The Pennsylvania State University

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**FRACTIONAL ATMOSPHERIC NITROGEN LOSS FROM TALL FESCUE HAY**

**SPRAY-IRRIGATED WITH MUNICIPAL WASTEWATER EFFLUENT**

A Dissertation in

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by

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## Abstract

Water reclamation and reuse through municipal wastewater effluent (MWE) irrigation reduces the pressure on global water resources and promotes environmental and human health protection. The design MWE irrigation rate is usually limited by the capacity of the soil to transmit water and nitrate ($NO_3$-N) concentration in the percolate water. Nitrogen (N)-based irrigation depths ($L_n$) are often determined from an N mass balance, which requires estimation of the fractional N loss ($f$) due to atmospheric N losses through denitrification and ammonia ($NH_3$) volatilization.

Design $f$ values are often chosen from the 0.15 to 0.25 range for secondary-treated effluents (C:N ratio = 0.9 to1.5) and 0.1 is suggested for tertiary-treated effluents (C:N ratio <0.9). A temperature-based guideline suggests an $f$ value of 0.2 for "cold" climates and 0.25 for "warm" climates. However, no scientific investigations have verified these values. Design procedures could be improved if $f$ estimates were replaced by empirically determined values. The overall goal of this research study was, therefore, to quantify $f$ values over the growing season in an effluent-irrigated crop field. The $f$ values were estimated using atmospheric N losses quantified using three approaches: measurements, model simulations, and "source-sink" N mass balances.

The field study was completed in 2011 and 2012 at the Pennsylvania State University (PSU) Living Filter (LF) in a tall fescue grass field (8.4 ha) in Central Pennsylvania. The bulk density for the 0 to 12-cm depth of the surface soil horizon is 1.25 g cm$^{-3}$, and the predominant soil series in the grass field is Hagerstown (fine, mixed, semiactive, mesic Typic Hapludalf) with loam and clay loam soil in the 0 to 30-cm depth of the surface soil

horizon. The field is irrigated with secondary-treated effluent (including biological nitrogen removal) at a rate of 5 cm $wk^{-1}$. Annual application of effluent N was 220 kg N $ha^{-1}$ in 2011 and 153 kg N $ha^{-1}$ in 2012, and on average, the effluent contained 70% and 87% $NO_3$-N in 2011 and 2012, respectively. Supplemental N fertilizer was added as urea-ammonium nitrate (30% N) (122 kg N $ha^{-1}$ (2011) and 112 kg N $ha^{-1}$ (2012)). In accordance with the 2006 USEPA design procedures for land treatment of municipal wastewater effluents, change in soil N storage was assumed to be negligible.

Emissions of $NH_3$ (gas) were measured in the field and laboratory with a photoacoustic field gas monitor immediately after effluent application. The maximum measured $NH_3$ emission rate of $10^{-4}$ kg $NH_3$-N $ha^{-1}$ $h^{-1}$ was roughly equivalent to 1 kg N $ha^{-1}$ $yr^{-1}$, which was insignificant relative to the effluent N applied during the study period. Thus, atmospheric N losses were mainly due to denitrification.

The $f$ values were estimated based on measured denitrification ($f$md), simulated denitrification ($f$sd) and a monthly N mass balance ($f$nb). The $f$md and $f$sd were estimated for twelve 7-day irrigation cycles. Denitrification gaseous fluxes (kg N $ha^{-1}$ $h^{-1}$) were measured from intact soil cores, collected from the surface soil horizon using 4.8 cm i.d. and 10.2 cm long aluminum cylinders, 6 to 7 h before irrigation (BI) began and 4 to 5 h after irrigation (AI) ceased. The cores were incubated in the laboratory for 6 h. Nitrous oxide concentrations in the core headspace were determined by gas chromatography. Daily denitrification fluxes were extrapolated from the hourly fluxes and the denitrification N loss per irrigation cycle (y) was estimated with the exponential equation $y = ae^{-bx}$ where x is the number of days after irrigation ceased. The constants a and b were determined using the AI and BI estimated daily denitrification fluxes.

Denitrification was also simulated using the DeNitrificationDeComposition (DNDC) crop model. The model was parameterized in the site mode for four categories of simulations, namely: LD (DNDC default clay fraction = 0.19 and saturated hydraulic conductivity ($K_{sat}$) = 0.025 m h$^{-1}$ for loam soil), CLD (DNDC default clay fraction = 0.4 and saturated hydraulic conductivity ($K_{sat}$) = 0.009 m h$^{-1}$ for clay loam soil), LM (measured clay fraction = 0.26 and saturated hydraulic conductivity ($K_{sat}$) = 0.017 m h$^{-1}$), and CLM (measured clay fraction = 0.31 and saturated hydraulic conductivity ($K_{sat}$) = 0.017 m h$^{-1}$).

Equation [1] was used to express *f*nb in terms of the measured and calculated monthly system parameters from April to September.

$$f_{nb} = \frac{\overbrace{L_n C_n}^{\substack{\text{Effluent} \\ \text{total N}}} - \overbrace{C_p(L_n + P_r - ET_c - R)}^{\substack{\text{N Leaching} \\ \text{term}}} - \overbrace{10U}^{\substack{\text{Crop N} \\ \text{removal} \\ \text{term}}}}{L_n C_n} \qquad [1]$$

Effluent N was quantified from the irrigation depth ($L_n$) and effluent total N, $C_n$ (mg L$^{-1}$). The N leaching term was calculated from the NO$_3$-N levels (mean of 8 composite samples per month), $C_p$ (mg L$^{-1}$) in soil water collected from 0.35 m-deep suction cup lysimeters and the monthly water balance ($L_n$ + $P_r$ - ET$_c$ - R). Rainfall, $P_r$ (cm), was recorded at the boundary of a non-irrigated field near (< 2 km) the study site. Crop evapotranspiration, ET$_c$ (cm) was estimated as a product of the monthly crop factor ($K_c$) and monthly reference ET$_o$ (cm). The $K_c$ factors used were: 0.85 (April), 0.9 (May), 0.92 (June), 0.92 (July), 0.91 (August), and 0.87 (September). The monthly ET$_o$ was summed

from the daily values calculated using the Penman-Monteith method. Runoff, R (cm), was estimated using the curve number method. The crop removal due to N originating solely from the effluent, U (kg N ha$^{-1}$), was estimated as the difference between the measured monthly N removals and estimated monthly crop N removal due to fertilizer. The latter was estimated from the monthly aboveground biomass proportions for tall fescue in PA, and here in is 0 (January, February, March, November, and December) 0.05 (April); 0.3 (May); 0.2 (June); 0.12 (July); 0.15 (August); 0.12 (September); and 0.06 (October), and the annual fertilizer applications was 122 kg N ha$^{-1}$ in 2011 and 112 kg N ha$^{-1}$ in 2012. If the difference was greater than the applied effluent N, U in Eq. [1] was assumed to equal effluent N.

The denitrification fluxes and $f$ estimates in July and November were likely least affected by UAN-30 fertilizer applications that occurred in April and August in both years. The measured and simulated denitrification fluxes followed similar trends and the AI fluxes were generally greater than the BI fluxes unless rainfall occurred within 2 days of the BI date. The model simulated denitrification in 2012 better than in 2011 and the BI denitrification rates better than the AI rates. The mean absolute error (MAE) values, for the BI denitrification rates were equal (for all the four simulation types), 0.3 in 2011 and 0.15 in 2012, and were smaller than the MAE values for the AI denitrification rates, which were all 0.98 in 2012 and 5.2 (LD simulations), 5.13 (LM simulations), 4.97 (CLD simulations), and 5.0 (CLM simulations) in 2011.

The average $f$sd (LM and CLM simulations)/ $f$md values were: 0.03/0.4 (2 to 6 June 2011), 0.01/0.98 (12 to 18 July 2011), 0.08/3.25 (12 to 15 August 2011), 0.16/3.45 (16 to 22 August 2011), 0.02/0.50 (21 to 27 September 2011), 0.01/0.21 (27 September to 3

October), 0.004/1.10 (25 to 31 October 2011), 0.02/0.70 (15 to 21 November 2011),

0.05/0.03 (15 to 21 May 2012), 0.03/0.74 (21 to 25 June 2012), 0.01/0.19 (10 to 16 July

2012), and 0.14/2.87 (7 to 13 August 2012).  The high $f$md estimates in August ($\geq$3) were

probably due to UAN-30 fertilizer application and the $f$md estimate of 0.7 in November

was probably due to lack of plant N removal. The average (n=24) $f$sd for the LM and

CLM simulation for 12 irrigations in both years was 0.05. The $f$sd estimates were all

smaller than the $f$md estimates except for the irrigation cycle between 15 and 21 May

2012 when the $f$sd (0.05) and $f$md (0.03) were similar.  The $f$sd estimates were also

smaller than the design $f$ values apart  from August when they were near the lower

boundary for design $f$ values for secondary-treated effluent (0.15 - 0.25).

The $f$nb estimates were 0.13 (April and May 2011), 0.22 (July 2011), 0.09 (August 2011),

0.23 (April 2012), 0.05 (June 2012), 0.13 (July 2012), and 0.72 (September 2012).

Negative $f$nb estimates obtained in June 2011 (-1.35), September 2011 (-0.40), May 2012

(-0.13), and August 2012 (-0.44) were due to the sum of the crop N removal and leaching

exceeding the applied effluent N in these months . Apart from September 2012, the $f$nb

values were less than or within the range of the design $f$ values. The $f$nb values generally

decreased with increase in crop N removal.

The $f$md estimates linearly decreased with the ratio of the BI to AI denitrification rates

($R^2$= 0.69 and $R^2$=0.63 for AI and BI rates that were significantly different and those that

were not ($\alpha$=0.05)) and the positive $f$nb estimates were negatively correlated to the

logarithm of the monthly crop N removal, with better correlation ($R^2$=0.99) in the warm

months (July and August-monthly mean temperature $\geq 20^0$C) than in the cooler months,

$R^2$=0.2 (April, May, June, and September-monthly mean temperature $< 20^0$C). Also three

of the four $f$nb estimates in July and August were similar to the design $f$ values.  Despite

the difficulty and complexity of quantifying atmospheric nitrogen losses from soil both in

the field and laboratory, the study results suggests $f$ values in MWE irrigation could be

refined especially during months with mean air temperatures of $\geq 20^0$C.

In conclusion, empirically-determined $f$ values contribute to improved nitrogen planning

and management in municipal wastewater effluent irrigation systems with crop removal.

At the study site, an $f$ value of 0.2 was deemed appropriate for the month of July and $f$

values in the range of 0 - 0.1 for the months of May and June and 0.1 - 0.2 for August and

September. The research study results suggest that for highly nitrified effluents (C:N

ratios of <1) smaller $f$ values than those suggested by USEPA could be used for designing

municipal wastewater effluent irrigation depths in humid climates.  The small $f$ values,

also suggest that the Cp value (see Eqn. 1) of 10 $NO_3$-N mg $L^{-1}$ (maximum contaminant

level for drinking water) commonly used for design purposes should be revised

downward.  The small $f$ values are likely due to the addition of nitrification and

denitrification treatment processes in the past two decades by many of the wastewater

treatment plants in order to comply with the increasing stringent regulations to meet

effluent N limits. Thus, more studies to determine empirical $f$ values are needed to refine

$f$ values used in designing municipal wastewater effluent irrigation systems with crop

removal.

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**Chapter 1. INTRODUCTION**

Wastewater is water that is discharged from homes, businesses, cities, industry and

agriculture, and includes industrial wastewater, storm water, and municipal wastewater

effluent (MWE) (Asano et al., 2007), and treated wastewater is increasingly being

considered as a resource rather than simply a "waste" (USEPA, 2012).  Water recycling is

a term that is generally used synonymously with water reclamation and water reuse

(Asano et al., 2007). Water reuse applications include urban reuse, industrial reuse,

impoundments, environmental reuse, groundwater recharge, and agricultural reuse

(USEPA, 2012).

In the U.S. the main water reuse applications are agricultural irrigation (29%) and

landscape/golf course irrigation (18%) and the other half of the water reuse applications

are distributed among several applications each contributing small proportions (Bryk et

al., 2011 as cited by USEPA, 2012).  However, in Pennsylvania, the main purpose of

effluent irrigation is to reduce nutrient (N and P) loading to surface waters while also

recharging groundwater (Schreffler and Galeone, 2005; Schreffler et al., 2005; Parizek,

2006; Walker and Lin, 2008). According to Bryk et al. (2011) groundwater recharge

comprises 5% of the U.S. water reuse applications. According to O'Connor et al. (2008)

the two most limiting conditions in designing effluent irrigation systems are the capacity

of the soil profile to transmit water and the nitrate ($NO_3$-N) concentration in the percolate

water.

Although the typical regulatory maximum MWE irrigation rate is set at 5 cm wk$^{-1}$

(USEPA, 2004; Asano et al., 2007) in the US, regulations  require the actual rates to be

determined, based on site-specific conditions and the plant or crop to be irrigated (Asano

et al., 2007).

Thus, in designing effluent irrigation rates, professionals select the fraction of the MWE total nitrogen (TN) expected to be lost to the atmosphere and/or result in change of soil N (*f*), from state MWE irrigation guidelines or from the USEPA process design manual (USEPA, 2006). However, the N loss factor *f* has not been adequately studied in actual MWE irrigation systems to verify the design values and thus is the focus of this dissertation. This chapter includes the background and justification of MWE irrigation in crop fields, motivation for the research study, research goal, objectives, research questions, and the dissertation format.

## 1.1 Background and justification

### 1.1.1 Global fresh water resources

About 2.5% of the earth's water is fresh water (Fig. 1-1) and its withdrawal is projected to increase with the largest portion used for agriculture, followed by domestic and industrial uses. Based on climatic and socio-economic drivers, Alcamo et al. (2007) projected that the percentage of the total global river basin area with severe water stress ($<1000$ $m^3$ $person^{-1}$ $yr^{-1}$) would increase from 14.2% in 2007 to 19% in the 2020s and 23% in the 2050s, and the number of people living in such areas would increase from 1.6 billion in 2007 to 3.7 billion in the 2020s and 5.8 billion in the 2050s. Due to the current and projected pressure on the earth's freshwater resources for multiple uses including sustaining ecosystems, the world is acknowledging wastewater as a supplement to fresh water sources (UNEP, UN-Habitat and Grid-Arendal, 2010; NRC, 2012).

Thus, MWE  irrigation lessens the pressure on freshwater resources needed to meet the crop irrigation demand, which is estimated to consume 70% of the renewable annual global surface and groundwater resources (Lazarova and Asano, 2005; UNEP, 2009).

**Figure 1-1 Global fresh water resources and withdrawals. (UNEP, 2008a; UNEP, 2008b).**

### 1.1.2 Environmental benefits of effluent irrigation

The benefits of MWE land application that go beyond wastewater treatment "involve the recovery and beneficial wastewater nutrients and other elements through good agriculture, silviculture and aquaculture practices, recharge of groundwater aquifers, reclamation of marginal land and preservation of open spaces for future greenbelts" (USEPA, 1977).

Land application of wastewater is still a growing practice even in areas that are not water stressed (Wallach et al., 2005; Miller, 2006) because it provides options for disposing nutrients that would otherwise pollute surface water (Wallach et al., 2005; Miller, 2006; O'Connor et al., 2008). Excess levels of N in surface and groundwater sources can result in adverse environmental effects such as eutrophication. The US Environmental Protection Agency defines eutrophication as "the process of fertilization that causes high

productivity and biomass in an aquatic ecosystem. Eutrophication can be a natural

process or it can be a cultural process accelerated by an increase of nutrient loading to a

lake by human activity". Nitrates and nitrites can cause serious illnesses such as

methemoglobinemia commonly known as "blue baby syndrome" disease in infants,

which can result in serious illnesses or even death (USEPA, 2009). Nitrate and nitrite N

are listed as drinking water contaminants by the USEPA with maximum contaminant

levels (MCL) of 10 mg $L^{-1}$ and 1 mg $L^{-1}$, respectively. Sources of contaminants include

runoff from fertilizer use; leakage from septic tanks, sewage and erosion of natural

deposits (USEPA, 2009).

### 1.1.3 Recycling effluent (water and nitrogen) via crop irrigation

In MWE irrigation, water and N recycling is achieved by applying effluent without

polluting water resources. The effluent N undergoes transformations in the soil and is

either removed via crop N uptake, leaching, and atmospheric N losses or stored in the soil

(Fig. 1-2). Atmospheric N losses include the following gases: ammonia ($NH_3$), $NO_x$,

nitrous oxide ($N_2O$), and dinitrogen ($N_2$) (Fig. 1-2): however, in this dissertation

atmospheric N losses refer to $NH_3$, $N_2O$, and $N_2$.

**Figure 1-2 Nitrogen transformations in a soil-plant matrix (original diagram from Johnson et al., 2005).**

Unlike N removal via crop N uptake and leaching, atmospheric N losses and soil N storage are quite difficult to quantify due to spatial and temporal variation, difficulty in determining residual N from added nitrogen sources such as MWE-TN, and also because the atmosphere contains about 78% $N_2$ (gas). Therefore, in designing MWE irrigation systems these N losses are accounted for as the N loss factor $f$.

### 1.1.4 Design *f* values

A "source-sink" N mass balance approach for the root zone (Fig. 1-3) is used to

determine the MWE irrigation rate. The MWE irrigation rate and the MWE total N

concentration are used to determine MWE total nitrogen, as shown in Figure 1-3.



**Figure 1-3 "Source-sink" N mass balance in a crop field irrigated with treated municipal wastewater (USEPA, 1981; Crites et al., 2006; USEPA, 2006; Asano et al., 2007).**

In the N balance, the leachate N concentration below the root zone is usually considered

to be 10 mg $L^{-1}$ (the USEPA MCL for $NO_3$-N in groundwater)  (Crites et al., 2006; Asano

et al., 2007), the crop N removal can be quantified from information in state agronomy

guides, and Table 1-1 suggests design *f* values. However, there is little scientific evidence

to support these *f* values.

**Table 1-1 Design *f* values**

| MWE treatment level | *f*[1] | MWE C:N ratio[1] | *f*[2] | MWE C:N ratio[2] |
|---|---|---|---|---|
| Primary | 0.25 to 0.5 | 1.2 to 8 | 0.4   (warm climate) <br> 0.25 (cold climate) | 3 to 5 |
| Secondary | 0.15 to 0.25 | 0.9 to 1.2 | 0.25 (warm climate) <br> 0.2   (cold climate) | 1 to 1.5 |
| Tertiary | 0.1 | <0.9 | 0.15  (warm climate) <br> 0.1    (cold climate) | <1 |

[1]USEPA (2006); [2]Crites and Tchobanoglous (1998)

**1.1.5. Atmospheric N losses in the surface soil horizon**

The greatest total denitrification (conversion of $NO_3$ to $N_2O$ and finally $N_2$) in the soil profile is expected to occur in the carbon-rich surface soil horizon where the greatest activity of C and N cycling processes occur (Shaffer and Ma, 2001). Total denitrification is commonly estimated as measurement s of $N_2O$ (gas) (as a proxy by inhibiting the conversion of $N_2O$ to $N_2$, since the atmosphere predominantly contains $N_2$). In addition to denitrification fluxes and $NH_3$ (gas) measurements, atmospheric N losses can also be estimated from outputs of model simulations of the C and N processes of the soil horizon. Agro-ecosystem models that simulate C and N processes in soil-crop-atmosphere systems support the evaluation of agricultural management and land use for sustainable production systems (Shaffer and Ma, 2001). Models are either lumped (treat a significant portion of the watershed or a whole watershed as one unit) or distributed (dividing the watershed into smaller units assumed to be homogeneous) and can be designed to run on an event basis or continuous basis (Novotny, 2003).

Continuous process models operate on a time interval and balance the masses of water and pollutants in a system continuously (Novotny, 2003). A synthesis of denitrification models in terrestrial and aquatic ecosystems categorized the use of the DeNitrificationDeComposition (DNDC) biogeochemical model as an agronomist's approach to modeling denitrification (Boyer et al., 2006). The DNDC model is a lumped, continuous, profile-based model, which simulates carbon and nitrogen processes for the 0 to 50-cm depth of the surface soil horizon (DNDC, 2012) and can be applied to field/site and regional scales (Boyer et al., 2006).

Bond (1998) noted that research challenges in effluent irrigation include quantitative prediction of N transformations to develop good management practices and the development of specific and more rigorous guidelines for effluent irrigation. To partly address this challenge, Sophocleous et al. (2008) suggested a combination of continuous field monitoring and use of simulation models to enhance "understanding the losses and transformation processes of effluent N in the soil as well as N management for the sustainable use of effluent irrigation in agriculture".

