 3 m), with four plants in a row, maintaining a distance between rows and plant of 50 and 30 cm respectively. The developed WSN system is deployed at the greenhouse, which monitored agricultural parameters such as air and soil temperature, soil water content, and plant characteristics. These parameters were periodically monitored and transmitted in a multi-hop to a centralized processing unit. This enables correlation of data with weather, plant information using models. The WSN system tested at the IIT lab facility was extended to Sula Vineyard, Nashik (India), for grape crop monitoring as shown in Fig. 3. The real time information of the fields provides information for the farmer to adjust strategies at any time which helps to enable early warning for any eventuality, like pests, crop diseases, etc. which in turn will facilitate early control action. WSN system was focused on establishing feasibility of capturing and analyzing data and facilitated global data accessibility from a small number of wireless sensor pods. An embedded gateway base station performed elementary data aggregation and filtering algorithms and transmitted the sensory data to Agri-information server via GPRS, a long distance, high data-rate connectivity as illustrated in Fig. 2. The server is situated at the Signal Processing Artificial Neural Network Lab, Department of Electrical Engineering, IIT Bombay (India) which is about 200 km away from the fields. The server also supports a real time updated web-interface giving details about the measured agri-parameters.

3. RESULTS AND DISCUSSION

3.1 Estimation of Evapotranspiration (ET) Rates

The reference ET was estimated using the modified Penman and Moneith model (equation 1) and then multiplied with crop coefficient, available in the literature (Allen et al. 1998) to get the actual crop evapotranspiration. The ET for okra was found to vary between 0.1 to 4.mm/d, with highest water demand (~ about 4 mm/d) during the months of October to December, 2007 as seen in Fig. 4. Every year, during the period of October to December, Mumbai experiences a dry climate which increases the ET. The field weather data values recorded during the months of study (March through May) have been averaged and the values observed are shown in Table 1. The calculated values of ET for sula vineyard, Nashik, were plotted against measured values of soil moisture in Fig. 5. Figure 5 indicates that soil moisture is influencing the ET loss. This is in agreement with the effect explained by Hatfield and Prueger (2008) and Brown (2000). The values of ET were found to be varying between 5 to 14 mm/d for the months of March until May, 2008. The rates of evapotranspiration decreased substantially with the decrease in soil moisture content measured over approximately the top 30 cm depth. Knowing the ideal soil moisture content for crops (from literature heuristics) and given soil texture we can compute the ET and hence irrigation requirement. The water requirement through a cycle of 110 days of grape cultivation in the field ranges between 500 to 1200 mm (www.ikisan.com) and the values computed through the sensed parameters in this work ranged from 550-1500 mm. The ET values in grape fields are found to be three times higher than those found in the test bed for okra at IIT Bombay. The field ET for the grape crop was computed for the summer months i.e. March to May. The higher ET values for grapevines is further explained by both higher wind velocities in open field and the higher crop coefficients for grapes (0.75) which is almost 1.7 times higher than for okra crop (0.45). The variation in ET values between 5 to 14 mm/day is primarily due to change in soil moisture as the variation in weather data was small (see Table1).

$$ET_0 = \frac{0.408\,(R_n - G) + \gamma \dfrac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34\,u_2)} \quad (1)$$

where,

ET_o	reference evapotranspiration [mm day^{-1}],
R_n	net radiation at the crop surface [MJ m^{-2}day^{-1}],
G	soil heat flux density [MJ m^{-2} day^{-1}],
T	mean daily air temperature [°C],
u_2	wind speed [m s^{-1}],
e_s	saturation vapour pressure [kPa],
e_a	actual vapour pressure [kPa],
$e_s - e_a$	saturation vapour pressure deficit [kPa],
Δ	slope vapour pressure curve [kPa °C^{-1}],
γ	psychrometric constant [kPa °C^{-1}]

3.2 Disease Prediction Using Leaf Wetness Values

Equation 2 developed by Broome et al. (1995) was used to compute the infection index for grapes as a function of temperature and leaf wetness duration. Figure 6 shows the infection index calculated for the month of August 2007 through February 2008 for the greenhouse at Bombay. As shown in Fig. 5, the infection index was high during the month of August which corroborated with 16 hrs of wetness duration with the average ambient temperature of 25 °C. While for the sula vineyards, the infection index calculated was zero, implying no risk of infection during the months of March-May, 2008. Table 2 shows the value of infection index for leaf wetness duration of 1-11 hrs with average temperature of about 17 °C. Table 3 gives the strategy for spraying pesticides using infection index values.

$$\text{Infection Index} = \ln\left(Y/_{1-Y}\right) = \{(-2.648) - (0.38W) + (0.061WT) - (0.001WT^2)\} \quad (2)$$

where,
W = leaf wetness duration in hours;
T = ambient temperature in Degree Celsius; and
ln (Y/1-Y) = the logit of disease incidence
Y = the proportion of infected berries.

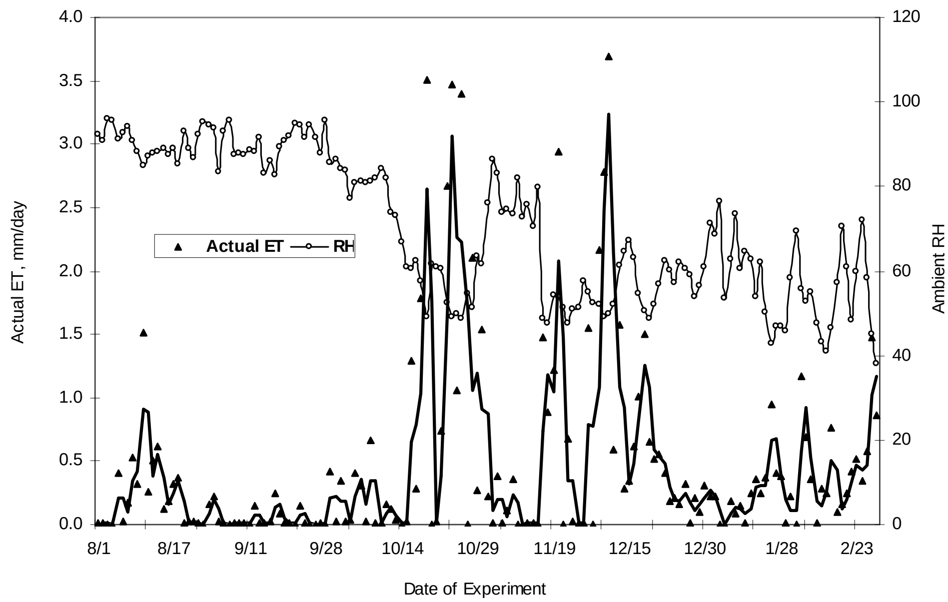

Fig. 4: Variation of evapotranspiration (ET) and ambient relative humidity (RH) in the greenhouse, IIT Bombay

