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Developing an Efficient Cover Cropping System for Maximum Nitrogen Recovery in Massachusetts

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DEVELOPING AN EFFICIENT COVER CROPPING SYSTEM FOR MAXIMUM NITROGEN RECOVERY IN MASSACHUSETTS

A Dissertation Presented

by

ALI FARSAD

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DEDICATION

To the loves of my life, Shadi and Arvin.

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ABSTRACT

DEVELOPING AN EFFICIENT COVER CROPPING SYSTEM FOR MAXIMUM NITROGEN RECOVERY IN MASSACHUSETTS

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Time of planting plays a critical role in nitrogen (N) uptake by rye cover crop (CC). Even a few days of delay in planting can severely decrease CC performance. Evaluating the amount of N accumulation related to time of planting is critical to the farmer who has to optimize the winter rye planting date based on completion of corn harvest, suitable weather conditions and time availability for fall manure application. Winter rye cover crop was planted at 6 planting dates in fall from mid August to early October at weekly intervals from 2004 to 2009.

The results suggest that delay from critical planting date (CPD) will decrease rye N uptake dramatically. Suggested CPDs for northwest parts of Massachusetts are not applicable because they are too early (third to fourth week of August). CPDs for central parts of the State are from first to second week of September. Farmers in these zones can take advantage of cover crop by a better time management and planting no later than

CPD. In Eastern areas of Massachusetts CPD is the third week of September. By evaluating the effect of planting date on rye growth and N accumulation throughout the State, this model provides a powerful decision making tool for increasing N recovery and reducing nutrient leaching.

Sixteen units of cost effective and accurate automated lysimeters were designed and installed to measure post-harvest nitrate leaching from a rye cover crop field during the falls and winters of 2007 to 2009. The electronic system was designed to monitor soil tension and apply the equal amount of suction to the sampling media. Hourly data from soil tension and vacuum applied to the system were collected and stored by each unit. A safety system was designed for protecting vacuum pump against unexpected major vacuum leakage events. The controller can be easily reprogrammed for different performance strategies. Other major parts of lysimeter included the power supply systems, vacuum pump, vacuum tanks, sampling jars, suction cups and plates, and electronic valves. The electronic system showed a very reliable and accurate performance in the field condition.

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CHAPTER 1

INTRODUCTION

Yield oriented cropping systems are responsible for exploiting natural resources such as soil and water and changing natural ecosystems to achieve higher crop and/or animal production. The 1992 national water quality inventory (USDA-EPA, 1992) reported that 72% of river water contamination issues were related to agricultural practices.

Nitrogen (N) especially in the form of NO_3-N is the major pollutant of underground and surface water (Gardi, 2001; Burkart and Stoner, 2001; Castillo et al., 2000; Sauer et al., 2001; Schilling and Libra, 2000; Prunty and Montgomery, 1991; Gulis et al., 2002). Major sources of nitrogen pollution are the mineral N fertilizers, animal and human wastes and to a lesser extent industrial wastes, waste waters and landfills (Vidal et al., 2000).

After harvest N leaching from crop lands is a major source of N pollution, especially when manure is applied over the soil in the fall. In Massachusetts, the capacity of dairy farm manure storage facilities are mostly only enough to hold manure produced in the past 6 months. Therefore, many dairy farmers and some livestock producers have no alternative but to empty their storage in the fall after the corn has been harvested and spread manure on crop lands (Herbert et al., 2007). At this time, nitrogen in manure and other sources of organic matter continues to be released as nitrate by microbial activity. Nitrate is highly soluble in water; therefore if it is not taken up by plant roots, it will be leached quickly by fall rainfall.

Some cover crops including winter rye are very efficient in recovering N and other nutrients released by microbial activity. Use of winter rye cover crop if managed properly, provides an economic incentive for farmers to adopt sustainable farming practices, which are environmentally sound.

Our goal in this research project was to maximize rye winter cover crop efficiency in taking up and recovering N so that the next crop could benefit from the available N released by cover crop decomposition in the spring. This project, therefore, had to address several related problems. Cover crop planting date plays a key role in N uptake efficiency. Therefore a part of this project was a multi-year, multi-location experiment on oat and rye cover crop planting date. The information from this portion of the study gave us a good understanding of the mechanisms of cover crop response to planting date.

There was also a need for an accurate device for collecting soil-water samples in order to study the dynamics of N leaching during the cover crop planting season. Unfortunately most regular soil-water sampling methods do not have sufficient accuracy for measuring leachate volume as well as sample concentration. Therefore one of our side projects was to design and develop an automated suction lysimeter as a relatively new and accurate method for collecting soil-water samples. Several automated suction lysimeters were installed and used in our cover crop experimental plots. The information from these devices improved our understanding of N leaching from cover crops planted on different planting dates.

Planting date recommendations have mostly local applications and are not applicable to other regions. Information from our cover crop planting date experiments in Deerfield, MA helped us develop a spatial Growing degree days (GDD) based model that determines critical planting dates for winter rye cover crop for the entire state of

Massachusetts. Delay from the critical planting date will cause a significant reduction in N uptake and recovery.

The final phase of the project was to study the feasibility of our planting date recommendations. The model suggested planting dates cannot always be applicable to the region due to some practical issues. In order to have a better idea about the farmers' current management practices in the state, data from a survey performed by Hashemi et al. (2007) was used to develop a spatial presentation of cover crop and corn planting and harvest dates. This was necessary for detecting any overlap between cover crop planting date recommendations made by our model and current corn growing seasons. The results from this phase of the project enabled us to have a more realistic idea about the current situation and our practical limitations in planting winter rye cover crops.

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CHAPTER 2

NITROGEN LEACHING DYNAMICS AND EFFECTS

Introduction

Intensive agriculture uses all possible means to maximize production and thus profit. This practice has led to exploitation of the natural resources such as soil and water, changing the natural ecosystem to achieve higher crop and/or animal production. Most of these changes in natural ecosystem are harmful and are almost irreversible. The 1992 national water quality inventory (USDA-EPA, 1992) reports that 72% of river water contamination issues were related to agricultural practices.

Nitrogen (N) especially in the form of NO_3-N is the major pollutant of underground and surface water (Gardi, 2001; Burkart and Stoner, 2001; Castillo et al., 2000; Sauer et al., 2001; Schilling and Libra, 2000; Prunty and Montgomery, 1991; Gulis et al., 2002). Major sources of nitrogen pollution are mineral N fertilizers, animal and human wastes and to a lesser extent industrial wastes, waste waters and landfills (Vidal et al., 2000).

The Water quality problems related to nitrate are becoming more and more important because of increases in application of nitrogen fertilizers (Burkart et al., 1999). The environmental risks of nitrate losses to groundwater have been understood for many years, and have been the subject of several studies (Baker, 1988; Thurman et al., 1992; USEPA, 1992; Goolsby and Battaglin, 1993; Follett and Walker, 1989). Once introduced to the ground water; it will cost communities millions of dollars for removal or to provide alternate drinking water sources (Altman and Parizek, 1995). For example, Des Moines, IA alone has spent in excess of $4.8 million for NO_3 removal from drinking waters between 1991 and 1999 (G. Benjamin, unpublished data, 2000). This has lead to establishment of a maximum acceptable concentration (MAC) of 10 mg.L^{-1} of NO_3-N in drinking water in Canada, United States and many other countries (Health Canada, 1992; Health and Welfare Canada, 1996). The MAC recommended by the World Health Organization (WHO) is 11.11mgL^{-1}. The recommended nitrate concentration in Europe is 5.56 mg L^{-1} NO_3-N (Van Maanen et al., 2000).

The concept of "human affected value" was introduced in 2001 (based on previous work conducted in the 1990s (Burkart and Kolpin, 1993; Eckhardt and Stackelberg, 1995), whereby any concentration greater than the background concentration of 3 mg L^{-1} NO_3-N is considered to be a result of human practices (McLay et al., 2001). In Prince Edward Island (PEI, Canada), nitrate levels in the range of 0.1 to 2 mg L^{-1} NO_3-N are considered to represent background levels for relatively un-impacted, "pristine" watersheds (Young et al., 2002). A limited study in PEI found a mean nitrate level of 1.15 mg L^{-1} NO_3-N for ground water from wells in non-cropped areas (Somers, 1998).

In many states of the United States, wells have exhibited NO3- concentrations exceeding the USDA-EPA and Canadian health standards limit of 10 mg L^{-1} NO3–N for drinking water (Health Canada, 1996; Randall et al., 1997; Thompson et al., 2000; Weil et al., 1990). Mueller et al. (1995) reported that 1% of community wells and 9% of rural domestic wells had nitrate concentrations above the maximum acceptable (10 mg L-1) level. These authors also reported that 26% of contaminated wells were in the areas with land use under intensive agriculture. Similarly Poe et al. (1998) reported that nitrate contamination mostly is related to areas with intensive agriculture land use or in urban areas. Researchers have shown that 50% of nitrogen leaches from agricultural applications to running water (Meissner et al., 1998; Hansen et al., 2000; Owens et al., 2000; Sogbedji et al., 2000). Baker et al. (1975) found average NO_3–N concentrations of 21mg.L^{-1} in drainage water in fields planted to corn–soybean or corn–oat. Several researches have reported considerable "edge-of-field" leachate of nitrate (Hanway and Laflen, 1974; Gast et al., 1978; Miller, 1979; Benoit, 1973; Logan et al., 1980; Baker and Johnson, 1981; Bergström, 1987; Kanwar et al., 1988; Drury et al., 1996). High recharge rates of N especially in thin, permeable overburden soils, increases the risk of leaching and ground water contamination (Young et al., 2002).

Intensive use of nitrogen fertilizer to increase crop production can intensify eutrophication of ponds, lakes and rivers by increasing algae growth (Yeomans et al., 1992). Eutrophication of running (rivers) and still (aquifers and reservoirs) waters, net phytoplankton productivity, and increased water hypoxia are some other consequences of leaching nitrate from agricultural areas (Justic et al., 1995; Rabalais et al., 1996). Several estuaries in the USA have been contaminated with excessive N levels (Economic Research Service, 1997), and in the northeastern USA, about 60% of estuarine areas showed a high level of eutrophication (USDA-EPA, 2001). This phenomenon can result in changing ecological functions and food webs (National Research Council, 2000). Nitrogen and phosphorus (P) are considered to be the most common causes of surface water eutrophication (Danalewich et al., 1998). For example a high inorganic N load within the Mississippi River has stimulated algal growth and eutrophication and ultimately contributes greatly to the hypoxic and anoxic zones in the Gulf of Mexico (Alexander et al., 1995; Rabalais et al., 1996; Turner and Rabalais, 2003) and along the coast of Louisiana (Rabalais et al., 1996; Turner and Rabalais, 1994). Fertilizer application most often exceeds the N requirement of crops, thus creating a pool of potentially leachable nitrate (NO_3^-) (Lowrance, 1992; Prakasa Rao and Puttana, 2000). Turner and Rabalais (1991) showed that high amounts of nitrate in the Mississippi River due to increased use of mineral fertilizer throughout the river basin increased the impact of hypoxic incidences in the Gulf of Mexico. Nitrate pollution in the Mississippi River is generally greatest in tributaries where drained fields are planted with corn and soybean (Burkart and James, 1999).

Nitrogen pollution can also be a threat to human (Gaynor and Findlay, 1995; Owens et al., 2000; Townsend et al., 2003; Zhao et al., 2001; NRC, 1978; Mansouri and Lurie, 1993; USDA, 1991; Tyson et al., 1992) and animal health (Lewis, 1951; Shirley et al., 1974). A number of leaching and drainage studies have consistently found that NO_3 (nitrate) is the dominant form of N present in the soil water (Willrich, 1969; Baker et al., 1975; Kladivko et al., 1991; Jacinthe et al., 1999). Some studies have shown that there is a correlation between nitrate concentration in drinking water and birth defects, cancer, nervous system impairments, and infant methemoglobinemia (also known as blue baby syndrome) which in some cases can casue death in children between the ages of 4 and 6 months (Comly, 1945; Gelberg et al., 1999; Health and Welfare Canada, 1996; Keeney, 1987; Jemison and Fox, 1994). Nitrate can also cause other disorders (Prasad and Power, 1995).

Nature of leaching and various factors that affect nitrogen leaching

In the Merriam-Webster dictionary the definition of the verb “Leach” is “to dissolve out by the action of a percolating liquid” and “to remove (nutritive or harmful elements) from soil by percolation”. As water moves through the soil profile, it picks up and carries away nitrate nitrogen. Leaching transports nutrients below the crop root system. The leached nutrients thus should be considered lost unless the roots grow deeper. Many factors affect the intensity of nutrient leaching and can be grouped into a) soil factors, b) climatic conditions, 3) plant characteristics and d) management practices. Among factors affecting the intensity of N leaching are some plant properties such as root system (Bowman et al., 1998; Sullivan et al., 2000) and plant growth stage (Ritchie and Hanway, 1982).

Soil factors

Soil texture

Soil texture is a very influential factor on leaching. Sand base soils have a very limited capacity for retaining water and nutrients; therefore need more frequent irrigation and N fertilizer application (Hahne et al. 1977; Lembke and Thorne, 1980; Brown et al., 1982; Bigelow et al., 2001). In these soils the rate of infiltration is very high therefore N leaching can also be high (Mancino and Troll, 1990; Shuman, 2001). Nitrate contamination of ground water is often greatest where a relatively shallow water table underlies coarse-textured soils that are used for irrigated crop production (Wu et al., 1997). In a three-year study in Quebec, Canada, Liang and MacKenzie (1994) measured the changes in soil NO_3 concentration as a result of N fertilizer application for a clay and a sandy clay loam soil. They reported an increase in soil NO_3 content (in the depth of 0 to 0.8 m) in the sandy soil as N fertilizer rate increased above the optimum (170 kg N ha^{-1}). Lund et al. (1974) found that soil texture within the root zone (0–1.8 m) explained 86% of the variability in NO_3 concentration below the root zone (1.8–8.0 m). At 15 study locations within a 30 ha field that had been managed uniformly with manure (76 Mg ha^{-}

$1.yr^{-1}$ for 4 years), the NO_3 concentration below the 1.8m depth decreased linearly as clay content in the root zone increased.

Soil structure

In a soil with good structure, water retention is high which can prevent leaching. However these soils also have a higher infiltration rates, meaning that leaching can be high in these soils. Preferential flow of water happens not only through the so-called macropores of shrinkage cracks (Bouma and Dekker, 1978; Bronswijk, 1988), inter-aggregate pore space (Rao et al., 1980; Cote et al., 1999), root channels (Ishiguro, 1991; Li and Ghodrati, 1994), earthworm burrows (Zachmann et al., 1987; Edwards et al., 1989), and fractures in rocks (Dahan et al., 1998; Pruess, 1999), but also through the soil matrices with macroscopic hydraulic heterogeneity (Nielsen et al., 1973; Kung, 1990; Roth, 1995) or water repellency (Ritsema et al., 1993; Dekker and Ritsema, 1996). All these path ways can short-circuit the soil water below the root zone and carry away nitrate.

Irrigation and precipitation

Leaching always occurs when the amount of precipitation plus irrigation exceeds evapotranspiration rate. Any excess N residue is likely to be leached. Furthermore, excess inorganic N may be released if irrigation increases net N mineralization rates of soil organic matter (Morton et al., 1988; Polglase et al., 1995). Irrigated agriculture is implicated as a contributor to NO_3 contamination of surface and ground water in many corn production regions (Ferguson et al., 1991; Schepers et al., 1991; Spalding and Exner, 1993; Burkart and James, 1999; Sogbedji et al., 2000). Monitoring studies of ground water nitrate contamination suggest that many major areas of contamination are located in the irrigated areas (Anderson, 1989; Power and Schepers, 1989; Spalding and Exner, 1993). Several studies have shown the impact of water management on NO_3 leaching under irrigated corn (Watts and Martin, 1981; Hergert, 1986; Spalding et al., 2001). Endelman et al. (1974) showed that 2.54cm of irrigation or precipitation can move soil NO_3 15 to 20 cm deep in a loamy sand soil. The management of irrigation, a prerequisite for profitable crop production (Fereres and Ceńa, 1997), plays a crucial role in controlling nitrate leaching (Díez et al., 2000; Sexton et al., 1996; Spalding et al., 2001; Cavero et al., 2003).

Precipitation can have a similar impact on N leaching in many ways. Smika et al. (1977) reported that for a loamy fine sand in Colorado, total NO_3 leached after harvest was highly correlated (r = 0.95) with the total water percolating below root depth. The timing of such precipitation relative to manure application seems to be critical, as about half of the total nitrate leaching may happen in the first few hours, although this may be greatly affected by the application method (Meisinger and Jokela, 2000). Irrigation must be managed carefully to maximize nitrogen fertilizer use efficiency and minimize nitrate loss, especially when N fertilizer at nominal, economic rates has been applied (Russelle et al., 1981). Periods of below average annual precipitation can lead to an increase of residual soil nitrogen that may be leached from the soil in wet years (Lucey and Goolsby, 1993; Randall and Iragavarapu, 1995; David et al., 1997; Randall and Mulla, 2001). Timing of rainfall also has an impact on N leaching. Intense precipitation in early spring before the uptake of fertilizer begins may intensify leaching of nitrogen (David et al., 1997).

Cultural Practices:

Agricultural practices can have a great impact on leaching. Any physical alterations in soil can potentially affect leaching amounts (Carpenter et al., 1998; Jolankai and Rast, 1999). Negative effects of agricultural practices on surface and ground water quality have been a matter of concern for many years, especially in cold and humid regions where the net leaching of water may cause considerable losses of nitrogen during the non-cropping interval (Kladivko et al., 1991; Davies and Sylvester-Bradley, 1995).

Conventional vs. Conservation Tillage

A three year study by Gaynor and Findlay (1995) reported that the concentration of N in drainage water from zero tillage was more than conventional tillage. The same result was reported by Eisenhauer et al. (1993) where NO_3-N leached from plowed fields was less than no-till cultivation. Sharpley et al. (2001) report no-till farming reduces erosion but can increase water infiltration. Perhaps the reason for this is that tillage destroys the soil macrospores (Hangen et al., 2002). However Kanwar and Baker (1993) and Power et al. (2001) found a greater concentration of NO_3-N in leached water in plowed than no-till fields. Other studies have shown no significant difference on NO_3-N leaching between tillage methods (Kanwar et al., 1995; Lamb et al., 1998).

Tillage alters the soil environment by aerating the zone of disturbance and raising the availability of oxygen to soil microorganisms. This increases different microbial species populations, and activities compared to a no-till system (Doran, 1987). The outcome of tillage is elevated aerobic microbial activity, leading to elevated oxidation of soil organic matter and mineralization of soil N (Randall et al., 1997a). This N mineralization response, often associated with pre-plant tillage, is also a benefit due to using cultivation for weed control during the growing time. However, using tillage practices to release N for crop growth has a negative impact on soil quality. Rapid degredation of SOM influences cation exchange capacity, soil structure, and water retention capacity. Soil tillage also increases the wind and water erosion (Reicosky et al., 1995). Moreover, depending on seasonal weather patterns, temperature, and rainfall, tillage during autumn or early spring can cause N mineralization too early and increase the risk for NO_3 leaching before subsequent crops have a chance to uptake the nitrogen released by this microbial activity.

Conventional vs. organic farming

Organic farming has been considered as a possible approach to decrease leaching of nitrogen from agricultural areas. In such farming systems, inorganic N fertilizers are not applied, and the nitrogen inputs are mainly provided from mineralization of animal and green manures. This has led to a growing interest in inclusion of legume- or grass-based green manures to agricultural farming systems (Dou et al., 1995).

According to Maeda et al. (2003) and Korsaeth and Eltun, (2000) there is significantly less NO_3-N leached from swine compost than from inorganic fertilizers (coated urea and ammonium). Also some researchers suggest a greater loss of nitrogen with conventional agriculture. Current practices related to N fertilizer management are often wasteful compared with organic systems and consequently increase the risk of contamination of water resources (Sanchez and Blackmer, 1988; Kanwar et al., 1993, 1996; Randall, 1997; Randall et al., 1997a; Cambardella et al., 1999). A study conducted on loamy and silty sand soils showed that 42% more N was leached to drainage from conventionally planted fields than from organically farmed areas (Korsaeth and Eltun, 2000). However there are some experimental studies that have shown no difference in leaching amounts between conventional and organic farming systems (Kirchmann and Bergstrom, 2001; Elliott et al., 2002; Carefoot and Whalen, 2003). Some reports indicated greater leaching from organic systems, especially those involving plow-down of leguminous crops (Armstrong Brown, 1993; Nguyen et al., 1995). More research on the differences in N leaching from organic and conventional farming practices is necessary to assess the impact of organic farming on water pollution.

Crop rotation

Plants are different in their needs and growth patterns. Planting the same crop for several years in the same farm field usually tends to a significant reduction in yield. Moreover, it can increase disease and pest problems. It can also increase the risk of nutrient loss through leaching. Grant et al. (2002) suggested that using soybean in rotation could reduce NO_3-N leaching because usually there is no N fertilizer application on soybean crops and plants would be forced to take up N from the soil for their needs. Some studies show 31 - 63% less concentration of NO_3-N in drainage water from corn-soybean rotation than continuous corn systems (Kanwar et al., 1997). Although rotation of corn-soybean is better than monoculture corn, still it contributes to significant amounts of leaching (Dinnes et al., 2002; Goldstein et al., 1998; Randall et al., 1997).

Including perennial legume or non-legume crops in rotations has been shown to decrease nitrate leaching. In Iowa, Baker and Melvin (1994) documented much lower nitrogen-nitrate concentrations beneath alfalfa root zones than for corn or soybean. Also, in Minnesota, Randall et al. (1997a) measured nitrogen-nitrate concentrations in drainage water from alfalfa farmlands and Conservation Reserve Program (CRP) areas planted to a mixture of alfalfa and perennial grasses and showed nitrate concentrations were 37 and 35 times lower than in drainage water from corn and soybean fields, respectively. Differences in residue and root decomposition activities, as well as soil–plant–water dynamics (i.e., soil water extraction capacity) among different plant species may also influence the leaching risk (Baker and Melvin, 1994; Randall et al., 1997a; Malpassi et al., 2000). The rate of nitrogen cycling is critical because although N-fixing legumes can release large amounts of nitrogen to soils over time, organic nitrogen resulting from plant and microorganisms is not as rapidly available to successive plants as inorganic nitrogen produced by most mineral fertilizers. Moreover, "the gradual release of organic N is often better synchronized with subsequent plant needs and microbial population dynamics than point-in-time applications of N fertilizers" (Dinnes et al., 2002).

Fertilizer application

Type of fertilizer

The type of fertilizer can obviously have a significant impact on leaching. Application of organic fertilizers (such as manure) can reduce leaching. The reason is that the nitrogen in organic material is not readily available. Organic matter releases N gradually and therefore increases the N-use efficiency. Snyder et al. (1977) found that nitrogen source and application rates considerably affected N leaching. Differences in NO_3 leaching related to nitrogen fertilizer types varied by as much as 30 fold (Guillard and Kopp, 2004). Mineral fertilizers are available for immediate crop use and leach more quickly than manure because mineralization of organic N occurs later in the growing season (Randall et al., 2000; Thoma et al., 2005). Organic nitrogen sources are more appropriate for application, especially in sandy soils. Still there is an increased possibility of nitrate leaching from soils receiving high amounts of liquid manure (Nielsen and Jensen, 1990; Beckwith et al., 1998; Jensen et al., 2000). Reports indicated that, when applied at adequate rates, lower amounts of nitrate are leached compared with soils receiving mineral fertilizers (Beauchamp, 1986; Zebarth et al., 1996; Randall et al., 2000; Díez et al., 2001; Daudén and Quílez, 2004). Controlled-release mineral fertilizers also can reduce nitrate loss (Paramasivam et al., 2001).

<u>Rate of fertilizer</u>

High rates of fertilizer application in the long run can contribute to greater amounts of leaching (Snyder et al., 1977; Hatfield and Cambardella, 2001). Some studies showed no difference between NO_3-N leaching from urea and manure when both were applied at excess levels of nitrogen (Randall et al., 2000; Zhao et al., 2001).

Power and Schepers (1989) suggested that the most important way to reduce N leaching is to apply suitable amounts of nitrogen fertilizer. Some researchers have shown that as N fertilization rates increased above crop needs, NO_3- N leaching increased (Gast et al., 1978; Baker and Johnson, 1981). Randall (1997) stated that rate and time of fertilizer application were the key factors that determined the amount of N loss related to leaching. Ferguson et al. (1991) found NO_3 concentrations below root depth in a silt loam soil were about 21kgN.ha^{-1} greater at N rates of 150 and 300kgN.ha^{-1} compared with 75kgN.ha^{-1} or unfertilized rates. Andraski et al. (2000) found a strong correlation ($r^2 = 0.88$) between excess N fertilizer applied and end-of-season soil NO_3 content (0–90 cm) in a Wisconsin silt loam soil under continuous corn cultivation. Bundy and Andraski (1996) also found a strong correlation ($r^2 = 0.73$) between end-of-season soil NO_3 content in a 60-cm profile and the amount of excess N. On a loamy sand soil corn field in New York, Sogbedji et al. (2000) found higher residual NO_3 levels in application 134 kg N ha^{-1} than 100 kg N ha^{-1}. In this study, over three years, the soil NO_3–N concentration below root level for the treatment 134kgN.ha^{-1} was more that 200% of the 100kgN.ha^{-1} rate. Therefore accurate N fertilizer recommendations can control the negative environmental impacts of leaching nitrate (Fox et al., 1989).