Thus, using a combination of methods to quantify the atmospheric N losses in MWE irrigation systems could lead to better estimation of the $f$ values. Previous studies in effluent irrigation measured the maximum ammonia volatilization (Smith et al., 1996; Saez et al., 2012) and denitrification N losses (Ryden et al., 1981) within 2 to 48 h after irrigation ceased.

## 1.2 Motivation for the research study

More broadly, the research goal here was to gain insight into refining $f$ values used in designing MWE irrigation systems. Specifically, the motivation for this study was to elucidate the $f$ values over the growing season in a crop field irrigated with MWE at a rate of 5 cm wk$^{-1}$ and compare the $f$ values observed to those suggested by USEPA (2006) and Crites and Tchobanoglous (1998) (Table 1-1), which are commonly used in designing MWE irrigation systems. In addition, the study also sought to estimate $f$ using a "source-sink" N mass balance approach, which is conventionally used in designing MWE irrigation rates for cropped fields.

**1.3 Research goal, objectives and questions**

The overall goal of this research study was to quantify $f$ values over the growing season in an MWE-irrigated crop (tall fescue) field. To achieve the research goal the following objectives were addressed:

1. Determine the atmospheric N losses (ammonia volatilization and denitrification) at the surface of the soil horizon in a MWE-irrigated crop field and estimate $f$ (discussed in Chapters 4 and 5).

2. Parameterize the DNDC model, simulate N losses using the model, and estimate $f$ based on simulated atmospheric N ($N_2O$-N and $N_2$) losses from a MWE-irrigated crop field (discussed in Chapter 6).

3. Estimate $f$ values from monthly "source-sink" N mass balances in a MWE-irrigated crop field (discussed in Chapter 7).

Based on the research goal and objectives the following research questions were evaluated.

a. How do the atmospheric N losses compare before and after irrigation over the growing season?

b. How do the measured and simulated atmospheric N losses compare over the growing season?

c. Do the $f$ values vary over the growing season?

d. How do the $f$ values compare to the $f$ values suggested by USEPA (2006) and those noted in Crites and Tchobanoglous (1998) for secondary and tertiary-treated effluent irrigation system design (Table 1-1)?

e.    What is the trend in $f$ estimates determined from the monthly "source-sink" N mass balances along with monthly mean MWE C:N ratio, air temperature and crop N removal?

**1.4 Dissertation format**

Chapter 2 is a review of the existing literature about atmospheric N losses and $f$ values in MWE irrigation and chapter 3 includes a description of the study site location and supporting data (e.g. weather data) referenced in other chapters.  The major research themes are presented in separate chapters (4, 5, 6, and 7). Chapters 4 and 5 address measurement of ammonia volatilization and denitrification N losses, respectively. Chapter 6 discusses the use of models to simulate atmospheric N losses and chapter 7 incudes the monthly "source-sink" N mass balances at the study site. Chapter 8 is the overall summary, major findings and conclusions of the research and suggestions for future work.

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## Chapter 2. LITERATURE REVIEW

### 2.1 Nitrogen in municipal wastewater effluent

Nitrogen (N) in municipal wastewater effluent (MWE) is comprised of total Kjeldahl nitrogen (TKN), nitrate-N ($NO_3^-$-N) plus nitrite N ($NO_2^-$-N), where TKN is the total of organic N, ammonia N ($NH_3$-N), and ammonium N ($NH_4^+$-N).   Raw municipal wastewater typically contains of 20 to 70 mg $L^{-1}$ of total nitrogen (TN) and MWE contains 15 to 35 mg TN $L^{-1}$ after conventional secondary treatment (Asano et al., 2007). The integration of biological nutrient removal (BNR) with secondary treatment systems further reduces the effluent's TN to 3 to 8 mg N $L^{-1}$ (Asano et al., 2007).  Tertiary N removal can be achieved through land application of MWE on vegetated soils before eventual discharge to natural water resources.

Nitrogen is often the most common limiting design factor in MWE land application, when protection of potable groundwater is of major concern (Reed et al., 1995; O'Connor et al., 2008). Therefore, in determining N limited hydraulic loading rates on vegetated soils, the N removal pathways need to be quantified. These N removal pathways include plant N removal, leaching N concentration, and the fraction of the MWE-TN lost as atmospheric N losses (ammonia ($NH_3$) volatilization and denitrification) and/or result in change in soil N (*f*).  A scientific literature review of atmospheric N losses and *f* values in MWE land application systems is presented.

### 2.2 Municipal wastewater effluent land application systems for N removal

MWE land treatment is "the application of appropriately pre-treated municipal and industrial wastewater to land at a controlled rate in a designed and engineered setting (Reed et al., 1995; USEPA, 2006)". The three principal land treatment processes include

slow-rate (SR), overland flow (OF) and the soil aquifer treatment (SAT) system (USEPA,

2006). The SR is the most popular type of land treatment system and the most efficient

amongst the three systems at reducing TN in the MWE to 3 mg $L^{-1}$ or less (Table 2-1).

Slow-rate systems are classified as type I (slow infiltration) when the principal objective

is wastewater treatment or as type II (crop irrigation) when the principal objective is

water reuse for crop production (Crites et al., 2006).

**Table 2-1 Types of municipal wastewater effluent land application systems (Source: USEPA, 2006).**

| Parameter | Type of MWE land application system | | |
|---|---|---|---|
| | Slow Rate (SR) | Overland Flow (OF) | Soil aquifer Treatment (SAT) |
| Typical loading rate (cm $wk^{-1}$) | 1.9 to 6.5 | 6.5 to 44 | 3 to 23 |
| Disposition of applied wastewater | Evapotranspiration and percolation | Evapotranspiration and surface runoff, limited percolation | Mainly percolation |
| Application techniques | Sprinkler, surface or drip | Sprinkler or surface | Usually surface |
| Need for vegetation | Required | Same as SR | Optional |
| Slope (%) | 0 to 20:Cultivated site 35: Uncultivated site | 2 to 8 for final slopes | Not critical |
| Soil Permeability | Moderate to slow | Slow to none | Rapid |
| Groundwater depth | 0.6 to 3 m (2 to 10 ft.) | Not critical | 1 m (3ft.) during application 1.5 to 3 m (5 to10 ft.) during drying |
| Climate | Winter storage in cold climates | Same as SR | Not critical |
| Total N in effluent (mg $L^{-1}$) | $3^1$ | 5 | 10 |

[1] Quality expected with loading rates at the mid to lower end of range for the weekly loading rate; percolation through 1.5 m (5ft) of unsaturated soil; concentration depends on loading rate, C:N ratio and crop N uptake and removal.

Forage crops or forest lands are usually used in type I SR systems, and a wider range of

vegetation selection is often used, including field crops or landscape/golf courses in type

II systems (Crites and Tchobanoglous, 1998). The SR MWE land application systems can

accomplish tertiary wastewater N removal processes, via soil-plant matrix

biogeochemical processes. Mineralization and nitrification processes increase plant

available N ($NO_3^-$ and $NH_4^+$), whereas $NH_3$ volatilization, denitrification and leaching contribute to N loss from the soil-plant-water matrix (see Chapter 1, Figure 1-2). Apart from N leaching and $NH_3$ volatilization, all the named processes are mediated by soil microorganisms (Olay, 2008) and result in six N oxidation states: -III (organic N, $NH_3$, $NH_4^+$), +V ($NO_3^-$), + IV($NO_2$), +III (nitrite ($NO_2^-$)), +II (nitric oxide (NO)), +I (nitrous oxide ($N_2O$)) and 0 (di-nitrogen ($N_2$)).

In addition to soil properties (e.g. soil pH, organic matter, cation exchange capacity), environmental factors, and land management, N transformation in SR systems is also influenced by forms of N in the effluent, rate, frequency and method of MWE application (USEPA, 2006; Livesley et al., 2007), MWE pH (Feigin et al., 1991), soil hydraulic conductivity and the type of vegetative cover. Effluents with high sodium adsorption ratio (SAR) may affect $NH_3$ volatilization since SAR may affect the soil's water infiltration capacity and thus soil water content.

### 2.3 Calculating municipal wastewater effluent land application rate from a "source-sink" N mass balance

The N-based irrigation rates ($L_n$) for SR systems are typically determined using a "source-sink" N mass balance approach for the soil-plant-water matrix for usually a month or a year, considering the maximum contaminant level (MCL) of $\leq 10$ $NO_3^-$-N mg $L^{-1}$ in the natural water resource nearest to the MWE land treatment system. Equation [2-1] is an expression of the N transformation processes (kg N $ha^{-1}$) in land application of MWE on a vegetated soil (Jarrett and Elliott, 2009).

$$\frac{\left(L_n\left(mx + y + z\right)\right) + cIP}{10} = U + \frac{C_pQ + vyL_n + d\left(zL_n + mxL_n + yL_n\left(1 - v\right) + cIP\right)}{10} \qquad [2\text{-}1]$$

**where:**

$L_n$ = MWE depth, cm

m = Fraction of organic N expected to mineralize to $NO_3$-N, unit less

x = Organic N in the effluent, mg $L^{-1}$

y = $NH_4^+$-N in the effluent, mg $L^{-1}$

z = $NO_3^-$-N in the effluent, mg $L^{-1}$

c = N in the rainfall, mg $L^{-1}$

IP = infiltration-percolation depth, cm

$C_p$ = N in the groundwater leachate, mg $L^{-1}$

Q = Deep percolation, cm

v = Fraction of $NH_4^+$-N expected to volatilize, unit less

d = Fraction of $NO_3^-$-N expected to denitrify, unit less

10 = conversion factor from "cm mg $L^{-1}$" to "kg $ha^{-1}$"

U = Plant uptake/crop N removal, kg N $ha^{-1}$

Based on the following assumptions, Eq. [2-1] was rearranged to solve for the MWE

depth in Eq. [2-2].

- No storage of effluent N (USEPA, 1981)
- All effluent organic N mineralizes, thus mx+y+z is the concentration of the total N (mg $L^{-1}$) in the effluent (Cn)
- N concentration in the rain is small compared to the N from the effluent, thus c= 0 mg $L^{-1}$
- Percolating water, Q, below the root zone is the difference between the sum of the applied water (Ln + IP) and water removal via evapotranspiration (ETc)
- IP is equal to the rainfall depth, Pr (cm), since no runoff (USEPA, 2006) is permitted in MWE irrigation.

Thus, Eq. [2-1] can be reworked to:

$$L_n = \frac{100\ U + C_p\left(Pr - ET_c\right)}{\left(C_n\left(1 - \left(d + d(1-v) + d\right)\right)\right) - vy - C_p} \qquad [2\text{-}2]$$

The ammonia volatilization term "vy" in Eq. [2-2] is usually omitted (USEPA, 1981;

Crites et al., 2006; Asano et al., 2007) and the term "d + d (1-v) + d" in Eq. [2-2] is

commonly referred to as the fractional atmospheric N losses ($f$) in Eq. [2-3]. For nitrate-

dominated effluents the "vy" term would be small and therefore negligible in the overall

N balance (unlike denitrification).

$$L_n = \frac{C_p [Pr - ET_c] + 10\,U}{[(C_n (1-f)) - C_p]}$$

[2-3]

## 2.4 Atmospheric nitrogen losses in slow-rate municipal wastewater effluent land application systems

### 2.4.1 Ammonia volatilization

Ammonia ($NH_3$) is abundant in nature and is formed from the biological degradation of

proteins in soil organic matter, plant residues and animal wastes (Freney et al. 1983). The

rate of $NH_3$ volatilization from the air-soil interface may be controlled by the change in

concentration of the $NH_4^+$ or $NH_3$ in the soil solution, the dispersion of $NH_3$ into the

atmosphere or the displacement of any of the equilibria in some way. Since $NH_3$ has a

very strong affinity for water, its reactions in water are fundamental in determining the

rate of $NH_3$ volatilization (Freney et al., 1983).

Figure 2-1 summarizes the $NH_3$ equilibria for an air-soil interface. Nitrogen enters the

$NH_4^+$ (aq) and $NH_3$ (aq) N pools from soil processes and external N source and the

equilibria between $NH_4^+$ and $NH_3$ in solution and between $NH_3$ in liquid and gaseous

phases are related through Eq. [2-1] to Eq. [2-9] (Freney et al., 1983) (Appendix A).

**Figure 2-1 Ammonia equilibria at the soil surface (Freney et al., 1983).**

Ammonia volatilization from the air-soil interface is influenced by several factors including: inherent soil properties (cation exchange capacity (CEC), pH, buffering capacity, and calcium carbonate), interacting processes (urease activity, plant uptake, leaching), environmental factors (water, temperature, wind speed, atmospheric $NH_3$ concentration) and agronomic factors (e.g. tillage and types of N source) (Freney et al., 1983).

Since $NH_4^+$ is a positively charged ion, it reacts readily with the cation exchange sites in soils (Freney et al., 1983). This process reduces the amount of $NH_4^+$ and thus $NH_3$ in solution at a given pH. According to several authors cited by Freney et al. (1983) a minimum CEC of 25 meq/100g is required to reduce $NH_3$ loss substantially. Temperature interacts between CEC and $NH_3$ loss through its effect on the $NH_4^+$-$NH_3$ equilibria.

As the soil pH rises, the proportion of the ammoniacal N in the form of $NH_3$ becomes larger and $NH_3$ volatilization can occur (Ferguson et al., 1984) (Eq. [2-4] in Appendix A). Therefore, due to the alkaline pH range (6.5 to 8.4) (Lazarova et al., 2005; Saez et al.,

2012) for MWEs, $NH_3$ volatilization may be an important pathway of N loss when effluent is applied to land (Feigin et al. (1991) as cited by Smith et al. (1996)). However, the actual $NH_3$ volatilization rates are ultimately determined by the soil's hydrogen ($H^+$) buffering capacity, which is the soil's ability to resist a change in pH due to the dissociation of the ammonium ions. The $H^+$ buffering capacity of a soil is mainly determined by its mineral and organic matter content (Meisinger and Jokela, 2000, as cited by Vaio, 2006). There is a strong correlation between $NH_3$ loss and the calcium carbonate content in the soil due to the alkalinity and buffering capacity (Freney et al., 1983). The alkaline pH range of MWE could be due to the amount of calcium carbonate content in the effluent, and therefore $NH_3$ loss is expected to be high if alkaline effluents are applied to calcareous soils.

Temperature has a major influence on $NH_3$ (gas) volatilization from soils because temperature directly affects the equilibrium between $NH_4^+$ and $NH_3$ in the soil solution (Fig. 2-1). As the temperature increases the $NH_4^+$ concentration increases due to an increase in the $NH_3$ dissociation constant $K_b$ (Eq. [2-5] in Appendix A) thus increasing $NH_3$ (gas) volatilization. Ammonia concentration in the liquid phase also increases with temperature (see Appendix A, Eq. [2-12]) (Emerson et al. (1975) as cited by Freney et al. (1983). Smith et al. (1996) and Saez et al. (2012) measured higher $NH_3$ volatilization during warmer weather than in cooler weather when MWE that contained 60 to 90% $NH_4^+$-N was used for irrigation.

The driving forces of $NH_3$ volatilization from the air-soil interface are the difference between the $NH_3$ concentration in equilibrium with the soil solution and that in the

atmosphere and wind speed (Freney et al. (1985) and Sherlock et al. (1995) as cited by Smith et al. (1996)). Increasing the wind speed promotes more transport of $NH_3$ away from a water surface (Freney et al., 1983). Wind speed, temperature and pH roughly have a similar effect on the $NH_3$ volatilization rate, and the three factors are used in the bulk aerodynamic expression in Eq. [2-15] to determine the ammonia flux density (Freney et al., 1983).

Ammonia volatilization from MWE collected in pans increased with wind speed (2, 4, 6, and 8 m s$^{-1}$) in a study by Saez et al. (2012). However, according to Bouwmeester and Vlek (1981), as cited by Freney et al. (1983), $NH_3$ volatilization rates at high pH may become insensitive to further increases in wind speed due the depletion of the $NH_3$ in the soil solution. The effect of soil water content on $NH_3$ volatilization depends on the $NH_3$ source, time and method of $NH_3$ application and depth of placement of the $NH_3$ source (from several authors cited by Freney et al. (1983)). Fenn and Escarzaga (1977) observed greater $NH_3$ volatilization from initially wet soils than from dry soils. The authors attributed capillary movement of water in the macropores in the initially wet soils, where the concentration of $NH_4^+$ in solution would be large. Smith et al. (1996) observed a good relationship between the $NH_3$ flux density and evaporation, and the authors concluded that this was because $NH_3$ volatilization predominantly occurs within 24 h following effluent irrigation when "free" water would be evaporating from the soil and plant surfaces. Schreffler et al. (2005) noted that the potential for $NH_3$ volatilization in MWE irrigation is reduced once the MWE infiltrates into the soil matrix and according to Freney et al. (1983), $NH_3$ concentration in the atmosphere is usually very low and therefore does not limit $NH_3$ volatilization rates in the field.

## 2.4.2 Denitrification

Denitrification can result from several biological and abiotic processes, but facultative bacteria under anaerobic conditions most commonly carry out denitrification (Cavigelli and Robertson, 2000). Biological denitrification (Fillery, 1983) is the dissimilatory reduction of $NO_3^-$ and $NO_2^-$ to NO or $N_2O$ and potentially to $N_2$ gas (Knowles, 1982). Chemodenitrification, which is the gaseous N loss associated with nitrite instability (Chalk and Smith, 1983), is beyond the scope of this literature review. The most often observed products in denitrification include $NO_2^-$, $N_2O$, and $N_2$ (Fillery, 1983). The ionic oxides act as terminal electron acceptors in the absence of oxygen (Knowles, 1982). The denitrification process can be described stoichiometrically by Eq. [2-16] in Appendix A (Jørgensen et al., 2004). Nitrous oxide is also produced during nitrification (Eq. 2-17] in Appendix A, a process mediated by autotrophic soil microorganisms.

Some of the conditions that favor denitrification include high organic matter, fine textured soils, frequent wetting, high groundwater table, neutral to slightly alkaline pH (Lazarova et al., 2005), vegetative cover, warm temperature, an abundant denitrifier microbial community, and no-till crop management (Nommik, 1956; Bremner and Shaw, 1958; USEPA, 1977; Knowles, 1982; Rice and Smith, 1982; Linn and Doran, 1984; Cavigelli and Robertson, 2000; Rochette et al., 2008). Denitrification is generally favored in fine-textured soils and no-till crop management because these conditions tend to be associated with higher soil moisture, which can promote the anaerobic conditions needed for denitrification. According to Nommik (1956), Bremner and Shaw (1958), Linn and Doran (1984), and Brady and Weil (2008) at least 60% to 70% water-filled pore space (WFPS) is needed for denitrification to occur. Denitrification occurs over a wide

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temperature range from $2^oC$ to $50^oC$ with an optimum temperature range between $25^oC$ and $35^oC$ (Brady and Weil, 2008).  Tsiknia et al. (2013) concluded that plant species (*Eucalyptus camaldulensis vs Arundo donax*) can directly affect the activity of denitrifiers due to a difference in the copy numbers of denitrification genes in their experiments with two plant species.

Total denitrification increases with WFPS and dissolved organic carbon (DOC) concentration (Weier et al., 1993). However, organic carbon availability is more important than the WFPS in determining the denitrifying enzyme content of habitats (Tiedje et al., 1982).  Stanford et al. (1975), as cited by Fillery (1983), observed that denitrification followed first-order kinetics in respect to $NO_3^-$ when $NO_3^-$ levels are lower than 40 mg $L^{-1}$ and the oxidizable substrate is not limiting. Denitrification fluxes determined by Jørgensen et al. (2004) under active flow in soil columns mainly followed first-order kinetics in forest and agricultural soils. Nommik (1956) and Wijler and Delwiche (1954), as cited by Fillery (1983), reported the inhibition of $N_2O$ during denitrification  due to the $NO_3^-$ concentrations; however, Ryden et al. (1981) found no relationship between the denitrification N loss and soil $NO_3$ concentration nor the effluent irrigation events from permanent pasture grasses irrigated with secondary-treated effluent.

In an unfertilized forest land irrigated at a rate of 5 cm $wk^{-1}$ with tertiary treated effluent, Barton et al. (1998) determined that 50% of the weekly denitrification occurred within 48 h after irrigation ceased. This was probably due to reduced anaerobic conditions that

favor denitrification. Meding et al. (2001) observed a linear relationship of the denitrification rates with time within 2 h after effluent irrigation ceased.