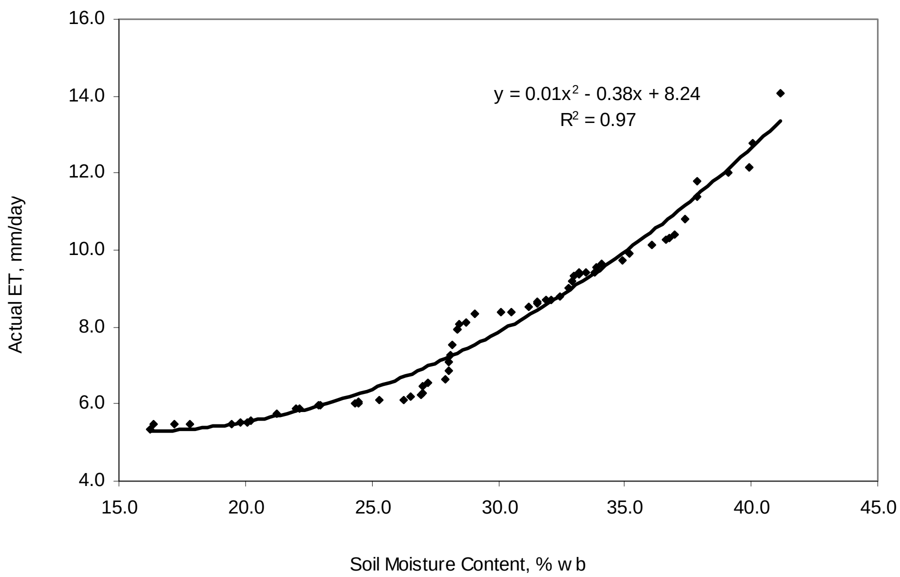

Fig. 5: Variation of ET as a function of soil moisture content, Sula vineyard, Nashik for the months of March to May 2008

Table 1: Weather data for Nashik, Maharashtra

Month	**Ambient Temp, ^0C**	**Ambient RH, %**	**Solar Radiation, Watt/m^2**
	Monthly Average		
March'08	23 (Max 35, Min 10)	43	864
April'08	25(Max 37, Min 13)	41	924
May'08	26 (Max 38, Min 14)	40	959

Table 2: Risk of infection during the months of March-May'08, Sula Vineyard, Nashik using leaf wetness values

Date	**Leaf Wetness Duration (hrs)**	**Temperature (°C)**	**Risk of Infection**
22/3/2008	4.18	21	No risk
24/3/2008	1.33	16	No risk
25/3/2008	2.81	16	No risk
29/3/2008	2.00	21	No risk
01/04/2008	8.63	16	No risk
02/04/2008	11.00	15	No risk
04/04/2008	5.6	15	No risk
05/04/2008	6.13	13	No risk
06/04/2008	2.0	16	No risk

[***Note**: The level of surface moisture on leaves, ranged from 0 (completely dry) to 15 (saturated). Leaf is assumed to be wet, when the value is equal or more than 6. (http://www.davisnet.com/weather/products/wx_product_docs.asp?pnum=06420)]

Table 3: Threshold values of Infection Index giving risk of infection

Infection Index Values	**Risk Levels**
Infection Index < = 0	*no risk of infection*
0 < Infection Index < 0.50	*low risk of infection*
0.50 < = Infection Index < 1.00	*moderate risk of infection*
1.00 > Infection Index	*high risk of infection*

(Source: Broome, J. C., English, J. T. Marois, J. J., Latorre, B. A. and Aviles, J. C. 1995. Development of an Infection Model for Botrytis Bunch Rot of Grapes Based on Wetness Duration and Temperature. Phytopathology, 85, pp. 97-102).

While the data in Table 2 indicates absolutely no risk of infection; the current practice and schedules in grape cultivation entail frequent use of pesticides which not only is a cost burden but also leaves unacceptable levels of chemical residues on berries. The faith in such a recommendation amongst the stakeholders will build with study data for 3 more seasons**.** Based on this study it may not be possible to work out economics of deploying WSN in agriculture, at this point in time. However the technical aspects of WSN deployment and use in agriculture are satisfactorily tested and demonstrated in field.

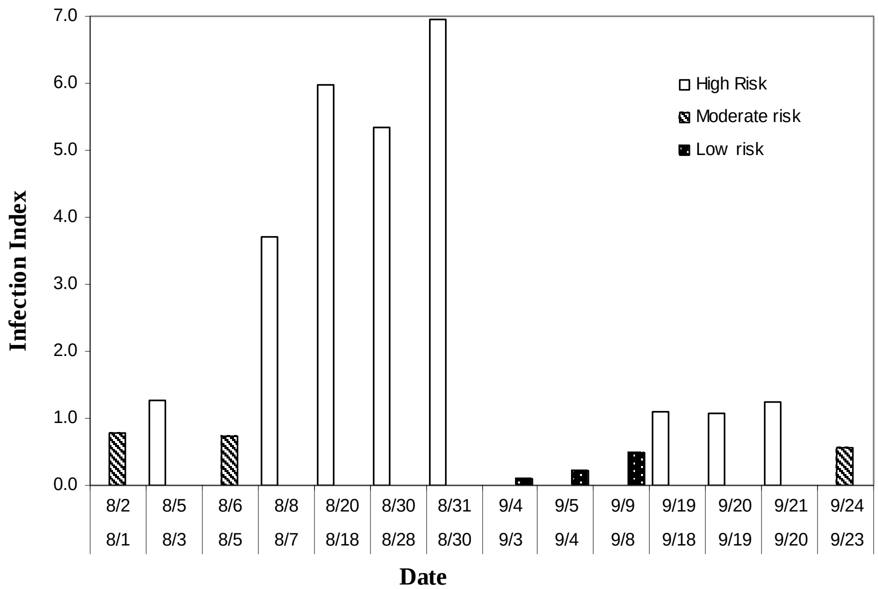

Fig. 6: Infection index for the months of August and September 2007 shednet house, IIT Bombay