Applying the proper amount of N has always been a challenge to the grower. Even in a single farmland, different areas may have different N demands. Power et al. (2000) reported that mid-western farmlands commonly have high levels of variability in soil nitrate content from place to place within a single field. They stated that "... soils are seldom uniform throughout a field, so applying sufficient N fertilizer to assure high yields for more productive areas of the field often results in over-fertilization of the less productive areas. This may lead to greater nitrate leaching, particularly in those areas of the field that are more susceptible to leaching". Kranz and Kanwar (1995) observed that within a given field, 70% of the nitrate losses typically comes from <30% of its area. Most conventional N fertilizer recommendation were developed on a state or regional scale, so it was not clear whether these strategies can practically be used for variable-rate nitrogen management that attempts to account for within-field spatial and temporal variability (Hergert et al., 1997). Several studies have found large variability in crop yield and crop nitrate response within individual fields (Ferguson et al., 1995; Kitchen et al., 1995; Vetch et al., 1995), confirming the need for reliable strategies to provide site-specific N recommendations (Hergert et al., 1997). Monitoring nitrate mineralization to better match the required amount of available nitrogen with crop needs is one method for reducing nitrate leaching risk. To accomplish this task, several methods of a preside-dress soil nitrate test (PSNT) (Magdoff et al., 1984; Fox et al., 1989; Magdoff et al., 1990) or modifications such as the late-spring nitrate test (LSNT) (Blackmer et al., 1997) have been developed. These tests usually suggest sampling the soil approximately 6 wk after planting. The logic behind these tests is that by late spring, the net effects of mineralization, leaching, and other potential losses that may have happened since the last crop was harvested, can be accurately determined. The results of the nitrogen test then can be used to predict the suitable amount of N fertilizer to apply.

Plot-scale researches using PSNT or LSNT methods to determine fertilizer N rates have mostly shown reductions in measured or potential nitrate leaching. In Iowa, these procedures resulted in nitrogen fertilizer applications ranging from 50 to 168kgN.ha^{-1} and significantly reduced nitrate leaching to drainage tiles compared with single pre-plant fertilization of only 112kgN.ha^{-1} (Kanwar et al., 1996). These results confirm that the PSNT or LSNT method for N management has the ability for reducing excess nitrogen application in comparison with yield-goal strategies (Magdoff, 1991; Durieux et al., 1995; Kanwar et al., 1996; Randall, 1997; Karlen et al., 1998).

Plant Factors

<u>Growth stage</u>

Plant nutrient uptake follows a complicated pattern and is influenced by genotype and growth stage of the crop. There is often a lag period between applications of fertilizers and N removal by plants. During this period, nutrients are susceptible to leaching (Zhang and Solberg, 1996; Hatfield and Cambardella, 2001). Therefore, growth stage can dramatically affect the amount of nutrient leaching. For example at the six-leaf stage (V6) (Ritchie and Hanway, 1982), the corn plant begins its most active growth where substantial amounts of N and water uptake takes place. Fertilization at V6 therefore, is more efficient than application at the planting date (Wells and Bitzer, 1984; Fox et al., 1986; Wells et al., 1992). Studies have shown that greater N uptake and yield obtained when N fertilizer was applied at V6 stage could be attributed to the decrease in N losses by denitrification (Wells and Bitzer, 1984), immobilization (Jokela and Randall, 1997), and leaching (Thomas et al., 1973) although some scientists believe that applying N fertilizer at V8 is superior (Russelle et al., 1981) however, its practicality can be challenging. Maximum corn rooting depth does not occur until about the tasseling stage. By this time only 60% of total N uptake has occurred (Hoeft et al., 2000). Therefore, the crop can still have a great N uptake.

Plant morphology

Studies have shown that morphology, size and depth of root system have a significant effect on N uptake (Bowman et al., 1998; Sullivan et al., 2000). Row crops as well as annual and perennial forage crops may show significant differences in amounts of N leaching (Anderson et al., 1997). A number of researches measured NO_3–N leaching potential in different crops species (e.g., Robbins and Carter, 1980; Bergstrom, 1987; Owens, 1990; Randall et al., 1997; Eriksen et al., 2004). In general, they found the highest NO_3–N amounts under maize; intermediate levels under less-fertilized annual crops (e.g., soybean [*Glycine max* (L.) Merr.] and wheat [*Triticum aestivum* L.]); and lowest levels under perennial crops (e.g., alfalfa [*Medicago sativa* L.] and grasses). Soil hydrologic patterns also varied among crops (Dinnes et al., 2002). Randall et al. (1997)

found drainage from row-crop cultivation surpassed perennial crops by 10 to more than 430%, apparently as a result of differences in crop water uptake timing and the depth of the root system. Bergstrom (1987) also found higher leaching under barley (Hordeum vulgare L.) than fescue (Festuca arundinacea L.) and alfalfa. Hence, the phenomenon of NO_3 leaching under different crops is the product of different factors such as soil hydrology, crop water and nutrient uptake, and cultural management strategies. The use of perennial crops compared to annual row crops was usually recommended as an alternative practice when NO_3 leaching was of great concern (e.g., Schertz and Miller, 1972; Meek et al., 1994; Randall et al., 1997; Yiridoe et al., 1997).

Turfgrass cultivars may also have different N leaching capacities. Based on measured nitrate amounts and model simulation of water percolation, Liu et al. (1997) suggested that N leaching among different cultivars was significantly different. Using two genotypes of creeping bentgrass (*Agrostis palustris* Huds.) in column lysimeter research, Bowman et al. (1998) concluded that deep-rooted turf grasses can absorb N more effectively than the shallow-rooted ones.

After harvest leaching

The interval between crop harvest in fall and planting in spring is a critical time for leaching nutrients especially in areas with high precipitation (Keeney and Follett, 1991). Winter precipitation has a great potential to wash out the nutrients especially where there is no crop to uptake nutrients (Watts and Martin, 1981; Martin et al., 1994).

Spring application of N is apparently more efficient than fall application. The reason is that N loss is less between the time of N application and plant uptake (Randall and Goss, 2001). The amount of nitrogen leaching increases as the time between N application and crop uptake increases (Magdoff, 1991; Karlen et al., 1998; Power et al., 1998).

Post-harvest soil NO_3 content is usually considered as evidence of excess N fertilizer application (Ferguson et al., 1991; Karlen et al., 1998; Andraski et al., 2000). Two main sources for post harvest N leaching are unused fertilizer from previous crops and mineralization of organic residues (Bartholomew, 1932). Manure application in fall increases the risk of N loss through both of these sources. Fall application of manure therefore, may lead to large amounts of leaching (Walter et al., 1987; Keeney and DeLuca, 1993; Dinnes et al., 2002; Patni and Culley, 1989; Smith et al., 1998; Cambardella et al., 1999; Martin et al., 1994; Ritter et al., 1993).

Every year the U.S. dairy sector was estimated to generate 216Mg of manure (USDA-NASS, 2002; American Society of Agricultural Engineers, 2005). Almost the entire amount is applied to farmlands as a nutrient source. Traditionally, locally produced manure is applied to the farm. However, large-scale producers are producing amounts of manure which may be far more than the farm needs (Kellogg et al., 2000). Since manure cannot be economically transported over long distances from where it is produced, much of it is applied to nearby fields. Excess manure applications to the same farmland can enhance soil nutrients including nitrogen to the extent that N moves out of the field into the soil or across the surface mainly through leaching and runoff, contributing to water pollution (Sims et al., 2005).

Paul and Zebarth (1997) measured leaching losses from fall-applied dairy cattle slurry on two soil types in coastal British Columbia (a poorly drained coarse-textured and a well-drained medium-textured soil) and estimated an average of 40 kg N ha^{-1} more than no-manure application treatment. In this study, denitrification accounted for only 17% of the total NO_3^- losses, and therefore was less important than leaching. Smith and Chambers (1993) in England also suggested that the application of high-nitrogen manures in the fall results in excessive nitrate leaching losses and recommended against application in fall. Application of manure in early spring may also result in NO_3^- release that exceeds crop uptake (Durieux et al., 1995), and therefore may result in significant leaching losses. Similarly, timing of manure application within seasons may have significant impact on leaching potential. A late fall application, when soil temperatures have decreased (near or below freezing), may result in less N release than early fall application, and more similar to spring application. For example, Gangbazo et al. (1995) did not detect increased nitrate leaching from late-fall-applied manure compared with no-manure application treatment. Generally, manure has two main components, a liquid phase with mostly unstable urea (NH_4) nitrogen and a solid portion which consists of more stable organic N (Klausner et al., 1994). NH_4 portion of manure can be easily lost through volatilization. The amount of loss depends on soil and weather conditions (Lauer et al., 1976). Even when manure is thoroughly incorporated into soil, NH_4^+ can easily be converted to NO_3^- and therefore is subject to leaching. The organic N fraction of manure mineralizes and becomes gradually available to the plant, typically represented by a decay series (Pratt et al., 1973; Magdoff, 1978; Klausner et al., 1994). However, it is recognized that the rate of N mineralization is strongly affected by variations in soil, weather, manure composition, and management factors (Barbarika et al., 1985; Douglas and Magdoff, 1991; Bernal and Kirchmann, 1992; Klausner et al., 1994; Jackson and Smith, 1997). Estimates for mineralization of the organic manure N fraction are lower for manure applied to poorly drained clay soil or left on the surface (compared with manure incorporated on well-drained soil and is about half of those on a well-drained loam [Magdoff, 197]).

The fall application problem is not only about manure, many U.S. corn producers, prefer to apply N fertilizer in the fall because they usually have more time, their manure storage facility is full, field conditions are better for application or the cost of N in the fall is usually less. Yet application of N fertilizer or manure in fall is not a very efficient practice. Sanchez and Blackmer (1988) reported that 49 to 64% of N fertilizer applied in fall was lost from 1.5m depth. Also Randall et al. (1992) and Randall (1997) reported 20% more efficiency for spring N fertilizer application in comparison to fall application.

Benefits of cover crops

Introduction

Cover crop has been defined as “Crops including grasses, legumes and forbs for seasonal cover and other conservation purposes” (NRCS, 2007). Cover cropping has been a fundamental tool in past decades to improve many conditions associated with sustainable agriculture. Cover crops primarily were used for soil surface cover and erosion protection (Nyakatawa et al., 2001; Kessavalou and Walters, 1999; Stivers-Young, 1998; Torbet et al., 1996; Wyland et al., 1998). Cover crops also have been used widely to improve soil properties (Doran, 1987; Smith et al., 1987; McVay et al., 1989; Roberson et al., 1991; Khanh et al., 2005; Nyakatawa et al., 2001). Other benefits from cover crops include snow trapping (Feyereisen et al. 2006); suppressing weeds (Blackshaw et al., 2001), pests (Shelton and Badenes-Perez 2006), and diseases (Potter et al. 1998, Vargas-Ayala *et al.* 2000); diversity to farming systems and wild life (Lu et al. 2000); and reducing the risk of environmental pollution (Eckert, 1991; Ditsch et al., 1993; McCracken et al., 1994; Brandi-Dohrn et al., 1997; Owens et al., 2000). Some cover crops like winter rye, wheat and triticale have been used extensively for nutrient recovery which otherwise would be lost to the environment (Sullivan, 2003; Snapp et al., 2005).

Erosion prevention

The role of cover crops in reducing soil erosion is well documented (e.g. Frye et al., 1985; Langdale et al., 1991). Providing ground cover in fall and winter or during fallow period, cover crops can support soil against wind and rainfall (Johnson et al., 1998; Kaspar et al., 2001). Residue of winter cover crops is a vital part in restraining soil erosion, especially on frozen soil or landscapes with steep inclinations (Cruse et al., 2001). The significant role of cover crops in preventing soil erosion during fall and winter has been emphasized when growing row crops, such as corn, soybean and cotton (Baughman et al., 2001; Dabney et al., 2001; Hutchinson et al., 1991; Mutchler and McDowell, 1990; Kaspar et al., 2001; Meisinger et al., 1991; Sainju and Singh, 1997).

Organic matter enhancement

Cover crops when returned to soil will improve soil organic matter (Dabney et al., 2001; Hutchinson et al., 1991; Varco et al., 1999). Green manure is another term used for cover crops when incorporated into soil to improve its organic matter content. Soil organic matter increases when inputs of organic C to the soil system are greater than organic matter loses related to decomposition, erosion and leaching (Paustian et al., 1997; Huggins et al., 1998). Decomposition is the main reason for in soil organic C reduction and has been subject to many studies (Wagger, 1989a, 1989b; Ruffo and Bollero, 2003a, 2003b).

Using winter cover crops for improving soil organic matter is more responsive where soil organic matter is low and winter conditions are mild, which allows the cover crop to grow fast and produce large amounts of biomass (Hargrove, 1986; Doran, 1987; Doran and Smith, 1987; Beale et al., 1955; Patrick et al., 1957; Utomo et al., 1987; Utomo et al., 1990; Kuo et al., 1997; Nyakatawa et al., 2001; Sainju et al., 2002). Winter cover cropping when planted at the right time, are an effective practice to maintain and/or improve soil organic matter compared with bare fallow soil in almost all areas. Winter cover increases additional crop residue that eventually increases soil organic matter (Hargrove, 1986; Kuo et al., 1997a, 1997b; Sainju et al., 2000). Elevation in soil organic matter contributes in enhancing crop productivity (McVay et al., 1989; Kuo and Jellum, 2000; Sainju et al., 2002) and can be translated to sequestering atmospheric CO_2 (Jastrow, 1996; Kuo et al., 1997a; Allmaras et al., 2000; Sainju et al., 2003). Farmlands that have been subject to intense cultivation and are low in organic matter, are very responsive to winter cover crops and have the potential to sequester CO_2 (Lal and Kimble, 1997; Paustian et al., 1997). Therefore many studies suggest the use of winter cover crops as a management practice for offsetting green house gas production (Karlen and Cambardella, 1996; Lal et al., 1998; Jarecki and Lal, 2003).

Improving soil properties

The positive effect of cover crops on soil health has been known for a long time (Odland and Knoblauch, 1938). Winter cover crops improve physical conditions of soil (Patrick et al., 1957; Scott et al., 1990) and soil quality (Breitenbeck et al., 1994; Dabney et al., 2001). As mentioned earlier, cover crops maintain and even enhance soil organic matter (Kuo et al., 1997; Sainju et al., 2003) and promote the formation and stabilization of soil aggregates (McVay et al., 1989; Meisinger et al., 1991; Reeves, 1994; Calkins and Swanson, 1998; Kabir and Koide, 2000; Sainju et al., 2003). A two year study on an arable soil that was converted to pasture showed a significant increase in satiability of soil aggregates (Haynes and Swift, 1990). Roberson et al. (1991) also reported greater stability in soil aggregates due to cover crop. Similar results were reported by Hermawan and Bomke (1997).

Cover crops can reduce bulk density (Latif et al., 1992) and increase porosity of soil (Ess et al., 1998). They can increase soil water holding capacity (Smith et al., 1987) and enhance water infiltration (McVay et al., 1989; Drury et al., 1991; Roberson et al., 1991; Folorunso et al., 1992). Many factors affect the potential impact of winter cover crops on soil physical properties. These factors include environmental conditions, cover crop species, soil factors and management practices (Kuo et al., 1997; Smith et al., 1987).

The impact of different cover crops on soil physical conditions varies due to the amount and composition of their residues in soil and their rooting system (Dexter, 1991; Martens, 2000b; Power et al., 1998). Deep-rooted cover crops can be a solution to compaction problems especially in no-till farming systems (Unger and Kaspar, 1994). The extensive root system of a cover crop penetrates into the soil profile and creates bio-pores which can later provide air to deeper layers and enhance water infiltration for successive plants (Meek et al., 1990; Rasse and Smucker, 1998). In a study conducted by Stirzaker and White (1995) lettuce yield was doubled due to biopores made by subterranean clover (*Trifolium subterraneum* L.) roots used as cover crop. Evidences suggest that these biopores can be used by the roots of successive crops as low resistance pathways, a process called "biodrilling" (Cresswell and Kirkegaard, 1995). Improvement of soil physical conditions can have a significant impact on yield of the following crop (Langdale et al., 1990).

Yield increase

The benefits of cover crops to subsequent crop's yield have been known for many years (Odland and Knoblauch, 1938). Many studies have shown that winter cover crop can increase yield of corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sugar beet (*Beta vulgaris* L.), green bean (*Phaseolus vulgaris* L.) and many other crops (Moore et al., 1994; Brandsæter and Netland, 1999; Nagabhushana et al., 2001; Reddy, 2001, 2003; Kobayashi et al., 2004; Petersen and Rover, 2005; Haramoto and Gallandt, 2005; Dhima et al., 2006). For example winter cover crop has a substantial effect on cotton yield especially in conservation-tillage systems (Brown et al., 1985; Keeling et al., 1989; Scott et al., 1990; Hutchinson et al., 1991; Boquet et al., 1994; Bauer and Busscher, 1996; Raper et al., 2000; Dabney et al., 2001; Schwenke et al., 2001). In one word, all benefits of cover crops to soil can potentially contribute to yield increase (Wagger, 1989; Clark et al., 1997; Kessavalou and Walters, 1997; Vyn et al., 2000; Kuo and Jellum, 2002; Snapp et al., 2005). However winter cover crops may not improve a yield compared to no cover crop in all conditions. For example residues from grass cover crops usually have a high C/N ratio which causes N immobilization, therefore requiring greater N fertilizer rates than when no cover crop is used (Reeves, 1994). Therefore, careful management is needed to benefit from winter cover crops contributions to subsequent crop.

Weed control

Winter cover crops act as living mulchs. They cover the soil surface and compete with weeds for space, light, water and soil nutrients and create an unfavorable environment for weed germination and establishment (Warnes et al., 1991; Ateh and Doll, 1996; Williams et al., 1998; Reddy, 2003; Khanh et al., 2005). Many studies reported some phytotoxic (allelopathic compounds) chemicals released from some cover crops (Shilling et al., 1985; Teasdale and Mohler, 1993) which may suppress weed population. Rye cover crop reduces soil temperature, slowing weed seed germination and establishment (Putnam and DeFrank, 1983). In many researches, rye, barley and triticale have been reported as suitable cover crops for weed control (Moore et al., 1994; Reddy, 2001, 2003; Kobayashi et al., 2004; Dhima et al., 2006). However environment and cultivar effects (Burgos et al., 1999; Kobayashi, 2004) and poor establishment of rye in fall may to contribute to some weed problems in spring (Masiunas et al., 1995; Koger et al., 2002; Reddy, 2003). Moreover, some researchers have reported issues with pre-emergence herbicide application either due to absorption by rye residue (Banks and Robinson, 1982) or unevenness in spraying (Erbach and Lovely, 1975).

Disease control

Cover crops together with the main crop create a rotation which is an effective strategy for controlling selected crop diseases. Cover crops act like a non-host plant or poor host and sometimes produce allelochemicals that are toxic or inhibitory to pathogens (Wang et al., 2002). The allelopathic properties of cover crops can break disease cycles and reduce populations of pathogenic bacterial and fungal organisms (Everts 2002) and parasitic nematodes (Potter *et al.* 1998, Vargas-Ayala *et al.* 2000). Some fungal disease such as fusarium can be controlled successfully by using some species of the Brassicaceae family such as mustards, which release some toxic chemicals during the degradation of glucosinolade compounds in their plant cell tissues (Lazzeri and Manici 2001).

Cover crops have been reported to be suitable for nematodes in many different cropping systems (Duncan and Noling, 1998; Abawi et al., 2000). During the last decades, nematode infestations have been managed effectively and economically with fumigant nematicides, but emphasis is being placed on development and implementation of alternative nematode management, including host plant resistance, cover cropping, crop rotation, and soil amendments (Roberts, 1993; Starr et al., 2002). Some cover crops produce nematicidal chemicals. For example, some species of Brassica produce glucosinolates that degrade in soil to form isothiocyanates, the *Tagetes* species produce terthienyl, and the *Crotalaria* species produce monocrotaline; all of these compounds have nematicidal properties (Chitwood, 2002). Several studies reported that some cover crops such as sunn hemp (*Crotalaria juncea*) and castor bean (*Ricinus communis*) may enhance activities of microorganisms antagonistic to nematodes (Kloepper et al., 1992; Wang et al., 2002; Wang and McSorley, 2002). Rapeseed (*Brassica napus* L.), sudangrass [*Sorghum bicolor* (L.) Moench.], sorghum–sudangrass hybrids [*S. bicolor* x *S. sudanense* (Piper) Stapf] have been used as cover crops and green manures for suppressing Columbia root-knot nematode (*Meloidogyne chitwoodi* Golden et al.) in potato (*Solanum tuberosum* L.) production in the Pacific northwest (Mojtahedi et al., 1991, 1993) and lesion nematode (Pratylenchus penetrans Cobb) in Ontario, Canada (McKeown and Potter, 2001). Velvetbean [*Mucuna deeringiana* (Bort.) Merr.] as a rotation crop controlled *M. incognita* in soybean (*Glycine max* L.) production (Vargas-Ayala and Rodriguez-Kabana, 2001), and millet [*Pennisetum typhoides* (Burm.) Stapf & Hubb] and cowpea as summer cover crops were shown to suppress *M. incognita* in Florida vegetable double-cropping systems (McSorley et al., 1999; Wang et al., 2003). It is important to note that the impact of cover crops on plant-parasitic nematodes depends on species of cover crops and nematodes (Phatak, 1998; McSorley, 1998; Abawi et al., 2000).

Other benefits of cover crop

Many other benefits for using cover crops have been suggested. For example Decker et al. (1994) reported that legume cover crops can increase soil water content for the subsequent corn crop. The same result was reported by Steiner (1994). It seems that cover crops do that by reducing evaporation and conserving water in the cropping system which may increase yield (Corak et al., 1991; Dabney, 1998). Other advantages of cover crops could be their influence on the cropping environment through reduction in light transmission and moderation of soil temperature fluctuations (Teasdale and Mohler, 1993).

Soil nitrogen recovery

Nitrate is the most common form of nitrogen in soil solution. Because nitrate is very soluble in water, it is very vulnerable to leaching. Nitrate leaching occurs when the amount of nitrate in the soil solution is more than crop requirements or when there is no crop to uptake it. A very significant portion of leaching occurs in fall, winter, and early spring, when there is no crop to uptake nitrate (Drury et al. 1996; Cambardella et al, 1999; Meisinger et al., 1991).

Nitrogen recovery is potentially an important aspect of winter cover crops, especially in conjunction with a high N demand crop like corn and cereal grains (Meisinger et al., 1991, and Aronsson, 2000). Winter cover crops extend growing season by producing biomass in fall and winter (Hoyt and Mikkelsen, 1991). They pick up nitrate and other nutrients from soil and store them in their tissues, therefore reducing nitrate leaching (Owens et al., 1995; Aronsson and Torstensson, 1998; Shepherd and Webb, 1999). In spring, cover crops will be incorporated into the soil and later decompose by soil microorganisms, releasing N and other nutrients. For this reason winter cover crops some times called a “catch” crop (Huntington et al., 1985; Vereijken and van Loon, 1990; Shipley et al., 1992).

Most winter cover crops can contribute to the N supply for the next crop (Hargrove, 1986; Clark et al., 1994; Kuo et al., 1997b) including non-legume (Ditsch and Alley, 1991; Ditsch et al., 1993; Vaughan and Evanylo, 1998) and legume cover crops (Moschler et al., 1967; Mitchell and Teel, 1977; Huntington et al., 1985; Scott et al., 1987; Wagger and Mengel, 1988; Ditsch and Alley, 1991; Ditsch et al., 1993). Legume cover crops can contribute significant amounts of nitrogen to the soil due to their ability to fix atmospheric nitrogen (Touchton et al., 1984; Hoyt and Hargrove, 1986; Bauer et al., 1993; Reeves, 1994; Daniel et al., 1999; Larson et al., 2001). Several studies have suggested that legume cover crops can significantly reduce or even eliminate the need for N fertilizer (Brown et al., 1985; Doran and Smith, 1991; Boquet and Coco, 1993; Varco et al., 1999; Griffin et al., 2000; Schwenke et al., 2001; Dabney et al., 2001). Several studies have reported that winter cover crops can supply most or all of the N needed for corn and sorghum (Touchton et al., 1982; Hargrove, 1986; McVay et al., 1989; McVay et al., 1989; Decker et al., 1994; Clark et al., 1994, 1995, 1997a). In other estimates, the N contribution of cover crops to the following crop was 20 to 55% of recovered N (Sims and Slinkard, 1991; Sainju et al., 2000b, Malpassi et al., 2000). Grasses (Meisinger et al., 1991; Meisinger and Delgado, 2002), cereals (Boesch et al., 2001) and small grains (Ditsch et al., 1993; Kessavalou and Walters, 1999) are more efficient species in up taking and therefore recovering nitrate. However the nitrogen recovery potential by other cover crop species has also been reported. For example, various Brassica species have shown satisfactory results (e.g., Bertilsson, 1988; Muller et al., 1989) or even more effective than legumes (Meisinger et al., 1990).