Using the Root Zone Water Quality Model (RZWQM) Sophocleous et al. (2009) simulated similar denitrification rates with four irrigation rates (100%, 88%, 75%, and 50%) of the irrigation rate in unfertilized corn fields irrigated with secondary-treated effluent in south western Kansas. The study results suggest that the post-irrigation soil conditions (e.g. WFPS) were roughly the same at all the irrigation levels.

### 2.4.3 Fractional atmospheric N losses ($f$)

### 2.4.3.1 Design $f$ values

Crites and Tchobanoglous (1998) and the USEPA (2006) suggest $f$ values based on the MWE C:N ratio (see Chapter 1, Table 1-1) due to the large influence of organic carbon on N transformation in soil. During decomposition of organic matter in soils, organic carbon compounds are oxidized to carbon dioxide and the associated N is transformed to $NH_4^+$ (Li et al., 1992). The $NH_4^+$ is consequently taken up by plants, stored in the soil, or lost through volatilization, leaching, or denitrification. In Chapter 1, Table 1-1, high $f$ values are suggested for effluents with higher C:N ratios, because soil microorganisms utilize water soluble organic carbon (McCarty and Bremner, 1993) during denitrification.

A few water reuse irrigation guidelines in the USA (Delaware (2014), Georgia (2010), Hawaii (2002), Iowa (1979), and Oklahoma (2012)) suggest $f$ values for designing MWE irrigation systems. The states of Delaware and Georgia suggest a fraction of 0.05 if the ammonia in the effluent volatilizes, and $f$ values of 0.15 for row crops (Delaware) and 0.1

for forage crops (Georgia) are considered to account for denitrification N losses. Based on the study by Henderson et al. (1955), the reuse guidelines for the state of Hawaii suggest that a fraction of no greater than 0.2 of the ammonia in the effluent volatilizes from sprinkler- irrigated MWEs with a pH in the range of 7.5 to 8.5 and that a fraction of 0.15 of the MWE-TN is lost to denitrification. The Iowa and Oklahoma water reuse guidelines and design manuals (USEPA, 1977) suggest an $f$ value of 0.2. Details of the water reuse guidelines are available at http://www.watereuse.org/government-affairs/usepa-guidelines.

### 2.4.3.2 $f$ estimates based on measured and simulated atmospheric N losses or estimated from"source-sink" N mass balances using measured N inputs and sinks

In past studies the fractional atmospheric N losses in MWE irrigation have been calculated based on either only $NH_3$ volatilization or gaseous denitrification or total atmospheric N losses; however, due to the difficulty in isolating the effluent N from the large soil N pool, few studies have investigated the fractional N losses in MWE irrigation.

Ryden et al. (1981) determined $NH_3$ fluxes by coupling a soil cover (20-gauge galvanized sheet metal of size 50 cm x 10 cm x 17 cm with a 60 ml, 2% boric acid absorption trap. External air was drawn through the soil cover and subsequently through the boric acid trap, and the amount of $NH_3$ was determined by titration with sulphuric acid. The authors also measured denitrification in the field using the acetylene inhibition method (Ryden et al., 1978). Ryden et al. (1981) reported atmospheric N loss rates between 77.7 and 107 kg ha$^{-1}$ (with the highest N fluxes occurring within two days after effluent irrigation ceased)

from permanent pasture grasses irrigated with effluent at a rate of 10 cm wk$^{-1}$ for 14 days in Santa Maria, California. According to Ryden et al. (1981) the fractional N loss due to denitrification was in the range of 0.07 to 0.09 of the total effluent N applied. Using a "source-sink" N mass balance Lund et al. (1981) estimated a fractional N loss of 0.09 in permanent pastures irrigated with secondary-treated effluent in Santa Maria, California.

Smith et al. (1996) determined $NH_3$ gas fluxes from permanent pastures irrigated with secondary-treated effluent irrigation using the integrated horizontal flux mass balance micrometeorological technique in Australia. In their study, effluent was applied at a rate of $9.7 \pm 0.6$ cm wk$^{-1}$ for six weeks, $NH_3$ volatilization increased with wind speed and evaporation rates and the estimated fractional $NH_3$ volatilization of the effluent $NH_4^+$-N concentration (60% to 90% of the MWE-TN) within two days after irrigation ceased was 0.24 (greatest fractional N loss per week). The high N loss within 48 h of irrigation could be due to the potential of reducing $NH_3$ volatilization once the MWE infiltrates into the soil matrix (Schreffler et al., 2005).

Micrometeorological techniques are preferred for $NH_3$ emission quantification since they do not disturb the soil surface processes, which can influence gaseous emissions (FAO, 2001; Leuning et al., 1985; Misselbrook and Hansen, 2001). Misselbrook and Hansen (2001) found no significant difference between the integrated horizontal flux mass balance, a meteorological technique, and an inexpensive method (Misselbrook and Hansen, 2001; Svensson, 1994), which uses a dynamic chamber and a passive diffusion sampler (PDS) technique to determine $NH_3$ emissions rates that are less than

400 g N ha$^{-1}$. The PDS technique "is essentially a micrometeorological approach suitable for small plots" (Misselbrook and Hansen, 2001).

In the Piedmont of Georgia, Meding et al. (2001) conducted field and laboratory denitrification studies using the acetylene inhibition method in unfertilized forested land treatment systems and estimated 0.024 as the fractional denitrification loss of the MWE-TN. The forest lands were irrigated with secondary-treated MWE at a rate of 6.4 cm wk$^{-1}$ resulting in annual N loading of 594 kg ha$^{-1}$ yr$^{-1}$ (Nutter et al., 1996, as cited by Meding et al., 2001). Barton et al. (1998) measured denitrification in the field using the acetylene inhibition method from an unfertilized forested land irrigated with tertiary-treated effluent in Australia. Roughly similar fractional denitrification N losses, 0.002 in one week and 0.011 in another week were determined from denitrification data from Barton et al. (1998).

Schreffler et al. (2005) estimated the fractional $NH_3$ volatilization N loss of 0.01 in fields spray-irrigated with nitrate-dominated MWE in Chester County, PA. The majority of this loss occurred during the growing seasons from 1999 to 2001. The authors attributed the $NH_3$ volatilization to higher air temperatures during the growing season. The authors determined $NH_3$ volatilization by relating temperature and wind speed to $NH_3$-N in MWE samples collected from the irrigation spigots and $NH_3$-N in MWE collected in containers placed in the field during irrigation. In cases when there was no relationship between temperature and the $NH_3$-N in the MWE samples, the difference between the $NH_3$-N collected from the irrigation spigot and containers placed in the field was used to estimate $NH_3$ volatilization.

Saez et al. (2012) calculated $NH_3$ volatilization for four seasons based on observed temporal changes in $NH_3$ concentrations from evaporation pans placed in MWE-irrigated sudan grass and 3-way grain (mixture of barley, oat, and wheat) in Palmdale, southern California. The authors estimated fractional $NH_3$ volatilization in the range of 0.15 to 0.35 of the effluent $NH_4^+$-N concentration. The effluent $NH_4^+$-N concentration was 60% to 90% of the effluent total N concentration and $NH_3$ emissions occurred within 2 h after irrigation ceased.

Simulation models provide an alternative option of assessing the fate and transport of N through the soil in effluent irrigation (Kunjikutty et al., 2007). However, there are inadequate comparisons of simulated and observed atmospheric N losses from effluent irrigation and, thus, fractional simulated atmospheric N losses. This could be partially due to the wide range of the amounts of inorganic and organic N in the effluent and, in addition, little is known about the mineralization rates of effluent organic N. MWE organic N may consist of complex compounds, which are not very reactive and hence may not be readily available for mineralization (Sedlak and Pehlivanoglu, 2004). Zhou et al. (2003) found that only one third of the effluent organic N was retained in calcareous clay soil columns and suggested that some of the organic compounds in effluent are hydrophilic and may be lost with preferential flow, which occurs in all natural soils. Hence, depending on the type and concentrations of the organic N in the effluent and the soil's mineralization rates, assumptions may be made about the bioavailability of effluent organic N. Zhou et al. (2003) also noted difficulties in separating transformations of effluent N from N originating from soil N biogeochemical processes.

Agroecological modeling involves using model inputs (e.g. crop, climate and management factors) to estimate the real world soil biogeochemical processes with mathematical or algorithm-based approximations and thus there are no right or wrong answers to approaches used in models (Shaffer and Delgado, 2001). Due to the complexity of carbon/nitrogen cycles in soil-crop systems, selecting a model to simulate the soil biogeochemical processes is not a trivial task and requires the user to have knowledge of the model capabilities and limitations, as well as the problem and location to be addressed (Shaffer and Delgado, 2001). Although partitioning simulated gaseous N emissions into NO, $N_2O$ and $N_2$ remains a challenge for modelers (Chen et al., 2008; Li et al., 2005), simulation models continue to be used in assessing soil-plant processes and, according to Sophocleus and Townsend (2009), are increasingly being used for various N management activities. According to Chen et al. (2008) the Daily Century (DAYCENT) and DeNitrification and DeComposition (DNDC) models are some of the most widely used $N_2O$ simulation models. In a comparison of three models (DAYCENT, DNDC and the Water and Nitrogen Management model (WNMM)) used for simulating denitrification and $N_2O$ emission, Li et al. (2005) found that the WNMM and DNDC models provided the best agreement with observed data of $N_2O$ emissions than did DAYCENT. The N outputs for the models are $N_2O$ and $N_2$ (WNMM); NO, $N_2O$ and $N_2$ (DAYCENT and DNDC); and soil $NH_3$ (DNDC).

**2.4.4 State of the science for fractional atmospheric N loss and change in soil N (*f*) in municipal wastewater effluent irrigation**

The review of literature shows that despite the differences in environmental factors, N forms in the effluent, and land management practices, the fractional N losses estimated from the measured atmospheric N losses are generally lower (0.09 (Lund et al. 1981);

0.24 (Smith et al., 1996); 0.002 and 0.011 (Barton et al., 1998); 0.024 (Meding et al. (2001); 0.01 (Schreffler et al. (2005); 0.15 to 0.35 (Saez et al. 2012 ) than the design $f$ values for secondary-treated (0.15 to 0.25) and tertiary-treated (0.1) effluents (see chapter 1, Table 1-1 and section 2.5.1).  However, the studies involved fractional N loss data for short periods of time (thus not accounting for seasonal crop N uptake patterns) and did not estimate the N losses using multiple methods for multiple years.   The literature also yielded no adequate results of determining the $f$ values from simulated atmospheric N losses or from a "source-sink" N mass balance which is conventionally used in designing SR MWE irrigation systems. Thus, more data are needed to better explain or identify the $f$ values for given crop and land management conditions.

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**Chapter 3. DESCRIPTION AND CHARACTERIZATION OF THE STUDY SITE**

This chapter includes a background of the Penn State University (PSU) wastewater treatment plant (WWTP), the Living Filter (LF), and the location and management history of the study site at the LF. Other information documented for the study site include soil bulk density, soil pH, soil organic matter (SOM), particle size distribution in the surface soil horizon (0 to 30 cm), nitrogen (N) application rates to the grass field, crop aboveground biomass yield (AGB) and N uptake, and weather data. The study site information and weather data are referenced throughout the dissertation.

**3.1 Penn State wastewater treatment plant and Living Filter**

**3.1.1 Penn State wastewater treatment plant**

The PSU WWTP was originally built in 1913 at its present location on the headwaters of Thompson Run and was the first wastewater treatment plant in the Spring Creek watershed (ClearWater Conservancy of Central Pennsylvania, 2008). The plant, which originally consisted of an Imhoff tank and a fixed-nozzle trickling filter, has had three major upgrades (in 1957, 1966, and 1999). In 1957, the Imhoff tank and a fixed-nozzle trickling filter were replaced with a 3.1-m diameter vortex grit removal chamber, primary aeration/settling tanks, two 23.2 m diameter rock media trickling filters, final clarification and chlorination for disinfection (ClearWater Conservancy of Central Pennsylvania, 2008). In 1966, the plant's capacity was doubled to 4.0 MGD by installing two circular activated sludge units, and in 1999 the plant was upgraded to include biological nitrogen removal (BNR) (ClearWater Conservancy of Central Pennsylvania, 2008; Jaiswal, 2010), following a design by Metcalf & Eddy Inc. The aim of including the BNR at the PSU

WWTP was to meet the US Environmental Protection Agency (USEPA) drinking water limit of 10 mg $NO_3^-$-N $L^{-1}$ in groundwater beneath the LF site (Jaiswal, 2010).

The trickling filters and the activated sludge trains each receive 50% of the primary effluent and are operated in parallel. Following clarification from the trickling filters and the activated sludge trains, the two effluents are combined prior to chlorination and finally pumped to the LF. Typical 12 month mean daily wastewater flows to the plant are 2.4 MGD (ClearWater Conservancy of Central Pennsylvania, 2008; Jaiswal, 2010), which is about 60% of the permitted design capacity of 4.0 MGD.

### 3.1.2 Penn State Living Filter and location of the study site

The PSU LF (gameland and astronomy sites) is located near the University Park campus off of Fox Hollow Road in Centre County, PA, and forms a major part of the University's wastewater management program (Fig. 3-1).



**Figure 3-1 PSU Living filter sites and wastewater treatment plant.**

The LF began in 1963 as a research project to investigate land-based MWE disposal (Parizek et al., 1967; Ferguson, 1982; Richardson, 2011) following a need to avoid

pollutant loadings to Thompson Run located near the PSU WWTP (Fig. 3-1).  Since

1983, all of PSU's MWE has been continuously irrigated at the LF (State Gamelands and

Astronomy sites) (Fig. 3-1). Currently over 600 ha of farm  (50%) and forest (50%) area

are spray-irrigated resulting in over 500 million gallons of water recycled annually into

the Centre region groundwater reservoir (PSU-OPP, 2013).

In 2001, biologically sensitive irrigation scheduling replaced the scheduled weekly

irrigations throughout the year (Jaiswal, 2010), in which only about 7% (14.6 ha) of the

total LF area is sprayed at any one time at an application rate of about 0.42 cm $h^{-1}$, which

permits effluent infiltration without runoff.  Biologically sensitive irrigation scheduling is

based on existing vegetation, stage of growth, soil type and priority requests from PSU

OPP and WWTP management to run selected irrigation laterals (Jaiswal, 2010).  The

three main soil series at the LF sites include: Hublersberg, Hagerstown and Morrison soil

series (Parizek et al., 1967).  The agricultural and forestlands are dominated by the

Hublersberg and Morrison soil series, respectively.

This research was conducted at the astronomy site (Fig 3-1) in a tall fescue (*Festuca*

*arundinacea Schreb.*) hay field, 15A; henceforth referred to as 'the grass field' or 'study

site'. The predominant soil series in the grass field is Hagerstown (fine, mixed, semi

active, mesic Typic Hapludalf) (NRCS, 2013). The Hagerstown soil is a limestone-

derived residual soil that is deep and well drained with a moderate permeability. About

9% of the total agricultural land in Pennsylvania is used as grassland for grazing or hay

production (NASS, 2007).  Tall fescue is one of the main cool season grasses in

Pennsylvania and is used primarily for conservation purposes, although it is well suited as hay, silage, or pasture (Hall, 2008).

## 3.2 Management history of the study site

Grass field 15A covers 8.4 ha of the 12 ha of tall fescue at the astronomy PSU LF site (84.6 ha) and has been continuously irrigated since 1963 (except between 1976 to 1982) (Jaiswal, 2010). Since 1982, the grass field has been vegetated with perennial grasses and corn silage (Fig. 3-2). The field was double-cropped between 1984 and 1990, mainly to gradually phase out the reed canary grass, which was not palatable to cows, and replace it with tall fescue (James Loughran, Farm Operations and Services Unit, College of Agricultural Sciences (FOS-CAS), personal communication, 2013), and for greater N removal via crop harvest (Jaiswal, 2010) to respond to concerns of increasing nitrate N ($NO_3$-N) levels in groundwater at the LF. Since the integration of the BNR system to the WWTP in 1999, 65 to 150 kg N $ha^{-1}$ of urea-ammonium nitrate (UAN) (30% N) fertilizer is applied annually to the study site to supplement effluent-supplied N.



**Figure 3-2 Crop history for the study site-Field 15A at the PSU Living Filter.**

### 3.3 Sampling locations at the study site

The landscape position between irrigation laterals 10-1 BR2 and 11-1 BR1 was chosen for sampling both soil and soil water (Fig. 3-3).   The criterion for choosing this position was based on the assumption of  being able to sample soil water from suction cup lysimeters  installed for the research study, since over the years the nearby lysimeter 8 (LYS 8) (Fig. 3-3) managed by OPP has reliably yielded  groundwater samples. Lysimeter 8 has two suction cup lysimeters, installed at 1.8 m and 3.6 m depths. The sprinkler (S) and irrigation lateral (L) spacings are 22.8 m and 30.5 m, respectively, and the nozzle size for sprinklers SP-3, SP-4, and SP-5 (Fig. 3-3) on lateral 10-1 is 0.56 cm i.d.

In this study, it was important to sample from a location in the field where no MWE overlap occurred, with the hope of possibly reducing soil moisture variation in the sampling location. Soil moisture variation in irrigated fields occurs due to the decrease in the volume of applied water with distance from the sprinkler.  High soil moisture conditions promote anaerobic conditions, which favor denitrification atmospheric N losses. The sampling distance from lateral 10-1BR2 where no MWE overlap occurred was determined from the wetted diameter of the sprinklers at the study site.  To achieve the necessary overlap in sprinkler irrigation, Jarrett (2000) suggested choosing a sprinkler with a wetted diameter about  two times the smaller of S and L, resulting in 50% spacing (% S = 0.5). Jarrett (2000) also suggested a 65% S spacing (% S = 0.65) in designing effluent sprinkler irrigation systems.

**Figure 3-3  Study site (Field 15 A at the PSU LF). Contour interval = 1 ft. (0.3 m). Locations a to i are referred to in section 3.4.**

Using 50% S and 65% S sprinkler spacings, the sprinkler-wetted diameter (WD) for

sprinklers on laterals 10-1 BR 2 and 11-1 BR 1 (Fig. 3-3 and Fig. 3-4)were determined

as:

$$WD = \frac{(S \text{ or } L)_{min}}{\%S} = \frac{22.8}{0.5} = 45.6 \text{ m, wetting radius} = 22.8 \text{ m.}$$

$$WD = \frac{(S \text{ or } L)_{min}}{\%S} = \frac{22.8}{0.65} = 35.1 \text{ m, wetting radius} = 17.6 \text{ m.}$$

Since the distance between the laterals is 30.5 m (Fig. 3-4), the distance from lateral 10-1

BR2, where MWE from laterals 10-1 BR2 and 11-1 BR1 would not overlap, was

determined as 7.7 m (i.e. 30.5 to 22.8 m) and 12.9 m (i.e., 30.5 to 17.6 m) based on the

50% and 65% sprinkler spacing, respectively.  Therefore, measurement of ammonia

volatilization following fertilizer application, soil and soil water samples, plant biomass

yield and N uptake were taken at four locations (numbers 1 to 4 in Fig. 3-4), located

4.5 m on the uphill side of lateral 10-1 BR2 (Fig. 3-4). Measurement of ammonia

volatilization is discussed in chapter 4, the soil and soil water sampling schemes are

described in chapter 5 (denitrification) and chapter 7 (N balance), respectively. The crop

biomass yield and N uptake are discussed in this chapter.

**Figure 3-4 Sampling locations in PSU LF field 15A.** SP-3 to SP-6 are sprinkler locations on lateral 10-1 BR2 (Fig. 3.3); P1-P10 are plots where samples for bulk density determination were collected. Locations 1 to 4 were used for soil and leachate sampling.

## 3.4 Soil properties

### 3.4.1 Soil pH, particle size distribution, and soil organic matter (%)

In 2010, composite disturbed soil samples were collected from 0 to 5-cm, 5 to15-cm and 15 to 30-cm depths from each of the nine landscape positions across field 15A (Fig. 3-3: a to i). The samples for each depth increment were composited from three samples and analyzed for SOM, pH and particle size distribution. The samples collected from the 0 to 5-cm depths were analyzed only for SOM. Other SOM measurements were done in May and June, 2011, and March and December, 2012, at 0 to 5-cm and 0 to 15-cm depths. The disturbed soil samples were composited from three (0 to 5-cm deep) and two (0 to 15-cm deep) samples from each of the four sampling locations, 1 to 4 (Fig. 3-4). All the samples were collected with a 5.1 cm diameter soil auger, and analyzed at the PSU Agricultural Analytical Services Laboratory (AASL). The lab uses the water method (Eckert and Sims, 1995), loss on ignition method (Schultze, 1995), and the hydrometer method

(Gee and Bauder, 1986) to determine pH, SOM, and particle size distribution in soil samples, respectively.

