International Journal of

Agricultural Research

ISSN 1816-4897

Academic Journals Inc.

www.academicjournals.com

International Journal of Agricultural Research 5 (5): 268-275, 2010
ISSN 1816-4897
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Phosphorus Loss in Subsurface Flow from Agricultural Lands after Manure Application to *Miscanthus* x *giganteus*-Impacts on Groundwater Quality

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Abstract: The objective of this study was to examine Phosphorus (P) loss from agricultural land under a range of conditions, to investigate the effects of applying various rates of cattle slurry on the P loss to drainage water under newly established *Miscanthus*×*giganteus* grass. The P concentration in drainage water was assessed for two years 2008 and 2009. The role of P from agricultural sources in the pollution (non-point source) of surface waters has been an environmental issue for decades because of the recognized contribution of P to the eutrophication (increase in the concentration of nutrients) of surface waters. Research to-date has concentrated mainly on the P losses by surface erosion and runoff, due to the relative immobility of P in soils. Consequently, P leaching and losses via subsurface runoff have rarely been considered important pathways for the movement of agricultural P to surface waters. However, there are situations where, environmentally significant exports of P in agricultural drainage has occurred (e.g., high organic matter soils or soils with high soil P concentrations). In this study, the crop received either no fertilizer (0-unfertilized control) or an annual application of 6, 12 or 18 kg P ha^{-1}. Soil water solution samples were collected fortnightly from porous ceramic cup samplers. The P levels in these soil water samples were determined and monitored. Soil water phosphorus concentrations were found in the range of 4.3-6.5 in 2008 and in 2009 levels of, 8.8, 8.2, 8.1 and 9.4 mg L^{-1} were recorded for 0, 6, 12 and 18 kg P ha^{-1}, respectively. However, there was no significant difference between treatments. Nutrient losses have a number of environmental consequences. N and P losses in particular can negatively affect the quality of soils, groundwater, surface water and the atmosphere; thus, contributing to eutrophication, toxic algal blooms and a general deterioration of water quality.

Key words: Phosphorus, subsurface flow, *Miscanthus*, manure application, ceramic cups, groundwater quality

INTRODUCTION

Miscanthus or *Miscanthus*×*giganteus* is a woody rhizomatous C_4 grass species which originated in South-East Asia and was initially imported to Europe as an ornamental plant

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(Jones and Walsh, 2007), it is a perennial plant with an estimated productive life span of at least 10-15 years. The remarkable adaptability of *Miscanthus* to different environments (Numata, 1974) makes it suitable for establishment and distribution under a range of European and North American climatic conditions (Lewandowski *et al.*, 2000). *Miscanthus* is a promising non-food crop, yielding high quality lignocellulosic material for both energy and fibre production. It is characterized by relatively high yields, low moisture content at harvest and high water and nitrogen use efficiencies (Jones and Walsh, 2007). Energy production and paper pulp production were the first end uses which were considered for *Miscanthus*, but the viability of other end uses are also being examined, such as, bioremediation of contaminated soils. This potential use of the crop has come about as the pressures exerted on soils have increased due to intensive agriculture, industrialization, the expansion of urban areas and other factors (Visser and Pignatelli, 2007).