The potential nitrogen recovery is highly correlated with cover crop biomass (Hesterman et al., 1992). According to some estimates, winter cover crops such as hairy vetch can supply up to 2 Kg N ha^{-1} day^{-1} (Holderbaum et al., 1990). Sainju and Singh (1997) reported that hairy vetch (*Vicia villosa* Roth) cover crop's contribution to corn yield was equivalent to 66 to $200KgN.ha^{-1}$. Another study reported 90 to 180 Kg N ha^{-1} supply by hairy vetch (Sainju et al., 1999, 2000a).

The amount of N supply by cover crop depends on year, location and cover crop species (Oyer and Touchton, 1990; Holderbaum et al., 1990; Hesterman et al., 1992; Kuo et al., 1996, Clark et al., 1997a; Smith et al., 1987). Organic nitrogen in cover crop is released by microbial decomposition. For the best results, N released should be synchronized with the N demand of the next crop (Stute and Posner, 1995). Poor synchronization in cover crop decomposition and the subsequent crop demands can reduce the efficiency of cover crop and immobilize nitrogen in the soil (Aulakah et al., 1991; Doran and Smith, 1991; Somda et al., 1991; Richards et al., 1996; Allison et al., 1998b; Vyn et al., 1999;

Schomberg and Endale, 2004). The immobilized nitrate can later leach during the next fall (Karen and Doren, 1991) or become available the following season (Garwood et al., 1999).

Cover cropping is a well known management practice for reducing leaching of nitrate and other nutrients (Hargrove, 1986; Martinez and Guiraud, 1990; Owens, 1990; Meisinger et al., 1990; Meisinger et al., 1991; McCracken et al., 1994; Kuo et al., 1997a, 1997b; Brandi-Dohrn et al., 1997; Kessavalou and Walters, 1997; Dinnes et al., 2002). In a three year study, Lewan (1994) estimated 83% reduction in nitrate leaching from cover crop compared with no cover crop. Several other studies reported a significant effect of legume cover crops in reducing nitrates leaching. Hairy vetch seems to be a suitable cover crop for reducing nitrate leaching (Sainju and Singh, 1997). Bergström and Jokela (2001) reported a 66% reduction in leaching when they used ryegrass as cover crop in barley production. A similar experiment on ryegrass cover crop in a wheat-corn rotation reported 67% reduction in leaching when compared to no cover crop (Martinez and Guiraud, 1990). In another study Brandi-Dohrn et al. (1997) reported a 37% reduction in N leaching in rye cover crop compared with bare fallow. McCracken et al. (1994) reported almost no leaching from rye cover crop. Other reports also indicated a significant reduction in N leaching when rye was used as cover crop (Meisinger et al., 1990; Rasse et al., 2000).

To be effective, winter cover crops should exhibit rapid germination, aggressive growth in the short and cold growing season in fall and early winter (Dinnes et al., 2002). They also should posses extensive rooting systems (Sainju et al., 1998), withstand cold winter (Duiker and Curran, 2003), and exhibit rapid growth in early spring. Many researchers concluded that cereals and brassicas are suitable cover crops to survive relatively harsh winter (Wagger and Mengel, 1988; Brinsfield and Staver, 1991).

However winter survival rate, amount of organic C production, and decomposition rates vary significantly with cover crop species, soil type, climate, and cropping management (Power and Biederbeck, 1991; Wagger et al., 1998). Therefore in some cases, planting winter cover crops may not pay off reasonably for the cost of the seed, agricultural operations, and herbicide application and more importantly, may not be able to supply adequate N to subsequent crops (Ruffo and Bollero, 2003a, 2003b).

Many current studies on application of winter cover crops for N recovery have been conducted in warm climates where the majority of N leaching occurs during the winter. In colder areas however, soil freezes during winter and most of N leaching occurs during early spring, before significant growth of the summer row crop. Furthermore, the precipitation regimes are significantly dissimilar between the warm climates and colder northern climate. For instance, the percentages of average annual precipitation falling during the period of October through March for a Washington state experimental site (Kuo et al., 1997), a Maryland site (Ranells and Wagger, 1997), and Lamberton, MN (Strock et al., 2004), were 75, 45, and 26%, respectively.

Legume cover crops can contribute nitrogen to following crops through N fixation which may increase crop yields compared with non-legume or no cover crops (Hargrove, 1986; Clark et al., 1994, Kuo et al., 1997b). For example Cowpea has many characteristics that make it an outstanding cover crop in the southwest. These characteristics include adaptation to sandy soils, and tolerance to heat and drought (Ehlers and Hall, 1997; Hall et al., 2002). On the contrary, non-legume cover crops are more effective in elevating soil organic C by producing higher amounts of biomass compared with legume or fallow (Kuo et al., 1997a, 1997b; Sainju et al., 2000). Non-legume cover crops also reduce N loss from the soil more effectively than legume or bare fallow (Meisinger et al., 1991; McCracken et al., 1994). An example is winter cereals which are successful cover crops in northern region because they are winter hardy, establish rapidly, produce acceptable ground cover and organic matter in winter and resume their growth early in the spring. Cereals also can recover soil nitrate and protect it from leaching due to fall, winter and early spring precipitation.

An alternative option can be a mixture of legume and non-legume cover crops to supply both organic matter and nitrogen in adequate amounts that help to promote soil conditions and decrease N loss compared with legume cover crop alone and to increase crop yield compared with non-legumes (Brandi-Dohrn et al., 1997; Owens, 1990).

Selection of cover crops can be complicated due to residue management, because it may pose negative effects on the successive crop. Cover crop residues can hinder planting activities and result in poor crop germination (Grisso et al., 1984). Incorporated residues may also negatively affect seedling establishment due to its allelopathic compounds in soil (White and Worsham, 1989; Rickerl et al., 1989). The cover crop killing date therefore, requires careful management practices. Ideally later killing dates (usually less than one week before planting the spring row-crop) provides more time for cover crop growth in spring and produce more organic C and N. However late killing time can cause some potential problems and can reduce crop yield (Liebl et al., 1992). Synchronizing cover crop decomposition with rapid growth stage of corn (or other row crop) is one important factor to be considered. Ruffo and Bollero (2003b) reported that killing cereal rye 1 week before planting corn was not optimal for adequate synchronization between N release from the residue and N demand for corn. Crandall et al. (2005) evaluated kill date and fertilization strategies with the goal of improving the synchronization of N demand for corn and N supply from the cropping system while minimizing N losses. They concluded that applying N fertilizer at planting and killing cereal rye 2 weeks before planting corn produced more yield compared to corn following no cover crop. Killing rye cover crop at planting time may result in stand and yield reductions (Eckert, 1988; Reddy, 2001). There is a potential risk of soil drought and water depletion by late-killed cover crop (Ebelhar et al., 1984; Raimbault et al., 1991). Some reports also suggested that late kill cover crop can have some negative alleliopatic effects on the successive row crop (Raimbault et al., 1990; Kessavalou and Walters, 1997). Killing rye 1 to 2 weeks before planting reduced the risk of allelopathic effects (Ewing et al., 1991). In another study, allelopathic effects and reduced corn yields were observed when rye cover crop was killed 1 week before planting corn (Kessavalou and Walters, 1997). In-row planting may be an alternative practice to reduce the risk of phytotoxic effect of rye on corn (Raimbault et al., 1991). Most of the time late killing date postpones planting the spring crop and perhaps the growers prefer to incorporate the cover crop into the soil as soon as possible so that they can make sure that they can plant the spring crop as soon as possible. The impact of killing date on crop yield performance is not consistent in all climates. In warmer climates, later killing date may have some positive impacts on the next crop because cover crops produce more biomass in the extended growing period (Clark et al., 1994, 1995, 1997a, 1997b). Researchers also did not find a depression in yield when rye winter cover crop was killed 1 week before planting soybean (Wagner-Riddle et al., 1994; Swanton et al., 1998).

Another important factor in cover crop management is cover crop planting date; especially in northern regions in USA where the growing season is relatively short, the cover crop has a limited time for growth and establishment in fall and early winter before freezing. Late planting of cover crops in fall can reduce their ability to recover nitrogen (Weinert et al., 2002, Delgado, 1998).

Winter rye cover crop

In Massachusetts and many other regions of the United States, rye is a preferred winter cover crop. It has exceptional growth ability in a relatively short growing season between the harvest of spring crop (usually corn or soybean) in fall and the onset of freezing conditions in winter and produces considerable amounts of biomass (Tisdall and Oades, 1982; Oades, 1984; Tollenaar et al., 1993; Kuo et al., 1996, 1997; Griffin et al., 2000). Rye is a winter hardy plant and resumes its growth early in the spring (Stoskopf, 1985; Wagger and Mengel, 1988; Ditsch and Alley, 1991; Shipley et al., 1992; Bollero and Bullock, 1994). It can uptake considerable amounts of N from the soil and prevent it from leaching (Wagger and Mengel, 1988; Ditsch and Alley, 1991; Meisinger et al., 1991; Shipley et al., 1992; Bollero and Bullock, 1994; Brandi-Dohrn et al., 1997; Kessavalou and Walters, 1997; Staver and Brinsfield, 1998; Vaughan and Evanylo, 1999; Kessavalou and Walters, 1999; Strock et al., 2004). Meisinger et al. (1990, 1991) assessed the reductions in after harvest leaching nitrogen from 59 to 77% with rye winter cover crop compared with bare fallow soil.

Significant surface cover produced by rye protects agricultural soil from wind and water erosion and suppresses weeds by competing for light, water and nutrients (Liebl et al., 1992; Williams et al., 1998; Reddy, 2003). Rye also has another mechanism for controlling weeds. Several workers have reported that rye can produce allelopatic compounds that suppress growing weeds (Barnes and Putnam, 1987).

There are other reports on the ability of a rye cover crop in conserving water for the successive crop by providing a mulch layer after it is killed in spring (Steiner, 1994). However there is a possibility that rye negatively influences the subsequent crop. Based on some reports, corn yield was reduced when it was planted after a rye cover crop. The reduction of yield was partly due to nitrogen immobilization (Tollenaar et al., 1993; Vaughan and Evanylo, 1998; Wagger, 1989). Some reports on soybean also indicate reduction in yield due to a rye winter cover crop. Soybean yield reduction was not as significant as corn and some studies reported no negative impact of rye on the main crop (Wagner-Riddle et al., 1994; Bauer, 1989). It is important to know that almost all of the reports about the potential negative effects of rye on crop yield were related to some mismanagement, such as delay in killing the rye in spring (Liebl et al., 1992), mowing rye instead of killing it (Bauer, 1989) or planting the row-crop into the rye residue (Bauer, 1989; and Eckert, 1988).

Status planting winter cover crop in Massachusetts

In Massachusetts, the capacity of manure storage facilities of dairy farms are mostly only enough to hold manure produced in the past 6 months. Therefore, many dairy farmers and some livestock producers have no choice but to empty their storage facilities in the fall after corn harvested and spread the manure on crop lands. At this time, nitrogen in manure and other sources of organic matters continues to be released by microbial activity. Nitrate is completely soluble in water; therefore if it is not taken up by plant roots, it will be leached quickly by fall rainfall. Some cover crops including winter rye could be very efficient in recovering N and other nutrients released by microbial activity. Use of winter rye cover crop if it is managed properly, provides economic incentive for farmers to adopt sustainable farming practices which are environmentally sound.

Multi-year and multi-location research projects conducted by UMass Extension at the UMass Crop and Animal Research Center and cooperating farmer's land have demonstrated:

- Winter rye requires about 1050 GDD for maximum N recovery after corn harvest.
- For collecting this much GDD, winter rye must be planted early September in most areas of the state.
- If planted on time, It has been demonstrated that winter rye can recover about 100 kg N/ha. Similar results have been reported by other researchers (McVay et al., 1989; Decker et al., 1994; Clark et al., 1995, 1997a).
- Soil samples taken in spring from various depths up to 2 feet from fields with no cover crops have shown almost no N left in the soil (Rahman paper). Therefore, 100 kg N/ha would have been lost to the environment if cover crops are not planted after corn harvest.
- Corn silage removes 140-180 kg N/ha from soil, depending on silage yield. Therefore, recovered N by winter rye cover crop plus manure applied in spring before

corn is planted could be sufficient for maximum yield without using other chemical sources of nitrogen.

Yet, the 2005-2006 comprehensive nutrient management survey conducted by UMass Extension (Herbert et al., 2007) indicated that almost 80% of dairy farmers and livestock producers either do not plant cover crop or plant them very late and therefore, must be considered inefficient in terms of nutrient recovery.

The goals of this research project were:

- Determine the critical planting date for winter rye cover crop.
- Evaluate the potential loss in biomass production and nitrogen uptake related to delay in planting rye cover crop
- Evaluate the potential economic benefits of planting winter rye with no delay.

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CHAPTER 3

SPATIAL MODELING OF CRITICAL PLANTING DATE FOR WINTER RYE COVER CROP TO ENHANCE NUTRIENT RECOVERY

Abstract

Time of planting plays a critical role in nutrient recovery from soils by a winter rye (*Secale cereale* L.) cover crop. A delay in planting can significantly decrease cover crop performance. This study evaluates cover crop planting dates for different areas of Massachusetts using a spatial model based on growing degree days (GDD). Field studies were conducted during 2004 through 2009 to estimate biomass production and nutrient recovery of rye under varying planting dates from mid August to early October. A spatial model identified critical planting dates (CPD) for all locations in Massachusetts based on field studies combined with long term weather data collected from 14 weather stations. In eastern areas of Massachusetts (Zone 5), CPD is the 3rd week of September. In this region, there is adequate time for planting winter rye after the corn is harvested. Critical planting dates for central parts of the state (Zones 3 and 4) are from 1st to 2nd week of September. Growers in these regions should consider alternative management strategies including selection of shorter-season corn hybrids to meet the suggested cover crop planting dates. The suggested critical planting dates (3rd to 4th week of August) for northwest regions of Massachusetts (Zones 1 and 2) may not be practical since corn (*Zea mays* L.) silage is usually not ready for harvest until mid September.

The model can be a powerful decision making tool for researchers and farmers, not only for winter rye in Massachusetts but it also can be adapted for use with other cover crop species and for use in other regions where cover crops are grown.

Introduction

Nonpoint sources of pollution continue to be a major threat to water resources of which nitrogen (N), especially in the form of nitrate (NO_3-N) is a major issue in agricultural landscapes (Burkart and Stoner, 2001; Sauer et al., 2001; Gulis et al., 2002). Commercial and residential fertilizer use, human and animal wastes, landfills and industries are the major sources of N pollution (Vidal et al., 2000). Almost 50% of N pollution is related to agricultural activities (Hansen et al., 2000; Owens et al., 2000; Sogbedji et al., 2000). Contamination of water resources can intensify eutrophication of water bodies, alter the natural conditions of lakes and rivers (Yeomans et al., 1992), and endanger the health of humans and animals (Shirley et al., 1974; Owens et al., 2000; Zhao et al., 2001; Townsend et al., 2003).

Due to its mobility, N can reach ground water through infiltration (leaching) and affect drinking water supplies. The interval between harvesting corn silage in fall and planting the succeeding spring crop is a critical water recharge period when soil nitrate is highly susceptible to leaching. This is especially the case when no crop is present to uptake N and when considerable amounts of rainfall are received during this period (Watts and Martin, 1981; Keeney and Follett, 1991; Martin et al., 1994). Our previous studies indicate that a significant amount of N can be released into the soil through mineralization of previously applied manure and plant residues due to warm weather in September and early October and activity of microorganisms, (data not shown). Further, in the northeast USA most dairy farmers must apply manure to the fields after harvesting silage corn due to limited manure storage capacity. Winter rye, when used as a cover crop, can play a key role in recovering the residual soil and manure N in fall and in reducing post harvest leaching (Staver and Brinsfield, 1998; Vaughan and Evanylo, 1999; Kessavalou and Walters, 1999; Strock et al., 2004). If planted on time, winter rye cover crop can accumulate as much as 100 kg N ha^{-1} or more, depending on amount of biomass yield, residual N present, and other soil properties. This N, that otherwise would have been lost to the environment, is held in the cover crop biomass and becomes available to crops in future seasons (Kessavalou and Walters, 1999 and Strock et al., 2004, Herbert et al. 2007,UMass Extension CLDE, 2010). Therefore, recovery of N by a winter rye cover crop, along with a manure application in the spring before corn is planted, could supply sufficient N for maximizing yield either without or with a limited amount of fertilizer N.

The time of cover crop planting is a critical factor to maximize nitrogen accumulation. Delay in planting winter cover crop can result in a dramatic reduction in N accumulation and thereby allow higher N loss through leaching. However, it is not always possible to plant winter rye early in the fall due to practical limitations such as timing of corn harvest, fall manure application, weather conditions, and other dairy farming activities. Therefore, it is important for farmers to know the critical planting date (CPD) of rye cover crop at a site-specific level. We define CPD as the latest planting date possible that allows maximum potential N accumulation.

To evaluate site specific CPD, the Geographic Information System (GIS) is useful in modeling spatial variation in Growing Degree Days (GDD) and biomass production. The GIS is a powerful tool that has been widely used in agricultural sciences for spatial analysis and decision making, especially in locating corn stover collection sites (Haddad and Anderson,2008), for locating animal waste areas, (Basnet et al., 2002), for identification of agronomically homogeneous areas (Gardi, 2001), and to assess tillage effects on soil compaction (Wiatrak et al., 2009).

In this study, we used GIS and field methods for developing a spatial model for determining CPD for winter rye cover crops for farming locations throughout the Commonwealth of Massachusetts. This model can be used as a decision-making tool for researchers, policy makers, and farmers to identify planting regimes that maximize N recovery and minimize its negative impacts on water quality. Specific objectives of this project were: (i) modeling the site specific CPD for planting of winter rye cover crop in Massachusetts; (ii) estimating the amount of biomass, N recovery, and economic loss related to the delay in planting of the cover crop; and (iii) identifying optimal decisions to plant rye winter cover crop in different locations of Massachusetts.

Materials and Methods

Field Experiments

Five field experiments with different seeding dates of rye (Table 3-1) within a corn-winter rye cropping system were conducted at the Crops and Animal Research Center Farm of the University of Massachusetts in Deerfield, MA from 2004 to 2009. Planting dates for cover crops each year were optimized based on the results of the previous years. Soil type is Hadley fine sandy loam (Typic Udifluvent, coarse-silty, mixed, nonacid, mesic).

Each year the same cultural practices were followed. Conventional tillage including moldboard plowing and disking were used. Each year plots (6.9 m by12 m) received 36 kg N ha^{-1}, 16 kg P_2O_5 ha^{-1} and 13 kg K_2O ha^{-1} prior to planting corn. Except in some years, dairy (*Bos taurus*) manure was applied uniformly at the rate of 42,000 L ha^{-1} in the spring prior to planting corn and immediately incorporated into the soil by disking. Nutrient content of manure is presented in Table 3-2. Corn was planted in early May in plots. Weeds were controlled by applying pre-emergence 4.68 liter ha^{-1} of Bicep (atrazine [6 – chloro – N – ethyl - N′ - (1-methylethyl) - 1,3,5 – triazine - 2,4,-diamine] + metolachlor [2 – chloro – N - (2 – ethyl – 6 - methylphenyl) – N - (2 – methoxy – 1 - methylethyl) acetamide]). The Presidedress Soil Nitrate Test (PSNT) (Magdoff et al., 1990) was taken when corn plants were 10-12 inches high. Side-dress N fertilizer was applied according to the PSNT results. . No irrigation was used since it is not a common practice in Massachusetts due to adequate rain during growing season. Corn was harvested as silage in late August.

Table 3-1. Winter rye cover crop planting dates in each year of the experiment.

2004	2005	2006	2008	2009
Aug 18	Aug 19	Sept 1	Sept 5	Sept 1
Sept 2	Sept 2	Sept 8	Sept 12	Sept 8
Sept 15	Sept 16	Sept 15	Sept 20	Sept 14
Sept 29	Sept 30	Sept 22	Sept 29	Sept 21
Oct 10	Oct 14	Sept 29	Oct 6	Sept 29
Oct 27	Oct 28	Oct 6		

Rye cover crop was spread at a rate of 112 kg ha^{-1} by hand. After spreading the seeds, soil surface was disturbed by a garden weasel in order to incorporate seeds into soil. After seeding the rye cover crop at each date 112 kg N ha^{-1} as calcium ammonium nitrate was applied to simulate a fall application of manure. Spreading manure on multiple dates on field plots and then incorporating the manure prior to seeding rye was not practical.

Tissue samples were collected starting approximately two weeks after seeding rye and every two weeks thereafter (depending on weather conditions). Samples were collected using a 0.1 m^2 quadrate. Three quadrates of cover crop plants cut with shears approximately 1 cm above the soil were randomly harvested on each sampling date with 0.5 m distance from the previous sampling sites. The samples were dried in a forced air oven at 80◦C for 36 hours. Dried samples were weighed and ground fine to pass through a 40 mesh screen. Samples were analyzed for total N using standard Quick-Chem Methods (Lachat Quick-Chem 8000 FIA; Zellweger Analytical, Milwaukee, WI, USA).

Table 3-2. Average moisture and nutrient content for manure applied during the field experiments.

Manure content	Fraction	Nutrient Value	Nutrients Applied
	---%---	-kg $(1000 L)^{-1}$-	------kg ha^{-1}------
Moisture	89.63		
Total Nitrogen	0.22	2.29	96.2
Ammonium Nitrogen	0.12	1.25	52.5
Organic Nitrogen	0.10	1.04	43.7
Phosphorus (P2O5)	0.13	1.35	56.7
Potassium (K2O)	0.27	2.82	118.4

The experimental design used each year was a Randomized Complete Block Design (RCBD) with four replications. Standard statistical analysis procedure was performed for data by SAS (SAS, 1988). Means were compared using least significant difference test.

Spatial Model of GDD

All field data were standardized to GDD units for comparison between years and for planting date recommendations. Weather data was collected onsite with a Spectrum Technologies, Inc weather station (WatchDog Model 2700) and from National Oceanic and Atmospheric Administration (NOAA/NCDC) web site for all years of the study

(2004 to 2009) for Deerfield location. For each day following planting, GDD was calculated using Equation [3-1].

$$g = \frac{t_{\max} + t_{\min}}{2} - t_{base}, g \geq 0 \qquad [3\text{-}1]$$

Where, g is daily GDD, $t_{\max}$ is maximum temperature of the day (◦C), $t_{\min}$ is minimum temperature of the day (◦C), and t_{base} is base temperature for winter rye (0◦C as observed by Stoskopf, 1985). Total accumulated GDD from planting date to each sampling date was calculated and a regression model was fitted to describe rye dry weight accumulation as a function of GDD (Figure 3-1). We used biomass data and cover crop tissue total N collected over several years, to develop a model that estimates tissue total N (N accumulation) based on biomass production (Figure 3-2).

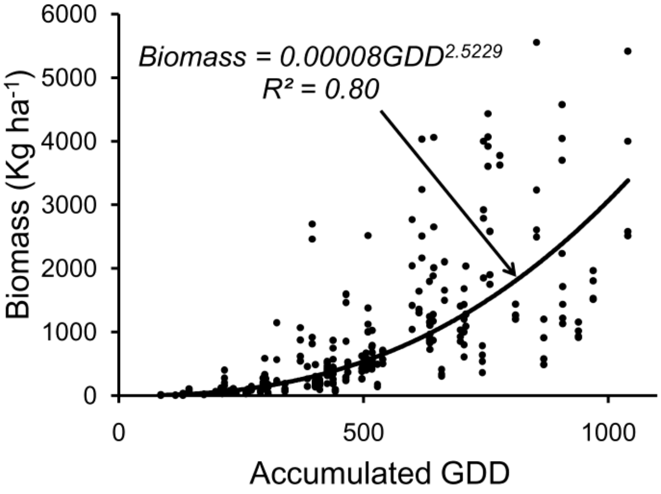

Figure 3-1. Scatter plot and functional fit for rye biomass response to accumulated growing degree days (GDD) using experimental data from 2004 to 2009 in Deerfield, MA. For each data point, accumulated GDD was calculated from planting date to the corresponding sampling date.

Herbert et al. (2007) suggested that planting rye earlier than 1 Sept. has no significant contribution to additional N uptake in Deerfield, MA. Therefore we assumed that Critical Planting Date (CPD) for winter rye cover crop in Deerfield was 1 Sept. Critical Planting

Date is the latest fall planting date that maximizes potential N accumulation by rye cover crop.

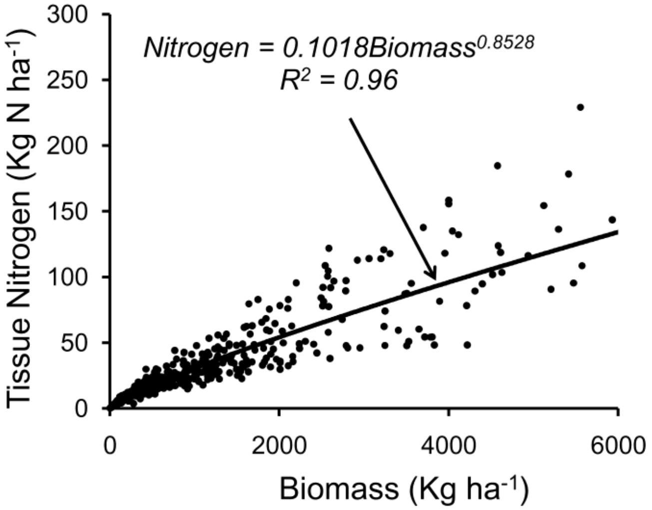

Figure 3-2. The relationship determined between tissue total nitrogen and biomass production for rye cover crop using experimental data from 2004 to 2009 in Deerfield, MA.