4. CONCLUSION

Weather data monitoring in the shednet house test bed facility at IIT Bombay helped find the ET values for okra ranging between 0.1 to 4 mm/day. The actual ET for grapes in Nashik vineyard, India was found to be varying between 5 to 14 mm/day as the soil moisture varied between 15 to 40 %. Computed infection index values based on ambient temperature and leaf-wetness values varied between 0 to 7 for okra in shed net (IIT-Bombay) and practically zero for grapevine crop (Nashik, India) implying no risk of disease infection for the period studied. The inadequacy of availability of all types of sensors during the course of the study for field deployment didn’t allow researchers to comprehensively present the evolution of crop and weather parameters. However the principle objective of this work, which is to test the ruggedness of WSN for decision making in rational use of inputs such as water and pesticide towards precision agriculture, has been achieved. While the ET and Infection Index computations were carried out based on data from one season, data for 3-4 seasons is required for any package of recommended practices as guidelines for entrepreneurs. We believe that WSN supported agriculture management will be particularly useful for larger farms because of its flexibility, more number of sampling points, ease in operation compared to wired-sensors-network system using wireless weather station. The wide scale appeal of sustainable practices in agriculture and the newer developments in providing low cost/robust sensor based systems are likely to provide the necessary fillip in future agriculture world-wide. Currently the WSN system has high probability of economic viability for high value crops. Further work in this direction and experience will consolidate the technical ease and economic attractiveness of the concepts deployed in the field.

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EFFECT OF FURROW LENGTH AND FLOW RATE ON THE PERFORMANCE OF SHORT-FURROWS USED TO IRRIGATE POTATOES IN GOJAM, ETHIOPIA

Sewnet Eshetu [1], Ketema Tilahun [2]* and Dawit Zerihun [3]

ABSTRACT

A field study was conducted to evaluate existing irrigation management practices in small-scale farm holdings in northwest Ethiopia. In this study, the effect of furrow length, as well as flow rate on irrigation performance, crop yield, and water use was studied. The field experiment was arranged in a split plot design; furrow length as main plot and flow rate as sub-plot. Each treatment has three levels; 10, 25, and 40 m furrow lengths and 0.4, 0.6, and 0.8 L/s flow rates. Irrigation performance indicators are: application efficiency, E_a, storage efficiency, E_s, distribution uniformity, *DU*, runoff fraction, R_f, deep percolation fraction, D_f, yield, *Y*, water use efficiency, *WUE*. The effect of furrow length was statistically significant ($p<0.05$) on all performance indices except E_s and flow rate has shown significant effect on all performance indices ($p<0.05$). The ranges of measured values of E_a, E_s, *DU*, R_f, and D_f were 18-34%; 46-80%; 93-98%; 81-95%; 11-57%; and 25-47% respectively. Both furrow length and flow rate had a significant effect on yield and WUE at $p<0.05$. The ranges of crop yield and WUE found in the study were 17-32 t/ha and 2.1-4.1 Kg/m^3 respectively. Crop yield and WUE have shown a decreasing trend as furrow length increases and increases as flow rate increases.

1. INTRODUCTION

Improper on-farm irrigation management practices lead to poor water distribution, non-uniform crop growth, excessive leaching in some areas, and insufficient leaching in others, leading to reduced yield per unit land area and per unit water applied. Ley and Clyma (1981) suggested that design of surface irrigation systems can be considered acceptable if the water application efficiency is greater than 70%, and deep percolation and runoff losses are less than 10 and 20%, respectively, and if storage efficiency exceeds 85%. However, water application efficiency in most traditional irrigation schemes is still very low, typically less than 50% and often as low as 30% (FAO, 1997). FAO (1995) reported that only 40 to 60% of water applied is effectively used by the crop, the remainder is lost in the system (either through runoff, percolation into the ground water, and evaporation from open conveyance surfaces).

Irrigation is playing an increasingly important role in Ethiopian agriculture by contributing to the expansion of cultivated land and to the increased productivity of croplands that are already under cultivation. Irrigation plays a pivotal role in Ethiopian agriculture where spatial and temporal distribution of rain is very high. However, most irrigation schemes are in fragmented small-scale peasant holdings, with poor irrigation water conveyance and control infrastructure and they are poorly managed – the net effect being very low performance. Field assessments made by FAO (2005) in small-scale irrigation projects in Ethiopia indicate that some irrigation schemes are not operating to their full potential and some are not functional at all due to factors related to shortage of water, damaged structures and poor water management. In the Gojam province of northwestern Ethiopia, where the present study was conducted, furrow irrigation, with very short furrows (<50 m), is widely used to apply water to croplands. Irrigation performance is generally very low, due to lack of adequate control over the inflow rate, poor land grading, and lack of management guidelines resulting in a situation whereby system variables such as flow rate, time of cutoff, and furrow length are not well matched up with requirements for optimal system performance as dictated by field conditions. Inflow rate is not controlled to yield optimal performance;

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most of the time furrow length is too short due to fragmented land holdings; no predetermined application time. Farmers prefer short furrows because it allows uniform water distribution in the field. However, labor requirement is higher compared to longer furrows and short furrow lengths require longer distribution system and hence more conveyance losses (Leul, 2005). Systems with short furrows will also take more crop-land out of cultivation. Wallender and Rayej (1987) conducted a study in which they maximized profits by analyzing two system variables (inflow rate and cutoff time) without considering deep percolation. They found that as the inflow rate increases, the application efficiency increases for longer furrows and decreases for shorter furrows. However, the application efficiency decreases as the furrow length increases and the inflow rate decreases. Excessively long furrows result in water being lost by deep percolation at the upstream end of the furrow by the time the downstream end is adequately irrigated. Generally the length of furrows should not exceed 200 m on sandy soil and 400 m on medium textured soils. On some low intake rate soils, the length of run may be as long as 800 m and still distribute water uniformly (Yonts et al., 2007). Furrow irrigation efficiency and uniformity are also sensitive to slope and length and these factors are interdependent: if slope increases then lengths must also increase to achieve a high efficiency and uniformity (Darouich et al., 2007).