The mean measured soil pH, 7.3, was near neutral at 5 to 15-cm and 15 to 30-cm soil depths. According to Wijler and Delwiche (1954), Nommik (1956), and Van Cleemput and Patrick (1974) the optimum pH range for denitrification is in the range 7.0 to 8.0. In 2010, the mean (n=9) SOM was 4.5%, 3.1 % and 2.3% at the 0 to 5-cm, 5 to 15-cm and 15 to 30-cm soil depths, respectively. The SOM in the depression area (lower elevation at the study site) was about 0.5 to 1% greater than SOM from the summit and mid-slope positions at the 0 to 5-cm depths, whereas the SOM at 5 to15-cm and 15 to 30-cm soil depths from the summit, mid-slope and depression landscape positions was similar.

The mean (n=4) SOM measured at 0 to 5-cm depth from the sampling locations 1 to 4 (Fig. 3-4) was 8.2 % (May, 2011), 6.2% (June, 2011), 7.2% (March, 2012), and 6.7% (December, 2012), and at 0 to 15-cm depth the SOM was the same in March and December, 2012 (4.4%).

On all occasions the SOM from sampling location 1 (Fig. 3-4), which was a depression area (lower elevation) was about 1 to 2% greater than at the other sampling locations. Thus, it was suspected that the denitrification rates in the samples from location 1 would affect the mean denitrification rates per sampling date more than the samples from the other sampling locations. The texture of the surface soils (5 to 30-cm depth) in the grass field comprised of loam and clay loam soil (Table 3-1). The soil textural class results suggest moderate water permeability for Hagerstown soil series enabling tertiary

wastewater treatment as the water moves through the soil profile to recharge groundwater.

**Table 3-1 Soil particle size distribution for the 5 to 15-cm depth and 15 to 30-cm depth at the study site.**

| Sampling locations (see Fig. 3-3) | 5 to 15-cm depth | | | | 15 to 30-cm depth | | | |
|---|---|---|---|---|---|---|---|---|
| | Sand | Silt | Clay | Soil textural class | Sand | Silt | Clay | Soil textural class |
| | | % | | | | % | | |
| a | 35.3 | 32.6 | 32.1 | Clay Loam | 28.7 | 17.1 | 54.2 | Clay |
| b | 34.8 | 36.8 | 28.4 | Clay Loam | 26.2 | 37.7 | 36.1 | Clay Loam |
| c | 42.3 | 31.9 | 25.7 | Loam | 38.8 | 33.9 | 27.3 | Clay Loam |
| d | 38.2 | 36.4 | 25.5 | Loam | 34.8 | 35.8 | 29.4 | Clay Loam |
| e | 40.2 | 35.7 | 24.2 | Loam | 39.9 | 35.5 | 24.6 | Loam |
| f | 24.0 | 45.5 | 30.5 | Clay Loam | 28.2 | 40.2 | 31.6 | Clay Loam |
| g | 37.3 | 30.7 | 31.9 | Clay Loam | 35.9 | 31.2 | 32.9 | Clay Loam |
| h | 38.2 | 34.8 | 26.9 | Loam | 38.6 | 34.9 | 26.4 | Loam |
| i | 41.0 | 32.9 | 26.1 | Loam | 38.9 | 34.3 | 26.8 | Loam |

## 3.4.2 Soil bulk density (g cm$^{-3}$)

The soil bulk density, and thus total porosity, can affect soil moisture and hence denitrification through the water-filled pore space. Undisturbed soil cores were randomly collected from plots P1, P2, P4 and P7 (Fig. 3-4) with metal rings (6 cm high and 5.4 cm internal diameter) at three depths 0 to 6 cm, 6 to 12 cm and 12 to18 cm. The collected soil cores were placed in tin foil cups (1.3 g) and oven-dried at 105$^{o}$C for 24 h to obtain soil bulk density. The mean (n=4) bulk densities at three soil depths were determined as 1.13, 1.37, and 1.49 g cm$^{-3}$ for 0 to 6 cm, 6 to12 cm, and 12 to18 cm soil depths, respectively.

## 3.5 Municipal wastewater effluent: pH, C:N ratio, and nitrogen (kg ha$^{-1}$)

The grass field was irrigated for 12 h (6 pm to 6 am) once a week from April to November in 2011 and 2012. The weekly total N in the effluent (MWE-TN) was determined from the irrigation depth and total N concentration (mg L$^{-1}$) in the MWE.

The irrigation depth was determined from the turn-ON/OFF time log for lateral 10-1 and an irrigation rate of 0.42 cm h$^{-1}$ based on irrigations lasting 12 h at the PSU LF.

From August, 2011, until December, 2012, for each irrigation event, one effluent sample (about 125 to 150 mL) was collected in an acid-washed plastic bottle from each of the sprinklers SP-3, SP-4 and SP-5 (Fig. 3-4), about 30 min after lateral 10-1 was turned on. The samples were refrigerated overnight and analyzed at Penn State's Institutes of Energy and Environment (PSIEE) water laboratory for total N (TN) and $NO_3$-N. The laboratory uses the Standard Methods (SM) 20th Edition 4500-NC presulfate digestion and the 4100B Ion Chromatography methods to analyze for TN and $NO_3$-N, respectively. From May to July 2011, the same procedure was followed to collect and store the effluent samples, however, the samples were analyzed for $NO_3$-N + $NO_2$-N at the AASL. The laboratory used the SM 4500-NO3-E to analyze for $NO_3$-N + $NO_2$-N in the effluent samples. The grass field received 220 kg ha$^{-1}$ and 153 kg ha$^{-1}$ MWE-TN in 2011 and 2012, respectively (Table 3-2).

Since effluent samples were not analyzed for TN from April to July, 2011, a mean TN value was determined from the monthly TN data from the PSU WWTP monthly reports (Table 3-3) for this period. The data in the PSU WWTP reports was for effluent samples collected from the chlorine contact tank and analyzed for ammonia N, total Kjeldahl nitrogen (TKN), nitrate and nitrite N by Fairway Laboratories in Altoona, Pa. The laboratory uses the SM 4500 or 300 series method for N analysis. Total N is the sum of TKN, nitrate and nitrite N. The MWE pH was determined as the mean of pH data from the WWTP monthly reports. Effluent samples were collected from the chlorination

contact tanks at the PSU WWTP as routine procedure, and analyzed at Fairway

Laboratories in Altoona, Pa.

The laboratory uses the SM 4500 H+B method for pH analyses of wastewaters.  During

the study period the mean monthly pH of the effluent was near-neutral (7.3 ± 0.3) (Table

3-3) similar to the soil pH (7.3) (Table 3-3). The pH range of 6.5 to 8.4 is typical for

MWEs (Lazarova et al., 2005; Saez et al., 2012).   Ammonia volatilization N loss is

enhanced under alkaline conditions when MWE is applied to land surfaces (Feigin et al.,

1991).

**Table 3-2 Effluent irrigation and nitrogen application rates at the PSU LF grass field 15A in 2011 and 2012.**

| | 2011 | | | | | | 2012 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **MWE depth** | **MWE-TN[1,2]** | **MWE-NO$_3$-N[1,2]** | **MWE-TN** | **MWE-NO$_3$-N** | **Date** | **MWE depth** | **MWE-TN[1,2]** | **MWE-NO$_3$-N[1,2]** | **MWE-TN** | **MWE-NO$_3$-N** |
| | cm | mg L$^{-1}$ | | kg N ha$^{-1}$ | | | cm | mg L$^{-1}$ | | kg N ha$^{-1}$ | |
| 18-Apr | 4.86 | 19.5 | 16 | 9.5 | 7.8 | 2-Apr | 4.86 | 15.1 | 9.6 | 7.4 | 4.7 |
| 25-Apr | 4.88 | | | 9.5 | 7.8 | 9-Apr | 4.87 | 9.8 (0.08) | 7.3 (0.36) | 4.8 | 3.6 |
| 2-May | 4.88 | 13.6 | 12.1 | 6.7 | 5.9 | 16-Apr | 4.85 | 17.1 (0.15) | 10.9 (1.15) | 8.3 | 5.3 |
| 9-May | 4.88 | | | 6.7 | 5.9 | 23-Apr | 4.86 | 12.2 (0.06) | 9.3 (0.19) | 5.9 | 4.5 |
| 16-May | 4.86 | | 9.2 (0.14) | 6.6 | 4.5 | 2-May | 4.85 | 10.5 (0.06) | 7 (0.05) | 5.1 | 3.4 |
| 23-May | 4.9 | | 12.1 | 6.7 | 5.9 | 7-May | 4.83 | 10.9 (0.15) | 8.8 (0.42) | 5.3 | 4.3 |
| 1-Jun | 4.77 | 8.9 | 6.8 (0.07) | 4.2 | 3.2 | 14-May | 5.01 | 6.8 (0.09) | 6 (0.11) | 3.4 | 3 |
| 6-Jun | 4.47 | | 6.3 (0.15) | 4 | 2.8 | 21-May | 5.00 | 13.2 (0.1) | 10.9 (0.5) | 6.6 | 5.5 |
| 13-Jun | 4.87 | | 6 (0.12) | 4.3 | 2.9 | 21-Jun | 4.85 | 3.9 (0.22) | 3.7 (0.34) | 1.9 | 1.8 |
| 27-Jun | 4.88 | | 14.3 (0.46) | 4.3 | 7 | 25-Jun | 4.97 | 3.9 (0.05) | 3.8 (0.15) | 2 | 1.9 |
| 4-Jul | 4.88 | 10 | 5.7 | 4.9 | 2.8 | 2-Jul | 4.88 | 4.4 (0.07) | 4.1 (0.02) | 2.1 | 2 |
| 11-Jul | 4.88 | | 10.8 (0.35) | 4.9 | 5.3 | 9-Jul | 4.86 | 8.7 (0.11) | 7.8 (0.22) | 4.2 | 3.8 |
| 18-Jul | 4.86 | | 10.3 (0.3) | 4.8 | 5 | 16-Jul | 4.8 | 6 (0.11) | 5.9 (0) | 2.9 | 2.8 |
| 25-Jul | 4.87 | | 5.8 (0.23) | 4.9 | 2.8 | 30-Jul | 4.86 | 12 (0.19) | 11.8 (0.12) | 5.8 | 5.8 |
| 1-Aug | 4.88 | 10.9 (0.35) | 10.3 (0.6) | 5.3 | 5 | 6-Aug | 4.86 | 6.3 (0.06) | 5.9 (0.07) | 3.1 | 2.9 |
| 11-Aug | 5.08 | 10.4 (0.1) | 7.1 (0.24) | 5.3 | 3.6 | 13-Aug | 4.88 | 9.8 (0.06) | 9.4 (0.3) | 4.8 | 4.6 |
| 15-Aug | 4.94 | 4 (0.03) | 3.5 (0.1) | 2 | 1.7 | 20-Aug | 4.86 | 10.4 (0.06) | 10.2 (0.11) | 5 | 5 |
| 22-Aug | 4.86 | 12.6 | 10.7 | 6.1 | 5.2 | 27-Aug | 4.84 | 13 (0.15) | 11.5 (0.01) | 6.3 | 5.6 |
| 29-Aug | 4.8 | 20.6 (0.93) | 15.7 (0.66) | 9.9 | 7.5 | 3 Sept. | 4.89 | 11.2 (0.1) | 11.1 (0.06) | 5.5 | 5.4 |
| 5 Sept. | 5.8 | 15.8 (0.07) | 13.5 (0.21) | 9.1 | 7.8 | 17 Sept. | 4.95 | 14.9 (0.67) | 12.4 (0.2) | 7.4 | 6.1 |
| 20 Sept. | 4.88 | 13.4 (0.06) | 11.4 (0.17) | 6.5 | 5.6 | 24 Sept. | 4.9 | 15.2 (1.4) | 12.4 (0.45) | 7.4 | 6.1 |
| 26 Sept. | 4.89 | 12.9 (0.06) | 9.8 (0.17) | 6.3 | 4.8 | 1 Oct. | 4.87 | 15.1 (0.4) | 13.1 (0.3) | 7.4 | 6.4 |
| 3 Oct. | 4.88 | 13.6 (0.06) | 10 (0.26) | 6.6 | 4.9 | 8 Oct. | 4.87 | 16.3 (0.7) | 13.5 (0.4) | 7.9 | 6.6 |
| 10 Oct. | 4.88 | 16 (0.1) | 7.5 (0.06) | 7.8 | 3.7 | 17 Oct. | 4.85 | 13.1 (0.1) | 11.3 (0.21) | 6.3 | 5.5 |
| 17 Oct. | 4.86 | 19.5 (0.21) | 9.6 (0.08) | 9.5 | 4.7 | 22 Oct. | 4.89 | 14.6 (0.98) | 11.4 (0.64) | 7.1 | 5.6 |
| 24 Oct. | 4.86 | 16.7 (1.21) | 8.6 (0.11) | 8.1 | 4.2 | 28 Oct. | 4.89 | 12.2 (0.25) | 10 (0.09) | 6 | 4.9 |
| 31 Oct. | 4.74 | 19.9 (0.06) | 10.4 (0.1) | 9.4 | 4.9 | 5 Nov. | 4.87 | 15 (0.4) | 13.8 (0.15) | 7.3 | 6.7 |
| 7 Nov. | 4.88 | 18 (1.1) | 10.6 (0.69) | 8.8 | 5.2 | 12 Nov. | 4.87 | 11.8 (1.41) | 11.2 (1.48) | 5.7 | 5.5 |
| 14 Nov. | 4.87 | 21.6 (0.06) | 9.9 (0.64) | 10.5 | 4.8 | **Sum-2012** | **136.63** | | | **152.9** | **128.7** |
| 21 Nov. | 4.89 | 10.3 (0.79) | 9.2 (0.87) | 5 | 4.5 | | | | | | |
| 28 Nov. | 4.82 | 12.4 (0.06) | 9.6 (0.31) | 6 | 4.6 | | | | | | |
| 5 Dec. | 4.88 | 10.8 (0.1) | 5.1 (0.13) | 5.3 | 2.5 | | | | | | |
| 12 Dec. | 4.87 | 10 (0.12) | 4.1 (0.3) | 4.9 | 2 | | | | | | |
| 19 Dec. | 4.88 | 12.2 | 7 | 5.9 | 3.4 | | | | | | |
| **Sum-2011** | 166.17 | | | **220.01** | **160** | | | | | | |

[1]MWE-NO3-N and MWE-TN are means for 2 or 3 samples. Standard deviations are in brackets. [2]Mean monthly data from the PSU WWTP monthly reports (Table 3-3) were used for data in the shaded cells, since no effluent samples were collected from the field.

**Table 3-3 Effluent monthly mean nitrogen and pH from PSU WWTP reports in 2011 and 2012.**

| Month | 2011 | | | | | | | | 2012 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PSU WWTP reports | | | | | | MWE samples from the field (mean[1]) | | PSU WWTP reports | | | | | | MWE samples from the field (mean) | |
| | TKN | NH$_3$-N[2] | NO$_2^-$ | NO$_3^-$ | TN | pH | TN | NO$_3$-N[3] | TKN | NH$_3$-N | NO$_2^-$ | NO$_3^-$ | TN | pH | TN | NO$_3$-N |
| | mg L$^{-1}$ (mean, n=7 to 9) | | | | | (mean[4]) | mg L$^{-1}$ | | mg L$^{-1}$ (mean, n=7 to 9) | | | | | (mean[4]) | mg L$^{-1}$ | |
| April | 3.1 | 1.9 | 0.4 | 16.0 | 19.5 | 7.3 | | | 5.0 | 4.5 | 0.5 | 9.6 | 15.1 | 7.4 | 14.7 | 9.2 |
| May | 1.3 | 0.2 | 0.2 | 12.1 | 13.6 | 7.4 | | 9.2 | 1.9 | 1.3 | 0.5 | 7.6 | 10.0 | 7.4 | 10.4 | 8.2 |
| June | 1.4 | 0.2 | 0.2 | 7.2 | 8.9 | 7.5 | | 8.3 | 1.2 | 0.3 | 0.2 | 5.0 | 6.4 | 7.4 | 3.9 | 3.7 |
| July | 1.6 | 0.8 | 0.3 | 8.1 | 10.0 | 7.5 | | 8.2 | 1.1 | 0.3 | 0.1 | 6.7 | 7.9 | 7.5 | 7.8 | 7.4 |
| Aug. | 1.5 | 1.7 | 0.4 | 10.7 | 12.6 | 7.5 | 11.5 | 9.1 | 1.4 | 1.0 | 0.3 | 7.9 | 9.2 | 7.6 | 9.9 | 9.3 |
| Sept. | 1.9 | 3.3 | 0.4 | 12.9 | 15.2 | 7.5 | 14.0 | 11.5 | 1.3 | 0.4 | 0.2 | 9.1 | 10.6 | 7.5 | 13.8 | 11.9 |
| Oct. | 6.8 | 8.1 | 1.6 | 9.5 | 17.9 | 7.5 | 17.1 | 9.2 | 2.4 | 1.0 | 0.2 | 11.2 | 13.8 | 7.5 | 14.3 | 11.9 |
| Nov. | 8.9 | 10.4 | 0.9 | 9.0 | 18.8 | 7.5 | 15.6 | 9.8 | 1.9 | 1.1 | 0.2 | 11.3 | 13.4 | 7.5 | 13.4 | 12.5 |
| Dec. | 2.7 | 2.2 | 2.5 | 7.0 | 12.2 | 7.5 | 10.4 | 4.6 | 1.8 | 0.7 | 0.2 | 12.1 | 14.1 | 7.5 | | |

[1] n=4, except May 2011 (n=2) and December 2011, single sample.
[2] From August to November NH$_3$-N was > TKN due to a difference in laboratory procedures.
[3] NO$_3$-N + NO$_2$-N in May, June and July 2011.
[4] n= Days in month.

The monthly mean MWE C:N ratio was in the 0.04 to 0.2 range and  was determined

using the monthly mean  total organic carbon (TOC) and mean (n=7 to 9) MWE-TN.

The TOC was estimated as half of the monthly mean (n= 18 to 20) carbonaceous

biochemical oxygen demand (cBOD), and was in the range of 0.77 to 1.47 mg $L^{-1}$

(Fig. 3-5). The cBOD and MWE-TN data were obtained from the PSU WWTP monthly

reports.



**Figure 3-5 Estimated effluent monthly mean TOC and C:N for 2011 and 2012 for the PSU WWTP.** (TOC was based on the monthly mean (n= 18 to 20) CBOD and C:N was based on TOC and monthly mean (n = 7 to 9) effluent total N).

## 3.6 Fertilizer and rainfall nitrogen

During the study period, two urea-ammonium nitrate (30 % N) fertilizer applications

were made annually to the grass field.  The fertilizer was applied on 22 April and 5

August in 2011 and on 6 April and 3 August in 2012.  The annual N (kg N ha$^{-1}$) from

rainfall was determined using the annual ammonium and nitrate nitrogen (mg L$^{-1}$)

concentration data obtained from the National Atmospheric Deposition Program

(NADP)/ Atmospheric Integrated Research Monitoring Network (AIRMoN) station

PA15 (http://nadp.sws.uiuc.edu/data/sites/siteDetails.aspx?net=AIRMoN&id=PA15), and

the annual rainfall (Appendix B) was measured at the study site. Station PA15 is located

at latitude 40 $^o$ 46 ' 48 " N, longitude 77 $^o$ 56 ' 23.9 " W at an elevation of 393 m.

In 2011 and 2012, 122 and 112 kg N ha$^{-1}$ of UAN-30 fertilizer was applied to the grass

field, respectively. The fertilizer application method is discussed in Chapter 4.  In 2011

and 2012, the annual $NH_4$-N+$NO_3$-N in the rain were only 8.4 kg N ha$^{-1}$ and 5.76 kg N

ha$^{-1}$, respectively. In 2011, the annual N in the rainfall was based on the annual $NH_4$-

N+$NO_3$-N concentration in the rainfall, 0.93 mg L$^{-1}$ (n=268), and annual rainfall, 90.3 cm

(Appendix B). The annual N in the rainfall in 2012 was based on an annual rainfall of

75.8 cm and annual $NH_4$-N+$NO_3$-N concentration in the rainfall of 0.76 mg L$^{-1}$ (n = 264).

## 3.7 Crop aboveground biomass yield and nitrogen removal

The AGB yields and N removal were used as parameters in Chapter 6 (simulating

atmospheric N losses) and Chapter 7 (N balance).  The grass was manually clipped and

collected in 30-day intervals to about 5 to 10-cm stubble height from 0.84 m$^2$ (May to

September, 2011) and 2.51 m$^2$ (April to September, 2012) areas between the sampling

locations 1 and 2, 2 and 3, and 3 and 4 (Fig. 3-4).   The crop N removal was not measured

in October because an adequate quantity of grass could not be collected to determine yield and thus crop N removal since the grass was too short; making relative uniform manual clipping quite difficult. The area from which the aboveground biomass was sampled was increased in 2012 to obtain a more representative biomass yield between the sampling locations. The rest of the biomass near the sampling locations 1 to 4 was mowed and removed within 1 to 2 days after collecting the aboveground biomass samples.