In order to establish a base line for determining CPD for all locations in the state, CPD unit was converted from date to GDD units by calculating the total sum of daily GDDs from 1 Sept. to 31 Dec. This value is called Critical Accumulated GDD (CAG) which is the minimum amount of accumulated GDD required for maximum potential N uptake by rye cover crop. One reason for calculating CAG from planting date to the end of the year rather than rye kill date in spring was that rye biomass production in spring has no significant contribution to N uptake (Herbert et al., 2007). Since daily GDDs may change by year we used 10-year daily temperatures of the experimental site for calculating averages of daily GDDs. For each arbitrary date of planting, accumulated GDD can be calculated using the following equation:

$$g = \sum_{d=p}^{e} G_d = \sum_{d=p}^{e} \left(\frac{1}{2} \times \frac{\sum_{y=y_1}^{y_2} t_{\max_{d,y}}}{y_2 - y_1} + \frac{\sum_{y=y_1}^{y_2} t_{\min_{d,y}}}{y_2 - y_1} \right) - t_{base}, G_d \geq 0 \qquad [3\text{-}2]$$

Where, g is accumulated GDD from the planting date p (is 1 Sept. for calculating CAG) to the end of the year (e), G is average GDD of day d of the year, y_1 is the first year of averaging period (in this case 1998), y_2 is the last year of averaging period (in this case 2008), y is year index, t_{max} is daily maximum temperature (◦C), t_{min} is daily minimum temperature (◦C), and t_{base} is base temperature for rye (0◦C).

Estimating Critical Planting Date for all locations in Massachusetts

Since the accuracy of planting date recommendation for a specific day does not seem realistic, week-based recommendations were made. The GDD accumulation for each week beginning 1 Aug. , which is the earliest potential planting date for rye cover crop in Massachusetts, was calculated using Eq. [3-2].

GDD-Week Raster Maps and Critical Planting Zones

Ten years of weather data from fourteen climatic weather stations within and around Massachusetts was downloaded from the National Oceanic and Atmospheric Administration (NOAA/ NCDC) online databases. A spreadsheet file was created containing values of weekly accumulated GDDs from first week of August to fourth week of December for all weather stations and then imported into ArcGIS software. For each weather station, latitude and longitude coordinates were used to digitize weather station sites. A raster (spatial representation in GIS) map of GDD information was created for each week of cover crop planting window (20 raster maps) for the entire state.

The Spline tool was used for interpolating data from the weather stations. This allowed the creation of each week's raster that contained accumulated GDD data from that week to the end of the year. Areas of the state for each raster-week that possessed GDD values closest to CAG were then selected. We called these areas Critical Planting Zones (CPZs). Eq. [3-3] is a mathematical description of the expression used in spatial analysis of raster's CPZ, using Raster Calculator Tool:

$$z_p = \sum_{i=s}^{e} z_i = \sum_{i=s}^{e} \left(\left(p_i < g_h \right) \& \left(p_{i-1} \geq g_h \right) \right) \times p_i \qquad [3\text{-}3]$$

Where, p is GDD raster map of week i, s is the number of the first GDD-week raster layer containing a CPZ (in this case third week of August or 35th week of the year), e is the number of the last GDD map containing a CPZ (in this case, the last layer is the third week of September or 39th week of the year), z_i is a raster map containing critical planting zone i, g_h is the upper limit of Critical GDD Range (explained more in the results section), and z_p is a raster containing all the CPZs (Figure 3-3). The amount of GDD loss due to each week delay from CPD was calculated (Eq. [3-4]):

$$P_{g_i} = \sum_{j=1}^{n} \left(\Delta \times P_{(i+j+m-1)} \right) \qquad [3\text{-}4]$$

Where, i represents delay in planting cover crop (week), P_g is a layer containing GDD data for ith week(s) delay in planting cover crop for all CPZs , P is GDD-week raster map, m is the first week that contains a CPZ (in this case third week of August or 35th week of year), n is the number of the weeks containing CPZ area and Δ is a normalizing factor that can have a value of "1" for all pixels in z_i raster (Eq. [3-3]) and "0" for others.

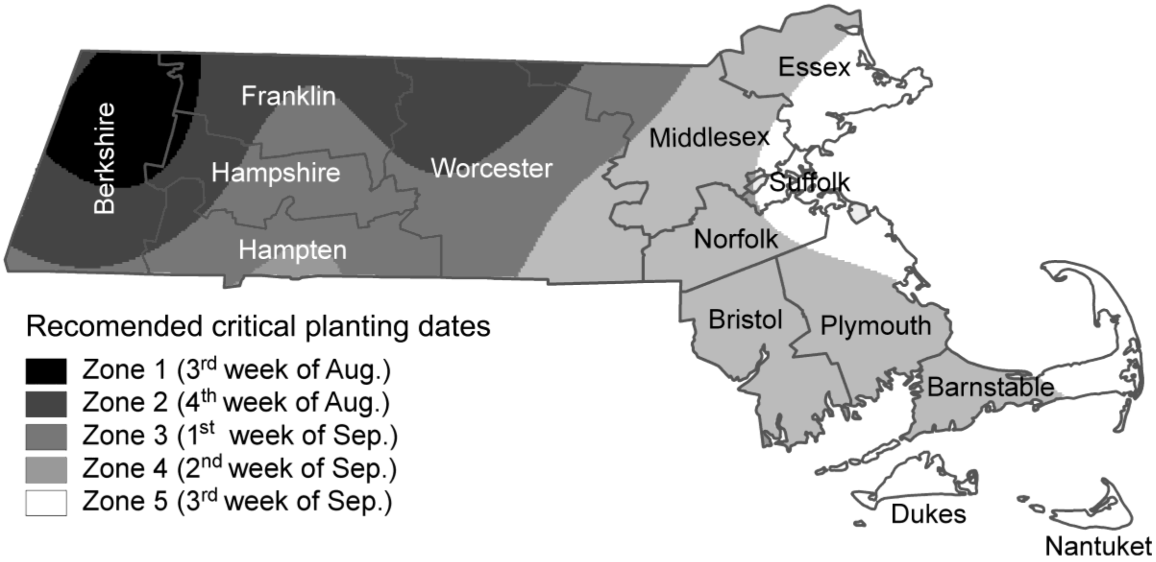

Figure 3-3. Critical Planting Zones for planting rye winter cover crop in Massachusetts. Model recommended planting date is different for each zone and is based on its temperature (GDD) regime.

Dairy Farm Survey

In order to test the feasibility of our CPD recommendations, a GIS layer map was created using the spatial data from a dairy farms' survey conducted by Hashemi et al. (2007). For each CPZ corn planting date, corn harvesting date and rye cover crop planting date information was extracted from the survey. This information was used to compare the current cover crop planting date for a CPZ with the critical planting date suggested by the model (Figure 3-4).

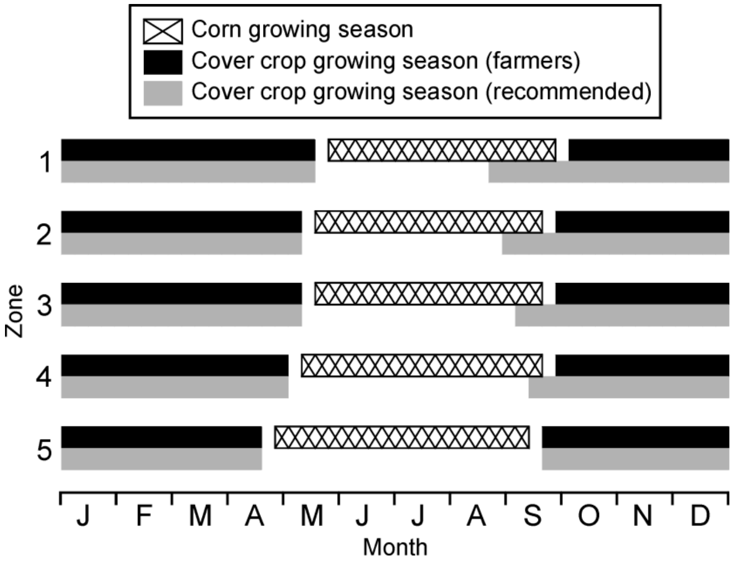

Figure 3-4. A graphical presentation of the corn-rye cropping system identified for the five Massachusetts zones. There is an overlap between corn and cover crop growing seasons in Zones 1 to 4 which suggests a need for change in current management practices.

Results and Discussion

Biomass production compared to GDD accumulation was derived from the multi-year (2004 to 2009) data set (Figure 3-1). This power function response indicated that relatively small reductions in GDD could have a dramatic negative impact on crop biomass accumulation. A statistical model was also fitted for estimating N accumulation from biomass production (Figure 3-2). A power function indicated a strong correlation between the two traits (R^2=0.96).

Using Eq. [3-2], CAG (with a September 1st seeding date) was calculated from 10 years average of daily GDD as 1032 units for Deerfield, MA. In order to determine CPD for all locations in the state, areas having a GDD value closest to 1032 (CAG) needed to be extracted from each GDD-week raster map. However, there were few areas found in each week- map with the exact GDD value of 1032, therefore a GDD range between 950 to 1100 units was used. This was called Critical GDD Range (CGR).

The negative impact caused by a delay in cover crop planting on biomass production, total N uptake and hence economics is shown in Table 3-3. For example, a one week delay in planting rye cover crop can reduce N accumulation by 27%. The amounts of reductions intensified to 49%, 66%, and 78% for 2, 3, and 4 weeks delay in planting rye cover crop, respectively. In order to maximize N recovery, it is important to plant rye cover crop using the recommended CPD.

Table 3-3. Average growing degree day (GDD) accumulation, biomass production, N uptake and economic saving across Massachusetts related to planting at Critical Planting Date and planting with up to 4 weeks delay from Critical Planting Date.

	Delay in planting (weeks)				
Parameter	No delay	1	2	3	4
Accum., GDD	1040	908	784	666	560
GDD Loss, %	0	13	25	36	46
Biomass, kg ha^{-1}	3284	2334	1609	1068	691
Biomass Loss, %	0	29	51	69	79
N Accum., kg ha^{-1}	106	79	57	40	28
N Loss, kg ha^{-1}	0	27	49	66	78
N Loss, %	0	25	46	62	74
Value †, \$ ha^{-1}	122	91	66	46	32
Value Loss, \$ ha^{-1}	0	31	56	75	90
Value Loss, %	0	25	46	62	74

† based on $1.15 per kg N accumulated fertilizer equivalent.

Management Strategies in Each Critical Planting Zone

Providing information to farmers about the economic loss and water quality impairment related to delay in planting cover crop can play a key role in sustaining agriculture in Massachusetts. Perhaps the most challenging factor for timely planting of rye cover crop is corn harvest date which, in turn, depends on corn hybrid maturity and the corn planting date. Since accumulated GDD is similar for all locations in a specific CPZ, any variations in corn planting dates among farms located in a CPZ should be attributed to the individual grower's management strategy. For example, current corn planting date in zone 2 is from early May to early June (Figure 3-4). It is quite possible for a farmer to plant corn in early May in this zone which will enable the establishment of a more effective cover crop system for optimum N recovery.

The farm survey (Hashemi et al, 2007) was used to calculate the average delay in weeks for planting rye cover crop in each CPZ (Figure 3-4). In zone 1, it is not practical to plant rye cover crop early enough to have an efficient N recovery. In this zone corn is normally planted in mid to late May due to relatively cold weather conditions (higher elevation). ,and thus harvested late in September. In zone 1, cover crops must be planted by 3rd week of August to collect CAG required for maximum N recovery (Figure 3-4). A rye cover crop planted with 5 to 6 weeks delay will likely only provide soil erosion prevention and will have no significant N accumulation and recovery.

Although in zone 2 the situation is better compared to zone 1, it still is difficult to plant rye cover crop on the recommended CPD (Figure 3-4). The average delay for cover crop planting in this zone is about 5 weeks, which is too much for achieving efficient N uptake. The average N uptake and relative loss in N uptake caused by the delay was calculated as 18 kg ha^{-1} and 83%, respectively for 5 weeks delay. Farmers in Northwest regions of the state (zones 1 and 2) may not be able to optimize the recovery of N but could benefit from combining operations, for example seeding their cover crop while harvesting the corn.

In zone 3 and zone 4 N loss can be prevented by adoption of an alternative management practice. Currently, dairy farmers in zone 3 plant cover crop with 2 to 3 weeks delay on average (Figure 3-4). This delay can reduce N uptake and recovery 49 to 66 kg N ha^{-1}

(46% to 62%) and the economic loss related to this delay can be \$56 to \$75 ha^{-1} (Table 3-3). This N loss can be prevented by planting rye only 2 to 3 weeks earlier. Use of shorter season corn hybrids can be considered as an alternative strategy which accommodates earlier harvesting and therefore, on-time establishment of winter rye cover crop. A 10-year corn hybrid evaluation study in Massachusetts has proven that shorter season corn hybrids, on average, produce similar silage yield as full season hybrids and can be harvested 7 to 14 days earlier (Herbert et al., 2008). Despite the use of shorter season corn hybrids, about 1 week delay in cover crop planting should be expected for zone 3. This is because corn rarely is harvested earlier than 1 Sept. in this or any other area in the state (Figure 3-4). The CPD in zone 3 is the first week of September and it usually takes a few days to complete harvest, apply and incorporate manure and then plant the cover crop.

Farmers in zone 4 have an additional week for planting cover crop, since CPD for zone 4 is the 2nd week of September. The warmer spring weather in this zone provides the opportunity to plant corn early in May and harvest it earlier in fall. Thus, it is quite possible to plant cover crop with no delay. However, there are still some growers who do not take advantage of this opportunity and plant their cover crops later than the suggested CPD (Figure 3-4).

Zone 5, closest to the Atlantic Ocean, has the warmest weather among the five zones. The CPD for this zone, that has the warmest fall weather, is the third week of September. The warmer climate for this zone also allows growers to plant corn earlier in the spring, a practice that supports early fall harvest and leaves enough time for planting rye cover crop on time. However, most of this zone is located in the urban area around Boston and the eastern part of Cape Cod where only a few dairy farms are currently operating.

Conclusion

The time of planting of the rye cover crop is a critical factor for maximizing nitrogen recovery from fields where manure was fall applied. Delay in planting winter cover crop can result in a dramatic reduction in N accumulation and thereby higher N leaching loss into ground water. A model was developed to estimate rye cover crop biomass production and N uptake and to determine critical planting dates for all locations in Massachusetts. In eastern areas of Massachusetts (Zone 5) critical planting date is the third week of September. Warmer climate in this zone provides a greater window for planting winter cover crop and no major change in management practices is required. Critical planting dates for central parts of the State (Zone 3 and Zone 4) are the first to second week of September. This is one to two weeks earlier than what farmers are currently using. Growers in these regions should make some adjustments in their management including selecting shorter-season corn hybrids to establish the most efficient cover crop system for maximum N recovery.

Suggested critical planting dates (3rd to 4th week of August) for northwest regions of Massachusetts (Zone1 and Zone2) which are the coldest regions of the State may not be practical for growers. This is because there is about four to seven weeks overlap between suggested cover crop planting date and the corn silage growing period.

The spatial GDD-based model, which was developed in this study for evaluating N uptake and recovery, can be used for other cover crop species and other locations.

Elevation, soil data layers and other spatial information can be added to the model to give it more robust, site-specific applications.

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CHAPTER 4

A REVIEW ON AUTOMATED LYSIMETER SYSTEMS

Abstract

Measuring water movement in unsaturated soil profile is a problematic process. Several methods have been introduced for collecting water sample from unsaturated soil. Container lysimeters are large and expensive and hard to install and maintain. Therefore they cannot be used in large numbers. Zero-tension lysimeters are inexpensive and easy to use and maintain. However they can only collect water samples from saturated soil profile. Capillary wick samplers also are not accurate. Their tension level is not adjustable and it seems that the fibers affect the solute concentration. Suction cups samplers recently became very popular. The reason is that they can be installed and used with ease and in large numbers and also can collect water samples from unsaturated soil. Since the vacuum level is always at 300 cmH_2O (field capacity) the volume and concentration of the samples would not be accurate. To address this problem, equilibrium tension lysimeters have been introduced. The suction level in the sampler container is adjusted daily with soil matric pressure. This way the samples would be more reliable. Since soil-water tension changes with time, the vacuum level of suction cup has to be regulated constantly. Automated suction lysimeters use an electronic controller as well as a set of soil-water tension sensors to keep the vacuum applied to the suction plates in equilibrium with soil matric pressure. Automated equilibrium tension lysimeter reads the soil matric pressure and applies the same amount of vacuum to the sampling container. This device has no direct control on matric pressure right above the sampler. Therefore the accuracy of the sample is questionable. Controlled suction period lysimeter uses a

tensiometer right above the sampler. It uses periods of vacuum and no-vacuum to adjust the soil matric pressure above the sampler. This method seems to be the most accurate method for collecting soil-water samples. However there are some minor issues like energy efficiency and tensiometer response rate which does not seem to be fast enough for the method. Minimum resistance automated lysimeter is suggested for eliminating a great amount of lysimeter resistance. This would increase energy efficiency and also decrease the response lag of the sensor above the sampler and improves the system performance. For maximum accuracy each lysimeter has to be calibrated after installation. In order to assess the performance of automated suction lysimeters, the dual soil column system is introduced. This is an accurate, direct and simple method for quantifying the performance of soil-water samplers.

Introduction

Direct measurement of solute flux from the vadose zone is difficult and results have been inconsistent (Barcelona and Morrison, 1988). Several methods have been used to collect soil water samples from the unsaturated zone: profile soil sampling (Roth and Fox, 1990; Liang et al., 1991), tile drains (Kladivko et al., 1991; Randall et al., 1997; Sogbedji et al., 2000), drainage from watersheds (Gburek et al., 1986; Lowrance, 1992), ground water wells (Weil et al., 1990; Cambardella et al., 1999), pan lysimeters (Russell and Ewel, 1985; Jemison and Fox, 1994; Toth and Fox, 1998), monolith lysimeters (Owens, 1987), porous cup samplers (Gerwing et al., 1979; An draski et al., 2000) and more. Litaor (1988) reported a comprehensive review of many of these methods, indicating their advantages and disadvantages in different situations. There has been no single and simple method for soil solution sampling under all soil conditions. Measuring leached water from the soil inherently is difficult. Most methods are costly, time consuming and difficult to install, manage and maintain and yet not accurate. Some of the most common methods of soil water sampling have been discussed in this article.

Monitoring of subsurface tile drainage water can be useful in estimating the impact of agricultural practices on surface and ground water quality (Baker and Johnson, 1981; Gast et al., 1978; Hallberg et al., 1986; Kanwar et al., 1988; Randall and Goss, 2001). Long-term drainage observations are critical in order to assess agricultural practices if accurate estimates of nitrate leachate and performance evaluation of the practices are desired. Short-term results performed under limited wet or dry periods could be misleading and inaccurate (Jaynes et al., 1999; Owens et al., 2000; Randall and Iragavarapu, 1995).

Perhaps the basic and also the oldest device for collecting soil water sample is lysimeter. Lysimeters have many different types and applications. Lysimeter is a term was made from two Latin words ”lysis” meaning ”dissolving” and ”metron” meaning ”measuring” (Aboukhaled et al., 1982). Mcllroy and Angus (1963) defined lysimeter as ”a block of soil, together with vegetation, if any, enclosed in a suitable container and exposed in natural surroundings to permit determination of any one term of the hydrologic equation when the others are known.” World Meteorological Organization (1968) has a more applicable definition: “containers of soil and vegetation from which the water loss is measured by weighing or accounting for all incoming water at the surface and all outflow from the bottom of the container”. Hillel et al. (1969) defined lysimeter as “large containers filled with soil, generally located in the field to represent the field environment, and in which soil-water-plant conditions can be regulated and monitored more conveniently and accurately than natural soil profile."

Although most definitions consider the lysimeter as "a container", or even "a big container", many new soil-water sampling methods which do not use any soil container, increasingly are being considered as lysimeters. Today the term "lysimeter" is mostly used for all devices that collect or extract water samples from soil profile.

Container lysimeters

Lysimeters are in various kinds, sizes, and applications. Perhaps container lysimeters are the oldest types of their kind. They basically are big soil containers mostly installed in field condition. The main application of these types of lysimeters is to study evapotranspiration and soil water balance. Precipitation enters the lysimeter from soil surface and percolated water from the bottom of the container is collected in a measuring container. Generally speaking, the amount of evapotranspiration would be the difference between precipitation and the water collected in the measuring container.

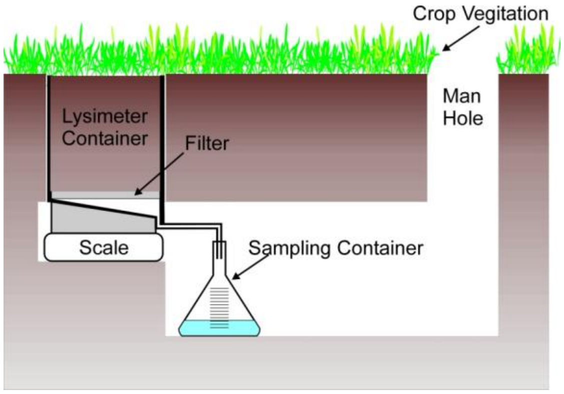

Figure 4-1. A schematic design of a Weighing Lysimeter.

Weighing and volumetric lysimeters

A weighing lysimeter (Figure 4-1) has a soil container on the top of a scale. It measures the weight of the water added to the soil through precipitation or irrigation and the water that has percolated out of the soil due to leaching or evapotranspiration. These devices are very big and expensive and difficult to install and manage. Volumetric lysimeters (Figure 4-2) measure the volume of drained water from the bottom of the container.

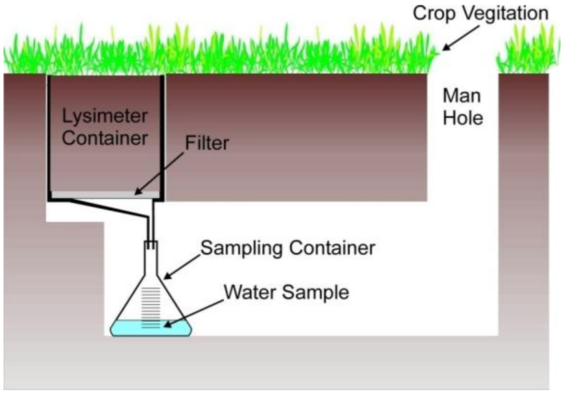

Figure 4-2. A schematic design of a Volumetric Container Lysimeter.

Free draining and suction lysimeters

A container lysimeter can be free-draining or suction-controlled. Free draining type is suitable for simulating the conditions when water table is not very deep and the soil profile has a shallow water table. In this situation, deeper part of the soil in container becomes saturated and water can drain freely to the sampling containers. These lysimeters are less expensive and easier to handle but they collect water only when the soil is saturated and in unsaturated condition their measurements may not be accurate. Lysimeters with suction-controlled systems are designed for unsaturated conditions. When soil is unsaturated and soil tension is not greater than field capacity (about -300

cmH_2O), these lysimeters can extract water sample by applying suction to the bottom of the container (Figure 4-3).

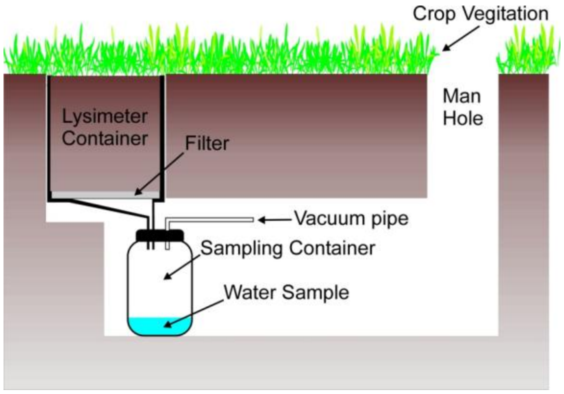

Figure 4-3. A Schematic design of a Vacuum container lysimeter. Water table is deep and the root zone is almost always unsaturated.

Filled-in and monolithic lysimeter

Most container lysimeters are "filled-in" lysimeters which means they have been filled with soil thus; they lack a natural soil structure. To address this issue lysimeters with monolith soils (undisturbed soil profile) have been introduced. Collecting a big undisturbed soil column is difficult, time consuming, and expensive procedure.

An alternative method is "soil coring" which means moving a relatively small volume (about several cubic centimeters) of undisturbed soil to a small container lysimeter. Soil coring is simple, relatively inexpensive, and appropriate for most types of soils. However, soil coring can be time-consuming, is destructive, and only provides a limited estimation of the soil dynamics. Some scientists suggest that soil coring may not be an accurate method for measuring soil nutrients leaching (nitrogen in particular) in sandy soils with lateral water gradients (Simonne et al., 2004). Willian and Nielsen (1989) also stated that soil coring is not appropriate for estimating N leaching unless it is combined with soil-water flow information.