Field evaluation of on-farm irrigation systems is essential for characterizing soil and crop hydraulic properties of the system, identifying limitations in existing management practices, and evaluating alternative management scenarios and formulating recommendations for improved system performance. The goal of this study is to evaluate farmer-managed furrow irrigated farms in northwest Ethiopia and to identify limitations of current management practices. The effect of furrow lengths and inflow rates on irrigation efficiency, uniformity, and yield and water use efficiency of a furrow irrigated potato crop is investigated using a field experiment.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The study was conducted at Yilmana Densa district of West Gojam (Ethiopia) at $11^{0}16^{'}$N latitude, $37^{0}30^{'}$E longitude, and 2240 m asl. The mean annual minimum and maximum air temperatures are 6 and 28°C, respectively. Farm holdings in the study area are highly fragmented due to population pressure and limited land resources. The experiment was conducted on a farmer's plot. The soil of the area is predominantly clay. Before planting, composite soil samples were collected from three randomly selected spots in the experimental plot to a depth of 60 cm (the effective crop root depth) in 30 cm intervals. Field capacity and permanent wilting point were determined using a pressure plate apparatus by applying pressures at 0.33 and 15 bars respectively. The percentage of sand, silt and clay of the composite soil sample was determined by sieve analysis (sand and silt) and hydrometer method (clay). Soil textural class was determined using USDA textural triangle. For bulk density determination, soil samples were taken at two depths, 0-30 cm and 30-60 cm, using core samplers of known volume. The soil samples were weighed and placed in an oven at 105°C for 24 hrs. After 24 hours the oven dried soil was weighed, and then bulk density was calculated.

2.2 Experimental Design

The experiment was designed in two treatments and three replicates. The treatments were furrow lengths and flow rates. Each treatment has three levels and three replications (Fig. 1).

2.3 Inflow Rate and Furrow Length

The maximum non-erosive flow rate was first determined using an empirical formula (Hart, 1983) as:

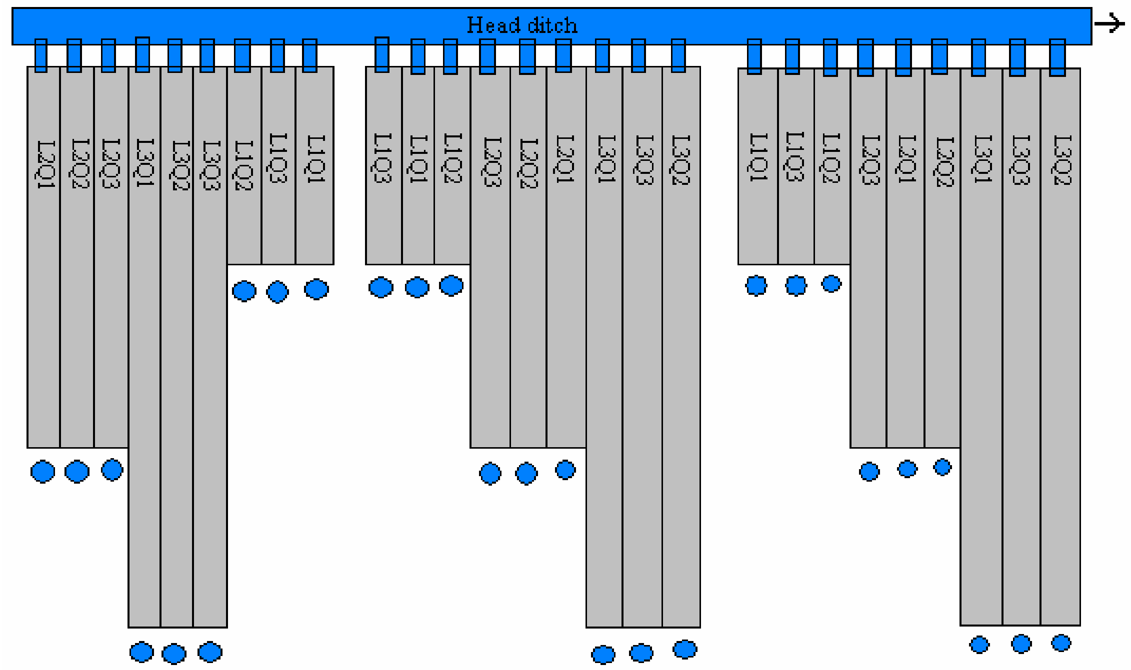
$$Q_{\max} = \frac{K}{S_o} \tag{1}$$

where, Q_{max} = maximum non-erosive flow rate (L/s); K = unit constant, 0.6 for Q_{max} (L/s); S_o = furrow slope in the direction of flow (%).

The maximum non-erosive flow rate, Q_{max}, obtained using Eq. 1 was 0.67 l/s. Using this value as an initial estimate of Q_{max}, the actual Q_{max} used in this study was determined using field trials on 10 m length furrow. The trial flow rates used were 0.6, 0.8 and 1.0 l/s. On the furrow which was supplied with 1 l/s, the furrow bottom was observed to be eroding. Whereas, on the furrows which were supplied with 0.6 and 0.8 l/s, there was no visible erosion. Therefore, 0.8 l/s was selected as the maximum non-erosive flow rate Q_{max}. Based on this value three levels of flow rates; $0.5Q_{max}$, $0.75Q_{max}$ and Q_{max} (i.e. 0.4, 0.6 and 0.8 l/s) were determined for the experiment.