Phosphorus (P) is an essential element for all forms of life (Havlin *et al.*, 1999). Adequate P supplies are necessary for seed and root formation, straw strength in cereals, crop quality and synthesis of microbial biomass in ruminant animals (Havlin *et al.*, 1999; Whitehead, 2000). Despite the fact that P is one of the most important mineral nutrients for biological systems, it is also one of the scarcest nutrients in terms of its demand in both terrestrial and aquatic environments (Moss, 1988). In natural systems, P is tightly cycled through the plant-soil continuum, but in agricultural systems soil P is removed in the crop or animal products and must be replaced, if P deficiency is to be avoided (Leinweber *et al.*, 2002). Therefore, mineral phosphate fertilizers and animal manures are applied to agricultural land to raise soil P levels and maintain crop yields (Sibbesen and Sharpley, 1997). Traditionally, P fertilizer has been applied to agricultural land with no concern over losses to water, because inorganic P is strongly fixed in the soil and prevented from leaching (Sample and Soper, 1980). However, while this is true from an agronomic standpoint, the small amounts of P lost from the soil can have severe impacts on water quality in receiving catchments, especially in terms of eutrophication and the growth of undesirable algae (Moss, 1996). Agricultural soils receive P from livestock (direct excreta and manures), mineral fertilizers and municipal sludges and wastewaters. Imbalances originate because P is applied at levels that are in excess of the amounts required for optimum crop yields (Leinweber *et al.*, 2002). This is often exacerbated where areas requiring P fertilizer (e.g., crop production areas) are spatially separated from areas with large P surpluses (e.g., areas of intensive livestock production). The driving force behind P transfer from land is the hydrology, because water provides the energy and the carrier for P movement (Haygarth and Jarvis, 1999). The route taken by water as it carries P off the land describes the pathway of P transfer. Pathways can be broadly separated into surface (overland flow) and subsurface pathways and the pathway taken is of critical importance in determining the extent of P loss from agricultural land. The traditional perception of P being strongly fixed in the subsoil has meant that research into transfer traditionally has focused on surface pathways. However, overland flow and subsurface flow, particularly in soil macropores and field drains are important contributors to the overall P load (Heathwaite and Dils, 2000). Overland flow is often associated with catastrophic events, which are considered to be the most severe in terms of loss, although there is evidence that lower frequency events that occur for a much greater time throughout the drainage period are equally important in P transfer (Fraser *et al.*, 1999). Subsurface pathways include lateral flow through the soil, vertical drainage, preferential flow through macropores and artificial drainage channels and are the subject of this study. Until recently, subsurface P losses were considered to be negligible, because of the propensity for P to be retained at depth in the soil profile. This was exacerbated by the fact that measured losses of P in subsurface flow were small compared with the total amount of P in the soil (Sample and Spoer, 1980). However, the change from an agronomic to an environmental perspective on soil P has refocused attention on subsurface P transfer, because small concentrations of P can cause significant problems for water quality (Tunney *et al.*, 1997; Turner and Haygarth, 2000). This phenomenon is not restricted to waterlogged soils or sandy-textured soils under heavy fertilizer addition as traditionally thought, but includes many soil types, especially clay soils that are susceptible to cracking and preferential flow (Turner and Haygarth, 2000). Studies using lysimeters have revealed that P concentrations in leachate water from a range of soil types occur at levels that could present problems for water quality (Leinweber *et al.*, 1999; Turner and Haygarth, 2000). Organic P constitutes, a large proportion of the total P transported in leachate (Turner and Haygarth, 2000), where its mobility in the soil, compared with inorganic P forms makes it an important mechanism by which P may escape from the soil. Unlike inorganic P, organic P is not strongly sorbed and can move easily through the soil to surface waters, where it can contribute to algal growth after the release of inorganic P by phosphotase enzymes (Whitton *et al.*, 1991). In sustainable agroecosystems, fertilizers and manures should be managed to maintain a productive soil while minimizing the potential for P loss in overland and subsurface flow and potential eutrophication of surface waters. The application of P in excess of plant requirements leads to a buildup of P, saturation of P sorption sites and greater potential for P desorption into soil solution and loss by transport mechanisms such as leaching (McDowell *et al.*, 2001). The objective of this study was to evaluate the effects of applying various rates of cattle slurry on P movement to drainage water and to measure P losses under field plots of *Miscanthus*.

MATERIALS AND METHODS

The experiment was carried out at University College Dublin, Ireland, Lyons Research Farm (53° 18' 28" N, 6° 31' 59" W). The site is relatively low-lying (80 m OD) and the topography is almost uniformly flat (slope 1°); the soil is a silty clay loam with the previous cropping history including the following: 2004-winter wheat (*Tritium aestivum* L.), 2005-sugar beet (*Beta vulgaris*) and 2006-spring barley (*Hordeum vulgare* L.). Following harvest of the spring barley in 2006, the site was left fallow over Winter (2006/07). In May 2007, soil cultivation commenced after the site had been treated with a glyphosate based herbicide. *Miscanthus* x *giganteus* (Greef and Deuter, 1993) was established from rhizomes in May 2007. A recommended planting density of 18-20,000 rhizomes ha^{-1} was used to obtain 10,000 plants ha^{-1} or 1 plant m^{-2}. Post establishment, the site was treated with a suitable sulphonyl urea based herbicide to suppress weeds. For practical reasons a conventional plot design was not possible; rather, sections of crop were divided into sub-plots and monitoring equipment (suction cup samplers) was installed in each sub-plot, i.e., 4 samplers per treatment.