The samples were weighed and one subsample was taken from each of the three samples, weighed and oven-dried at $55^{o}$C for 48 h. On drying, the samples were weighed again and the monthly mean (n=3) dry matter (DM) yield was determined. A subsample was collected from the dried samples, weighed and analyzed at the AASL for %N on a DM basis using the combustion method with the Elementar Vario Max N/C Analyzer (Horneck and Miller, 1998).

In 2011 and 2012, the annual AGB yield was 9856 kg ha$^{-1}$ and 6989 kg ha$^{-1}$, respectively (Table 3-4).  In 2011, the annual yield was comparable to that measured by FOS-CAS (9318 kg ha$^{-1}$). However, in 2011 the crop N removal (248 kg N ha$^{-1}$) was higher than that measured by FOS-CAS (165 kg N ha$^{-1}$) probably due to non-uniformity in stubble heights to which the grass was manually clipped.  The annual crop N removal in 2011 (248 kg N ha$^{-1}$) was also higher than in 2012 (183 kg N ha$^{-1}$) (Table 3-4) probably due to the dry weather experienced in 2012.  Biomass yields in June 2012 (246 kg N ha$^{-1}$) were very low compared to those in June 2011 (3136 kg N ha$^{-1}$), due to lack of  irrigation between 25 May and 20 June 2012 while repairs were being done on lateral 10-1.  In 2012, the FOS-CAS did not measure crop biomass yield and N uptake.

**Table 3-4 Aboveground biomass yield and N removal for tall fescue hay field spray irrigated with municipal wastewater effluent at the Penn State Living filter in 2011 and 2012.**

| Month | 2011 | | | 2012 | | |
|---|---|---|---|---|---|---|
| | Mean[1] AGB (DM) yield | Mean[1] crop N | Mean[1,2] crop N removal | Mean[1] AGB (DM) yield | Mean[1] crop N | Mean[1,2] crop N removal (kg ha^{-1}) |
| | (kg ha^{-1}) | (%, DM basis) | (kg ha^{-1}) | (kg ha^{-1}) | (%, DM basis) | |
| April | | | | 1670.92 (128.15) | 2.9 (0.05) | 48.3 (3.06) |
| May[3] | 2764.3 (455) | 2.1 (0.3) | 59.2 (17.68) | 2354.42 (857.57) | 2.3 (0.32) | 53.1 (17.07) |
| June | 3139.33 (1186.71) | 2.2 (0.43) | 71 (36.43) | 237.98 (74.12) | 3.4 (0.23) | 8.3 (3.01) |
| July | 722.02 (312.64) | 2.8 (0.38) | 19.7 (5.58) | 1198.28 (325.03) | 2.6 (0.23) | 31.5 (9.54) |
| August | 1398.92 (340.70) | 3.1 (0.3) | 43.2 (13.78) | 1297.37 (269.82) | 2.6 (0.16) | 34.4 (8.11) |
| September | 1850.18 (413.6) | 2.9 (0.43) | 55.1 (19.66) | 213.87 (79.8) | 3.4 (0.06) | 7.3 (2.6) |

[1]n = 3; [2]Based on mean (n=3) AGB (DM) yield (kg ha-1) and mean (n=3) crop N (%, DM basis); [3]AGB was measured at the end of May 2011, thus represents the April and May, 2011 period. Standard deviations for means are in brackets.

The monthly AGB yield distribution for tall fescue in PA is estimated to be 0 in January, February, March, November, and December; 0.05 (April); 0.3 (May); 0.2 (June); 0.12 (July); 0.15 (August); 0.12 (September); and 0.06 (October) (Dr. M. H. Hall, Penn State University, University Park, personal communication) (Fig. 3-6). Based on the monthly growth distribution for tall fescue growth in PA, it seems the drop in summer growth occurs in July rather than generally in August for cool season grasses (Fig. 3-6 inset (a) Craig et al., 2009)).

**Figure 3-6 Estimated proportions of monthly AGB yield  for tall fescue hay in Pennsylvania.** (Dr. M. H. Hall at Penn State University, University Park, personal communication). Inset is the general AGB yield curve for cool season grasses (Craig et al., 2009).

## 3.8 Rainfall

Rainfall data were recorded using the TR-525USW (Texas Electronic Inc.) sensor installed at the boundary of a non-irrigated field near the study site (< 2 km) (Fig. 3-7). The sensor recorded data every 2 min and has been in operation since 2008. Any missing data due to the sensor malfunction were predicted using linear regression equations between official rainfall data from a standard National Weather Service 8" rain gauge surrounded by a standard wind screen located at elevation 356.62 m (latitude 41° 19' 33 N" and longitude 78° 27' 12 W"; Site ID: STCP1; Site No.: 36-8449-07) on Walker Building at the Penn State University Park campus approximately 4 km from the study site and data from the TR-525USW rainfall sensor.

**Figure 3-7 Rainfall sensor and AWOS III weather station near study site-grass field 15A at the PSU LF.** Border around study site is not to scale.

Rainfall data were recorded daily at 7 am or 8 am at the Walker Building and represented precipitation for the preceding 24 h. The daily sensor rainfall data were determined by summing the 2 min rainfall data for 2011 and 2012. Equations [3-1] and [3-2] were developed from regressing 2011 (n=198) and 2012 (n=207) data from the standard National Weather Service 8" rain gauge, on Walker Building at Penn State University Park Campus (located at elevation 356.62 m, latitude 41° 19' 33 N" and longitude -78° 27' 12 W"; Site ID: STCP1; Site No.: 36-8449-07)) and that from the rainfall sensor in Figure 3-7, respectively.

$$Y = 0.78\ x + 0.25 \qquad\qquad R^2 = 0.79 \qquad\qquad\qquad [3\text{-}1]$$

$$Y = 0.71\ x + 0.03 \qquad\qquad R^2 = 0.91 \qquad\qquad\qquad [3\text{-}2]$$

**where:**

        Y = Predicted daily rainfall, cm

        x = Daily rainfall measured with standard National Weather Service 8" rain
            gauge, at Penn State University Park Campus, cm

### 3.9 Weather data

The daily air temperature, relative humidity (RH), wind speed, and solar radiation were

used in Chapter 6 (simulating atmospheric N losses) and Chapter 7 (N balance). The

daily mean (n=24) air temperature, relative humidity (RH) and wind speed were

measured with a Kestrel 4500 weather meter installed 2 m above the ground along lateral

10-1. Some of the data were corrupted and thus lost before being transferred from the

weather meter. The corrupted data were for the period between 1 January and 21

December 2011 and from 20 April to 31 December 2012. The missing data were

predicted using the regression equations developed for the period with data from 22

December 2011 to 19 April 2012. The missing data for daily mean air temperature, RH,

and wind speed were predicted using regression equations [3-3], [3-4], and [3-5],

respectively. The equations were developed using daily mean air temperature, RH, and

wind speed, measured with the Kestrel 4500 weather meter and data from the automated

weather observation system (AWOS) III at the University Park airport and located near

the study site (Fig. 3-7).

*Daily air temperature ($^{o}$C)*

The air temperature and RH were measured at 2-m height whereas wind speed was

measured at 10-m height at the AWOS III station. The wind speed at 2-m height was

determined by multiplying the wind speed at 10-m height by a factor of 0.748 (Allen et

al., 1998). The correlation of determination ($R^2$) of 0.99 (Eq. [3-3]) suggest the mean

daily air temperatures measured at 2-m heights at the study site and the air temperature

computed for the 2-m height at the AWOS III weather station (Fig. 3-7) (Eq. [3.3]) were

strongly and positively correlated, and thus, extrapolation of equation [3-3] outside the

period that was recorded at the study site could be reasonable.  The daily maximum and

minimum air temperatures from the AWOS III weather station were used in computing

the daily reference evapotranspiration used in the N balance (Chapter 7).

$$Y = 0.98 \ x + 0.01 \qquad\qquad R^2 = 0.99 \qquad\qquad\qquad [3\text{-}3]$$

**where:**

$Y$ = Predicted air temperature at study site, $^{o}C$

$x$ = Air temperature at AWOS III, $^{o}C$

*Daily relative humidity (%)*

The mean relative humidity determined using Eq. [3-4] was used in Chapter 4 (ammonia

volatilization). According to Eq. [3-4] the mean daily RH from the  AWOS III weather

station (Fig. 3.6)  was correlated ($R^2 = 0.82$) to the mean daily RH measured at  the study

site.  However, in Chapter 7, the maximum and minimum RH were used since they are

preferred to the mean RH in computing the evapotranspiration (Allen et al., 1998). The

maximum and minimum RH were computed using vapor pressure data for latitude 40 $^{o}$

49 ' 44.4 " N and longitude 77 $^{o}$ 52 ' 12 " W (approximate location for LYS 8 in Fig. 3-3

and near the sampling locations) obtained from Thorton et al. (2014) and Thornton et al.

(1997).

$$Y = 0.89 \ x + 16.99 \qquad R^2 = 0.82 \qquad\qquad\qquad [3\text{-}4]$$

**where:**

$Y$ = Predicted relative humidity at study site, %

$x$ = Relative humidity at AWOS III, %

*Daily wind speed (m s$^{-1}$) and solar radiation (MJ m$^{-2}$)*

Since the slope and correlation of determination were low (see Eq. [3-5] below), wind

speeds were obtained from National Aeronautics and Space Administration (NASA),

Prediction of Worldwide Energy Resource (POWER), Climatology Resource for

Agroclimatology (http://power.larc.nasa.gov/) for latitude 40 $^{o}$ 49 ' 44.4 " N and longitude

77 $^{o}$ 52 ' 12 " W. Solar radiation data were also obtained from the NASA/POWER online

resource.   The weather data are summarized in Appendix B.

$$Y = 0.38 \ x + 0.15 \qquad R^2 = 0.54 \qquad\qquad\qquad [3\text{-}5]$$

**where:**

   Y = Predicted wind speed (2-m) at study site, m s$^{-1}$
   x = Wind speed (2 m) at AWOS III, m s$^{-1}$

## 3.10 Summary

The soil, crop, and weather data were collected and documented during the study period.

These included soil bulk density, pH and particle size distribution in the surface (0.3 m)

soil horizon, N application to the study site, crop biomass yield and N uptake, rainfall, air

temperature, relative humidity, wind speed and solar radiation.  The data which were

acquired through measurements at the study site or from official sources were used

throughout the dissertation. Fertilizer N application data were used in chapter 4

(ammonia volatilization).  The MWE nitrogen application data were used in chapter 5

(denitrification), chapter 6 (simulations of atmospheric N losses), and chapter 7 (N

balance). The soil bulk density, pH and particle size distribution were used in chapter 6.

Rainfall and weather data were used in chapter 6 and 7. Crop aboveground biomass yield

and crop N removal were used in chapter 6 and 7, respectively.

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**Chapter 4. AMMONIA VOLATILIZATION FOLLOWING SURFACE APPLICATION OF UREA AMMONIUM NITRATE TO TALL FESCUE HAY SPRAY-IRRIGATED WITH MUNICIPAL WASTEWATER EFFLUENT**

**Abstract**

The fraction (*f*) of treated municipal wastewater effluent (MWE), total nitrogen (TN) lost as atmospheric N losses (ammonia ($NH_3$), volatilization, and denitrification), and soil N storage is used to determine N-based MWE irrigation rates. It is, therefore, important to study and quantify *f* values used in designing MWE irrigation systems. The goal of this study was to test the assumption that $NH_3$ (gas) volatilization was negligible from tall fescue irrigated with secondary-treated effluent at a rate of 5 cm wk$^{-1}$ at the Penn State University (PSU) Living Filter (LF), apart from when urea-ammonium nitrate (UAN-30) fertilizer was applied to the grass field. Negligible $NH_3$ (gas) volatilization from the grass field was assumed because of the near neutral pH of the MWE and soil and the low $NH_4^+$-N concentration in the effluent (the monthly mean total Kjeldahl nitrogen (TKN) was in the range of 2 to 3 mg L$^{-1}$ of the monthly mean total N in the effluent (12 to 15 mg L$^{-1}$) during the study period in 2011 and 2012.

Effluent samples collected from the sprinkler irrigation nozzles were analyzed for total N and applied to 8.9 cm i.d. and 15.2 cm long intact soil cores, and $NH_3$(gas) emissions from the cores were measured in the laboratory with a photoacoustic field gas monitor over one-week periods . Ammonia emissions following UAN-30 fertilizer applications were also measured in the field over one-week periods, with passive diffusion samplers (PDSs) located near the soil surface under ventilated chambers. Fertilizer applications to

the grass field were made on 22 April 2011, 5 August 2011, 6 April 2012, and 3 August 2012.

The maximum cumulative $NH_3$ (gas) fluxes in a 24 h period were 0.89, 0.18 and 0.02 kg $NH_3$-N ha$^{-1}$ h$^{-1}$ following fertilizer applications in April 2011, August 2011, and April 2012, respectively. The total cumulative fractions of $NH_3$ (gas)-N of the applied UAN-30 fertilizer N were determined to be 0.4, 0.2, and 0.03 in April 2011, August 2011, and April, 2012, respectively. In general, the greatest $NH_3$ (gas) fluxes occurred within 24 to 48 h of commercial fertilizer application; however, the effect of MWE irrigation on the $NH_3$ (gas) fluxes could not be determined since measurements were done in closed chambers.

On the other hand the $NH_3$ (gas) emissions measured from cores following effluent application in the laboratory were in the order of $10^{-7}$ and $10^{-6}$ kg $NH_3$-N ha$^{-1}$ h$^{-1}$. Based on the total N (1.78 kg ha$^{-1}$ wk$^{-1}$) in the effluent, the mean (n=13) fractional $NH_3$ (gas)-N losses (kg ha$^{-1}$ wk$^{-1}$) were calculated to be $10^{-4}$, thus confirming the assumption of negligible $NH_3$ (gas) fluxes due to MWE. Thus, for highly nitrified effluents with near neutral pH, $NH_3$ (gas) volatilization in the N loss factor (*f*) is negligible and attempts to quantify (*f*) should be directed toward quantifying denitrification.

## 4.1 Introduction

Tall fescue (*Festuca arundinacea Schreb.*) is one of the main cool season grasses in Pennsylvania and is used primarily for conservation purposes, although it is well suited as hay, silage, or pasture (Hall, 2008). The grass produces acceptable forage yield and quality under conditions of adequate irrigation (Smeal et al., 2005). Since 1999, to increase forage yield from the site, in addition to municipal wastewater effluent (MWE) nitrogen (N) applications, 65 to 150 kg N ha$^{-1}$ of urea-ammonium nitrate (UAN-30) fertilizer has been applied annually to tall fescue at the Penn State University (PSU) Living Filter (LF). Fertilizer application in the grass field was initiated in response to a decrease in MWE total nitrogen (TN) following the integration of biological nitrogen removal (BNR) processes at the PSU Wastewater Treatment Plant (WWTP). The goal of enhanced nutrient removal at the WWTP was to meet the US Environmental Protection Agency's (USEPA) maximum contaminant level drinking water limit of 10 mg $NO_3$-N L$^{-1}$ in the groundwater beneath the LF site. As a result of BNR at the PSU WWTP, the MWE-TN decreased from about 25 to 30 mg L$^{-1}$ prior to BNR to the current levels of about 12 to 15 mg L$^{-1}$, and the proportion of TN present as ammonia N concentration decreased from 10 to 15 mg L$^{-1}$ to $< 0.2$ mg L$^{-1}$ (non-detect concentration) (PSU WWTP monthly reports).

Ammonia ($NH_3$) volatilization may occur with land-based MWE irrigation, especially when MWEs high in ammonium-N concentrations are applied, since MWE usually has a near neutral to slightly basic pH (Lazarova et al., 2005; Saez et al., 2012). Feigin et al. (1991), as cited by Smith et al. (1996), suggested that "ammonia volatilization may be an important pathway of N loss when MWE is applied to land surfaces", due to the alkaline

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characteristics of the MWE. Alkalinity promotes $NH_3$ volatilization because of the associated increase in the soil solution $NH_3:NH_4^+$ ratio. The extent of $NH_3$ volatilization is determined by soil moisture, temperature, pH, N source, method and rate of N source application, exchangeable cations, water evaporation, relative humidity, irrigation rates (Fenn and Escarzaga, 1977; Fenn and Hossner, 1985; Ferguson and Kissel, 1986; Al-Kanani, et al., 1991; Vaio et al., 2008; Holcomb et al., 2011) and soil pH buffering capacity (Ryden et al., 1981). Soil buffering capacity is the soil's ability to maintain a constant pH after a known quantity of acidity or alkalinity is added to a soil. Ammonia volatilization from near-neutral soils irrigated with low $NH_4^+$-N MWEs, such as at the PSU LF, was expected to be low apart from when commercial fertilizer was applied. Quantifying $NH_3$ volatilization in MWE irrigation is important because the fraction (*f*) of MWE-total nitrogen lost through $NH_3$ volatilization, denitrification, and change in soil N storage (USEPA, 2006) is used to determine N-based hydraulic loading rates for MWE irrigation. Thus, the goal of this study was to quantify $NH_3$ emissions in the tall fescue field at the PSU LF due to MWE irrigation and to compare these to the emissions following commercial fertilizer (UAN-30) application.

**4.2 Materials and methods**

**4.2.1 Ammonia emissions due to MWE application**

Field and laboratory measurements were made to test the assumption that $NH_3$ (gas) volatilization from the grass field is negligible except following fertilizer (UAN-30) application. Preliminary field $NH_3$ (gas) measurements were made on 6 April 2010, one day after MWE irrigation but before fertilizer application on 9 April 2010. Ammonia volatilization was measured with a photoacoustic field gas monitor (INNOVA 1412)

connected to a 25.4 cm diameter and 10.16 cm tall closed (non-ventilated) chamber. Measurements were done from nine random locations at the study site (Figure 3-3).

Ammonia emissions were also measured from 14 intact soil cores (8.9 cm diameter and 15.2 cm tall) in the laboratory at the USDA's Pasture Systems and Watershed Management Research Unit (PSWMRU). Six cores were collected from each of the four sampling locations (1, 2, 3 and 4) (see Chapter 3, Fig. 3-4) using a tractor mounted hydraulic Gidding's probe. Nylon mesh (150 micron openings) was attached at the bottom of the cores to retain soil. A flexible PVC coupling fitting 8.5 cm i.d. was fastened at the top of each core, and effluent (290 mL; based on irrigation depth of 5 cm and the diameter of the PVC coupling fitting) was applied to each core from the top. In July 2013, one effluent sample (about 125 to 150 mL) was collected in an acid-washed plastic bottle from each of the sprinklers SP-3, SP-4, and SP-5 (see chapter 3, Fig. 3-4) and analyzed for TN, $NO_3^-$-N, and $NH_4^+$-N at the Penn State Institutes of Energy and Environment (PSIEE) water laboratory (see chapter 3, section 3.5 for laboratory method used). Effluent that was not applied to the cores immediately was stored at $4^o$C. Each core was put in a 3.8 L clear glass jar, which was connected to a photo acoustic gas monitor (INNOVA 1412) via an automated 8-port sampler (California Analytical Instruments). The automated sampler allowed sequential sampling of air from the jars, with sampling from an individual jar every 15 min. To avoid carryover of $NH_3$ from the preceding jar, the system was flushed with room air prior to sampling from each jar. Continuous air flow was maintained through the jars. The cores were analyzed in two sets of seven cores over one-week periods.

## 4.2.2 Ammonia emissions following fertilizer application

During preliminary studies, $NH_3$ emissions were measured in the field one day after fertilizer application with a photoacoustic field gas monitor (INNOVA 1412) connected to a 2.54 cm diameter and 10.2 cm tall closed (non-ventilated) chamber. The emissions were measured from six random locations in the grass field for short periods (10 to 20 min). Also, the emissions were measured for longer (one-week) periods following UAN-30 fertilizer application. The grass was clipped to about 5 to 10-cm stubble height and removed before fertilizer application. Liquid UAN-30 was applied with $110^o$ flat spray tips TeeJet nozzles having air induction (AI1100*-VS, Schaben Industries) at rates of 66 kg N ha$^{-1}$ on 22 April 2011 and 56 kg N ha$^{-1}$ on 5 August 2011, 6 April and 3 August 2012.