In summary, container lysimeters are relatively accurate and reliable but they are expensive, laborious and are hard to install and maintain. It can take several months and thousands of dollars to install one of these devices ready to use. In recent years more scientists are willing to use other methods for collecting soil-water samples that are more accurate, easier to install and handle, and less expensive.

Zero-tension pans

Zero-tension pan or zero-tension funnel lysimeter is perhaps the simplest device for collecting soil water samples. It is easy to maintain and inexpensive (Zhu et al., 2002). Zero-tension pan consists of a pan or plate with a porous surface. This surface allows the soil water to pass through and collected in a sampling container. In most cases porous pans are installed in field and under an undisturbed soil profile.

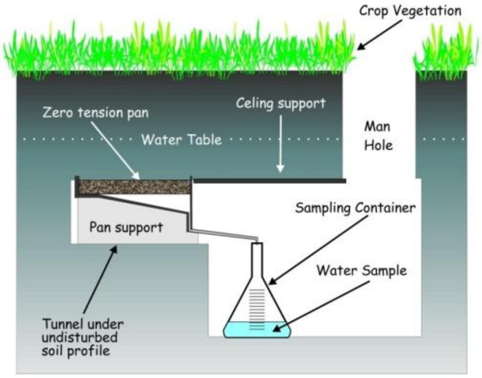

Figure 4-4. A Schematic diagram of Zero Tension Pan Lysimeter.

Zero-tension pan collects water mostly when the soil is saturated (Zhu et al., 2002; Barbee and Brown, 1986) and since it collects mainly macropore water flow; it is not suitable for below saturation conditions.

Drainage lysimeters

Drainage systems are primarily installed for declining water table in the areas that soil water table is too shallow or when soil is saline and/or sodic. Drainage systems are also commonly used to monitor nutrient leaching. They capture almost the entire leached nutrients and water which can then be used to estimate nutrient load passing below a particular soil depth. Similar to the use of ceramic suction cups, the use of drainage lysimeters allows for direct and relatively consistent and accurate measurement of nitrate leaching (Webster et al., 1993). An additional advantage of this method is that it is an "integrative approach" (both in time and space) which may be a more sensible way of measuring total N loads compared with other methods that represent a very limited spatial dimension and only measures a narrow estimate of N leaching dynamics. However, installation of drainage systems could be very expensive and may result in considerable soil disturbance.

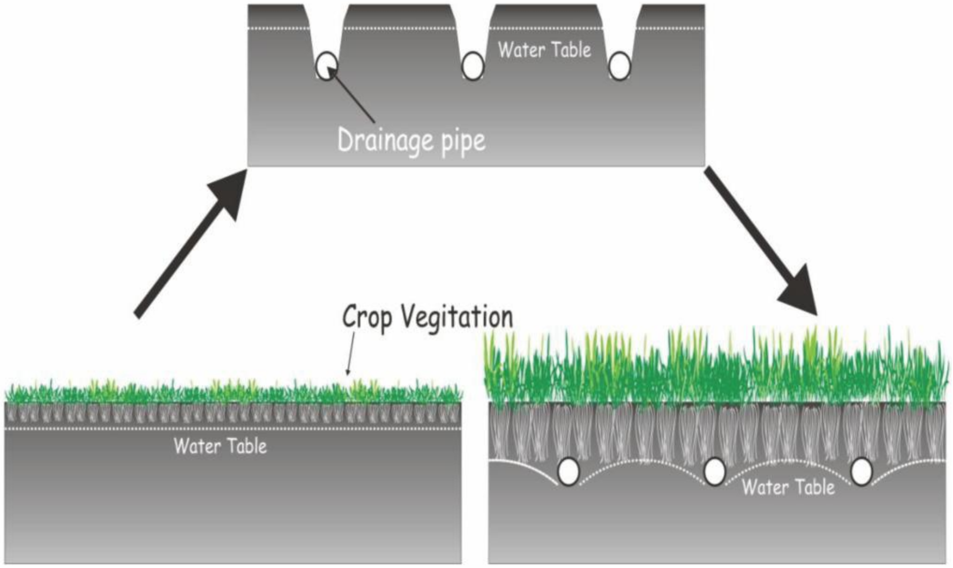

Figure 4-5. Drainage systems are primarily installed to lower the depth of water table and improve root growth.

Passive capillary wick sampler

Passive capillary wick sampler (Brown et al., 1986) is very similar to zero-tension lysimeter. It consists of some fiberglass fibers that produce capillary tension and have the ability of extracting soil water. Passive capillary wick sampler can collect up to 100% of percolation water (Zhu et al., 2002) yet in unsaturated soils its ability to extract water is limited to the capillary tension that wick fibers produce. This tension is not adjustable. Different wick samplers have different tension levels. Constant tension of capillary wick can negatively affects the level of accuracy of results. Only in an ideal situation when the wick capillary tension is equal to soil-water tension, the results may be accurate.

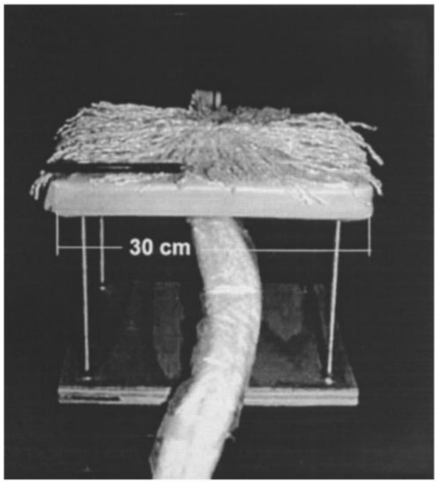

Figure 4-6. Passive capillary fiberglass wick lysimeter design (Zhu et al., 2002).

Fixed-tension, passive capillary wick samplers are commonly used because of their advantages of low cost for a large sampler array, ease of construction, high efficiency of leachate collection (Zhu et al., 2002), and relatively little effect on leachate solutes

(Knutson and Selker, 1996). However, it has been suggested that capillary wick samplers over-sample leachate when the soil water potential is near saturation (Holder et al., 1991) and alter chemical forms and concentrations of solutes in dilute soil-water samples (Goyne et al., 2000).

Suction pan/cup samplers

Suction pan or cup samplers have been made to address the problem in the previously mentioned lysimeters; which is sampling from unsaturated soil profile. Suction lysimeter consists of a porous cup or pan that is mostly placed under an undisturbed soil profile. The porous part is in full contact with soil. Applying suction on lysimeter container creates a tension against soil tension and extracts soil water. Suction lysimeter is a common device for soil-water sampling (Gross et al., 1990). The suction level is usually fixed on 300 cmH_2O (field capacity).

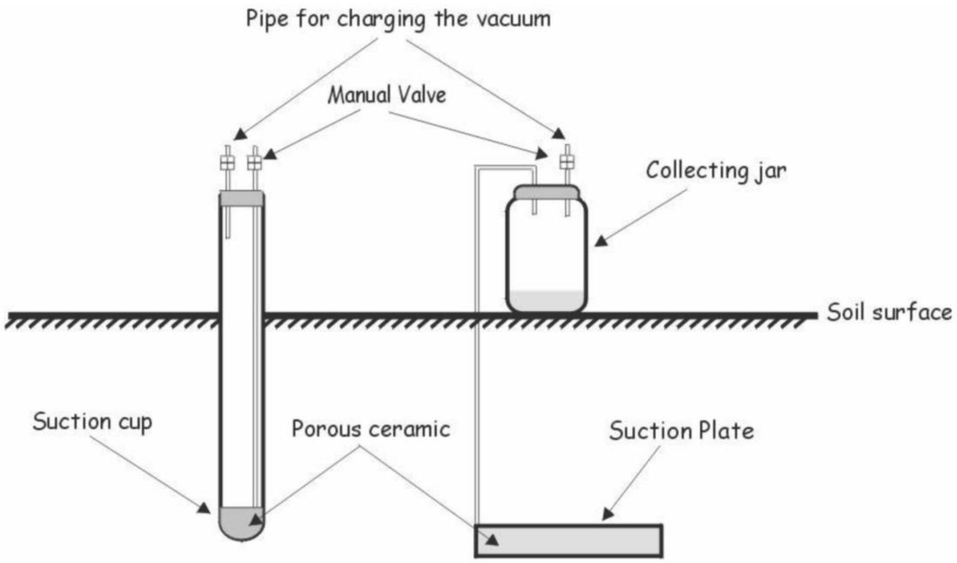

Figure 4-7. Schematic diagram of suction cup and suction pan lysimeters.

Equilibrium Tension Lysimeters

Suction cup lysimeter is easy to install and maintain (Lord and Shepherd, 1993) and is a suitable tool for measuring concentration of different solutes in unsaturated soil (Webster et al., 1993). However, it may not provide a realistic estimate of the amount of water that is percolating under the root zone. The reason is that suction cup is hardly in equilibrium with soil tension which causes the sample volume to be less or more than the correct amount. For most accurate results water sampling rate (q_p) has to be equal to vertical water flux (q_s) in the same depth at all times (Kosugi and Katsuyama, 2004):

$$q_p(t) = q_s(t) \tag{4-1}$$

The way for achieving this condition is to make sure that the matric pressure (potential) at the water sampler (Ψ_p) is equal to matric pressure at the undisturbed soil profile (Ψ_s) at the same depth:

$$\Psi_p(t) = \Psi_s(t) \tag{4-2}$$

Therefore, some researchers have introduced Equilibrium Tension Lysimeters (for e.g., Brye et al., 1999). These lysimeters are similar to suction lysimeters but with adjustable level of suction. The idea is to keep the lysimeter suction level equal to soil tension. This way one can make sure that the amount of water that lysimeter collects is equal to the amount of water leaches to under ground levels.

Automated Suction Lysimeters (ASLs)

The main concern with equilibrium tension lysimeters is that the lysimeters need continuous supervision because water tension is not constant in the soil and it changes due to precipitation, evapotranspiration and other factors. This could be a major issue, especially with large number of lysimeters. To address this problem, some scientists (e.g. Van Grinsven et al., 1988, Brye et al., 1999; Kevin et al., 2003; Lentz and Kincaid, 2003; Masarik et al., 2004; Morari, 2006) have developed different kinds of equilibrium lysimeters which operate automatically. An automated suction lysimeters (ASL) has the ability to measure the soil water tension by means of a tensiometer or other common methods and apply the proper level of tension to a suction cup or pan. Because the vacuum applied to the sampling media is constantly regulated during the sampling period, the sample volume as well as solute concentration is accurate. In fact, many researchers believe that ASLs are more accurate than other soil water samplers (e.g. Barzegar et al., 2004; Lentz and Kincaid, 2003; Kosugi and Katsuyama, 2004; Masarik et al., 2004). Automated suction lysimeters also can operate and log data with minimal supervision for a relatively long period of time. Therefore, the researchers have the opportunity of collecting water samples and log soil matric pressure data for the whole year (or even more) and have a holistic idea about water dynamics in the soil. This system also is very easy to replicate and can be used in large numbers (for example one in each experimental plot). This way the accuracy of the results will improve and it may be possible to study the effect of various treatments or management practices on soil-water dynamics.

There is however some drawbacks related to using ASL. For example installation of electronic parts and programming and maintaining the device needs skilled work force and each electronic system can practically control only one or two lysimeters which usually limits the number of lysimeters that can be used in each experiment due to fanatical and technical limitations. Also there would be a need for electric power to operate the system which makes it even harder to use ASLs in remote areas. However, solar panels can be successfully used for this purpose.

Lentz and Kincaid (2003) developed an ASL for collecting soil-water sample (Figure 4-8). Their soil-water sampler is a ceramic media that is installed in the bottom of a stainless steel beaker. The beaker has a sidewall to prevent lateral water movement above the ceramic plate. A tensiometer is installed in the neighboring natural soil profile and measures the water tension in the soil. The controller device uses this information to adjust the vacuum level applied to the water sampler. The vacuum applied to the sampler therefore, can be readjusted continuously during the sampling period. This system is not designed to correct the vacuum if it exceeds the soil tension. Instead, the water flow to sampler and a slight leakage reduces the vacuum level over the time.

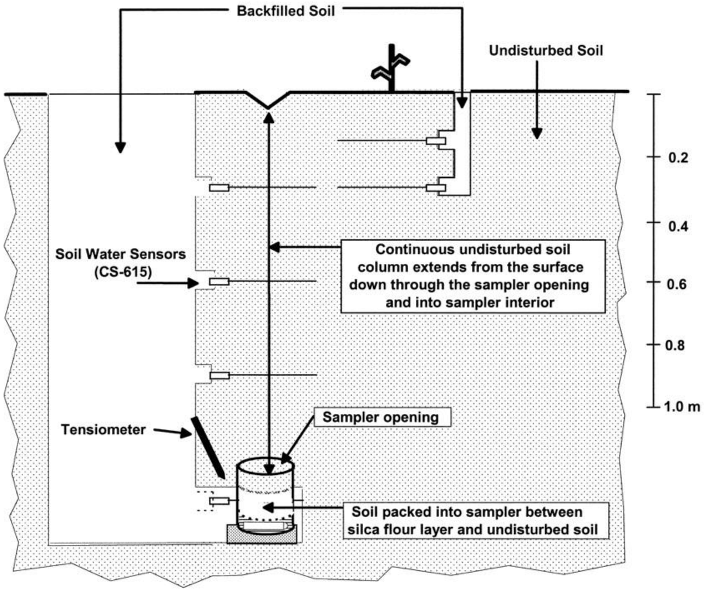

Figure 4-8. Field installation and placement of soil water percolation samplers (Lentz and Kincaid, 2003).

The designers have performed a laboratory design to evaluate the performance of the system. Assuming that their lab experiment provided accurate results (which we will study later), its applicability in the field condition is uncertain and it is hard to determine if soil tension above the sampler is in equilibrium with the soil tension in the neighboring undisturbed profile (Masarik et al., 2004). Thus although the system tracks the intact soil tension, there is no direct evidence to make sure that the sampler is in equilibrium with undisturbed soil profile. To address this problem, Masarik et al. (2004) suggested installing a heat-dissipation sensor right above the suction plate. This way one can verify the system accuracy in performance. However in their system (automated equilibrium tension lysimeter), the sensor above the water-sampler has no particular rule in controlling the system performance. It means that the controller does not use the information from this sensor for adjusting the vacuum applied to the sampler and just stores it for future assessing the device performance. Other than that, automated equilibrium tension lysimeter (AETL) is not more accurate than Lentz and Kincaid (2003) device.

Controlled-suction period lysimeter (CSPL)

Kosugi (2000) and Kosugi and Katsoyama (2001, 2002, 2004) developed this type of lysimeter because they believed that other ASLs have some technical problems. They studied Lentz and Kincaid (2003) and using Darcy's law, they suggested that the vacuum control should be calibrated for any given soil and suction plate type. Meaning applying Ψ_s to the vacuum tank does not guarantee the same matric pressure at the soil-water sampler. Therefore lysimeters usually set the target pressure (the pressure at water sampler) on:

$$\rho_c(t) = \Psi_s - \Delta_v \tag{4-3}$$

Where Δ_v is a constant, usually between 2 to 5 kPa, ρ_c is the air pressure applied to porous plate and Ψ_s is soil matric pressure. Based on Darcy's law, and equations [4-1] and [4-2], Kosugi and Katsoyama (2004) calculated Δ_v as:

$$\Delta_v = L\left[\frac{q_s(t)}{K_{s,p}} - 1\right] \tag{4-4}$$

Equation [4-4] suggests that Δ_v will change with thickness of suction plate (L), type of soil ($K_{s,p}$) and antecedent soil-water moisture condition (q_s). Therefore Δ_v cannot be constant during the sampling period, and it changes constantly with changing soil-water tension (Ψ_s). Moreover in order to know Δ_v, a lysimeter has to be calibrated. To address this problem, Kosugi and Katsoyama (2004) decided to eliminate the need for the Δ_v concept and they introduced the controlled-suction period lysimeter (CSPL). This lysimeter controls the vacuum application duration instead of controlling the amount of vacuum applied to the suction plate (Kosugi and Katsoyama, 2004). Figure 4-9 shows different parts of a CSPL system.

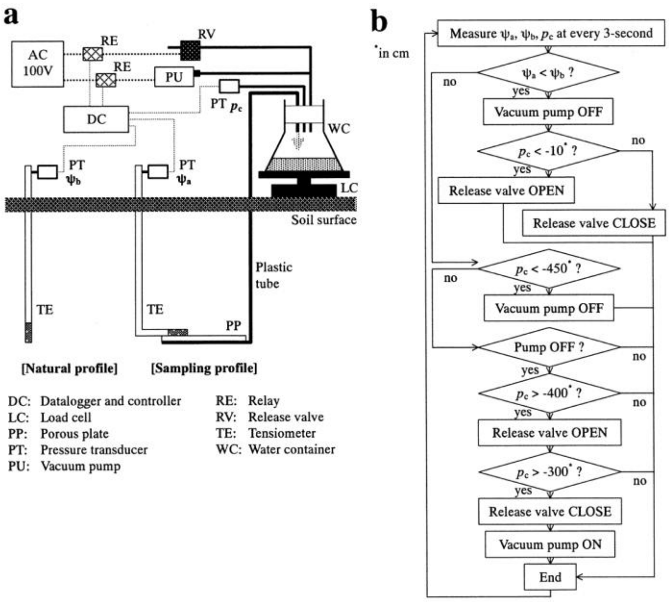

Figure 4-9. (a) Schematic diagram of the controlled-suction period lysimeter and (b) flow chart of the control system for the suction system by which soil water is extracted (modified from Kosugi, 2000).

In CSPL, a small tensiometer is installed right above the suction plate. It measures the water tension of the soil above suction plate. There is another tensiometer in an undisturbed part of the neighboring soil which measures soil-water tension in a soil profile. CSPL is programmed so that when the soil matric pressure above suction plate (Ψ_p) exceeds soil matric pressure in the natural soil profile (Ψ_s), a great amount of negative pressure (about -450 cmH_2O) is applied to the water sampler. This vacuum application continues until $\Psi_p \leq \Psi_s$. Then the water sampler pressure increases to zero. When $\Psi_p > \Psi_s$, the algorithm starts over (Figure 4-9b). They also defined Δ_t as the interval for monitoring Ψ_p and Ψ_s. They noted that a small Δ_t and a strong water sampler vacuum are critical to make Ψ_p close to Ψ_s.

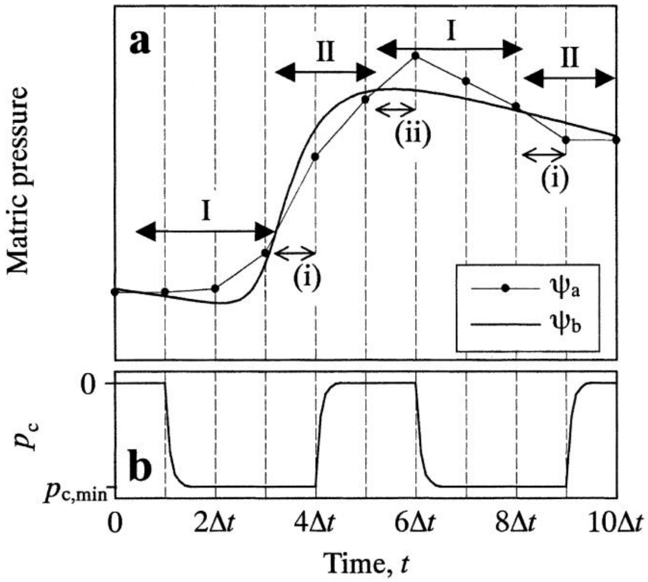

Figure 4-10. Illustration of (a) matching Ψ_p with, Ψ_s and (b) controlling air-pressure in the water-sampler container, ρ_c.

Potential problems of Controlled Suction Period Lysimeter:

Although Kosugi and Katsoyama (2004) illustrated the weakness of AETL and its failure to adjust an accurate target pressure (ρ_c), it seems that their proposed system needs some modifications. In this section we will explore the dynamics of an ASL system and explain the CSPL issues and finally suggest an alternative design for ASL.

Because Darcy's law is comparable with Ohm's law in electricity, a suction lysimeter system can be illustrated like an electronic circuit (Figure 4-11). Also soil-matric pressure and negative pressure applied to an ASL is a concept similar to electrical potential difference (voltage), and water flow rate in soil profile or other media is similar to electrical current. Similarly soil or other media resistance against water or air flow is comparable to electrical resistance. In Figure 4-11, R_S represents soil profile resistance against vertical water movement. It can be calculated as $\frac{H_s}{K_s}$ where, H_S is soil depth (the depth of suction plate) and K_s is soil unsaturated hydraulic conductivity. R_p represents suction plate resistance against water flow which can be calculated as $\frac{H_p}{K_p}$. Where, H_p is the thickness of suction plate and K_s is the plate hydraulic conductivity. Also R_l is lysimeter total resistance against vacuum or water flow and can be partitioned into R_p and R_b components ($R_l=R_p+R_b$), where, R_b is the resistance of lysimeter components (mostly vacuum pipe) from sampling jar to the point right below the suction plate.

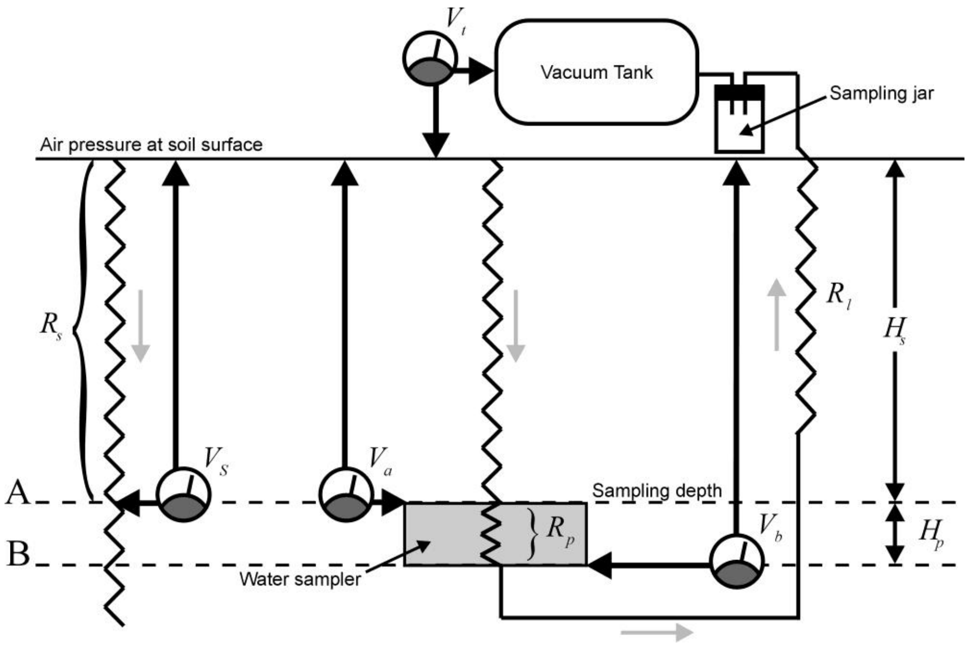

Figure 4-11. A schematic illustration of a vacuum lysimeter as an electronic circuit. Arrows represent the direction of water flow. Conceptual tensiometers show the potential difference between the point and ambient air. Point A is right above the suction plate and Point B is right below the suction plate.

Air ambient pressure at soil surface is considered as the base level for comparison and it has the value of zero. Also V_t is the amount of pressure (negative) at the vacuum tank (we assume that the resistance between vacuum tank and sampling jar is zero thus the vacuum in sampling jar is also equal to V_t), V_b is matric pressure at the point right below the suction plate. Also V_a is soil matric pressure right above the suction plate. V_s is matric pressure in the undisturbed soil profile at the depth of suction plate. It should be noted that for having an accurate sampling, both conditions in equations [4-1] and [4-2] must be satisfied. Using the parameters in Figure 4-11, equation [4-1] can be rewritten as below:

$$I_p = I_s \tag{4-5}$$

Where I_p is sampling rate and I_s is vertical flow rate of water in soil profile. Also equation [4-2] can be written as:

$$V_a = V_s \tag{4-6}$$

Where V_a and V_s are defined as above. In a CSPL system a great negative pressure is applied to the vacuum tank (V_t is about 450 cmH$_2$O) to ensure V_b is much less than V_s and for creating a quick change in V_a in response to changes in V_s. Vacuum application continues until V_a becomes equal to or less than V_s then V_t increases to zero. High vacuum application starts again when V_a becomes greater than V_s.

Although this algorithm is reasonably acceptable, there are some issues that need to be considered. As it was mentioned earlier, in a CSPL system, pressure fluctuates frequently between zero and -450 cmH$_2$O. These extreme amounts of vacuum applications are to make sure that V_a has a quick response to changes in V_s. Perhaps one main problem with this method is asymmetrical response of V_a to V_s (Figure 4-12c) where the slope of increase in V_a (Ψ_a in the Figure 4-12) is not equal to its declining slope. In other words, it takes less time for V_a to increase than to decrease. Consequently, V_a mostly stays above the V_s (Ψ_b in the Figure 4-12) and thus the collected sample volume would be less than what it should be. This problem becomes more serious in soils with high matric potentials since soil-water flows to the sampler and increases the V_a more quickly.