Table 1: Physical properties of soil of the experimental area

Soil characteristics	Soil depth (cm)		
	0 - 30	30 - 60	Average
Texture	clay	clay	clay
Sand (%)	24	23	23
Silt (%)	31	31	31
Clay (%)	45	47	46
Bulk density (g/cm^3)	1.25	1.28	1.26
Field capacity (%)	36.6	34.6	35.6
Permanent wilting point (%)	19.1	18.3	18.7



Legend

Runoff collectors, Spiles (conduits)

L1, L2 and L3 are furrow length levels of 10, 25 & 40 m

Q1, Q2 and Q3 are flow rate levels of 0.4, 0.6 and 0.8 l/s

Fig. 1: Schematic view of the experimental setup

Due to fragmented land holdings, short furrows, ranging in length from 10 to 40 m are commonly used by farmer-managed small-scale irrigation schemes in the study area. Therefore, three furrow lengths (10, 25 and 40 m) were adopted in this study. The experiment was arranged in a split plot design with furrow length as main plot factor and flow rate as a sub plot factor. Furrow spacing of 0.75 m was used in accordance with potato crop row spacing.

2.4 Potato Cultural Practice and Yield Collection

After land preparation was completed, sprouted potato tubers were planted at a depth of about 10 cm with a spacing of 75 cm (between rows) and 30 cm (between plants). About 7050 potato tubers were used to cover 1510 m^2 net planting area. After planting, 15 mm depth of water was applied to all treatments for crop establishment purpose. Diammonium phosphate (DAP) was applied at the rate of 150 kg/ha at the time of sowing and Urea was applied at the rate of 100-Nkg/ha in split application, at first and second hoeing during vegetative and flower initiation stages.

Each treatment plot has four furrow beds. The border furrow beds were used as buffers; of the middle two furrow beds, one furrow bed was used for soil moisture observation. Therefore, sample yield was collected from the remaining one furrow bed. In order to see if there is yield variation along the furrow length due to non uniformity of irrigation, each furrow was divided into three sections and the yield collected from each section was weighed separately.

There are four important questions in the irrigation management: 1) How much to irrigate? 2) When to irrigate? 3) What rate to irrigate? 4) How long to irrigate? The first two questions deal with on-farm irrigation management and the last two concern estimation of crop water requirement and irrigation scheduling.

2.5 Crop Water Requirement and Irrigation Scheduling

Crop water requirement and irrigation scheduling of potato was determined based on the meteorological data, the soil characteristics of the experimental plot, and crop data. CROPWAT computer program (FAO, 1992) was used to determine crop water requirement and irrigation scheduling (Table 2). A 20 year meteorological data collected at the nearby Adet Agricultural Research Center (Amhara Region, Ethiopia) was used in this study. Meteorological data of minimum and maximum temperature, relative humidity, wind speed and daily sunshine hours were used for driving the reference evapotranspiration (ET_o) using Penman-Monteith method (Allen *et al.*, 1998). Crop coefficient (Kc), crop rooting depth, and management allowed deficit (MAD) at different growth stages were adopted from literature (FAO, 2002). A summary of the proposed irrigation schedule is summarized in Table 2.

Table 2: Irrigation scheduling of potato at the experimental site (2006/07)

Date	TAW (mm)	RAW (mm)	Effective Rain (mm)	ET_c (mm/d)	SMD (mm)	Interval (Days)	Net Irr. (mm)
14/11	51.9	12.9	0.0	1.4	13.6	0	14.0
19/11	72.5	22.1	0.0	1.8	23.2	6	23.2
03/12	94.2	34.1	0.0	1.8	37.4	14	37.4
19/12	101.9	43.8	0.0	2.8	44.1	16	44.1
03/01	120.7	46.9	0.0	4.0	47.5	14	47.5
15/01	126.0	50.4	0.0	4.5	52.2	12	52.2
26/01	126.0	50.4	0.0	4.8	52.6	11	53.0
06/02	126.0	50.4	0.0	5.0	51.9	11	51.9
20/02	126.0	53.9	0.0	4.7	54.1	14	54.1
23/02	126.0	57.0	1.7	4.3	25.0		
28/02	126.0	59.5	4.5	4.0	41.1		
05/03	126.0	62.0	6.1	3.6	54.0		
Total			12.3	396.1			377.4

TAM = Total available moisture RAM = Readily available moisture
ET_c = Evapotranspiration of the crop SMD = Soil moisture depletion

2.6 Measurement of Independent and Dependent System Variables

A) Flow Rate Measurement: Water was diverted to the furrows from the head ditch by spiles (conduits). Since the available flow was limited, only a maximum of four furrows were irrigated at a time. The flow rate into the individual furrows is a function of the diameter of the spile used and head at the inlet to the spile. The spiles used were of different diameters, so as to control the discharge at the three flow rate levels. Considering a constant head difference of 5 cm and using a standard discharge formula for orifices, Eq. 2 (Michael, 1978), spile diameters of 29 mm, 25 mm (two) and 40 mm were selected to convey discharges of 0.4, 0.6 and 0.8 L/s, respectively.

$$Q_o = C * 10^{-3} * A * \sqrt{2gh} \qquad (2)$$

where, Q_o = flow rates (L/s), A = Cross sectional area of spile (cm^2), g = acceleration due to gravity, 9810 (cm/s^2), h = effective head causing the flow (cm); and C = coefficient of flow, 0.65.

The inflow rate into individual furrows through the spile was also counter checked by a 2-inch Parshall flume constructed based on the specification of Walker and Skogerboe (1987). At the tail end of each furrow a pit was excavated, which serves for receiving surface runoff using 20 litre buckets installed in the pits dug just enough to accommodate the bucket.