Ammonia emission measurements began about 4 to 5 h after fertilizer application and were determined by the dynamic chamber technique (Svensson, 1994), which uses a combination of two types of passive diffusion samplers (PDSs) and ventilated chambers to measure cumulative $NH_3$ emissions in the air immediately adjacent to the soil surface. Misselbrook and Hansen (2001) found $NH_3$ emissions determined with the PDS method to be comparable to those measured with the integrated horizontal flux technique, considered to be the most accurate $NH_3$ emission measurement technique.

The PDSs were assembled so that acid-treated filter papers in the L-type samplers were exposed directly to the atmosphere, whereas the filter papers in the C-type samplers were placed 1 cm below a membrane filter (Appendix C).

In both cases, the exposed filter area was about $2 \times 10^{-4} \ m^2$. Ammonia flux calculation is based on the difference of the $NH_3$ concentration on the filter papers (Myers et al., 2013) in the C-and L-type PDSs.

The filter papers (Fisher GR 540, 8-μm pore, 2.4 cm diameter) used in both types of PDSs were rinsed in distilled boiled water for 2 min, then for 2 min in each of two-150 mL methanol batches, after which the filter papers were dried in a sealed glove box. The dried filter papers were then stirred in a 3% (w/v) acid solution (6 g of tartaric acid in 200 mL methanol) for 2 min and dried in the glove box. A fan was placed in the glove box to circulate air and a beaker with 5 mL of concentrated HCl was placed in the box to react with any $NH_3$ present. The membrane filters (Millipore Fluropore PTFE, 1.0-μm pore size, 2.5 cm diameter) were cleaned by soaking them in a 1:1 solution of methanol and distilled water for 2 min and then dried in the glove box. Duplicates of each of the PDS were put in Ziplock$^®$ bags and stored at $4^o$C before installation in the field.

Duplicate sets of both types of PDSs were placed in a plastic holder (about 10 cm x 10 cm) and suspended approximately 3 to 5 cm above the soil surface (Fig. 4-1a), both inside the chambers and at ambient air sampling locations. The PDSs in the ambient locations were used to determine $NH_3$-N concentration of air entering the chambers (Dell et al., 2012) and were covered with plastic disks to protect them from rainfall. Three rectangular plastic chambers (24 cm x 39 cm x 22 cm), constructed from 19 L plastic storage containers (white, high density polyethylene), were deployed about 4.5 m from the irrigation lateral 10-1 BR2 (Fig. 4-1b). The chambers were built following the design of Svensson (1994). Two sample holders with duplicate set of PDSs were placed the same distance from lateral 10-1 BR2 to sample $NH_3$ in ambient air (Fig. 4-1b).

Based on relatively constant readings from ambient PDSs, Misselbrook and Hansen (2001) concluded that the number of locations for sampling ambient air could be smaller than the number of chambers used.



**Figure 4-1 Ammonia measurement site layout.** (a) Passive diffusion samplers (PDSs) anchored near the ground. (b) Ammonia measurement using PDSs outside and inside fan-ventilated chambers.

The chambers were attached to metal anchoring frames inserted about 2.5 to 4 cm into the ground. Each chamber had two 4 cm diameter openings on one of the 24 cm x 22 cm sides of the plastic cover, to allow ventilation. A fan was installed (opposite the openings) on the inside of the cover and a 12-V controller on the outside of the cover supplied with current from two 12-V automobile batteries connected in series. The fans recirculated air within the chambers to prevent $NH_3$ condensation on the internal walls of the chamber (Misselbrook and Hansen, 2001). A metal wind screen was placed in front of the chamber openings to prevent direct influence of external wind on chamber characteristics (Svensson, 1994). To measure any potential $NH_3$ contamination during preparation and handling, PDSs in Ziplock® bags were put inside the chamber during randomly selected sampling periods and removed after 24 h to provide blank values.

The PDSs were changed daily for seven days and the chambers remained in the same position throughout the one-week study period.  Other researchers (Misselbrook and Hansen, 2001; Dell et al., 2012) changed the PDSs more frequently because of higher anticipated $NH_3$ emissions from manures.  In total, 21 pairs of C and L-type PDSs were anchored in the chambers in April 2011, August 2011 and April 2012, and 12 pairs of C and L-type PDSs were used in April 2011 to measure $NH_3$ in the ambient air. In August 2011 and April 2012, 14 pairs of C and L-type PDSs were used to measure $NH_3$ in the ambient air.

Following exposure, all the exposed PDS filter papers were put in plastic vials for immediate extraction and analysis or stored at $4^o$C when immediate extraction was not possible.  All  filter papers were extracted with  10 mL of deionized water and the extracted  $NH_4^+$-N was determined using a Lachat flow injection auto analyzer (Lachat method # 10-107-06-1-C; Lachat Instruments,  2001).

## 4.2.3 Processing $NH_4+$-N concentration data for use in calculating $NH_3$ fluxes

If the blank filters for both the C and L-type PDSs had $NH_4^+$-N below the 0.10 mg $L^{-1}$ laboratory detection limit (DL), a value of 0.05 mg $L^{-1}$ was used in the $NH_3$ flux calculations. On the other hand, if the $NH_4^+$-N concentration for the exposed filter papers in both the PDS types was below the DL, the minimum value for the C and L-type PDSs were used in the $NH_3$ flux calculations.

The minimum $NH_4^+$-N concentration in the filter papers for both PDS types was determined following the method by Misselbrook and Hansen (2001). These authors determined the minimum $NH_4^+$-N concentration for the filter papers in the C-type PDSs

as the sum of the mean $NH_4^+$-N concentration from the filter papers in the blank C-type

PDS and the blank's least significant difference (LSD), since the $NH_4^+$-N concentration in

the filter papers in the C-type PDSs should be greater than the blank value but less than

the filter papers from the L-type PDSs. The minimum $NH_4^+$-N concentrations in the

filter papers for the L-type PDS were determined as the sum of the minimum values for

the filter papers in the C-type PDSs and the blank's LSD. The filter papers in the C-type

PDSs that had $NH_4^+$-N concentrations above that of the L-type filter paper and those

with $NH_4^+$-N concentration less than the minimum for the C and L-type PDSs were

excluded. Instead the minimum $NH_4^+$-N concentration determined for the filter papers in

the C and L-type PDS were used for these data points. Unfortunately the $NH_4^+$-N

concentration data for August 2012 were lost and thus $NH_3$ emissions were not

determined for the sampling period.

### 4.2.4 Soil pH change following UAN-30 fertilizer application

To assess the soil pH change associated with UAN-30 fertilizer application, soil samples

(0 to 5 cm depth) were collected before and after fertilizer application in August 2013

from each of the three locations where the $NH_3$ measurement chambers had been placed

in 2011 and 2012 (Fig. 4-1b). Three composite soil samples were collected with a 3.81

cm dia. soil auger up to 5 cm depths from each of the three locations three days prior to

fertilizer application. Each sample was composited from three samples. Soil samples (0 to

5 cm) were also collected with a 2.54 cm dia. sampling probe, 3 to 4 h after UAN-30

fertilizer application and 1, 2, 3, 6, 8 and 10 days thereafter. On each of these days, one

composite sample was collected from each of the three locations (Fig. 4-1b). Each

composite sample was composited from 10 individual samples collected in the plot.

All the samples were analyzed for pH at the PSU AASL (see chapter 3, section 3.5 for laboratory method used).

## 4.2.5 Ammonia emission flux: Theory and calculation

The theory and calculations used to determine $NH_3$ fluxes near the soil surface with the PDS method are summarized in this section; details are provided in Svensson (1994) and Misselbrook and Hansen (2001). Ammonia fluxes were determined from Eq. [4-1].

$$\varphi_{NH3} = K_a * (C_{eq} - C_a) \qquad\qquad [4-1]$$

**where:**

$\varphi_{NH3}$     = $NH_3$-N flux near soil surface, $\mu g \ m^{-2} \ s^{-1}$
$K_a$     = Ambient mass transfer coefficient in the air near the soil surface, $m \ s^{-1}$
$C_{eq}$     = Equilibrium $NH_3$ concentration in the air near the soil surface, $\mu g \ m^{-3}$
$C_a$     = Ambient air $NH_3$ concentration near the soil surface, $\mu g \ m^{-3}$

Applying Eq. [4-1] to $NH_3$ emissions inside the chamber yields Eq. [4-2], where $K_a$ and $C_a$ in Eq. [4-1] are replaced by $K_{ch}$ and $C_{ch}$, respectively. Also, applying a mass balance calculation to the dynamic chamber technique yields Eq. [4-3] (Svensson, 1994; Misselbrook and Hansen, 2001). $C_{eq}$ was determined from Eq. [4-4], which was derived from combining Eq. [4-2] and [4-3]. The exposure time, t (min), for the PDSs inside the chamber and at ambient positions was the same.

$$\varphi_{NH3} = K_{ch} (C_{eq} - C_{ch}) \qquad\qquad [4-2]$$

$$\varphi_{NH3} = (F/A) * (C_{ch} - C_a) \qquad\qquad [4-3]$$

$$C_{eq} = C_{ch}\left(1 + \frac{F/A}{K_{ch}}\right) - C_a\left(\frac{F/A}{K_{ch}}\right) \qquad\qquad [4-4]$$

**where:**

$\varphi_{NH3}$ = NH$_3$ flux from area covered by the chamber, µg m$^{-2}$ s$^{-1}$
$K_{ch}$ = Mass transfer coefficient inside the chamber, m s$^{-1}$
$C_{eq}$ and $C_a$ = as defined for Eq. [4-1]
$C_{ch}$ = NH$_3$ concentration of air inside the chamber, µg m$^{-3}$
$F$ = Air flow rate through the chamber, m$^3$ s$^{-1}$
$A$ = Soil area covered by chamber, m$^2$

For a given chamber design and surface conditions, the mass transfer coefficient inside the chamber, $K_{ch,}$ was assumed to be constant for a given air flow rate (F) (Svensson, 1994; Misselbrook and Hansen, 2001). Svensson (1994) suggested a minimum F/A value to avoid water vapor condensation especially when relative humidity of the ambient air is high. For the chambers used in this study, prior experiments (by Dr. C. J. Dell at the USDA-ARS-PSWMRU) determined F/A to be 0.001 m s$^{-1}$. The $C_{ch}$ and $K_{ch}$ values were derived from Eq. [4-5] and Eq. [4-6] using the NH$_4$-N concentration data from the chamber PDSs, whereas $C_a$ and $K_a$ were derived from Eq. [4-5] and Eq. [4-6] using the NH$_4$-N concentration data from the ambient PDSs.

$$C_{ch} \text{ or } C_a = \frac{(X - B_C)V_R (L_R + L_{LBL})*1000}{DtA_R ((Y - B_L) - (X - B_C))} \qquad [4\text{-}5]$$

$$K_{ch} \text{ or } K_a = \frac{D}{L_{LBL}} \qquad [4\text{-}6]$$

$$L_{LBL} = \frac{(X - B_C)L_R}{((Y - B_L) - (X - B_C))} \qquad [4\text{-}7]$$

$$D = 4.59 \times 10^{-9} \times T^{1.5} \qquad [4\text{-}8]$$

**where:**

$X$ = $NH_4^+$-N in C-type PDS filter paper, mg $L^{-1}$
$B_C$ = $NH_4^+$-N in blank C-type filter paper, mg $L^{-1}$
$V_R$ = Extraction volume, mL
$L_R$ = Distance between the membrane filter and filter paper of the C-type PDS, m
$L_{LBL}$ = Laminar boundary layer for PDSs inside chamber and in ambient positions, m
$D$ = Temperature-adjusted diffusion coefficient. T is the absolute air temperature ($^oK$) (Svensson, 1994), $m^2 s^{-1}$
$t$ = Exposure time (in the range from 1410 to 1490 min per sampling period), minutes
$A_R$ = 2 x $10^{-4}$ (exposed area of the filter), $m^2$
$Y$ = $NH_4^+$-N in the L-type PDS filter paper, mg $L^{-1}$
$B_L$ = $NH_4^+$-N in the L-type blank filter paper, mg $L^{-1}$

The air temperature at approximately 5 cm above the soil surface was assumed to be near the mean soil surface temperature and was empirically determined using Eq. [4-9] and Eq. [4-10] from Parton (1984). This assumption was supported by the fact that the diffusion coefficient (D), which is temperature dependent, is used to derive the mass transfer coefficients in the chamber ($K_{ch}$) and ambient positions ($K_a$). The $K_{ch}$ is then used to derive $C_{eq}$, and thus the $NH_3$ flux was determined using Eq. [4-4]. In addition, $C_{eq}$ is influenced by fertilizer/soil temperature, $NH_3$ content in the fertilizer, pH and method of application (Svensson, 1994).

$$T_{xs} = T_x + \{24[1 - \exp(-0.038S_t)] + 0.35T_x\}[\exp(-4.8B) - 0.13] \qquad [4\text{-}9]$$

$$T_{ns} = T_n + 6B - 1.82 \qquad [4\text{-}10]$$

**where:**

$T_{xs}$ = Predicted maximum temperature at the soil surface, $^oC$
$T_x$ = Maximum air temperature at 2-m height above the ground, $^oC$
$S_t$, = Solar radiation, MJ $m^{-2}$
$B$ = Aboveground biomass, kg $m^{-2}$
$T_{ns}$ = Predicted minimum temperature at the soil surface, $^oC$
$T_n$ = Minimum air temperature at 2-m height above the ground, $^oC$

Equation [4-9] includes a factor for the elevation of the $T_{xs}$ over the $T_x$, and the effect of plant canopy on the $T_{xs}$. Increasing the plant biomass decreases the elevation of $T_{xs}$ over $T_x$, and according to Parton (1984), plant biomass level above 0.4 kg m$^{-2}$ results in $T_{xs}$ to be lower than $T_x$. The grass was manually clipped from 0.836 m$^2$ in 2011 and 2.5082 m$^2$ in 2012. The AGB yield, B (kg m$^{-2}$) in equations 4-9 and 4-10 was determined from the AGB yield (kg ha$^{-1}$) in Table 3-4 in chapter 3. In April 2011, the aboveground biomass yield, B was estimated as 0.05 kg m$^{-2}$ (5% of the 2011 annual AGB yield, see chapter 3, Fig. 3-6 and Table 3-4), since the grass was not manually clipped at the end of April. In August, 2011 the mean (n=3) B was determined as 0.14 kg m$^{-2}$. In April and August 2012, the mean (n=3) B was determined as 0.17 kg m$^{-2}$ and 0.13 kg m$^{-2}$, respectively.

The mean relative humidity data were obtained from the AWOS III near the University Park Airport. Rainfall was measured with a TR 525 USW rainfall sensor installed at the boundary of a nearby non-irrigated field. Solar radiation, air temperatures, the predicted mean soil surface temperature, rainfall, and relative humidity data per $NH_3$ emission measurement period are summarized in Appendix D. For each sampling period, the mean (n=3 chambers) cumulative $NH_3$-N flux and the fraction of the $NH_3$-N loss of the fertilizer N were determined.

## 4.3 Results and discussion

### 4.3.1 Ammonia emissions due to MWE application

The preliminary field ammonia ($NH_3$-N) emissions were essentially zero

($10^{-5}$ to $10^{-4}$ kg $NH_3$-N $ha^{-1}$ $h^{-1}$) one day, following MWE application. Also the one-week

$NH_3$ -N emissions measured in the laboratory from soil cores were even lower ($10^{-7}$ to $10^{-6}$ kg $NH_3$-N $ha^{-1}$ $h^{-1}$). Based on the MWE-TN (1.78 kg N $ha^{-1}$ $wk^{-1}$) applied to the cores in

the laboratory, the mean (n=13) fraction of the $NH_3$-N loss of the MWE-TN was only in

the range of $10^{-5}$ to $10^{-4}$, which confirmed the assumption that low $NH_3$-N losses occur

due to MWE application at the study site apart from when UAN-30 fertilizer is applied.

The relatively high cation exchange capacity (CEC) of the Ap soil horizon of the

Hagerstown soil, 30.5 meq/100 g (Johnson and Chu, 1983), suggests applied effluent

$NH_4^+$ was readily bound in the surface soil. Also, according to Schreffler et al. (2005),

the potential for $NH_3$ volatilization in MWE irrigation is decreased once the MWE

infiltrates into the soil matrix and away from the soil surface where $NH_3$ volatilization

occurs.

In a climate similar to the LF (Chester County, PA), Schreffler et al. (2005) reported a

small fraction of $NH_3$ volatilization (0.01) due to MWE spray irrigation.  However,

significant $NH_3$ (gas) volatilization  has been documented for systems where secondary

MWE is spray irrigated in climates characterized by high temperature, low humidity and

windy conditions and with MWEs high in ammonium N (Ryden et al., 1981; Smith et al.,

1996; Saez et al., 2012).   According to Smith et al. (1996) when surface soil

temperatures were high (20 to $40^{o}C$) the volatilized fraction of $NH_4^+$-N in the effluent

was 0.24. In their study, the $NH_4^+$-N represented 60% of the MWE-TN.  In high

temperature, low humidity and windy conditions in Palmdale, California, Saez et al.

(2012) measured mean $NH_3$ volatilization fluxes of 7 x $10^{-3}$ kg N $ha^{-1}$ $h^{-1}$ for MWE in a

study in which the effluent total nitrogen was 60% $NH_4^+$-N. Also with $NH_4^+$-N

dominated effluent; Ryden et al. (1981) observed similar ammonia fluxes ($2 \times 10^{-3}$ to $4 \times 10^{-3}$ kg N ha$^{-1}$ h$^{-1}$) in a permanent pasture in Santa Maria, California.

Ammonia fluxes due to MWE irrigation at the LF study site were small because of the neutral MWE and soil pH, low $NH_4^+$-N concentration in the MWE-TN, and climatic conditions (moderate air temperature, humid, and calm conditions) not conducive for rapid $NH_3$ volatilization.

## 4.3.2 Ammonia fluxes following fertilizer application (kg $NH_3$-N ha$^{-1}$ h$^{-1}$)

The $NH_3$-N emissions measured in the field one day after UAN-30 fertilizer application were small ($10^{-5}$ to $10^{-4}$ kg $NH_3$-N ha$^{-1}$ h$^{-1}$) and similar to those measured prior to fertilizer applications. The low emissions after fertilizer application were probably due to the short measurement periods (10 to 20 min), thus not allowing for cumulative emissions that could occur during longer measurement periods. However, ammonia fluxes measured in chambers over one-week periods in the field following UAN-30 fertilizer application were in the range of $4 \times 10^{-3}$ to $8.9 \times 10^{-1}$ kg $NH_3$-N ha$^{-1}$ h$^{-1}$. Ammonia emissions in the chambers varied among seasons probably in response to inherent soil properties (e.g. CEC), changing environmental conditions (e.g. temperature and RH), and urease activity. The mean (n=3) $NH_3$ flux from the chambers per sampling period (typically ~ 24 h) was greatest in the first 24 h following fertilizer application on all occasions. The highest $NH_3$ flux in April 2011 (Fig. 4-2) was attributed to the UAN-30 fertilizer application rate (66 kg N ha$^{-1}$) being greater than the rate (56 kg N ha$^{-1}$) in both August 2011(Fig. 4-3) and April 2012 (Fig. 4-4).

In April 2011, the mean (n=3) $NH_3$ flux per sampling period declined from 0.89 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on day 1 to 0.02 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on day 4 of the experiment. The flux on day 1 was significantly different (p<0.05) from the mean fluxes on the rest of the days during the one-week period (Fig. 4-2). Ammonia emissions were probably enhanced by rapid urea hydrolysis as a result of rain that occurred on the afternoon of the day of fertilizer application. In August 2011, the mean (n=3) $NH_3$ flux on day 2 was significantly different (p<0.05) from the fluxes on day 4 to day 7 (Fig. 4-3). Ammonia fluxes in April 2012 decreased from 0.01 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on day 1 to 0.004 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on day 4 of the experiment and increased to 0.02 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on day 5. The flux on day 5 was significantly different (p<0.05) from the fluxes on the rest of the days (Fig. 4-4).

The $NH_3$ flux on day 5 increased due to an increase in the ambient mass transfer coefficient ($K_a$), which resulted from low $NH_4^+$-N concentration values in all the C-type PDSs which were below the DL, resulting in a small laminar boundary layer ($L_{LBL}$) and hence an increase in $K_a$. In general, $NH_3$ emission calculations that resulted in small negative values were because the $NH_3$ concentration in the chamber dropped to ambient levels. Ammonia emission rate calculations are summarized in Appendices E, F and G. The $NH_4$-N concentration in both the blank C and L-type PDSs were 0.06 mg $L^{-1}$ in April 2011 and 2012 and 0.09 mg $L^{-1}$ in August 2011.