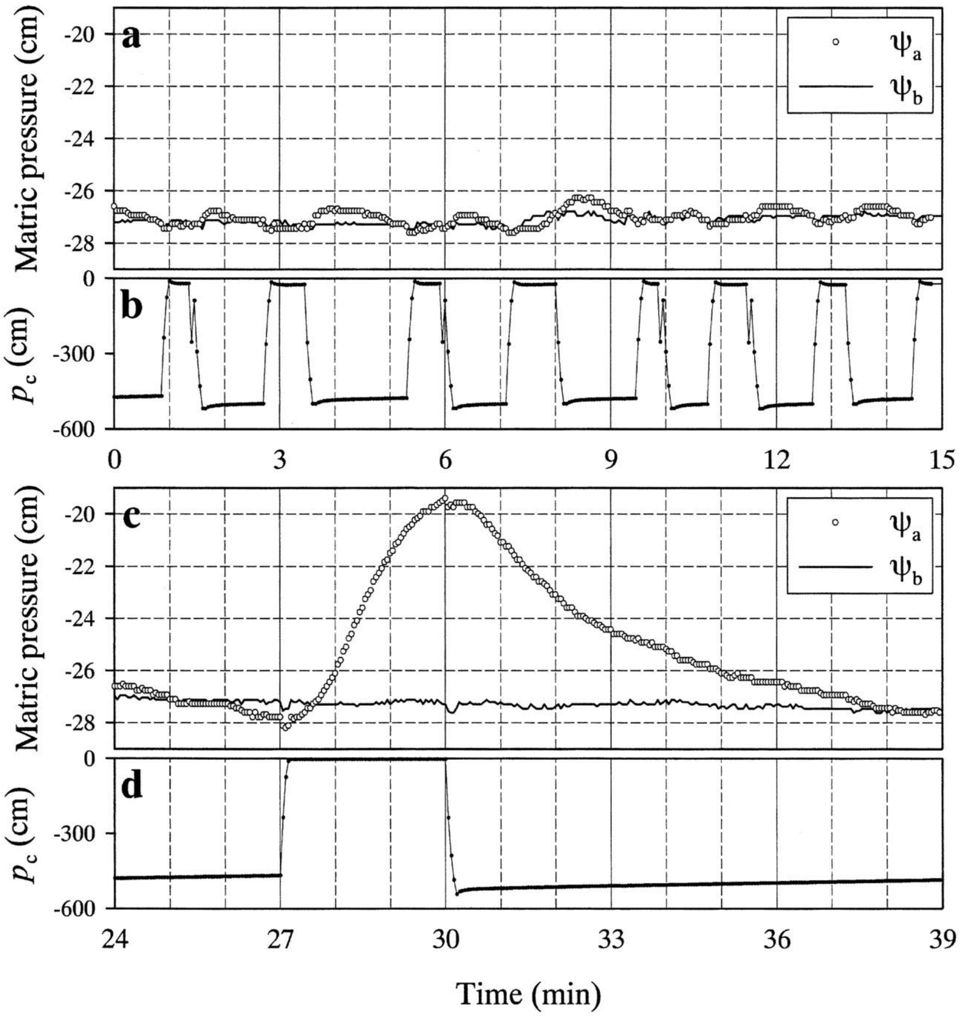

Figure 4-12. Changes of (a) Ψ_a and Ψ_b and (b) p_c with the monitoring interval, Δ_t, of 3 s, and changes of (c) Ψ_a and Ψ_b and (d) p_c with Δ_t of 3 min. lost (Kosugi and Katsoyama, 2004).

Reducing Δ_t can be an appropriate solution to this issue. Although Kosugi and Katsoyama (2004) used three seconds for Δ_t, it does not seem that even three seconds is low enough for eliminating this effect and therefore the problem still exists in soils with low soil-water tensions. Using faster controllers, Δ_t can be reduced to even less than 3 seconds. However reducing Δ_t below three seconds seems to have some practical limitations in a CSPL system.

Low energy efficiency of CSPL is another issue related to this method since V_t constantly fluctuates between zero and -450 cmH_2O and the vacuum tank (or at least a sampling jar) needs to be charged and discharged with vacuum frequently. This puts a great burden on the vacuum pump and consumes a lot of power and can be important if one needs to use several ASLs in a project.

Another issue with CSPL is installing a tensiometer right above the suction plate which seems to be problematic and hard to implement. Tensiometer prevents a full contact between the plate and soil profile and the response rate of tensiometer is low and may not be fast enough for monitoring rapid changes in plate tension due to application of great amounts of suction. On the other hand tensiometer response is slow and it may take several seconds before the tensiometer above the plate shows the correct value and during this period an inaccurate amount of vacuum (either zero or -450 cmH_2O) is applied to the plate. This problem can be addressed to some extend by using a miniature tensiometer which responds faster and are simpler to install. Nevertheless even a miniature tensiometer might be too slow to be used above the plate in a CSPL system. A faster method for measuring soil-water tension to reduce the response time is inevitable.

Exploring the best strategy for operating an ASL

Assume that the resistance between the vacuum tank and sampling jar is zero and also that the flow rate of suction plate (I_a) is equal to sampling rate (I_t). This is mainly because soon after the pipe is filled with water, I_a can not be greater than I_t :

$$I_t = I_a \tag{4-7}$$

Knowing V_s, the amount of V_t can be calculated to satisfy Equation [4-5]:

$$I_t = I_s \Rightarrow \frac{V_t}{R_s + R_l} = \frac{V_s}{R_s} \tag{4-8}$$

Solving the equation for V_t:

$$V_t = V_s + V_s\left(\frac{R_l}{R_s}\right) \tag{4-9}$$

Equation [4-9] indicates that in order to have a sampling rate greater than zero; pressure applied to the suction plate has to be less than soil-water tension. This excess amount of vacuum (Δ_v) is applied to overcome the lysimeter resistance.

$$\Delta_v = V_s\left(\frac{R_l}{R_s}\right) \tag{4-10}$$

Equation [4-10] suggests that Δ_v is not a constant but in fact changes with changes in V_s. Consequently, Δ_v in dryer soils (smaller V_s) is less than wetter soils (greater V_s). Therefore water samples collected by ASLs that are using a constant Δ_v (e.g. Masarik, 2004) are not very accurate. However it is not clear that how much Δ_t accuracy actually affects the samples. Another outcome of Equation [4-10] is that Δ_v is a function of R_l and R_s. Therefore for adjusting the V_t, one needs to know the resistance of lysimeter (R_l) and the resistance of the soil column above the suction plate (R_s). Since calculating Δ_v based on soil and lysimeter resistances is not possible in many conditions, calibration is required for accurate determination of Δ_v (Kosugi and Katsoyama, 2004).

It is notable that based on Equation [4-9], when soil is saturated, Δ_v and V_t are zero and thus sampler collects no water. This may seem wrong in the first look however it actually makes sense because in the case that soil is saturated, determining the accurate amount of vertical water flux based on soil tension (which is zero) is not feasible.

Minimum Resistance Automated Lysimeter (MRAL): a new method for operating ASLs

Kosugi and Katsoyama (2004) suggested that for collecting an accurate soil-water sample, an ASL must satisfy two conditions which can be seen in Equation [4-5] and Equation [4-6]. Since the ultimate goal is to measure the volume of vertically percolated water in the soil profile, a sampling rate equal to the rate of vertical water flow guarantees that the volume of soil-water sample is equal to the volume of the water that has vertically percolated through the soil. Hence Equation [4-6] is in fact the condition that guarantees the satisfaction of Equation [4-5]. When a suction equal to V_s is applied to the vacuum tank it will result in a lower vacuum level above the suction plate (point A) and no water will be collected due to the lysimeter resistance (R_l). Most ASLs try to control V_a by adjusting V_t. Some researchers have added a constant amount of vacuum to V_t between 20 to 50 cmH_2O to overcome the lysimeter resistance (Kosugi and Katsoyama, 2004) which -as was said before- is not accurate. The other approach for controlling V_a is the CSPL method. Although it seems that CSPL is the most accurate ASL up to day, it seems that it not perfect and still needs some modifications (see the previous section). Here we try to suggest some modifications in ASL method to make it more efficient and more accurate.

It was mentioned earlier that Equation [4-6] is used to satisfy the Equation [4-5] condition. Therefore, the first step is to measure V_a. Failure in precisely measuring V_a

results in collecting inaccurate samples. Installing a tensiometer right above the suction plate created some technical issues. Alternative method is using a faster response rate device such as heat dissipation sensor instead of a tensiometer. It seems that vacuum sensors have the fastest response rate. Two setups illustrated in

Figure 4-13 are suggested for measuring vacuum at point A (right above the suction plate).

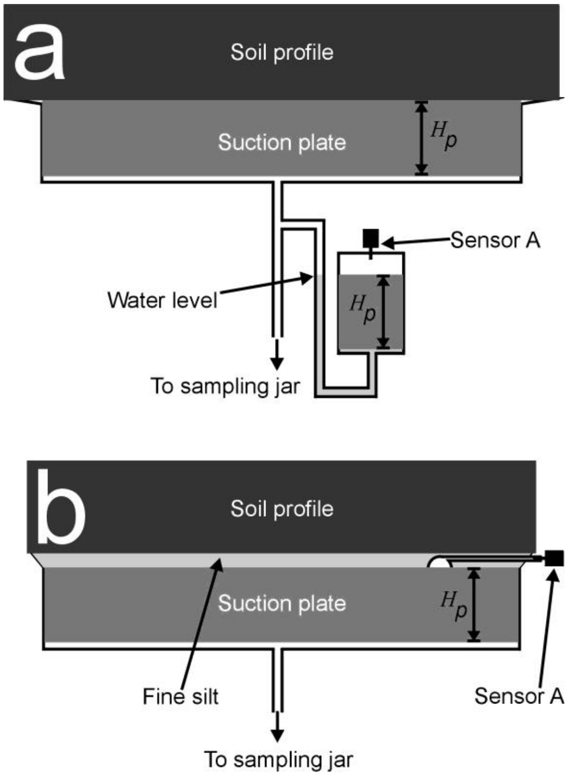

Figure 4-13. A schematic design of two setups for measuring tension right above the suction plate.

In Figure 4-13a, a piece of porous media of suction plate with the same thickness (H_p) is placed in a small chamber filled with water and is piped close to point B (right below the suction plate). As a result, the sensor A can show the impact of vacuum application to point B on point A. The porous media inside the chamber is submerged in water because its resistance may differ in wet and dry conditions. The setup is easy to use and it does not interfere with sampler installation. In the setup illustrated in Figure 4-13b, a very small vacuum chamber is glued to the top of the suction plate and is piped to a vacuum sensor (sensor A). Inside the chamber is always in equilibrium with the top of the suction plate. Therefore sensor A shows the tension of point A precisely. Installation of this setup is relatively easy because the vacuum chamber and the tubing connected to it are very small. The advantages of these methods to a tensiometer (such as in CSPL) are that the new methods are more accurate since they do not have resistance and they do not need to be corrected for the height of water column (like in tensiometer), their response rates are much faster than a tensiometer, they do not need water to operate, and are much smaller and easier to install and operate and maintain.

The other main difficulty of all ASLs is adjusting the tank vacuum (V_t) on a certain level that yields a tension equal to soil tension (V_s) at the point A (a V_t that yields a V_a equal to V_s). Equation [4-9] suggests that soil and lysimeter resistances are needed to be known for solving this problem (which are not easy to measure). As a result, the only practical way seems to be calibrating the system. After installing the lysimeter in place, it can be calibrated as follows:

- Read soil tension (Vs).
- Adjust the vacuum tank on the same vacuum (adjust Vt equal to Vs).
- Wait until Va stops changing.
- If Va is more (less negative) than Vs, decrease Vt by Δs (the accuracy level of the system, e.g. 1 cmH2O).
- Repeat step 4 until Va is equal to Vs.
- Record Vt and Vs.

- Repeat the steps 1 to 6 in several different soil moisture conditions.
- Calculate the model $V_t = f(V_s)$.

The system can be calibrated with even one data point and the calibration model can be fine-tuned during the sampling period and using V_s, V_t and V_a data points. Even the controller can be programmed to calibrate the system automatically. The advantage of calibration to CSPL method is that it is more energy efficient, does not apply extreme vacuum application (V_a will always have a value close to V_s), reading is faster and more accurate (it uses a vacuum sensor for reading the tension in point A), and it can constantly be fine tuned (calibrated) to have the most accuracy possible.

When calibrating or operating the lysimeter, an important practical concern is the time lag between change in V_t and response of V_a, because after adjusting V_t on a certain value, it will take a while for V_a to fully respond. During the response lag, the soil tension (V_s) may change and affect the V_a and reduce the accuracy of calibration model. Using a very low resistance suction plate (low R_p) could be considered as a part of the solution. Low R_p suction plate (like the 1-mm-thick porous stainless steel plate used by MASARIK et al., 2004) will lead to a fast response to changes in applied vacuum. Therefore the vacuum applied to the plate (point B) will quickly transfers to the soil profile (point A) and reduces the response lag. A low R_p also reduces Δ_v (see Equation [4-10]) and thus increases the energy efficiency of the system.

Another part of the solution is reducing (or even eliminating) the resistance of the vacuum pipes from vacuum jar to the suction plate (reducing R_b). This vacuum pipes are usually very narrow to help elevating water from suction plate (deep in soil) to sampling jar (above the soil surface). Narrow vacuum pipes create a significant resistance against vacuum which increases by length of the pipe. Using a pipe with a greater size and shorter length can reduce R_b and thus response lag dramatically. The setup in Figure 4-14a is suggested for the lysimeters that have accessible suction plate during the sampling period. The lysimeters that have a back-filled installation trench have to use a little more complicated system for pumping up the sampled water (Figure 4-14b).

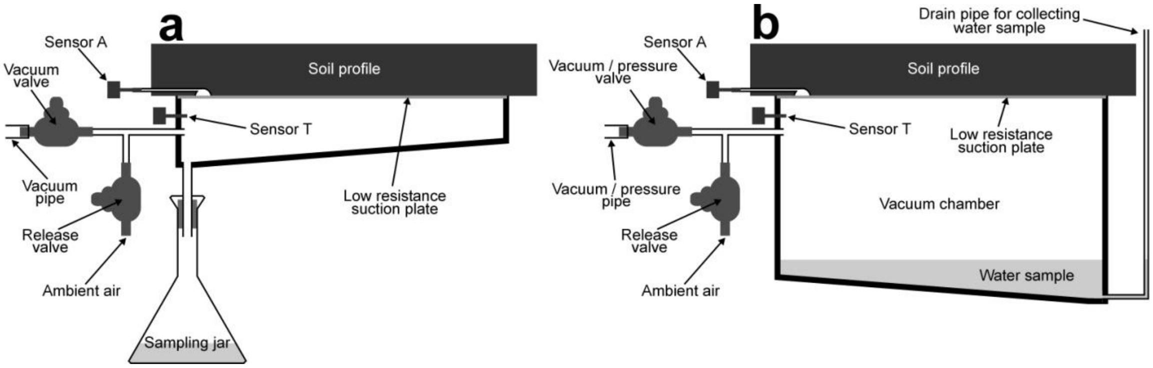

Figure 4-14. Illustration of an ASL with low response lag time. All components are directly connected to a vacuum chamber right below the suction plate therefore the only resistance of the system is the plate resistance (Rp) which is negligible. (a) For collecting the extracted water from the sampling jar, one has to have access to it. (b) For pumping the extracted water up to the soil surface a positive pressure is applied to the vacuum chamber and sample is collected from the drain pipe.

In ASLs illustrated in Figure 4-14, all components such as solenoid vales and sensor T are directly connected to a chamber right below the suction plate. Vacuum and release solenoid valves adjust the vacuum level in the chamber. Sensor A reads the vacuum in point A (right above the suction plate) and sensor T monitors the vacuum level of vacuum chamber. Since in this system there is no R_b (system resistance from sampling jar to suction plate) and since R_p is very low, V_a will respond to changes in V_t quickly. Also since the only component of the system resistance (R_l) is R_p (which is known from manufacturer information), Δ_v and thus V_t can be estimated using only R_s (estimated from soil texture and structure) and R_p using Equation [4-10]. This gives the user a good start point for calibrating the system because calibrated V_t can not be very different from its estimated value using Equation [4-9].

The advantages of the Figure 4-14 setup include a very low response lag (no R_b and low R_p), very energy efficient (Δ_v is low), fast and accurate vacuum adjustment (fast tension monitoring above the plate and fast response at point A due to low R_p), and finally easier calibrating the new setup due to its smaller response lag and also quicker response rate of sensor A.

Suggesting a laboratory setup design for assessing the performance of ASLs:

Since there has been no direct method for measuring water flux in unsaturated soil, assessing the accuracy of an ASL performance is not a simple task. Some researchers have tried to use some controlled systems or modeling methods to study the accuracy of ASL measurements (Wohling, 2009; Morari, 2006; Lentz and Kincaid, 2003). Assuming there is no lateral water flux in soil profile in a controlled system, the main goal of an ASL is to extract an accurate amount of water sample from a soil. Assessment systems that use modeling methods (Wohling, 2009; Morari, 2006) cannot be considered as direct methods for assessing the performance of ASLs. Lentz and Kincaid (2003) have developed a soil column system for evaluating the performance of an ASL system (Figure 4-15). The technical specifications of the system can be found in their paper.

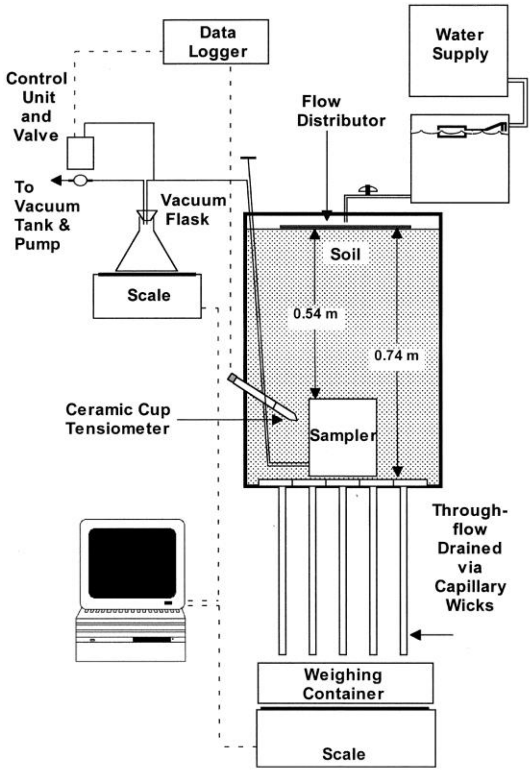

Figure 4-15. Laboratory setup for testing automated percolation samplers (Lentz and Kincaid, 2003).

A constant rate of water flow is applied to the top of the soil column. Water extracted by water sampler and drained water from the bottom of the column are collected and measured separately at any time step by a computer data logger. Water sampler is installed at the bottom of a stainless steel beaker to reduce the negative impact of lateral water flux on measurements. Glass fiber wicks drain the column under tension. The soil matric pressure is measured by a tensiometer installed at the same depth as the water sampler. The computer uses this information for adjusting the level of vacuum that has to be applied to the water sampler. Assuming the vertical water flux is uniform in the column, Lentz and Kincaid suggested that if an ASL works accurately, the system has to satisfy the following equation:

$$\frac{V_p}{V_p + V_d} = \frac{A_p}{A_p + A_d} \Rightarrow \frac{V_p}{V_c} = \frac{A_p}{A_c} \qquad [4\text{-}11]$$

where V_p is the volume of water extracted by the sampler, V_d is the volume of water drained from the bottom of the column, V_c is the total amount of water extracted from the system (the summation of V_p and V_d), A_p is cross sectional area of water sampler, A_c is cross sectional area of the column and A_d is cross sectional area of the draining part of the column (the difference of A_c and A_p). Although the condition in Equation [4-11] seems to be reasonable, there are some practical issues that may impact the accuracy of results obtained from the system. For example the tensiometer is not installed at exactly the same depth as the sampler. Therefore its information may not be very accurate for adjusting water sampler vacuum. On the other hand, since the sampler is installed at the bottom of the column, the tensiometer cannot be installed at the same depth as the sampler. The bottom of the column does not have similar characteristics of the soil profile.

The other problem is the soil-column draining system which seems to be not very irrelevant to the results of the sampler. The reason is that the amount of drained water from the bottom of the column depends directly on the tension level of the capillary wick. Therefore by changing the tension of the wick (changing its fiber type) the amount of drained water from the column (V_d) will change, especially if the water in column is under tension (is not free/gravitational water). Moreover, in relatively high tension (more than the tension level of the wick) no drainage can be collected which then limits the operation range of the testing system. Consequently the column setup is very much like a comparison between a capillary wick sampler and an ASL. Although V_p and V_d can be compared as the outcomes of two methods for collecting soil-water sample, V_d can not be used as a representative of vertical water flux in a natural soil profile or as a base for evaluating the accuracy of the ASL.

One other issue is the interaction between the sampler performance and the tensiometer installed in the column. When water sampler creates a divergence in water flow, it will affect the soil surrounding the tensiometer and reduces the soil tension (a fraction of excess water flows towards the tensiometer). Consequently, the ASL controller reduces the vacuum applied to the sampler due to reduction in soil-water tension which in turn, creates more divergence. The opposite situation can occur when the sampler creates a convergence in water flow. This positive feedback effect of the setup can dramatically reduce the system's accuracy and reliability.

Introducing Dual Soil Column System (DSCS) for evaluating the performance of different types of soil-water samplers

Figure 4-16 is a schematic design of a DSCS setup. This system consists of two soil columns. The columns are identical in every aspect except that column II has a water sampler inside it. The soils of both columns are sieved and homogenous and uniformly compacted to desired bulk density. Homogeneity and identicality of the soils in columns is crucial for obtaining the correct results.

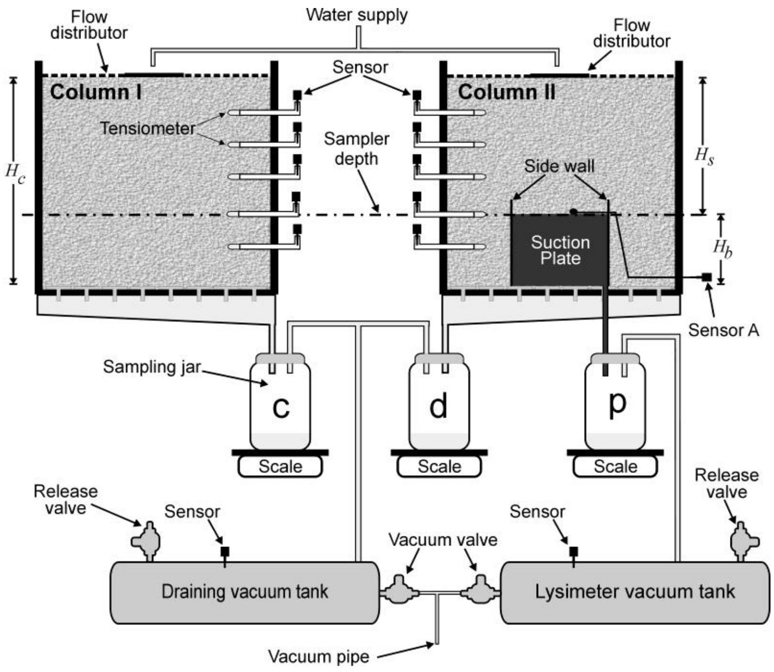

Figure 4-16. A schematic design of a Dual Soil-Column System. Sensors, solenoid valves and scales are connected to controller/data-logger units.

Water supply is applied to the columns uniformly. A flow distributer in each column helps promoting the uniformity of vertical water flow in the column. Therefore, we expect that the dynamics of water movement in both columns to be identical. Water sampler in column II is installed in a beaker and side wall of the beaker reduces the impact of lateral water movement (if there is any). Since column I represents the natural soil profile, it has a tensiometer at the same depth of the sampler, connected to a controller and provides the soil-tension information that is used for adjusting the vacuum of ASL sampler.

Drained water from column I (control column) flows into container *c*. Also drained water from column II (lysimeter column) flows into container *d* and extracted water from water sampler is collected in container *p*. Containers *c* and *d* is under the same vacuum level. Draining vacuum (vacuum applied to containers *c* and *d*) has to be adjusted on a level that guarantees a drainage flow. The precise amount of draining vacuum is not much important and as a rule of thumb, it can be 50 cmH_2O less than the readings from the lower most tensiometer in column I. The vacuum applied to container *p* is adjusted by the ASL controller. Several miniature tensiometers are installed in different depths of columns to monitor the soil tension continuously.

In a DSCS, there are two major ways for assessing the performance of an ASL. First is to study the data from several tensiometers that are installed in both columns and compare the patterns of soil tension. When ASL works properly, the patterns of soil tension in the two columns should be the same. The reason is that the ASL should mimic the dynamics of soil profile precisely and therefore, there should be no difference in water dynamics between the columns. Although this method seems to be reliable and accurate, yet it is not a direct method for verifying the accuracy of the water sample volume and results can not be easily quantified. The second way for assessing the performance of the ASL is by comparing drainage rates of the two columns. In case that ASL has a good performance; the following condition is true:

$$I_c(t) = I_d(t) \Rightarrow \frac{V_c(t)}{A_c} = \frac{V_d(t)}{A_d} \qquad [4\text{-}12]$$

where I_c is flow rate of drainage from the bottom of the column I, I_d is flow rate of drainage from the bottom of the column II, V_c is volume of drainage from the bottom of the column I, V_d is volume of drainage from the bottom of the column II, A_c is drainage cross-sectional area of the column I and A_d is drainage area of the column II (is equal to $A_c - A_p$ where A_p is water sampler cross-sectional area).