B) Advance and Recession Times: In each test furrow advance and recession trajectories were measured at 6 (for 10 and 25 m lengths) or 10 points (for 40m length) spaced at regular distance intervals along the furrow. To mark the measuring stations, stakes were set at each of them prior to a test irrigation event. Four people were monitoring the advance in four furrows at a time. The advance data was used to determine the distribution uniformity. Infiltration opportunity time (IOT) was determined as a difference between advance and recession curves. Once IOT is determined, the depth of infiltration at specified points along the furrow lengths was determined using the Kostiakov equation as follows. The cumulative infiltration function is given as:

$$Z(t) = kt^a \qquad (3)$$

where,
Z = cumulative infiltration
t = infiltration opportunity time
a *and* k = empirical fitting coefficients

Infiltration parameters in the Kostiakov equation were determined using double ring infiltrometer.

2.7 Performance Indices and Methods of Determination

Soil moisture content was determined before and two days after the irrigation at the initial and mid-season growth stages of the crop for the purpose of performance evaluation using gravimetric method. The data at the two growth stages was aggregated for the purpose of analysis since the interest is in the evaluation of the performance of the system during the whole season.

A) Application Efficiency: Application efficiency (E_a) is defined as the percentage of applied water that is stored in the crop root zone and is used to meet crop consumptive use (e.g., Zerihun et al., 1997). A general expression for E_a (%) is

$$E_a = \frac{W_s}{W_f} * 100 \qquad (4)$$

where, W_s = water stored in the root zone of the plants and became available to the crop (m^3); W_f = water delivered to a furrow (m^3). W_s was determined as the difference of soil moisture content determined before and two days after irrigation event. W_f was determined from furrow inflow rate measurements. It is the gross irrigation applied to each furrow as determined from net irrigation requirement (crop evapotranspiration, ETc).

B) Storage Efficiency: Storage efficiency (E_s) is defined as the ratio of the volume of water actually stored in the crop root zone to the volume of water that can be stored (e.g., Zerihun *et al.*, 1997). The general form of E_s (%) is

$$E_s = \frac{W_s}{W_n} * 100 \qquad (5)$$

where, W_n = water needed in the root zone prior to irrigation (m^3). W_n was determined as the difference of readily available soil moisture and the soil moisture content before irrigation.

C) Irrigation Uniformity: Distribution uniformity (*DU*): defined as the ratio of the minimum infiltrated amount to the average infiltrated amount over the length of the furrow (e.g., Zerihun *et al.*, 1997). The general expression for DU is

$$DU = \frac{Z_{\min}}{Z_{av}} * 100 \quad (6)$$

where, Z_{min} = infiltrated amount at the downstream end (m^3/m); Z_{av} = average infiltrated amount over the length of run of the furrow (m^3/m).

D) Water Use Efficiency: Water use efficiency (WUE) is defined as the ratio of crop yield to the total amount of water applied to the field during the growing season as:

$$WUE = \frac{Y}{WA} \quad (7)$$

where, Y = crop yield (kg/ha); WA = water applied to the field (m^3).

E) Irrigation Water Loss Indicators: Runoff and deep percolation fractions are important parameters in guiding design and management decisions which can increase irrigation efficiency.

F) Runoff Fraction: The runoff fraction is defined as the ratio of the volume of runoff to the volume of water diverted into the crop root zone (Zerihun *et al.*, 1997). The general expression for R_f is

$$R_f = \frac{Vol.\, of\ runoff}{Vol.\, of\ water\ applied\ to\ the\ field} * 100 \quad (8)$$

G) Deep Percolation Fraction: The deep percolation fraction (D_f) is defined as the ratio of the volume of water percolated below the bottom boundary of the crop root zone to the total volume admitted into the crop root zone (Zerihun *et al.*, 1997) given as

$$D_f = \frac{Vol.\, of\ deep\ percolation}{Vol.\, of\ water\ applied\ to\ the\ field} * 100 \quad (9)$$

Alternatively, deep percolation can be calculated as

$$D_f = 100 - E_a - R_f \quad (10)$$

In this study, Eq. (10) was used to determine D_f. In these short furrows the water stays on the soil surface only for a short period of time and hence evaporation was not considered.

For each treatment combination of L and q, the time of cutoff was estimated as (James, 1988),

$$t_{co} = \frac{L * W * Z_r}{60 * q * E_a} \quad (11)$$

where, t_{co} = time of cutoff (min), L = furrow length (m), W = furrow spacing (m), Z_r = net depth of application (mm), q = flow rate (l/s), E_a = application efficiency (fraction).

Since the time of cutoff for a particular treatment combination is the same for all blocks/replications, statistical analysis was done.

FAO (1997) indicates that field application efficiency in most traditional irrigation schemes is still very low, typically less than 50% and often as low as 30%. Therefore, application efficiency of 40 was assumed to estimate time of cutoff in Eq. (11). Net depth of irrigation Z_r was taken to be 37 mm and 53 mm during the initial and mid-season stages respectively.

2.8 Statistical Data Analysis

Measured irrigation performance indices were analyzed for variance using *Mstat* Software (MStat, 1988). The least significant difference (LSD) test at 5% probability level was used for comparing the means.

3. RESULTS AND DISCUSSION

Irrigation performance indices from the experimental plots were measured at two growth stages of potato: at the initial and flowering period, stages at which the crop effective rooting depth was expected to be 0.25 and 0.60 m respectively. The data of the two growth stages was integrated and statistically analyzed. The results of the analysis are discussed in subsequent sections.

3.1 Application Efficiency

Application efficiency was determined using Eq. 4 and presented in Table 3. It can be seen that the effect of furrow length on E_a was significant ($p<0.05$). Generally, E_a has shown an increasing trend as furrow length increase. The E_a found in this study is lower than the recommended E_a for irrigation system design, 50% (MoAFS, 2002). Smith *et al.* (2005) reported an average E_a of 48%, with the range of 17 to 100%, for irrigated cotton in Australia. Melaku (2005) found E_a to be in the range of 29 to 40%, with a mean E_a of 34% for the furrow lengths of 24 to 50 m. The low values of E_a found in this study might be attributed to the very short furrow lengths.