In 2008, the P treatments used were 0, 6 and 12 kg P ha^{-1} while in 2009, a rate of 18 kg P ha^{-1} was added to give an overall treatment programme of 0, 6, 12 and 18 kg P ha^{-1}. P was supplied in the form of cattle slurry which was applied to the crop using a side chute attached to a vacuum tanker. By using the side chute slurry was applied without driving on the crop. The slurry was collected on Lyons Farm and was agitated immediately prior to spreading to ensure uniformity. Representative slurry samples were taken from each load prior to application and there physiochemical characteristics determined (Table 1). A portion (50 mL) of these samples was homogenized by shaking for 10 min and then analyzed in the laboratory, in keeping with Díez *et al.* (2001).

Table 1: Physiochemical characteristics of cattle slurry used in the experiment

Parameter	Total amount
Dry Matter (%)	6.9
N (kg ton^{-1})	3.7
P (kg ton^{-1})	0.7
K (kg ton^{-1})	4.3

In January 2008, ceramic cup samplers were installed in each plot at 60 cm deep. Samplers were placed in the centre of the plot; a description of the installation and use of the ceramic cups is given in Curley *et al.* (2010). Prior to fertilizer application, soil solution samples from the ceramic cup samplers were extracted and samples analyzed for P to assess baseline levels. Throughout the trial period a vacuum of 80 kPa was applied to the samplers and maintained for a period of 7-10 days (Johnson *et al.*, 2002). Samples of the soil solution were then extracted using negative pressure and P determined for the extracted samples. Sampling took place on a fortnightly basis for 4 months post-fertilizer application. Samples were analyzed for P using the vanadomolybdophosphoric acid method. All agro-meteorological data (soil moisture, drainage potential, soil moisture deficit and potential evapotranspiration) was supplied by Met Éireann for Casement Aerodrome, a synoptic weather station 6 km from Lyons farm for the duration of the experiment. In addition to this, soil moisture was measured gravimetrically each autumn and volumetric soil water content was assessed using handheld Time Domain Reflectometry (TDR) probes; vertical tensiometers (capable of measuring water pressure of 0-90 kPa) were installed according to Díez *et al.* (2001).

Statistical Analysis

Statistical analysis was performed using Minitab 15 (Minitab Inc., 2009) statistical software. For statistical evaluations of treatment effects and sampling dates, a one-way ANOVA was used. Differences between treatments and the P levels in the soil solution samples were analyzed and compared using Tukey simultaneous confidence intervals. Significance was set at $p<0.05$.

RESULTS

Agricultural and urban activities are major sources of P to aquatic ecosystems and are deemed to be non-point sources of nutrient inputs, thus, making them difficult to measure and regulate because they are derived from activities dispersed over wide areas of land and are variable due to effects of weather. In the aquatic ecosystem, such nutrients cause diverse problems such as toxic algal blooms, loss of oxygen, fish kills, loss of biodiversity and other related problems (Carpenter *et al.*, 1998). Nutrient enrichment seriously degrades the aquatic ecosystems and impairs the use of water for drinking, industry, agriculture, recreation and other purposes.

In 2008, mean soil water nitrate concentrations were high; 4.3, 4.7 and 6.5 for 0, 6 and 12 kg P ha^{-1}, respectively. As fertilizer P rates increased, there was a corresponding significant increase in soil water P concentrations with the highest soil water P concentration recorded in the treatment that received 12 kg P ha^{-1}. The frequent application of animal manures has been shown to promote the downward movement of P (Hountin *et al.*, 2000). The aquatic environment is highly sensitive to P loss from agriculture because critical concentrations for eutrophication control (10-20 μm L^{-1}) are an order of magnitude lower than soil P concentrations required for the crop growth (200-300 μm L^{-1}). Thus, P loss