The presumption behind Equation [4-12] is that in column I there is no significant lateral water flow and vertical water movement is homogenous. Since column II is identical to column I the same dynamics are expected in column II. The only factor that can cause a convergence or a divergence and create a difference in soil tension patterns of the columns and thus flow rate, is the sampler in column II. When ASL works accurately, there would be no convergence or divergence in water flow and thus the Equation [4-12] is correct. Any difference between drainage rates of the columns is a direct indicator of malfunctioning of an ASL. An Ideal ASL has to collect all the vertical water flow from soil- profile above it without creating any significant disturbance in homogenous pattern of water movement. A good ASL should have a satisfactory performance under different soil moisture conditions from zero to field capacity (beyond field capacity there is no water flux in soil profile). It also has to perform accurately in all soils with different texture and structure.

Advantages of DSCS method:

- Its logic is simple and straightforward.
- Is a direct and objective method.
- Does not need expensive or complicated instruments.
- Can assess any type of ASL or other types of soil-water samplers.
- Can distinguish convergence from divergence that is created by the ASL. When $I_c(t) < I_d(t)$, the ASL is applying vacuum less than the proper amount and the

sampler creates a flow divergence. Similarly, $I_c(t) > I_d(t)$ indicates that the ASL applies excess vacuum to the water sampler which creates convergence.

- Theoretically it can be used for any type of soil at any level of soil moisture.
- Since it is a direct method for assessing soil water samplers, it provides the opportunity to actually measure the level of accuracy of different water sampling methods rather than just comparing them. In a perfect performance, Ic and Id should be exactly the same. Therefore, a sampler error ratio (SER) for any soil-water sampler can be calculated using the following equation:

$$S(t) = \frac{I_d(t) - I_c(t)}{I_c(t)} \times \frac{A_d}{A_p} \times 100 \qquad [4\text{-}13]$$

Where, S is sampler error ratio (%). In the case that the sampler has a perfect performance, SER is zero A negative value indicates that the sampler causes convergence, while a positive value indicates water divergence over the sampler. It is important to note that if the ASL does not work accurately, I_d can change with change in $\frac{A_d}{A_p}$ ratio. Therefore, SER has this ratio as a correction term in its formula. SER can be calculated for most water samplers and their volume measurements can be corrected due to their SER values.

Conclusion

Automated suction lysimeter is the most accurate method for collecting soil-water sample. It is easy to use and maintain and can sample and log data all year around with minimum supervision. It also can be installed in large numbers and different places; for example one in each plot. It gives researchers the opportunity of studying the spatial and temporal dynamics of water in soil for a long period of time. However there are some issues that limit the ASL application. For example ASL installation needs skilled work force and may cost more time and money than many other water sampling methods. It is more complicated than regular methods such as suction cups. Currently, there is no commercial ASL in the market, hence every researcher has to design and make own system which could be an important barrier in the way of using ASLs. It seems introducing a commercial ASL system may encourage more researchers to use the system.

Automated lysimeters need a considerable amount of power to operate the vacuum pump and solenoid valves. This can potentially be a problem in remote areas, especially when a great number of ASLs are required. Using solar panels and battery backup systems may solve the problem although the cost and complexity of the system may increase.

Another concern about ASLs is their vulnerability against vacuum leakage. Rodents usually are responsible for most leakage events by chewing on tubing. Adding a leakage detection system seems to be a necessary component for every ASL.

Although CSPL tries to eliminate the need for calibrating automated lysimeters, it still seems that calibrating ASLs is inevitable for proper operation. Currently, controlled suction period lysimeter is the most accurate method but their power efficiency and practicality when great numbers of ASLs are required is questionable.

It seems that lysimeter resistance is the main technical constraint for adjusting soil matric tension right above the sampler. Minimum Resistance Automated Lysimeter eliminates the lysimeter resistance and by using low resistance porous media increases the response rate of the water sampler to applied vacuum and thus increases the system accuracy.

Dual Soil-Column System was introduced in this paper as a new type of laboratory test setup for directly assessing the performance of ASLs and other soil-water samplers. This method has the ability of distinguish divergence from convergence and even quantify the level of ASL accuracy.

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CHAPTER 5

AN AUTOMATED SUCTION LYSIMETER FOR IMPROVED SOIL WATER SAMPLING

Abstract

Leaching of chemicals from urban and commercial areas (e.g. fertilizers, manure, pesticides, and petroleum products) is one of the main sources of underground non-point source pollution. Assessment of chemical leaching has been a problematic issue. Most methods are not accurate and reliable since they do not represent normal leaching conditions in the soil. Thus the volume of soil-water collected, as well as its solute concentration may not be accurately estimated. Sixteen units of cost effective and accurate automated lysimeters were designed and installed to measure post-harvest nitrate leaching from a rye cover crop field during the falls and winters of 2007 to 2009. Major parts of the electronic system were electronic controller, data logger memory, digital clock and its battery backup circuit, relays, LCD display and electronic signal conditioning interfaces for amplifying, off-setting and digitizing the signals from vacuum sensors. The electronic system was designed to monitor soil tension every second with accuracy of 1 cmH_2O and apply the equal amount of suction to the sampling media (suction cup or plate). Hourly data from soil tension and vacuum applied to the system were collected and stored by each unit. A safety system was designed for protecting vacuum pump against unexpected major vacuum leakage events. The controller can be easily reprogrammed for different performance strategies. Automated lysimeter showed an accurate and reliable performance in lab and field conditions.

Soil ambient matric pressure matric pressure above the samplers showed a strong linear correlation in lab and field conditions, which means that the lysimeter was successful in maintaining the sampler vacuum in equilibrium with soil although there was a time lag between changes in soil matric pressure and responses of pressure above the samplers. Soil matric pressure and the sampler vacuum level were in an almost perfect correlation.

Introduction

Leaching of nutrients and agricultural chemicals is a main cause for non-point source pollution. Monitoring the amount and content of leachate from urban and agricultural areas is a growing need. However, accurately measurement of the volume of percolated water through the soil profile has been problematic (Barcelona and Morrison, 1988) since there is no direct way for measuring the water flux in the soil profile. Several methods have been introduced for extracting soil-water from the unsaturated soil profile, including soil sampling (Roth and Fox, 1990; Liang et al., 1991), collection from tile drains (Kladivko et al., 1991; Randall et al., 1997; Sogbedji et al., 2000), drainage from watersheds (Gburek et al., 1986; Lowrance, 1992), ground water wells (Weil et al., 1990; Cambardella et al., 1999), pan lysimeters (Russell and Ewel, 1985; Jemison and Fox, 1994; Toth and Fox, 1998), wick pan lysimeters (Boll et al.,), monolith lysimeters (Owens, 1987), porous cup samplers (Gerwing et al., 1979; Andraski et al., 2000) and other methods.

Automated suction lysimeters (ASL) have been developed for accurately collecting soil-water samples from vadose zone. The ASL keeps the suction applied to the water sampler in equilibrium with the soil-water tension at the same depth. The ASL method is the result of several previous studies (e.g. Duke et al., 1970; Van Grinsven et al., 1988; Brye et al., 1999; Lentz and Kincaid, 2003; Masarik et al., 2004; Morari, 2006). The devices used by these researchers had the ability to measure soil matric pressure by means of a tensiometer or other methods and then apply an equivalent level of tension (vacuum) to a porous media (e.g. suction cup or pan) to extract the correct amount of leachate water. Because the vacuum applied to the sampling media is constantly regulated during the sampling period, the sample volume as well as solute concentration is more accurate than would be the amount collected if the vacuum was more or less than the soil matric pressure. For this reason many researchers believe that ASLs are more accurate than other soil water samplers (e.g. Lentz and Kincaid, 2003; Barzegar et al., 2004; Kosugi and Katsuyama, 2004; Masarik et al., 2004). Since soil water content is constantly changing in response to precipitation, soil drainage and plant uptake the ASLs need to be capable of operating and logging data with minimum supervision for long periods of time.

Lentz and Kincaid (2003) developed an ASL that was able to regulate the vacuum applied to the water sampler and keep it in equilibrium with the neighboring bulk soil. They placed a ceramic-cup sampler in the bottom of a stainless steel beaker to prevent the impact of lateral water flow in the soil profile and filled it with soil slurry before pushing it to the desired depth in an intact soil profile. In this system (Lentz and Kincaid, 2003) a soil matric pressure sensors was installed in the neighboring soil profile and another pressure sensor in the sampling container. A controller reads the sensors in each controlling cycle and if the sampler pressure (which is negative) was more (less negative) than the soil matric pressure, more vacuum was applied to the sampler. The Lentz and Kincaid (2003) system has no direct adjustment method for reducing sampler excess vacuum, and relied on system leaks to reach the proper level of vacuum as soil matric pressure decreased (became wetter).

Masarik et al. (2004) introduced the automated equilibrium tension lysimeter (AETL) to address some deficiencies of previous ASLs. They used porous stainless steel plates (0.2μm) with 2.5 cm sidewalls for extracting water. In addition to the two sensors used by Lentz and Kincaid (2003), a third sensor was added by Masarik et al. (2004) over the sampler to verify the accuracy of the system in adjusting the sampler vacuum. This third sensor had no direct influence on improving the system performance since its measurements were not been used for controlling the ASL, rather in assessing the performance of the system. To overcome the system resistance in the AETL the applied to the sampler was about 20 cmH_2O more than the concurrent soil tension.

The main deficiency of most ASL systems (e.g. Lentz and Kincaid 2003 and Masarik et al., 2004) is that they have no direct means for adjusting the soil tension right above the sampler, which is the main goal of an ASL (Duke and Haise, 1973; Van Grinsven 1988).A controlled suction period lysimeter (CSPL) was introduced by Kosugi and Katsuyama (2004) to address this problem. The CSPL controls the vacuum application duration instead of controlling the amount of vacuum applied to the suction plate (Kosugi and Katsoyama, 2004). In a CSPL, a small tensiometer was installed directly above the suction plate. This tensiometer measured the soil matric pressure or water tension of the soil at the interface with the suction plate. The CSPL had another tensiometer in an undisturbed part of the neighboring soil to measure soil-water tension in the natural soil profile. The CSPL was programmed so that every time the soil matric pressure above the suction plate (Ψ_p) was more (less negative) than the soil matric pressure in the natural soil profile (Ψ_s), a greater amount of negative pressure (about -450 cmH_2O) was applied to the water sampler. The CSPL vacuum application was continued until $\Psi_p \leq \Psi_s$ and the water sampler pressure becomes zero (equal to ambient air pressure). When $\Psi_p > \Psi_s$, the algorithm starts over. Kosugi and Katsoyama (2004) also defined Δ_t as the time interval for monitoring Ψ_p and Ψ_s and suggested that a small Δ_t and a strong water sampler vacuum were critical to keep Ψ_p close to Ψ_s.

The CSPL approach seems to be an accurate way for controlling an ASL. However it has some minor issues. For example it is not energy efficient. Vacuum fluctuates frequently in the vacuum tank (or sampling container). This puts a huge burden on the vacuum pump, especially if several ASLs are installed. Another potential problem is installing a tensiometer right above the suction plate which is problematic. The first reason is that it is relatively hard to implement. Placement of the tensiometer may prevent full contact between the plate and soil profile. Also, since the response rate of a tensiometer is relatively slow, placement above the plate may not be fast enough for monitoring rapid changes in plate tension and with the CSPL changes in plate tension may occur more frequently due to the application of great amount of Vacuum. Further, since it may take several seconds before the tensiometer above the plate shows the correct value during this time an inaccurate amount of vacuum (either zero or -450 cmH_2O) would have been applied to the plate. This problem seems to be of more concern in wet soils and especially if a low resistance (stainless steel vs. ceramic) water sampler is used. In this case, if the response time of sampler is less than response time of the tensiometer above the plate (which usually is the case) the plate acts like an electric short circuit and with an over-application of a great amount of vacuum (-450 cmH_2O), and resultant sampling rate being unreasonably high. This problem can be addressed to some extent with a miniature tensiometer (they have faster response rates and are simpler to install) or heat-dissipation sensor. However, even with these sensors the response time may be too slow to be used above the plate in a CSPL system.

Although researchers have been trying to promote the performance of ASLs, even simple types of these devices seem to be significantly more accurate than the other soil-water sampling methods (Bazegar et al., 2004). Our objectives in this study were to design, develop and test a reliable, cost effective, and easy to install ASL system to track the soil-water tension and apply the proper amount of suction to the water sampler which can be deployed and used in great numbers (one in each experimental plot).

Materials and methods

Laboratory test

We first tested our ASL during summer 2007. The main goal of the test was to assess the accuracy of the system and to see if it would maintain the sampler vacuum (Ψ_t) near equilibrium with the soil matric pressure (Ψ_s). A minor modification of Lentz and Kincaid (2003) setup was used for the laboratory setup (Figure 5-1). The inside diameter of the column was 45 cm and the height was 50 cm. The soil-water sampler was a Soilmoisture Equipment Corp. ceramic pressure plate (1 mH_2O) with 27.30 cm diameter, 0.70 cm thickness. It was installed over a plastic support with 5 cm height. Hadley fine sandy loam (TypicUdifluvent, coarse-silty, mixed, nonacid, mesic) subsoil was sieved through a 5 mm screen. An aluminum cylinder (27.30 cm diameter and 15 cm height) was placed over the suction plate to prevent lateral water movement over the plate. A tensiometer was installed in the same depth as the sampler to measure soil-water matric pressure (Ψ_s). Another tensiometer was installed right above the sampler to measure soil matric pressure at that point (Ψ_p). A Slurry of the soil was poured into the soil column in several portions above a 5 cm layer of fine sand. At the base of this fine sand layer at the bottom of the column six fiberglass wicks with 25 mm diameter and 40 cm length each, were installed to provide drainage of gravitational flow water. In-flow water was supplied to the top of the soil column at the rate of 0.25 mm h^{-1}. The sampling period was 5 h. During the sampling period, sampler-drainage (collection)-rate as well as total-drainage-rate (sampler collection/drainage plus gravitational water) were recorded every minute. The sampler drainage fraction (SDF) was calculated as (sampler-drainage-rate) over (total-drainage-rate). Also, the sampler cross-sectional fraction (SCF) was calculated as sampler cross-sectional area over total drainage cross-sectional area. The system was deemed to work accurately if SDF was equal to the expected drainage for the SCF (Lentz and Kincaid, 2003).The experiment was repeated 3 times. Each time the soil and all the components of the setup were removed, inspected and reinstalled.

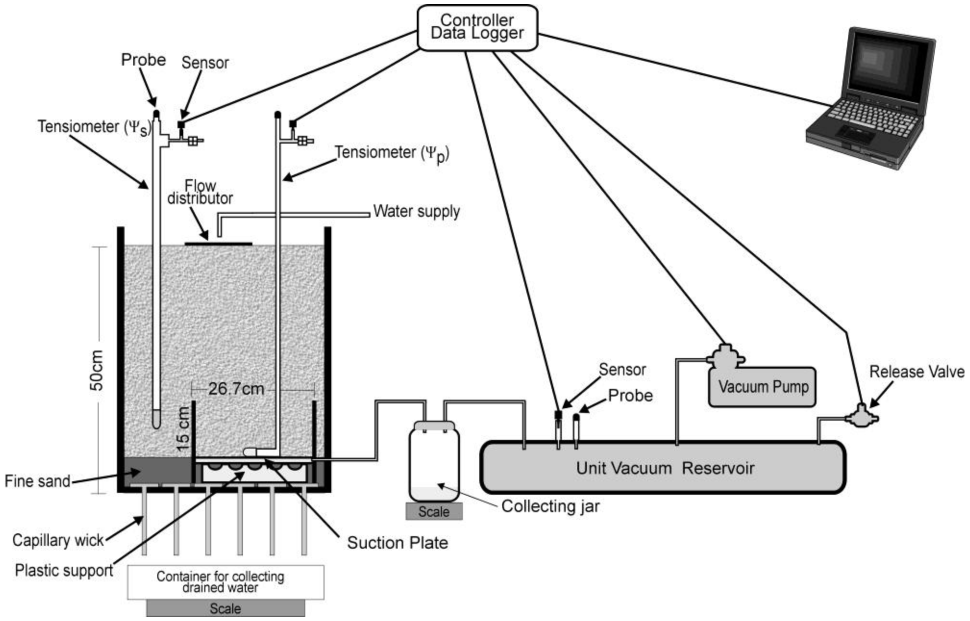

Figure 5-1. A schematic design of the laboratory setup for evaluating the performance of our ASL (modified from Lentz and Kincaid, 2003).

Field Experiments

Primary Experiment in fall 2007

Nine ASLs were made and installed in a private farm field in Deerfield, MA as a primary test in fall 2007. The spring crop was silage corn. The experimental design was Completely Randomized Design (CRD) with rye cover crop planting date as the treatment (Sept. 07, Sept. 21 and no cover crop) variable with three replications. A trench was dug in the middle of each plot for installing each suction plate samplers (Soilmoisture Equipment Corp. ceramic pressure plate (1 mH_2O) with 27.30 cm diameter, 0.70 cm thickness) at the depth of 60 cm. Each plate was placed over a plastic base and the trench was backfilled and packed to the similar bulk density to surrounding soil after installation of the plate. A tensiometer was installed 1.00 m away from the water sampler and in the same depth of 60 cm. A 3.17 mm OD Teflon tubing (Soilmoisture Equipment

Corp) was used for connecting the sampler to the sampling container. For other connections 4.76 mm ID tubing was used. Sampling containers and electronic system were placed over the soil surface on the boarder of plots.Sampling period was between 9/25/2007 to 11/15/2007.Soil-water tension was logged from two depths of 30 cm and 60 cm during 9/1/2007 to 12/1/2007.

Field experiment in 2008 and 2009

The experiment was conducted in Crops and Animal Research Center Farm of the University of Massachusetts in Deerfield, MA during the years 2008 to 2009. Soil type was Hadley fine sandy loam (TypicUdifluvent, coarse-silty, mixed, nonacid, mesic). The experimental design was Completely Randomized Design (CRD) with four replications with four rye cover crop planting date as treatment (Sep. 5th, Sep 20th, Oct. 6th and no cover crop in 2008 and Sep. 1th, Sep 14th, Sep 29thand no cover crop in 2009).In each plot, a suction plate, a suction cup (both connected to ASL) and a fixed suction cup (at -300 cmH_2O and as the control treatment) were installed. In order to install the suction plates under the undisturbed soil profile, a trench (0.9 m width, 1.5 m length and 1.2 m depth) was dug between each two experimental plots (8 trenches in total). A plywood box (with the same dimensions as the trench) was installed in each trench to protect the trench walls from collapsing. The box had a plywood cover to protect the instruments inside it from natural elements. From each end of the boxes and at the depth of 60cm, a horizontal tunnel (0.4 m width, 1.0 m length and 0.5 m height) was dug for installing the suction plate. Special care was taken to make the ceiling flat and smooth in order to make a full contact between soil profile and the suction plate.

Table 5-1. Components list used in ASLs in field experiments for 16 ASL units through 2008 to 2009.

Item	Quantity	Specifications
Electronic system + enclosure	8	280 mm × 260 mm × 70 mm (Controls two ASLs)
Mounting board	8	Plywood (300 mm × 300 mm)
Vacuum tank	16	12 liter (10.16 cm OD × 152.40 cm PVC pipe)
Differential pressure transducer	48	26PC Series (Honeywell)
Solenoid valves	32	¾’’ Orbit (WaterMaster)
SPDT Relays	32	(PD PhotoMos, AQY272, Panasonic)
Sampling container	16	1.6 liter volume
Suction plate	16	Soilmoisture ceramic pressure plate (1 bar)
Suction cup	16	1900L (3 feet, Soil Moisture Equipment Corp)
Fixed suction cup	16	Same as above at-300 cm
Signal conditioning interface	48	Specially designed
LCD display	8	2×16 rows, Positive Transflective
Push button	16	normally open
Digital clock circuit	8	Specially designed
Digital clock battery backup circuit	8	Specially designed
Main tank controller + enclosure	2	280 mm × 260 mm × 70 mm
Vacuum tank	2	24 liter (10.16 cm OD × 304.80 cm PVC pipe)
12 VDC power supplier	2	3.33 amp, Input 100-240V
24 VDC power supplier	2	6.5 amp, ITE power supply, Input 100-240V
Tensiometer	16	3 feet, Soil Moisture Equipment Corp
Miniature tensiometer	16	Soilmoisture Equipment Corp, 1 bar, 0.953 cm OD
Vacuum pump	2	Gast, DOA-P707-AA, 4.2 amp, 4.08 bar

A specially designed plane tool and the fine texture of subsoil helped to achieve this goal. Subsoil slurry was poured over plate immediately before the installation. The plate was pushed against the ceiling using a specially designed jack. A miniature tensiometer (Soilmoisture Equipment Corp, 1 bar, 0.953 cm OD, 2.858 cm length, round bottom ceramic cup) was installed over the suction plate after plate installation for monitoring the soil tension at the surface of the suction plate. All the ASL components (Table 5-1) were installed in the soil or placed inside the plywood box which protected them from the environment.

Electronic controller and data logger system

Each electronic system was designed and made in the way that control and log data from two ASLs (8 electronic system in total) independently. The main part of the electronic system was a 24pin (16+2 Dedicated Serial I/O digital ports, 32K program size) controller. Programmability of the controller gave it the flexibility of being used for different types of ASLs and operating strategies.

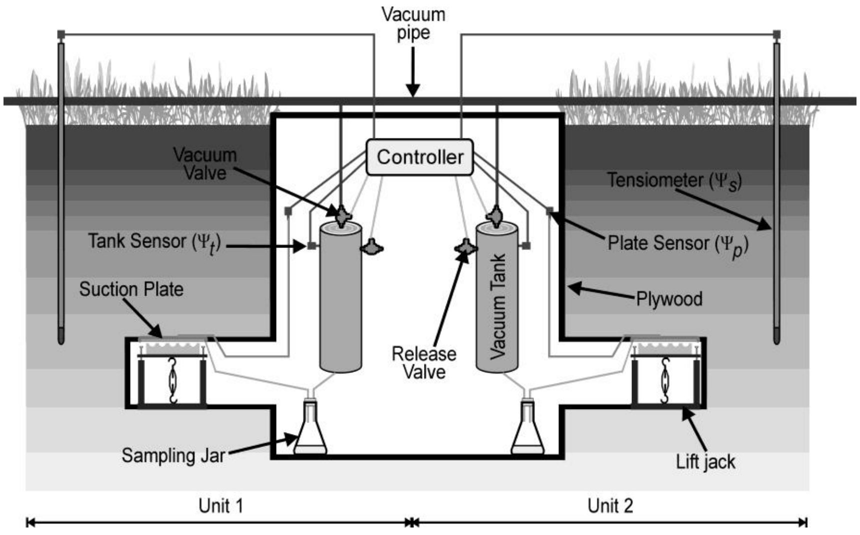

Figure 5-2. Field installation of ASLs of two adjacent plots. An electronic system (controller and data logger) operated the two ASLs.

Part of the Controller's memory was used for data logging and storage. It had the capacity of storing data for four months for the two units. A digital clock circuit as well as a separate battery and a battery backup circuit were designed and added to the system to track time. Time information was used mostly for the data logger. A serial port allowed reprogramming of the system as well as downloading the logged data to a PC.

An LCD (Table 5-1) and two push buttons were added to the system in order to make the system more convenient to use and eliminate the need for having a PC in the field for monitoring the performance of the system. This is a huge advantage for the system compared with the older ASLs. Six pressure transducers were connected to the system (3 for each ASL). Since these sensors were analog and were not electronically compatible with the controller, an electronic interface was designed and made to amplify, offset and digitize the sensor's signal and make it compatible to the controller. The accuracy of the system was 1 cmH_2O. Also four SPDT Relays was included in the system (2 for each unit) for controlling a vacuum and a release solenoid valve in each unit.

Two main vacuum tanks (one for 8 units) supplied the vacuum needed for ASLs. Each main vacuum tank was connected to a controller that kept the vacuum on constant level of -400 cmH_2O. These controllers were equipped with leakage detection modules that protected the main pumps against unexpected major leakages. A vacuum pump supplied the vacuum for each vacuum tank. Main tanks were connected to the vacuum tanks in each plot by ¾ inch Pex pipes. These pipes are flexible and easy to handle and also are very durable. All the vacuum pipes and power wires were collected and reinstalled to facilitate plowing the field.

Calibrating the sensors

After assembling and testing each electronic system, its sensors were calibrated to ensure that all work accurately and show the correct value. This is very important because the accuracy of the samples depends on the accuracy of the sensors. The accuracy of a Tensimeter (NM 88001, Soil Measurement Systems) was verified using a mercury manometer (as a direct method for measuring pressure). The Tensimeter then was used for calibrating the sensors in each electronic system. All six sensors of each electronic unit were connected to a single vacuum tank. The vacuum then was adjusted on several different levels. The data from each sensor was used for calculating a calibrating function. The parameters of these linear functions were used in the source code of the corresponding controller.