**Figure 4-2 Mean hourly NH$_3$-N fluxes measured in the field in April 2011**. (Bars are standard errors (n=3)).



**Figure 4-3 Mean hourly NH$_3$-N fluxes measured in the field in August 2011**. (Bars are standard errors (n=3)).

**Figure 4-4 Mean hourly NH$_3$-N fluxes measured in the field in April 2012.** (Bars are standard errors (n=3)).

### 4.3.3 Mass and fractional ammonia nitrogen loss

### 4.3.3.1 Ammonia nitrogen loss in April 2011 (kg NH$_3$-N ha$^{-1}$)

In April 2011, the mean (n=3) NH$_3$ emissions decreased from 22 kg NH$_3$-N ha$^{-1}$ on Day 1 to 0.56 kg NH$_3$-N ha$^{-1}$ on Day 4 of the experiment, and the total cumulative NH$_3$-N fraction of the fertilizer N  was 0.40 (Fig. 4-5a). The mean (n=7) air temperature, calculated soil surface temperature, and RH were 16.0$^{\circ}$C, 21.8$^{\circ}$C, and 74.3%, respectively (Fig.4-5b).

**Figure 4-5 Mass and fractional ammonia N loss in April 2011.** Mean (n=3) NH$_3$-N emissions and cumulative N loss fraction of fertilizer N (b) Mean air temperature ($^{\circ}$C), estimated daily surface soil temperature ($^{\circ}$C), and daily mean relative humidity (%).

An increase in soil temperature from day 2 may not have affected $NH_3$ emissions substantially since the maximum $NH_3$ emissions had already occurred on day 1. According to Parton (1984) the elevation of the predicted soil temperature above the air temperature increases with increasing air temperature up to $25^{o}C$ and plant biomass greater than 0.4 kg m$^{-2}$. In addition, the elevation of the soil temperature due to a solar radiation factor also contributed to the predicted soil temperature being greater than the air temperature.

**4.3.3.2 Ammonia nitrogen loss in August 2011(kg NH$_3$-N ha$^{-1}$)**

In August 2011, the mean (n=3) emissions per sampling period increased from 3.82 kg $NH_3$-N ha$^{-1}$ on Day 1 to 4.42 kg $NH_3$-N ha$^{-1}$ on Day 2 and decreased to below the detection limit from Day 4 up to the end of the experiment (Fig. 4-6a). The $NH_3$-N emissions were 0.12 and 0.29 kg $NH_3$-N ha$^{-1}$ on Day 5 and 6 and the total cumulative N loss fraction of the fertilizer N was 0.19 (Fig. 4-6a). Ammonia emissions were probably enhanced by the temperature increase between Day 1 and 2 of the experiment (Fig. 4-6a). The mean (n=7) air temperature, calculated soil surface temperature, and RH were $21.6^{o}C$, $25.4^{o}C$, and 73.9%, respectively and all had a general downward trend throughout the measurement period (Fig. 4.6b).

**Figure 4-6 Mass and fractional ammonia N loss in August 2011.** Mean (n=3) NH3-N emissions and cumulative N loss fraction of fertilizer N (b) Mean air temperature ($^o$C), mean surface soil temperature ($^o$C), and mean relative humidity (%).

**4.3.3.3 Ammonia nitrogen loss in April and August 2012 (kg NH$_3$-N ha$^{-1}$)**

Ammonia emissions in April 2012 decreased from 0.34 kg NH$_3$-N ha$^{-1}$ on day 1 to 0.09

kg NH$_3$-N ha$^{-1}$ on day 4 of the experiment (Fig 4-7a). On day 5 emissions increased to

0.47 kg NH$_3$-N ha$^{-1}$ due to an increase in the ambient mass transfer coefficient (K$_a$). In

April 2012, the total cumulative N loss fraction of the fertilizer N was 0.03. The lower

temperatures and fertilizer application rate in April 2012, than in April 2011, probably

contributed to the relatively smaller NH$_3$ emissions in 2012 than in 2011.  In April, 2012,

the mean (n=7) air and calculated soil surface temperature and RH were 7.2$^o$C, 9.5$^o$C, and

48.4% (Fig.4-7b), respectively. Furthermore, although the UAN-30 fertilizer application

rate in August 2011 and April 2012 was the same (56 kg N ha$^{-1}$), NH$_3$ emissions in

August were higher (see section 4.3.3.2) probably due to the higher summer

temperatures.

**4.3.4 Effect of irrigation, soil pH and water condensation on NH$_3$ emissions**

**4.3.4.1 MWE irrigation**

The effect of MWE irrigation (applied 72 h after UAN fertilizer application) on NH$_3$

emissions could not be determined since the PDSs were sheltered from the irrigation. Fox

and Hoffman (1981) found insignificant NH$_3$ emissions from urea fertilizers, including

sprayed UAN, applied to no-till corn in Central Pennsylvania, if 1 cm of rain occurred

within 48 h of fertilizer  application and  slight  NH$_3$ emissions (<10% of applied N) if 1

cm or  more rainfall occurred  within 3 days  after fertilizer  application. The authors

compared their results to other field experiments and found similar trends in NH$_3$

emissions if rainfall occurred within 3 days after urea application.  Vaio et al. (2008)

observed a reduction in NH$_3$-N emissions when a 4 cm rain occurred 3 to 4 days after

spring fertilizer application (urea, UAN and Nitamin® fertilizer) to tall fescue.



**Figure 4-7 Mass and fractional ammonia N loss in April 2012.** Mean (n=3) $NH_3$-N emissions and cumulative N loss fraction of fertilizer N (b) Mean air temperature ($^o$C), mean surface soil temperature ($^o$C), and mean relative humidity (%).

**4.3.4.2 Soil pH**

In general, $NH_3$ emissions were highest within 24 h after fertilizer application, probably due a temporary increase in soil pH caused by urea hydrolysis. Emissions decreased to nearly zero within one week after fertilizer application, probably due to movement of $NH_4^+$ ions into the soil profile and their retention on the soil cation exchange sites. The percentage of ammoniacal N in the form of $NH_3$ at pH 6.0, 7.0 and 8.0 was reported by Ferguson et al. (1984) to be 0.026, 0.26 and 2.6%, respectively. Smith et al. (1996) observed an increase and decrease in soil pH during night and day times, respectively, following urea application. The authors attributed the increase and decrease in soil pH to urea hydrolysis and loss of $NH_3$ from the soil solution, respectively. There was no measurable increase in pH following fertilizer application, which suggests a relatively strong pH buffering capacity known to occur in clay soils and soils with high organic matter (SOM). Although the soil textural classes in the 5 to 15-cm depth in the surface soil horizon was identified to be loam and clay loam soil (see chapter 3, Table 3-1), the mean (n=4) SOM measured in 0 to 5-cm depth of the surface soil horizon was between 6.0 and 8.2% (see chapter 3, section 3.4.1). According to Ferguson et al. (1984) a soil with a strong pH buffering capacity has less potential for $NH_3$ volatilization provided all the other factors are constant.

**4.3.4.3 Water vapor condensation inside chambers**

In the PDS technique, condensation of $NH_3$-containing water on the L-type PDSs may occur, which can increase the $NH_4$-N concentration in the filter paper. Water condensation inside the chambers may occur due to lack of ventilation and, in the case of this study, probably when the fans were off due to a low battery charge. However, in this

study water condensation was also observed even when the fans were on, probably due to relative humidity (annual mean RH of 71%-calculated as the mean of the maximum and minimum RH in Appendix B) at the study site. Water-vapor condensation may occur inside the chamber at high relative humidity (Svensson, 1994). In April 2011, the RH decreased from about 80% to 60% between day 6 and day 7, and in August 2011, the RH decreased from 85% to about 60% from day 4 up to the end of the experiment. In this study, water condensation occurred inside the chambers on some days and was dried out at the time of changing the PDSs. Although the mean RH during the experiment in April 2012 was lower (48.4 %) than the RH (74.3%) in April 2011, the $NH_3$ fluxes measured in April 2012 were smaller (0.01 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on Day 1) than the fluxes in April 2011 (0.89 kg $NH_3$-N $ha^{-1}$ $h^{-1}$ on day 1). In April 2012, water condensation occurred inside the chambers on days 4, 5 and 6, even though the fans were running, probably due to an increase in RH on day 4 and 5 of the experiment (see Figure 4-7). An increase in RH and water condensation may have influenced the increase in the $NH_3$ fluxes on day 5; however, apart from an increase in the mass transfer coefficient ($K_a$) in the ambient location, it was not clear why the $NH_3$ emissions on day 5 increased.

In summary, the annual UAN-30 fertilizer application rates of 122 kg N $ha^{-1}$ (2011) and 112 kg N $ha^{-1}$ ( 2012) represent 72.6 % and 66.6 % of the N requirement for tall fescue in Pennsylvania (168 kg N $ha^{-1}$) (PSU Agronomy Guide, 2012). Based on the estimated fractional cumulative N loss, the annual fertilizer N loss measured in the chambers in 2011 was 71.5 kg $ha^{-1}$; however the actual fertilizer N loss was probably less than what was measured in the covered chambers since the grass field was irrigated 3 days after fertilizer application. Some studies (Fox and Hoffman, 1981; Vaio et al., 2008) have

observed a decrease in ammonia N loss if rainfall occurred within 24 to 72 h following UAN fertilizer application. Therefore, any fertilizer loss was more than compensated for by effluent N (220 kg N ha$^{-1}$) added in 2011 (see Chapter 3, Table 3-2).

**4.4 Summary and conclusions**

The ammonia emissions were extremely small ($10^{-7}$ to $10^{-6}$ kg ha$^{-1}$ h$^{-1}$) except following UAN-30 fertilizer application. The fraction of ammonia emission of the MWE-TN was essentially zero ($10^{-5}$ to $10^{-4}$). The ammonia fluxes were small due to near neutral MWE and soil pH, low $NH_4^+$-N in the effluent applied at the Living Filter, high CEC of the Hagerstown soil, and the irrigation application carrying $NH_4^+$ downward away from the soil surface. Ammonia emissions following UAN-30 fertilizer application were in the range 0.004 and 0.89 kg $NH_3$-N ha$^{-1}$ h$^{-1}$, and the fraction of fertilizer N loss due to $NH_3$ emissions were 0.40, 0.19 and 0.03 in April 2011, August 2011 and April 2012, respectively. Since ammonia measurements in the field were made under covered chambers, the effect of effluent irrigation on ammonia emissions from the UAN-30 fertilizer applications was not captured. Conclusions from the study are:

(a) The greatest $NH_3$ emissions following commercial fertilizer (urea-ammonium nitrate) application measured under closed chambers, occurred within 24 to 48 h of fertilizer application. Future research is needed to investigate the effect of effluent irrigation on ammonia emissions from crop fields also fertilized with other nitrogen sources, e.g. commercial fertilizer.

(b) $NH_3$ emissions due to effluent application at the study site were small (in the range of $10^{-5}$ to $10^{-4}$ of the effluent total N) and thus negligible in the overall N balance.

(c) For nitrate-dominated MWEs, attempts and efforts to quantify the N loss factor ($f$) should be directed toward quantifying denitrification.

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**Chapter 5. FRACTIONAL MEASURED ATMOSPHERIC DENITRIFICATION NITROGEN LOSS FROM TALL FESCUE HAY SPRAY-IRRIGATED WITH MUNICIPAL WASTEWATER EFFLUENT**

**Abstract**

Atmospheric nitrogen (N) losses in municipal wastewater effluent (MWE) irrigation are mainly due to denitrification if nitrate-dominated effluents are used for irrigation. However, few scientific investigations have quantified the fractional N loss ($f$) used in the design of N-based MWE irrigation depths. The goal of this study was to determine $f$ based on denitrification measurements ($f$md) (fraction) in the surface soil horizon over the growing season in a crop field irrigated with MWE. The study was done in 2011 and 2012, in a tall fescue grass field at the Penn State University (PSU) Living Filter (LF) in Central Pennsylvania. Secondary-treated (including biological nutrient removal) MWE was irrigated at the LF at a rate of 5 cm wk$^{-1}$. In addition to MWE nitrogen, urea-ammonium nitrate (UAN-30) fertilizer was applied to the grass field to supplement effluent-supplied N.

Denitrification fluxes were estimated in the laboratory using the acetylene inhibition method in 4.8 cm i.d and 10.2 cm tall intact soil cores. The soil cores were collected 4 to 5 h after irrigation ceased (AI) and 6 to 7 h before the next irrigation began (BI) and incubated in the laboratory for 6 h. The core headspace nitrous oxide concentrations were determined by gas chromatography. The daily denitrification fluxes were extrapolated from the hourly fluxes and the denitrification N loss per irrigation cycle was estimated using the model, N$_2$O-N (kg N ha$^{-1}$day$^{-1}$) = ae$^{-bx}$, where x is number of days after irrigation ceased. The constants a and b were determined for each irrigation cycle using

the AI-and-BI estimated daily denitrification fluxes. Effluent samples were collected weekly and were analyzed for TN and $NO_3$-N. The $f$md estimates were calculated from denitrification (kg N ha$^{-1}$) and the applied MWE-TN (kg N ha$^{-1}$) per irrigation cycle for 12 irrigation cycles.

About half (57.8%) of the denitrification fluxes (kg N ha$^{-1}$h$^{-1}$) measured on 63 sampling dates were normally distributed ($\alpha = 0.05$) and the mean (n=8) AI denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$) were greater than the BI fluxes; possibly due to temporary anaerobic conditions and increased availability of denitrification substrates (e.g. dissolved organic carbon and soil $NO_3$ concentration). The water-filled pore space (WFPS) (0 to 6 cm) was in the range of 65 to 97%, with higher WFPS values measured after irrigation. On average, the MWE-TN loading was 4 to 5 kg N ha$^{-1}$ per irrigation cycle.

In 2011, the $f$md estimates were 0.40 (2 to 6 June), 0.98 (12 to 18 July), 3.25 (12 to 15 August), 3.45 (16 to 22 August), 0.50 (21 to 26 September), 0.21 (27 September to 3 October), 1.1 (25 to 31 October), and 0.7 (15 to 21 November). In 2012, the $f$md estimates were 0.03 (15 to 21 May), 0.74 (22 to 25 June), 0.19 (10 to 16 July), and 2.87 (7 to 13 August). The $f$md estimates in July 2011 and 2012 and November 2011 were likely least affected by fertilizer applications on 22 April 2011, 5 August 2011, 6 April 2012 and 3 August 2012, and $f$md estimate in November 2011 was probably due to lack of plant N uptake. Irrespective of the UAN-30 fertilizer effect on the $f$md values, $f$ values greater than or equal to one are unreasonable for design purposes or even the $f$md estimates of 0.40 (2 to 6 June 2011) and 0.74 (22 to 25 June 2012) due to the high tall fescue N uptake and removal expected in June.

Apart from the *f*md estimates of 0.21 (27 September to 3 October 2011), 0.2 (10 to 16 July 2012), and 0.03 (15 to 21 May 2012) the *f*md estimates were greater than the design values suggested by the USEPA for secondary (0.15 to 0.25) and tertiary (0.1) treated effluents. These *f*md estimates could represent these months since the measured aboveground biomass yield and crop N removal was realistic for tall fescue in Pennsylvania. The *f*md estimates decreased linearly with the ratio of the BI to AI mean hourly denitrification fluxes measured within the same irrigation cycle.

For future research, daily denitrification data are needed per irrigation cycle and in the absence of commercial fertilizer to refine the *f*md values and the relationship between the *f*md values and the ratio of the BI to AI mean hourly denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$) within an irrigation cycle.

## **5.1** Introduction

The fractional atmospheric nitrogen (N) loss (*f*) due to municipal wastewater effluent (MWE) irrigation at the Penn State University (PSU) Living Filter (LF) was assumed to be mostly due to denitrification N loss since ammonia volatilization was previously determined to be essentially zero (see chapter 4, section 4.3.1) at the study site (see chapter 3, sections 3.2 and 3.3). Due to the several factors, such as high organic matter, fine textured soils, frequent wetting, neutral to slightly alkaline pH warm temperature, and abundant denitrifier microbial community (see chapter 2, section 2.4.2), denitrification fluxes in MWE irrigation can vary considerably, both temporally (between seasons and over short periods in response to MWE irrigation or rainfall) and spatially due to inherent variability and uneven distribution of applied MWE (Barton et al., 1998). Varying conditions within soil microsites can lead to high variability in denitrification

over short distances (Parkin, 1987). One way of dealing with spatial and temporal variability in studies of denitrification is to accommodate the characteristics of temporal and spatial variation of the site in the sampling design (Tiedje et al., 1989). This can be achieved by sampling from locations that represent the spatial variability of a study site during different climatic conditions throughout the year.

Denitrification following effluent irrigation has been mostly studied in the surface soil horizon in forestlands or grass fields (Brar et al., 1978; Ryden et al., 1981; Barton et al., 1998; Meding et al., 2001; Fedler et al., 2003; Hooda et al., 2003). The surface soil horizon is often a carbon-rich layer where the greatest activity of N cycling processes occur (Shaffer and Ma, 2001). In the past, denitrification studies in MWE irrigation have focused on the denitrification potential (Brar et al., 1978; Fedler et al., 2003), measurement of gaseous denitrification products (Ryden et al., 1981; Hooda et al., 2003), and quantification of the fractional denitrification N loss (Meding et al., 2001). However, to date, there has been little scientific investigation of denitrification activity in the surface soil horizon over the growing season in MWE irrigated crop fields, with the goal of verifying the fractional atmospheric N loss values suggested in the literature.

## 5.2 Research goal and questions

The research goal was to determine the fractional denitrification N loss (*f*md) over the growing season in a grass hay field irrigated with treated municipal wastewater effluent. The research goal was achieved through measurement of denitrification N loss in the surface soil horizon and quantification of the total N in the MWE. The questions addressed in the research include:

1. How does denitrification compare before and after irrigation over the growing season?

2. Do the $f$md values vary over the growing season?

3. How do the $f$md values compare to the $f$ values suggested by USEPA (2006) and those noted in Crites and Tchobanoglous (1998) for secondary and tertiary-treated effluent irrigation system design?

4. What is the relationship between the before and after irrigation denitrification fluxes and the $f$md values?

## 5.3 Materials and methods

Denitrification was measured using the acetylene ($C_2H_2$) inhibition method (Yoshinari et al., 1977; Knowles, 1982; Ryden et al., 1987; Mosier and Klemedtsson, 1994; Groffman, 2006) in the surface soil horizon of a tall fescue field at the Pennsylvania State University Living Filter site (see chapter 3, sections 3.2 and 3.3). Acetylene blocks the conversion of $N_2O$ to $N_2$, and researchers take advantage of this fact to measure the amount of $N_2O$ produced as a proxy for total denitrification. The acetylene inhibition method is appropriate for N balance studies, since it quantifies $N_2O$ that could ultimately be converted to $N_2$ gas (Li et al., 2005). The method is reasonably good in terrestrial systems with high to moderate levels of $NO_3$ concentrations (Groffman, 2006) and is still one of the most widely used techniques in denitrification studies (Tiedje et al., 1989; Groffman et al., 2006). However, the method has some drawbacks such as the potential for $C_2H_2$ to inhibit the first step of nitrification (Fig. 5-1) (Walter et al., 1979, and Mosier, 1980, as cited by Ryden et al., 1987; Groffman et al., 2006). Inhibition of nitrification would reduce production of $NO_3$, the terminal electron acceptor for denitrification.

**Figure 5-1 Acetylene inhibition of total denitrification** (Groffman et al., 2006).

Gaseous denitrification products were measured in intact soil cores in the laboratory

using $C_2H_2$ inhibition method (Tiedje et al., 1989; Groffman, 1995; Groffman et al.,

2006). According to Ryden et al. (1987), in very wet soils (e.g. for cores sampled

immediately following irrigation in this study) the $C_2H_2$ inhibition method in intact soil

cores is superior to alternative methods that use *in situ* treatment of soil with $C_2H_2$ and

an enclosed cover over the soil surface. This is due to the difficulty of introducing $C_2H_2$

and the slow diffusion of $N_2O$ out of the wet soils with *in situ* methods.

### 5.3.1 Soil sampling and handling in the field

During preliminary studies in 2010, 4.8 cm i.d. by 10.2 cm long and 4.8 cm i.d. by 15.2

cm long aluminum cylinders were used to collect undisturbed soil cores from the surface

soil horizon at a distance of about 4.5 m on the uphill side of lateral 10-1 (see chapter 3,

Fig. 3-3). The purpose was to determine whether it was practical to sample a 15.2 cm

depth (since the surface soil horizon at the study site is quite rocky) or if a shallower

sampling depth was sufficient. The undisturbed soil cores were collected using a 5.1 cm

i.d. by 30.5 cm long sampler cup (coring tube) attached to a slide hammer.