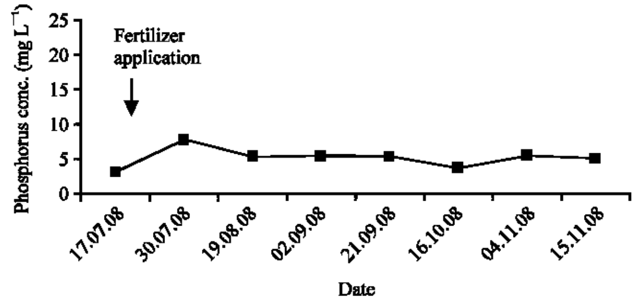

Fig. 1: Phosphorus levels in soil water samples in 2008-year 1 of trial

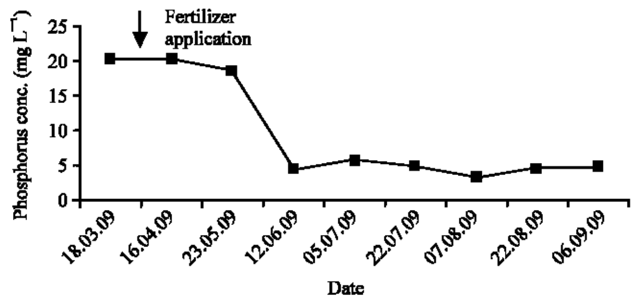

Fig. 2: Phosphorus levels in soil water samples in 2009-year 2 of trial

from agricultural land may accelerate the eutrophication of P-sensitive water (OECD, 1982). The application of phosphorus fertilizer (as slurry) increased P concentrations, shown in the higher concentrations on the treatments where, P was applied. However, there was no significant difference in P concentrations between the unfertilized treatments and the P fertilizer programmes. P levels in soil water samples peaked at 7.7 (Fig. 1). In 2009, for the spring applied fertilizer there was no significant difference in phosphorus levels between the P fertilizer programmes. Mean soil water P concentrations were higher than in year one, 8.8, 8.2, 8.1 and 9.5 mg L^{-1}, respectively for 0, 6, 12 and 18 kg P ha^{-1}, peaking at 20.3 mg L^{-1} before decreasing significantly (Fig. 2). Diffuse P loss from agriculture occurs when P is transported from the land to water sources. Fields and farmyards are the main sources of P from agriculture and water from precipitation transports it to water bodies. Thus, the environment and management practices affect both P source and transport pathways from land to water body. Sources and transport mechanisms determine the amount of P delivered to a water body (Tunney *et al*., 2007).

DISCUSSION

With stringent water quality standards being set for many large point source nutrient discharges in response to European legislation, the relative contribution of Non-Point Sources (NPS) to deteriorating water quality is increasing (Foy and Withers, 1995). Nutrients derived from agricultural NPS are currently viewed as the main cause of eutrophication in many European rivers and lakes (Heathwaite *et al*., 1996). Non-point source pollution from agricultural land can be detrimental to water quality because discharges are untreated, often contain high nutrient and organic matter loads. Also, losses occur sporadically during intense rainfall events and sources can be difficult to identify, quantify and control (Heathwaite and Dils, 2000).

In 2008, the application of P fertilizer (as slurry) increased phosphorus concentrations in soil water samples, shown in the higher concentrations on the treatments where, P was applied (4.3-6.5 mg L^{-1}). Furthermore, during the first year P concentration in soil water was high partly as a result of previous agricultural practices and inherently high soil P levels. In 2009, there was no significant difference in soil water P concentration between the 0-18 kg P ha^{-1}, however, the mean P concentrations were higher than in the previous year (8.1-9.5 mg L^{-1}). *Miscanthus* x *giganteus*, as a rhizomatous perennial grass producing an annual crop of stems has the potential to translocate nutrients to the rhizomes. This minimizes nutrient off-take and the pollution resulting from combustion of nutrient-rich material, while returning nutrients to the rhizomes for the support of the next year's growth. Fertilizer application had a positive affect on P concentrations in soil water samples. The relationship between increasing fertilizer P rate and concentration in the soil water samples in response to higher fertilizer P rates indicated a positive correlation between levels of fertilizer P and soil water P concentration. Thus, the application of P fertilizer increased P concentrations in soil water samples, shown in the higher concentrations on the treatments where P was applied, further more, the overall levels of P in the soil solution greatly exceeded critical concentrations for eutrophication control. The European Union Water Framework Directive (EU, 2000) requires the attainment or maintenance of good ecological status for surface waters. However, eutrophication is still a severe problem in surface and coastal water with diffuse losses of P from agriculture one of the main causes (Carpenter *et al*., 1998).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions made to this work by Mr. David Tyrell and Mr. Paddy O'Toole, Quinn's of Baltinglass, Co. Wicklow, Ireland.

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