For the short furrows on the clay soil in this study, E_a increases when the flow rate is decreased and furrow length increased (Table 3). This is due to the fact that for such soils, runoff is the major concern rather than deep percolation. For a given flow rate, E_a can be improved up to a certain optimal level by increasing the furrow length.

There was a significant difference ($p<0.05$) between the E_a obtained under the flow rates of 0.6 L/s and 0.8 L/s. Melaku (2005) reported a maximum E_a of 37% for 0.5 l/s flow rate in a furrow irrigated onion in Batu Degaga area, Ethiopia. In a study on farmer-managed irrigation plots in Dire Dawa area (Ethiopa), Zerihun and Ketema (2006) found E_a in the order of 16-35% and 79-100% respectively for potato and sorghum and concluded that E_a of shallow rooted crop is much lower than deep rooted crops.

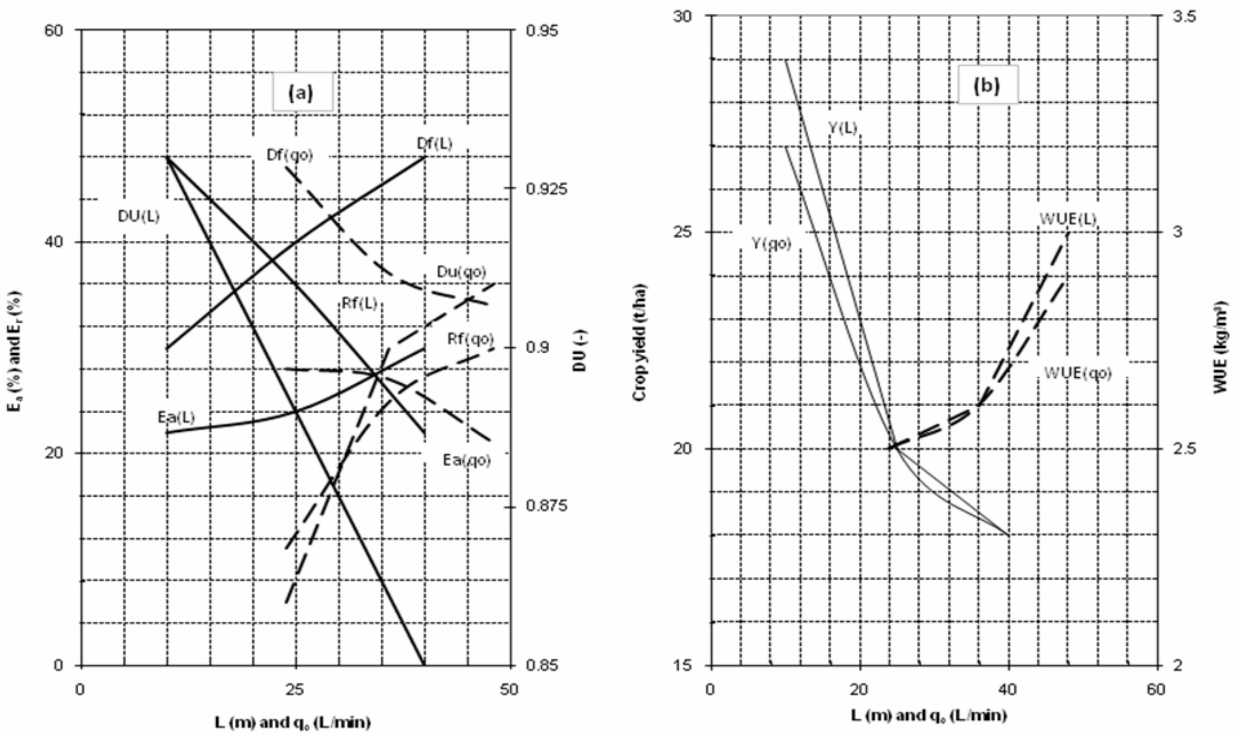


Figure 2: (a) Application efficiency, E_a, Water requirement efficiency, E_r, Distribution uniformity, *DU*, and Runoff fraction, R_f, expressed as a function of furrow length, *L*, and inflow rate, q_o; and (b) Crop yield, *Y*, and Water use efficiency, *WUE*, expressed as a function of furrow length, *L*, and inflow rate, q_o.

Table 3: Application efficiency and storage efficiency for different furrow lengths and flow rates

	Application efficiency E_a (%)			
	Flow rate (l/s)			
Furrow length (m)	0.4	0.6	0.8	Mean
10	22	27	18	22^b
25	29	23	21	24^b
40	34	32	26	30^a
Mean	28^a	27^a	21^b	
	Storage efficiency E_s (%)			
10	55	47	68	57^a
25	79	75	57	71^b
40	80	66	59	69^b
Mean	72^a	63^b	61^b	

3.2 Storage Efficiency

From Table 3 it can be observed that storage efficiency (E_s) has shown an increasing trend as furrow length increases from 10 m to 25 m then declines slightly as furrow length increases to 40 m. However, the effect of furrow length on E_s was not statistically significant ($p<0.05$) within the limited range of length variation evaluated in this study. The effect of flow rate on E_s was found to be significant ($p<0.05$) (Table 3). These values are lower than the findings of Melaku (2005), mean E_s of 93%. The value of E_s showed a decreasing trend as flow rate increases. Interaction effect between furrow length and flow rate was significant ($p<0.05$). The minimum and maximum values of E_s were found to be 46 and 80% for treatments L_1Q_2 and L_3Q_1, respectively. This result shows that in shorter furrows more tail runoff is produced resulting in lower E_s, but as the furrow length increases up to a certain optimum point, tail water runoff water gets reduced; consequently the amount of stored water in the soil increases (Figs. 2b, 3b).

3.3 Irrigation Efficiency

The analysis of variance (Table 4) shows that the effect of furrow length on uniformity was significant ($p<0.05$). Furrow length and uniformity have shown an inverse relationship; as furrow length increases uniformity shows a slight reduction.