Source code

Main cycle in controller program takes about one second and consists of the following modules:

Control module refreshes every second adjusting the unit vacuum tank pressure (Ψ_t) according to soil-matric pressure (Ψ_s). In each controlling cycle, controller reads the value of all sensors. If $\Psi_s<\Psi_t$ (soil matric pressure is more negative than unit tank vacuum level) then release valve is closed and vacuum valve is opened to decrease Ψ_t. On the other hand, if $\Psi s>\Psi_t$, then vacuum valve closes and release valve opens to increase Ψ_t. In the case that Ψ_t is in the range of $\Psi_s \pm 10$ cmH_2O then both vacuum and release valves are closed. Also in the case that $\Psi s< -300$ cmH_2O (field capacity), Ψt stays at -300 cmH_2O and does not go beyond this value (the value is programmable). This is because beyond field capacity no water flow is expected in the soil profile. The control module controlled each unit independently.

Data logger module stores collected data from each unit every hour. This data consists of month, day, hour, soil matric pressure of unit 1, tank pressure level of unit 1, soil matric pressure right above suction plate of unit 1, soil matric pressure of unit 2, tank pressure level of unit 2, soil matric pressure right above suction plate of unit 2. All the pressure units are cmH_2O.

Leakage detection module supports the system against unexpected major leakage incidences and is programmed to turn off the leaking unit. Each electronic system had two independent leakage detection modules (one for each unit). The data logging module in each unit is also independent from its leakage detection module. Meaning the system continues logging data from a unit even when the unit is turned off due to a major leakage. The system is programmed to turn the leaking unit on every hour and check if it still leaks. This is for reducing the need for human attention and also for increasing the potential water sampling period.

Display module was designed to show the system status (controlling, downloading data, formatting the data storage, and sensor calibration), date and time (for making sure of the accuracy of the system clock), sensors values, valves status (close or open), unit leaking status (leaking, non-leaking), unit status (on, off), the volume of stored data (in days) and the remaining storage capacity (in days). LCD made it very easy and convenient to work with the electronic systems and troubleshoot and maintain them.

Results and discussion

System performance

The electronic system was successful in maintaining vacuum tank matric pressure in laboratory. However the T-test was used for comparing several SDFs (one per minute) with SCF and a significant difference (%5) was detected. It is not clear that this amount of difference can suggest that the system is not accurate. One reason for this difference can be the effect of capillary wicks on the amount of water collected. Meaning the amount of water collected from capillary wicks depends directly on their tension and this can affect the results.

Soil matric pressure (Ψ_s) and Ψ_p measurements showed a strong linear correlation (R^2=94.85) which means that the lysimeter was successful in maintaining the sampler vacuum in equilibrium with soil although there was a time lag between changes in Ψ_s and Ψ_p responses. It seems that this time lag might reduce the system accuracy especially during rapid changes in soil tension. Ψ_s and the sampler vacuum (Ψ_t) were in an almost perfect correlation (R^2=99.73). The controller was programmed to always keep the sampler vacuum in the range of $\Psi_s \pm 10$ cmH_2O.

Five minutes (300 seconds) of system performance can be seen in Figure 5-3a. Data was recorded per each program cycle (about one second). It may take several minutes after starting the system for Ψ_p to be in an acceptable range from Ψ_s. Therefore the system was working for 1 hour before the beginning of data recording period. The system was allowed to leak in order to test its performance under varying and adverse conditions.

Therefore, the controller had to adjust the vacuum by operating solenoid valves constantly. A good performance was defined as keeping Ψ_t in the range of Ψ_s ±10 cmH_2O.Despite induced severe leaking, the system managed to achieve this goal. Figure 5-3b shows the ASL performance result in the laboratory experiment. Ψ_s, Ψ_t and Ψ_p were recorded at the end of every minute with no averaging over time. Also Figure 5-3c demonstrates the system performance in field condition from 22nd to 30th of 2009. During two precipitation events (from 23rd to 24thand from 27th to 27th) soil matric pressure increased significantly. Ψ_t and Ψ_p followed the soil tension closely.

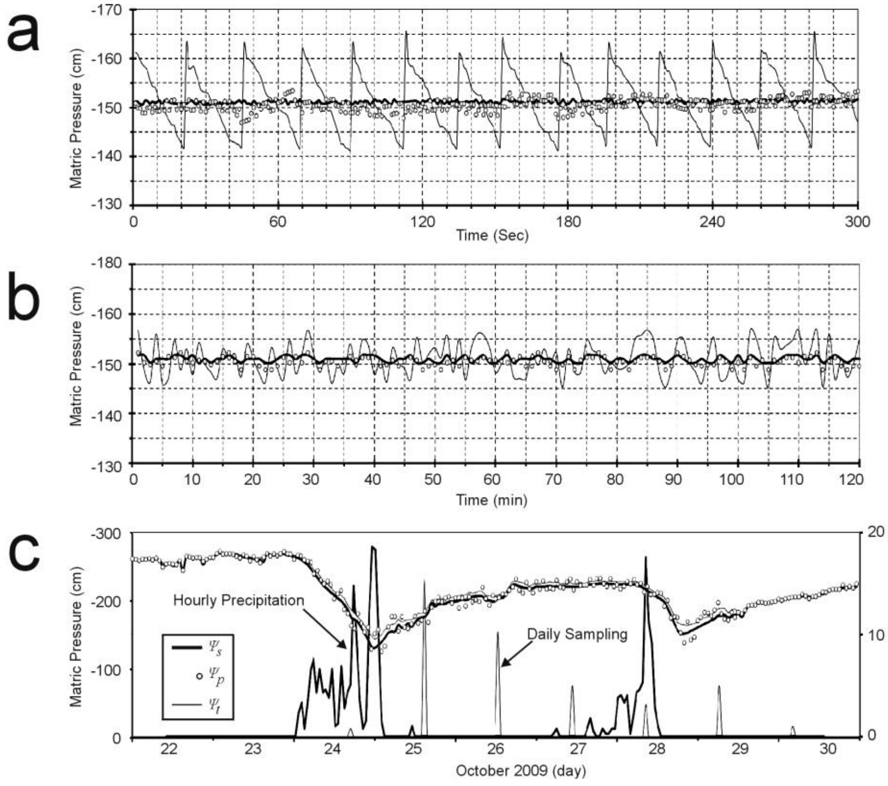

Figure 5-3. (a) System performance during 300 seconds of the laboratory experiment (data record per each program cycle). (b) During 120 minutes of laboratory experiment (data record every minute without averaging). (c) Field performance from 22ndto 30th of 2009 (data record every hour without averaging).

In field conditions and during the sampling period of 2009 the average difference between Ψ_s and Ψ_p was 1.99cmH_2O with standard deviation of 6.34cmH_2O. The maximum difference between these two parameters was 22.86cmH_2O.Also the average difference between Ψ_s and Ψ_t was 2.05cmH_2O with standard deviation of 2.03 cm and the maximum difference of 15.83 cm. These results were within an acceptable range and confirm the accuracy of the system.

Some leakage incidence occurred during the sampling period. Each time the leakage detection system managed to turn off the leaking system and continue recording Ψ_s. All ASLs were checked at least every other day. Therefore the leaking units were fixed in two or three days. Rodents were responsible for leakage events. Chemical deterrents were then used to keep them away from the instruments. It seems that they (as well as snakes and insects) like to dig around the plywood boxes and make nests close to the boxes. Therefore, it may be better to backfill the installing trenches and keeps all the instruments above the ground and out of the experimental plots. This also reduces the need for walking over the edge of plots for maintenance. No major leakage happened for the main vacuum tanks and the vacuum pipes connected to them.

Suction plates and suction cups that were installed for collecting soil-water samples performed satisfactory during 3 yr experiment. After each sampling period (early December) suction cups as well as power wires and vacuum pipes were collected while suction plates and vacuum tanks remained in plywood boxes for the next year. It took about 24 man-hours for each ASL initial installation. While preparing in the next year took only about 6 hours for each ASL (re-installing suction cups and vacuum pipes). Also collecting the equipment at the end of each year took about 3 man-hours for all sixteen lysimeters. Maintenance of the ASLs was mostly related to the leaking events. The electronic parts were very reliable and they had a perfect performance.

Variability of matric pressure in different depths

Figure 5-4 demonstrates the variations in soil matric pressure in undisturbed soil profile in the depths of 30 and 60 cm during the sampling periods of 2007, 2008 and 2009. In 2007, soil matric pressures in both depths followed the same pattern, although 30 cm had more variation and in general it was more wet (more matric pressure). Precipitation was almost evenly distributed throughout the sampling period. After each precipitation soil matric pressure increased. The highest soil matric pressure for 30 cm was on Nov. 18th (-90.0 cmH_2O) after the highest precipitation in the sampling period (30.7 mm on Nov. 15th). The same pattern was followed at 60 cm except it was less variable and was dryer. The minimum soil matric pressure was -266.1 cmH_2O on Sep. 18th.

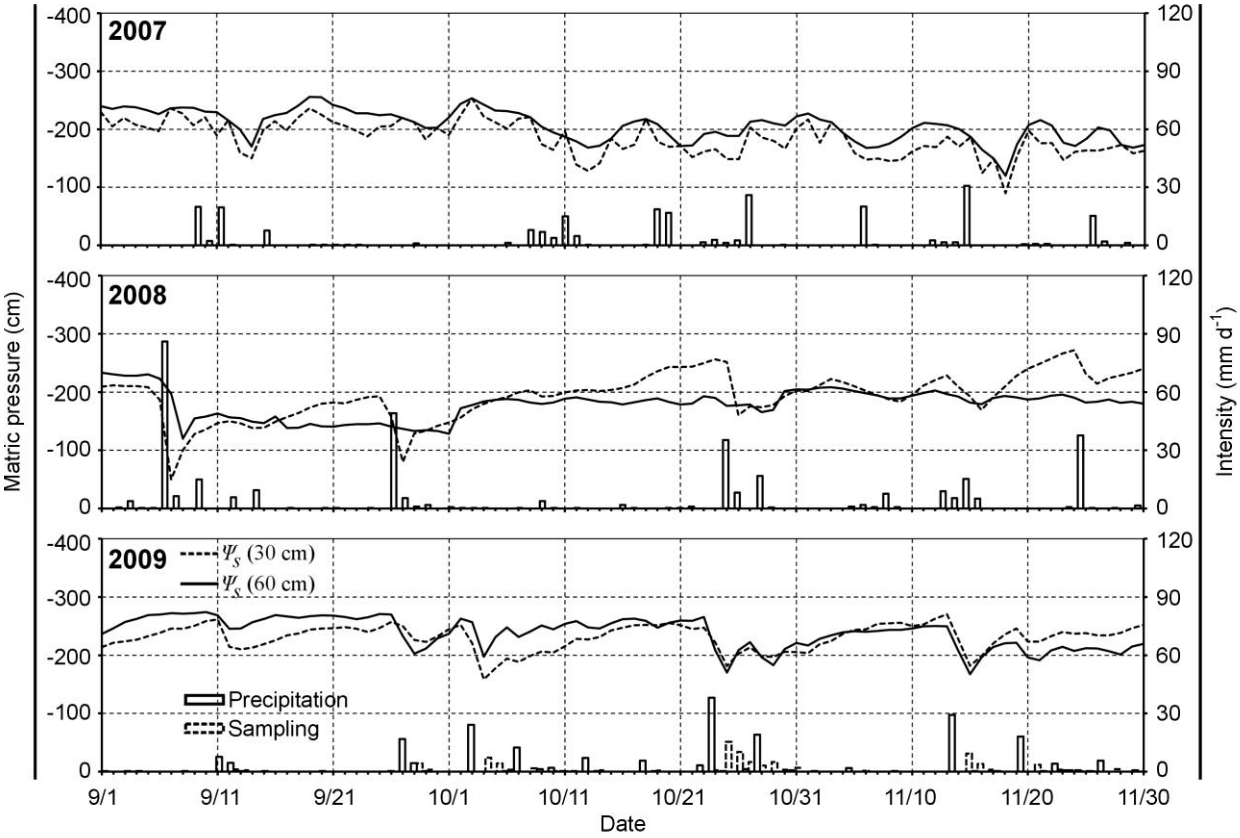

Figure 5-4. Daily average of soil matric pressure (30 and 60 cm), precipitation and water sampling during the sampling periods in years 2007 to 2009.

A very intense precipitation event on Sep. 6th 2008 (86.1 mm) caused a dramatic increase in 30 cm soil matric pressure. After that there were four more major increases in soil matric pressure due to rain events on 9/26, 10/25, 11/15 and 11/25. Soil matric pressure fluctuated less at 60 cm in 2008.The sampling period can be divided into two periods. One wetter period was from Sep. 6th to Oct. 1st (with average about 150 cmH_2O) and a dryer period from Oct 1st to the end of the sampling period. It seemed that the intense precipitation event on Sep. 6th had triggered the wetter period and it was amplified by another rain event on Sep. 26th (49 mm).

In 2009, Ψ_s for 30 cm and 60 follow the same pattern. For the first half of the sampling period soil matric pressure in 30 cm was more than that at 60 cm, while the pressure at 30 cm was almost equal or less than at 60 cm for the rest of the period. This could be due to more precipitation in the second half of the fall period that made the top soil wetter. 2009 was the only year that we implemented and collected a complete set of water samples. The average water sampling volume was consistent with the precipitation event. The maximum sampling rate was on Oct. 25 and 26 with 15.33 and 10.24 mm respectively. Soil water samples were collected every day (during the rain periods) and every other day or less during dryer periods of time.

Temporal and spatial variability in soil matric pressure

For most of the sampling period in 2009,Ψ_p was close to Ψ_s, suggesting that the system was successful in maintaining the soil-water tension condition at the sampler close to the moisture conditions in the natural soil profile (Fig. 5).The mean absolute difference between Ψ_t and Ψ_s was 2.09 cmH_2O with standard deviation of 2.05 cmH_2O and maximum of 15.82 cmH_2O. Mean relative difference (Kosugi and Katsuyama, 2004) was 0.92%. These results suggest acceptable accuracy of the ASL in controlling the vacuum applied to the sampler. Also the mean absolute difference between Ψ_p and Ψ_s was 4.98 cmH_2O with standard deviation of 6.57 cm and maximum of 27.86.Mean relative difference was 5.12%. This also confirmed that the system managed to control the Ψ_p adequately in relation to Ψ_s.

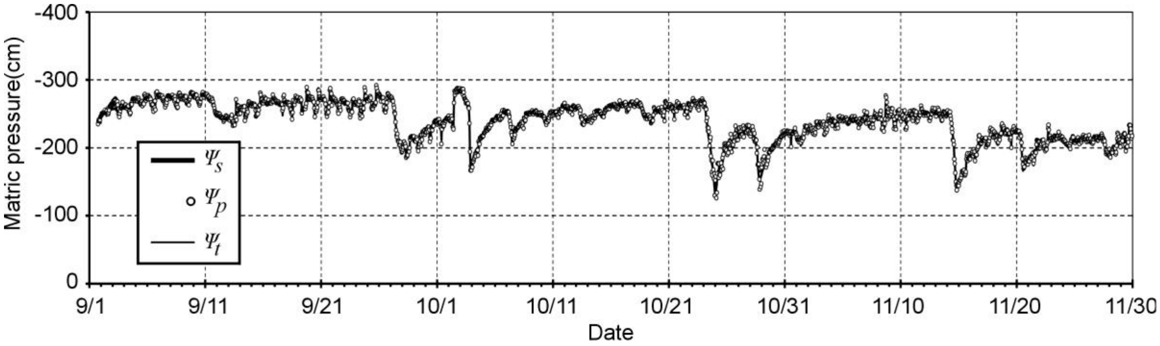

Figure 5-5. Hourly record of Ψs, Ψ_t and Ψ_p during the 2009 sampling period.

The greatest differences between Ψ_s and Ψ_p were seen after major precipitation events. The greatest difference was in Oct. 25 and after the most intense rain event in Oct. 24 (38.1 mm). It seemed that after reaching the wetting head to the depth of the sampler, soil above the sampler stayed dryer for a longer period of time, compared with Ψ_s. This could be because of a slightly different infiltration rate. Since similarity in infiltration rate (between natural soil profile and soil profile above the water sampler) is a critical presumption for all ASLs, heterogeneity in infiltration rate could reduce the system accuracy dramatically (Kosugi and Katsuyama, 2004). This problem can be address to some extends by increasing the number of ASLs and sampling area (Radulovich and Sollins, 1987).

In order to have an idea about the effect of soil heterogeneity on tensiometer readings, the average of hourly absolute difference was calculated for five pairs in plots with identical treatments. The average distance between each pair of tensiometer was 23m. The total average of absolute difference between pairs was 21.99 cmH_2O with maximum of 35.81 cmH_2O. Figure 5-6 suggests that the greatest absolute differences are after rain events and when wetting head reaches the sampler depth. In this time even a slight heterogeneity between soil profiles will cause a dramatic difference between tensiometers reading (late hours of Oct. 24th in Figure 5-6). This difference will decrease by the time and as the soil becomes dryer and the differences would be related more to soil variability not the instrumentation.

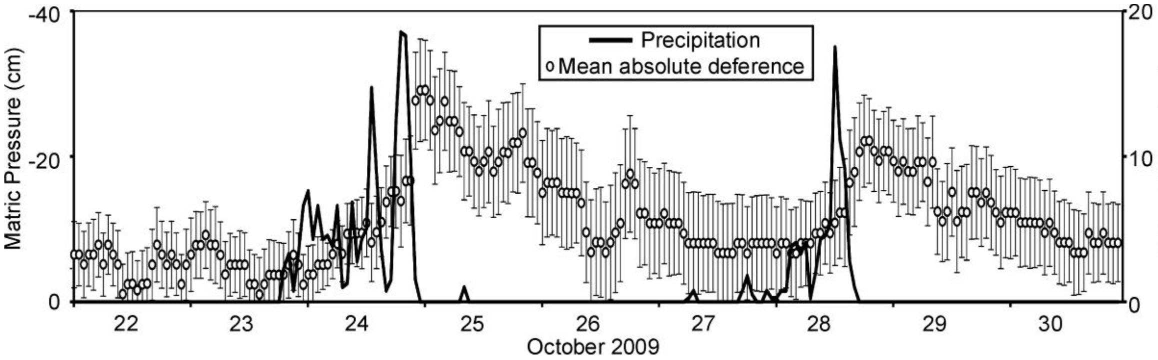

Figure 5-6. Mean absolute difference of hourly tensiometer readings of five pairs of tensiometers in plots with identical treatments. The average distance of tensiometerswas about 23 m. Error bars are standard error of difference.

Temporal variability of soil matric pressure during the sampling period of 2009 can be seen in Figure 5-7. Each cell of the matrix represents an hour in the sampling period and different levels of gray color represent different levels of soil matric pressure. After each rain event there is a gradual brightening in the color which represents an increase in soil matric pressure. Using this graph it is possible to determine the time that wetting front reaches to the sampling depth. Having the hourly precipitation data it is possible to roughly estimate the soil hydraulic conductivity. Figure 5-7 also has another trend in changing color which has mostly a horizontal direction and starts with darker color in September and ends in lighter color in November which suggests a gradual increase in soil matric pressure during the sampling period. This means that soil gradually becomes wetter during (later in) the sampling period. Therefore, more leaching volume is expected in November compared with September which agrees with our sampling results.

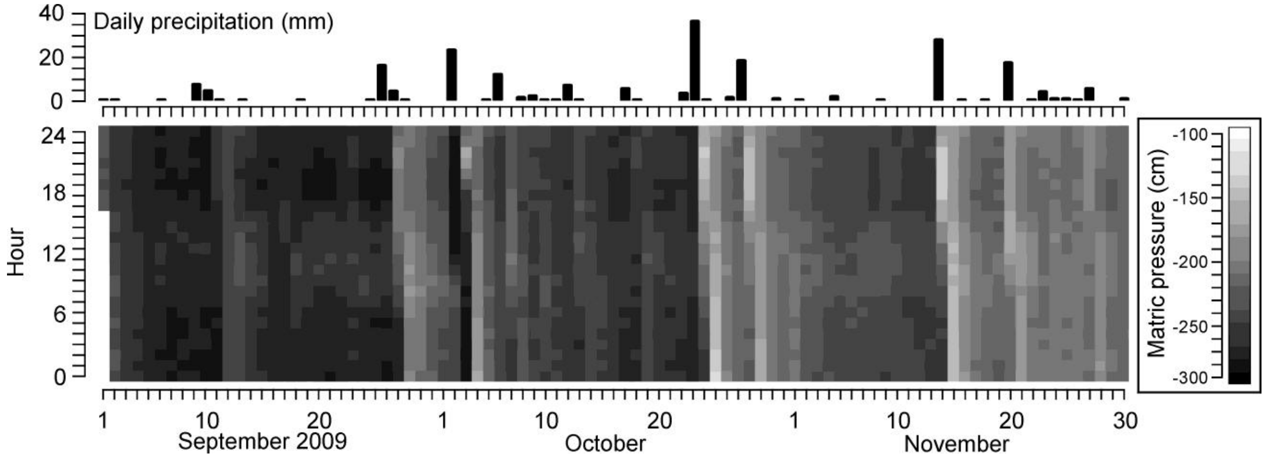

Figure 5-7. A graphical illustration of temporal variability of soil matric tension during the 2009 sampling period.

Conclusion

Our ASL had a satisfactory performance in laboratory and field conditions. This study indicates that our ASL can be used as an accurate soil-water sampler in agricultural experiments. The device gives the researchers the opportunity of collecting samples and data over long time periods with minimum maintenance and supervision. The leakage detection module protected the system against potential damage related to unexpected leakage events. The leakage detection module feature is a critical component for any ASL system. Our ASL showed a reliable performance in field, it is cost effective and accurate, and is easy to install and maintain. Therefore, our ASL has the potential of easily being used with multiple units in large experiments. The data logging feature of the system provides continuous and long term soil moisture data which can be used in studying wetting and drying periods, and their potential for adverse effects in the agricultural landscape.

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CHAPTER 6

CONCLUSION

Dairy farmers in Massachusetts can significantly reduce the amount of after-harvest nitrogen (N) leaching and recover N by planting a rye cover crop early in fall. The amount of N that can be stored in cover crop tissue and be released to subsequent crops was estimated to be more than 100 Kg ha^{-1}. This considerable amount of N can easily leach to ground water when no cover crop is used after fall manure application. It was shown that one week delay in planting cover crop reduced N recovery by more than 20%. Therefore, the economic savings from recovered N for the next crop is significant to the farmers.

An automated suction lysimeter (ASL) was developed for collecting leachate samples from cover crop experimental plots planted at different dates. The ASL performed satisfactory in both laboratory and field conditions. The current study indicated that the ASL can be used as an accurate soil-water sampler in agricultural experiments. The device provides the researchers the opportunity to collect long term samples with low maintenance and supervision. A leakage detection module protected the system against potential damage related to unexpected leakage events. This feature is a critical component for the system. The leakage detection module showed reliable performance in the field. The ASL was cost effective, accurate, and also easy to install and maintain. Therefore ASLs can be used in large numbers (for example one in each experimental plot) in extensive research projects. Data logging feature of the system provided continuous soil moisture data which was used in studying the wetting and drying periods and their effect on experimental parameters. Soil-water tension data was collected every hour and showed a close correlation with precipitation. The volume of leachate from different planting dates did not show significant differences. However, the N concentration in leachates collected from early planted cover crops was significantly lower than later plantings. This finding confirmed the importance of early planting of coverer crops on minimizing N leaching.

We concluded that cover crops should be planted no later than September 1st in the Connecticut River valley area for maximum N recovery. Since the current rye planting date is from mid September to early October, farmers in this area should consider some alternative management practices such as using shorter season corn hybrids in order to have more time for planting early cover crops and minimize N leaching.

A GDD-based spatial model was developed using the results of the multi-year cover crop planting date research and long term weather data. The model determines the critical planting date of winter rye for maximum N recovery for the entire state of Massachusetts. Northwest Massachusetts is the coldest region of the state. This is because of its higher elevation. Because of the cold weather, rye has to be planted very early in the fall (third to fourth week of August) in order to collect sufficient GDD before freezing starts. This planting date overlaps with the corn growing season; therefore, cover crops cannot be planted early enough to achieve their maximum N recovery. Critical planting dates for central parts of the State are between the first and second week of September. Current corn harvest dates in these areas are one to two weeks later. Therefore for planting winter rye with no delay, growers should consider alternative management practices such as selecting early maturity corn hybrids so they can meet the suggested critical planting date and achieve the maximum nutrient recovery by winter rye cover crop. In eastern areas of Massachusetts the model suggested planting date is the third week of September. This zone is close to the ocean and is the warmest zone in the state. The corn planting date is earlier in the spring and its growing season is a little shorter and therefore it can be harvested sooner in fall. On the other hand, due to warmer weather, rye growing season is shorter and therefore it can be planted later in fall. As a result, a warmer climate creates a greater planting window for winter cover crops and there is enough time for planting winter rye efficiently. Te spatial GDD-based model for evaluating N uptake and recovery for the state is a powerful decision making tool for researchers and farmers. It can be used for other crops and research projects. Elevation and soil data layers as well as other spatial information can be added to the model to give it more robust, site-specific applications.

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