The effect of flow rate on uniformity was significant ($p<0.05$). Flow rate and uniformity show a direct relationship, as the flow rate increases uniformity also steadily increases. Zerihun *et al.* (1993) showed that at lower furrow lengths and higher flow rates, higher uniformity values can be achieved. The variation of means due to interaction effect between furrow length and flow rate was not significant at $p<0.05$ in this very low range of length. Zerihun and Ketema (2006) reported DU of 75% under farmer-managed irrigation management condition. The reason for achieving higher values of uniformity in this study might be due to the shortness of the furrows and the clayey nature of the soil.

3.4 Runoff Fraction

As it can be observed from Table 5, the effect of furrow length on runoff fraction was significant ($p<0.05$). R_f showed an inverse relationship with furrow length; as furrow length increased R_f decreased and the vice-versa. The effect of flow rate on R_f was found to be also significant ($p<0.05$). Runoff fraction showed a decreasing trend as flow rate increased (Fig. 2a). The interactions effect of flow rate and furrow length was also found to be significant ($p<0.05$). Longer furrows with lower flow rates produce lesser R_f, but shorter furrows with higher flow rates have higher R_f. This is due to the fact that in the case of longer furrows and lower flow rates the advancing water gets sufficient time to infiltrate (more infiltration opportunity time). As a result, less water is left for runoff, but this condition may cause much water to percolate beyond the root zone.

The minimum and maximum runoff values of R_f were 11 and 57% for treatments of L_3Q_1 and L_1Q_3, respectively. Longer furrows with lower flow rates produce lesser R_f, but shorter furrows with higher flow rates have higher R_f. This is due to the fact that in the case of longer furrows and lower flow rates, the advancing water gets sufficient time to infiltrate (more infiltration opportunity time) as it advances along the furrow. As a result, less water is left for runoff. However, this condition may cause much water to percolate beyond the root zone. In the case of shorter furrows and higher flow rates the advancing water front will reach fast to the end of the furrow (less infiltration opportunity time), resulting in water loss as tail runoff.

3.5 Deep Percolation Fraction

The effect of furrow length on deep percolation fraction was significant ($p<0.05$) with deep percolation fraction showing a steady increment as furrow length increased (Table 5). The effect of flow rate on deep percolation fraction was also significant at $p<0.05$ with deep percolation fraction showing a declining trend as the flow rate increased (Fig. 2a). The difference of means due to the interaction effect of furrow length and flow rate was also found to be significant ($p<0.05$). Highest values of D_f were found for longer furrows and lower flow rates. The minimum and maximum values of D_f were found to be 25 and 55% for treatments L_1Q_3 and L_3Q_1, respectively. Under small scale farmers' irrigation management condition and for end diked furrows (no runoff), Zerihun and Ketema (2006) found that deep percolation water loss between 65 and 83% with an average value of 70% for potato crop. This value is equivalent to the total water loss found in this study (R_f plus D_f).

3.6 Crop Yield and Water Use Efficiency

The analysis of variance showed that the difference between the means due to the effect of both treatments (furrow length and flow rate) on crop yield was significant at $p<0.05$ (Table 6). Higher crop yield was observed at shorter furrow length and showed a declining trend as furrow length increased from 10 to 40 m (Fig. 2b). However, better yield was observed at higher flow rates. This can be due to the fact that better irrigation uniformity was attained in shorter furrows (Table 4). The effect of interaction between furrow length and flow rate on yield was not found to be significant at $p<0.05$. The minimum and maximum yield achieved were 17 and 32 t/ha for treatments of L_3Q_2 and L_1Q_3, respectively.

Table 4: Christiansen uniformity coefficient and distribution uniformities under different furrow lengths and flow rates

Treatment	DU (%)
Furrow length (m)	
10	93[a]
25	89[ab]
40	85[b]
Mean	89
Flow rate (l/s)	
0.4	86[b]
0.6	90[a]
0.8	91[a]
Mean	89

Table 5: Runoff fraction and deep percolation fraction for different furrow lengths and flow rates

	Runoff fraction R_f (%)			
	Flow rate (l/s)			
Furrow length (m)	0.4	0.6	0.8	Mean
10	40	47	57	48[a]
25	24	36	46	36[b]
40	11	25	30	22[c]
Mean	25[c]	36[b]	45[a]	
Furrow length (m)	Deep percolation fraction D_f (%)			
10	38	26	25	30[c]
25	47	42	33	40[b]
40	55	43	44	48[a]
Mean	47[a]	37[b]	34[c]	

Table 6: Crop yield and water use efficiency under different furrow lengths and flow rates

Treatment	Yield (t/ha)	WUE (Kg/m^3)
Furrow length (m)		
10	27[a]	3.4[a]
25	20[b]	2.5[b]
40	18[b]	2.3[b]
Mean	23	2.7
Flow rate (l/s)		
0.4	20[b]	2.5[b]
0.6	21[b]	2.6[b]
0.8	24[a]	3.0[a]
Mean	22	2.7

In order to see if there is any yield variation along the furrow length, potato yield was collected from three different sections of furrows (results not presented here). It was found that, in shorter furrows (10 and 25 m), no yield variation was observed. However, on 40 m furrow, yield was better at the first section and declines at the second and third sections. This might be due to non uniform infiltration along the furrow length in the longer (40 m) furrows.

The respective values of these components for the cropping season were 755, 12, and 22 mm. The effect of both furrow length and flow rate on WUE was significant ($p<0.05$). The variation of WUE due to the interaction effect of furrow length and flow rate was not found to be significant ($p<0.05$). The value of WUE decreased as the furrow length increased and increased as flow rate increased (Fig. 2b).

4. CONCLUSION

The analysis of field experimental data indicated that furrow length and flow rate have significant effect on irrigation performance indices. As furrow length increases, yield and water use efficiencies decrease for lower inflow rates. This is attributed to the non-uniform water application in the relatively longer furrows. Furrow length of 23 m and inflow rate of 0.38 l/s results in maximum water application efficiency of 38% for the condition in this study. This can be generally taken as an optimum length and inflow since almost all the farm holdings in the region are similar in size to the case in this study.

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