Denitrification fluxes for the two core lengths were not significantly different ($\alpha=0.05$)

(data not shown). Therefore, based on these preliminary results, the 10.2 cm long core depth was chosen for this research. In addition, collecting shorter cores would reduce the possibility of compaction during sampling, which reduces porosity and, in turn, the gas diffusion rate from the core. The core diameter (4.8 cm) was within the 3 to 8 cm range suggested by Mosier and Klemedtsson (1994).

In both years, intact soil cores were collected from the soil surface horizon in the mid-morning of the day irrigation commenced at 6 pm (Tuesday) and mid-morning the day after irrigation ceased at 6 am. These sampling times have been designated BI (before irrigation) and AI (after irrigation). In 2012, additional samples were collected 3 days after irrigation ceased (on Fridays). According to Ryden et al. (1978), the most reliable estimates of the daily N loss as $N_2O$ can be obtained from samples collected in the mid-morning since the temperature during this time is likely to be near the daily average. The sampling scheme was designed to evaluate the effect of the change in $NO_3$-N and soil moisture on denitrification fluxes between two consecutive irrigations. On average, 70 to 85 % of the total N in the effluent irrigated at the LF contained $NO_3$-N (see chapter 3, Table 3-2 and 3-3) during the study period.

The soil cores were collected before and after at least two irrigation events each month and around the same dates from May to November in 2011 and 2012. For each sampling event, two cores were collected from one random location within 2 m of a set of three suction cup lysimeters installed at each of the four sampling locations (see chapter 3, Fig. 3-3). The N concentration in the soil water samples from the lysimeters was determined, and the data were used in the N balance presented in chapter 7. The grass was clipped to

about 1.3-cm height above the soil surface prior to collecting the soil core with a 5.1 cm i.d. by 30.5 cm long sampler cup (coring tube) attached to a slide hammer. The cores were held in a cooler and transported within 2 to 3 h of sampling to a laboratory at the U.S. Department of Agriculture (USDA) Pasture Systems and Watershed Management Research Unit (PSWMRU) at Penn State.

*Soil temperature, moisture content, water-filled pore space (WFPS), and soil nitrate*
Before collecting a core, soil temperature was measured with an AquaTuff[TM] 351 (Atkins) temperature meter attached to a 16.5 cm long probe and the volumetric soil moisture content was measured with a 6 cm TH2O ML2X portable moisture probe (Dynamax®). Two additional soil moisture content measurements were made in close proximity to the location where the soil cores were removed. The moisture probe was calibrated following the method of Kaleita et al. (2005). Equation [5-1] was developed from a linear regression of the volumetric water content measured in the field and volumetric water content estimated from the gravimetric water content and porosity (estimated from assumed particle density of 2.65 g cm$^{-3}$ and the soil bulk density, g cm$^{-3}$). The gravimetric water content was determined in 12 aluminum cylinders (4.8 cm i.d. and 10.2 cm long).

$$\theta_c = -35.341\ \theta_f^3 + 44.362\ \theta_f^2 - 17.259\ \theta_f + 2.4921; \qquad R^2 = 0.94 \qquad [5\text{-}1]$$

**where:**
   $\theta_c$ = Calibrated fractional volumetric soil water content
   $\theta_f$ = Fractional volumetric soil water content measured in the field

The water-filled pore space was determined as the percentage of $\theta_c$ of the total porosity of 0.57, which was based on mean (n =3) bulk density of 1.13 g cm$^{-3}$ (0 to12 cm) (see chapter 3, section 3.4.2) and an assumed particle density of 2.65 g cm$^{-3}$.   Three disturbed soil samples (0 to 5-cm depth) were collected (near the hole where the core for denitrification measurement was removed) with a 5.1 cm diameter soil auger. The samples were composited, air dried in a greenhouse and analyzed for $NO_3$-N and ammonium ($NH_4$-N) at the PSU Agricultural Analytical Services Laboratory (AASL) using the ion specific electrode methods defined by Griffin (1995) and Mulvaney (1996). The purpose of measuring soil $NO_3$-N and $NH_4$-N concentrations was to monitor the change in the mineral N before and after irrigation. The 0 to 5 cm sampling depth was adopted to minimize disturbance of the sampling area, which could affect the WFPS and ultimately denitrification.

**5.3.2 Measuring denitrification fluxes in the laboratory**

**5.3.2.1 Handling soil cores in the laboratory**

The laboratory temperature was maintained at 21$^o$C.  Each core was placed in a 5.2 cm i.d and 12.7 cm deep schedule-40 polyvinyl chloride (PVC) sleeve with a cap cemented to the bottom, leaving a 2.54 cm deep headspace above the soil. The sleeves were topped with PVC caps that were fitted with a rubber septum (0.14 cm, Supelco Analytical). To avoid gas leakage, silicon sealant was applied around the edge between the PVC cap and sleeve.

About 15 min after capping and sealing the cores, 15 mL of air was drawn from the core headspace through the rubber septum using a 35 mL plastic syringe.  Immediately after,

15 mL of $C_2H_2$ was added to the core headspace. The 15 mL air volume was determined as being 10% of the sum of the headspace (53.9 mL) and total soil pore volume (106.8 mL). The total soil pore volume was determined from the product of the core volume (186.2 mL) and total porosity (0.57).

Fifteen mL of air was drawn from the headspace at 2 h and 6 h after adding $C_2H_2$ to cores obtained from May to August 2011, and the same volume of air was sampled from the headspace at 2 h and 4 h for the soil cores collected from September to November 2011 and from April 2012 to October 2012. The air samples were transferred to evacuated 12 mL vials. Before drawing an air sample at each sampling time, the air in the core headspace was first mixed with slow pull and push strokes via the rubber septum. The pull and push strokes helped to identify any broken spots along the silicon seal which needed mending. The core headspace was sampled at shorter incubation times than those suggested by Mosier and Klemedtsson (1994) (3, 12, and 24 h), to avoid changes in the core microclimate that could potentially affect the denitrification response. Furthermore, the purpose of processing the cores immediately after sampling and the short incubation times was to give a denitrification response closely representative of field conditions.

### 5.3.2.2 Total denitrification (kg N ha$^{-1}$) measured as $N_2O$-N in head space of undisturbed soil cores in the laboratory

Total denitrification was estimated by measuring the $N_2O$ concentrations in the air samples drawn from the core headspace and determining the corresponding mass of N. The $N_2O$ was measured using a Varian 3800 gas chromatograph (GC) equipped with an electron capture detector, a column packed with Porapak Q, and a Combi-Pal auto sampler. The chromatograph oven and injector were maintained at 50°C and the detector

at 285°C. Nitrogen was used as the carrier gas. The air samples were analyzed on the GC along with 5 - 6 sets of $N_2O$ standards. Each set of $N_2O$ standards had four 12 mL vials, two of the vials contained 1 ppm (0.00194 µg mL$^{-1}$) $N_2O$ standard and another two contained the 10 ppm (0.0194 µg mL$^{-1}$) $N_2O$ standard. The GC injection volumes were 1.0 mL for the air samples drawn from the soil core headspace before $C_2H_2$ was added and 0.2 mL for the air samples drawn after adding $C_2H_2$.

The GC produces plots of peak areas dependent on the amount of gas species injected. Thus, the GC peak areas for each set of $N_2O$ standards and their corresponding mass (µg) were fit to a quadratic equation (calibration curve) because of deviation from linearity over the range of standard concentrations. Thus, $N_2O$ (µg) in the air samples from the soil core headspace was determined using the quadratic equation and the GC peak areas for the air samples. The mass of $N_2O$ (µg) was then used in Eq. [5-2] to determine the $N_2O$-N in the samples.

$$N_2O - N = \frac{0.0636 \ N_2O \ V_g}{AV_i}$$
[5-2]

**where:**
  $N_2O$-N = estimated gaseous total denitrification, kg N ha$^{-1}$
  0.0636 = 0.636 (N fraction in $N_2O$) x 0.1 (unit conversion from µg cm$^{-2}$ to kg ha$^{-1}$)
  $N_2O$  = $N_2O$ in core headspace, µg
  $V_g$   = total gas volume ($V_h$+$V_a$), mL
  • $V_h$    = Vol. of headspace above core, mL
  • $V_a$    = volume of air filled porosity calculated as: $V_f$ -[( $\theta_c$ /f)*$V_f$], mL
    • $V_f$    = volume of total porosity (f  x $V_c$), mL
    • f      = total porosity,
    • $V_c$    = core volume, mL
    • $\theta_c$    = calibrated volumetric water content, fraction
  A     = Surface area of core, cm$^2$
  $V_i$    = injection volume on the GC, mL

### 5.3.2.3 Total denitrification fluxes measured as $N_2O$-N in head space of undisturbed soil cores in the laboratory (kg N ha$^{-1}$ h$^{-1}$)

The $N_2O$-N from each soil core was determined using Eq. [5-2] (Mosier and Klemedtsson, 1994). The denitrification fluxes were corrected to the *in-situ* soil temperature using a $Q_{10}$ temperature coefficient value of two (Knowles, 1981; Rolston et al., 1984).

$$Q = \frac{M_s - M_1}{T_s - T_1}$$ [5-3]

**where:**

$Q$ = $N_2O$-N flux, kg N ha$^{-1}$ h$^{-1}$
$M_s$ = $N_2O$-N produced in soil core during the second sampling interval, $T_s$ (determined using Eq. [5-3]), kg N ha$^{-1}$
$M_1$ = $N_2O$-N produced in soil core during the first sampling interval, $T_1$ (determined using Eq. [5-3]), kg N ha$^{-1}$

$T_s$ = Second air sampling time of core headspace after initiation (6 h (May to August 2011) and 4 h for the rest of the study), h

$T_1$ = First air sampling time of core headspace (2 h after adding $C_2H_2$), h

### 5.3.2.4 Denitrification flux and *f*md per irrigation cycle

The exponential model $y = ae^{-bx}$ (where y is the estimated denitrification N loss (kg N ha$^{-1}$day$^{-1}$) and x the number of days after irrigation ceased) was used to estimate denitrification per irrigation cycle. The assumption of using an exponential model to estimate denitrification per irrigation cycle was based on what others have observed in denitrification studies in MWE irrigation.  Ryden et al. (1981) and Barton et al. (1998) observed an exponential decrease in the denitrification fluxes 24 h after irrigation ceased

until the next irrigation cycle began unless rainfall occurred. In addition, denitrification

appeared to decrease exponentially during preliminary studies of this research (Fig. 5-2).

The denitrification fluxes in Fig. 5-2 were determined following the method described in

sections 5.3.2.2 and 5.3.2.3 with Ts and $T_1$ at 6 h and 2 h, respectively.



**Figure 5-2 Mean (n=4) hourly denitrification flux between two irrigations in August 2010.** AI = 4 to 5 h after irrigation ceased and BI= 6 to 7 h before subsequent irrigation began.

The exponential equation ($y = ae^{-bx}$) was fit to the data in Figure 5-2 and the correlation

of determination ($R^2$) for the plot of the denitrification fluxes to the days from 10 to 14

August 2010 was 0.81, and the $R^2$ was 0.11 for the plot of the denitrification fluxes to the

days from 10 to 16 August 2010. The latter $R^2$ (0.11) was probably due to the rainfall

event on 15 August. Furthermore, simulated denitrification ($N_2O+N_2$) (kg N $ha^{-1}$ $d^{-1}$)

between two consecutive irrigations for model simulations completed with the

Denitrification Decomposition (DNDC) model and Cycles, a PSU Agro-ecological model (developed by Dr. Armen Kemanian at Penn State University, University Park) in this study also tended to decrease exponentially.

For each irrigation cycle, the constants a and b in the equation $y = ae^{-bx}$ were determined by dividing $y = ae^{-bx}$ (where y =estimated daily AI denitrification flux; x= 1) by $y = ae^{-bx}$ (where y=estimated daily BI denitrification flux and x = 7). The AI and BI daily denitrification fluxes were extrapolated from the mean hourly denitrification fluxes calculated in section 5.3.2.3 by multiplying the mean hourly denitrification fluxes by 24. The *f*md value was calculated from the estimated denitrification N loss (kg N ha$^{-1}$) and the MWE-TN application rate (kg N ha$^{-1}$) per irrigation cycle.

The estimated *f*md values were assessed against the ratio of the BI mean hourly denitrification flux to the AI mean hourly denitrification flux per irrigation cycle. The ratio was expected to be less than unity since AI denitrification fluxes were expected to be greater than the BI fluxes due to the potential of having increased WFPS after irrigation, which partly favor denitrification. The motivation for the assessment of the *f*md values against the BI and AI denitrification fluxes was because Hooda et al. (2003) observed an exponential decrease in the ratio of the denitrification flux on the days (10 to 14 days) between irrigations to the denitrification flux on the first day after irrigation ceased.

## 5.4 Statistical analyses

Soil denitrification is known to be very highly variable (Rice and Smith, 1982; Folorunso and Rolston, 1984; Parkin et al., 1987), with coefficients of variation (CVs) sometimes exceeding 100% and soil denitrification is usually log normally distributed

(Parkin et al., 1988; Parkin and Robinson, 1989). The variability is often manifested in data sets where most samples have low (or undetectable) rates, and a few samples displaying very high rates (Parkin and Robinson, 1989). The denitrification fluxes for the eight samples collected on each sampling date were tested for normality in Minitab 16 using the Anderson-Darling test, by evaluating the null hypothesis ($H_o$) that the hourly denitrification fluxes on each sampling date followed a normal distribution at a 0.05 level of significance. The estimated AI and BI mean (n=8) daily denitrification fluxes were compared using one-way analysis of variance (ANOVA) and the Tukey's pairwise mean comparison test at a 95% confidence interval using Minitab 17.

## 5.5 Results and discussion

About half (57.8%) of the denitrification fluxes (kg N ha$^{-1}$h$^{-1}$) measured on 63 sampling dates were normally distributed ($\alpha = 0.05$) (Appendix H). The mean (n=8) AI denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$) were greater than the BI fluxes-possibly due to temporary anaerobic soil conditions that favor denitrification and increased availability of denitrification substrates (e.g. dissolved organic carbon and soil $NO_3$ concentration). In laboratory studies of potential denitrification at the PSU LF, Brar et al. (1978) measured increased denitrification in water-extracted soils, and the authors concluded that in addition to removing possible water-soluble substances toxic to denitrification, the

increase in denitrification was also possibly due to the release of easily decomposable carbon.

During the study period the WFPS (before and after irrigation) was always above 60% (Fig. 5-3), which is generally considered to be the threshold WFPS needed for anaerobic conditions that favor denitrification according to Nommik (1956). Hooda et al. (2003) measured high denitrification fluxes when the WFPS was greater than 60% for MWE irrigation events in *Eucalyptus globulus* plantations. On 26 September 2011, rainfall occurred after soil samples were collected, hence, the WFPS at sampling time did not include the additional 2.64 cm of rain (about half of the irrigation depth) (Appendix H). The denitrification fluxes were not linearly correlated to the WFPS. Fernandes (2011) also found no predictive linear relationship between denitrification and WFPS.



**Figure 5-3 Mean hourly denitrification fluxes vs water-filled pore space.**

Figure 5-4 suggests denitrification was not limited by soil nitrate at the soil surface (0 to 5 cm), since some of the smallest denitrification fluxes in this study were observed when soil nitrate was the highest and vice versa. In pasture grass, Ryden et al. (1981) found no relationship between the denitrification N loss and soil $NO_3$ concentration nor effluent irrigation events.



**Figure 5-4 Mean hourly denitrification fluxes vs soil nitrate at 0 to 5-cm soil depth.**

Three of the four denitrification fluxes greater than 0.1 kg ha$^{-1}$ h$^{-1}$ occurred when the measured soil temperature at 0 to 16.5-cm depth was between 20$^{o}$C and 25$^{o}$C (Fig. 5-5). This result supports a higher *f* value of 0.25 noted by Crites and Tchobanoglous (1998) for "warm" climates than 0.2 for "cold" climates for secondary-treated MWE.

The chart shows a scatter plot with the equation:

$$y = 0.14\ x + 0.17$$
$$R^2 = 0.02$$

The y-axis is labeled "Mean denitrification flux (x $10^{-2}$) (kg N ha$^{-1}$ h$^{-1}$)" and the x-axis is labeled "Soil temperature ($^{o}$C)".

**Figure 5-5 Mean hourly denitrification fluxes vs soil temperature measured at 0 to 16.5-cm depth.**

## 5.5.1 Denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$)

The AI denitrification fluxes varied more than the BI denitrification fluxes. The coefficients of variation (CV) for all the data varied from 42% on 28 September 2012 (BI) to 626% on 17 July 2012 (AI) with higher CVs tending to be on the AI sampling dates (Appendix H). The highest AI denitrification fluxes of 12.1 x $10^{-2}$ kg N ha$^{-1}$ h$^{-1}$, 27.8 x $10^{-2}$ kg N ha$^{-1}$ h$^{-1}$, and 15.1 x $10^{-2}$ kg N ha$^{-1}$ h$^{-1}$ were measured on 12 July 2011, 12 August 2011, and 25 October 2011, respectively. The lowest AI flux of 1 x $10^{-3}$ kg N ha$^{-1}$ h$^{-1}$ was measured on 17 May 2011 and 15 May 2012 (Appendix H).

The low denitrification fluxes in May were probably because the greatest fescue biomass yield accumulation occurs in May (see chapter 3, Fig. 3-5), hence greater nitrate uptake by roots and less nitrate available for denitrification. Irrigation and the rainfall events of 0.76 cm on 17 May 2011 and 4.82 cm on 14 May 2012 contributed to the WFPS of 97% on 17 May 2011 and 81% on 15 May 2012 (Appendix H), which would favor denitrification, the low denitrification fluxes (compared to the others in the year) might have been due to slow diffusion of nitrous oxide and dinitrogen from the soil cores.

The highest BI fluxes of $8.3 \times 10^{-2}$ kg N ha$^{-1}$ h$^{-1}$ and $5 \times 10^{-2}$ kg N ha$^{-1}$ h$^{-1}$ were measured on 15 August 2011 and on 6 August 2012, respectively. The lowest BI flux of $2 \times 10^{-4}$ kg N ha$^{-1}$ h$^{-1}$ was measured on 21 May 2012. This low denitrification flux was comparable to $4 \times 10^{-4}$ kg N ha$^{-1}$ h$^{-1}$ measured on 21 June 2012 after the grass field had not been irrigated for a month. The WFPS was 67.2% on 21 May 2012 and 65.2% on 21 June 2012 (Appendix H), just above the threshold WFPS of 60% needed for anaerobic conditions that favor denitrification.  The denitrification fluxes in July were likely least affected by the UAN-30 fertilizer applications on 22 April 2011, 5 August 2011, 6 April 2012 and 3 August 2012.

According to a Tukey's pairwise comparison test the means (n=8) of the AI and BI hourly denitrification fluxes per irrigation cycle were statistically different ($\alpha$=0.05) for the irrigation cycles in July and August (2011 and 2012) and September and October 2011. However, the means of the AI and BI fluxes were not  statistically  different ($\alpha$=0.05) for the irrigation cycles between 2 and 6 June 2011, 15 and 21 November 2011, 15 and 21 May 2012, and 22 to 25 June 2012.

Apart from the irrigation cycle from 2 to 6 June 2011, rainfall occurred a day before the BI date or on the BI date in these irrigation cycles and probably resulted in denitrification fluxes similar to those caused by irrigation. Rainfall events on or near the BI dates were 4.75 cm (21 November 2011), 1.93 cm (21 May 2012), 1.07 cm (24 June 2012), and 0.08 cm (25 June 2012) (Appendix B).

The mean (n=8) BI denitrification fluxes on Mondays were linearly correlated to the fluxes measured on Fridays, three days after irrigation ceased in the irrigation cycle (Fig. 5-6). The pairs of denitrification fluxes plotted in Figure 5-6 are 18 and 14 May (BI), 25 and 21 May (BI), 29 and 25 June (BI), 13 and 9 July (BI), 20 and 16 July (BI), 10 and 6 August (BI), 17 and 13 August (BI), 26 and 22 October (BI). The fluxes were linearly correlated probably due to rainfall that occurred a day before or on Monday or Friday. The relevant rainfall events were 0.94 cm (13 May), 4.83 cm (14 May), 1.93 cm (21 May), 1.07 cm (24 June), 0.58 cm (15 July), 1.23 cm (19 July), 1.27 cm (20 July), 1.65 cm (9 August), and 0.99 cm (13 August) (Appendix B). Based on the good correlation between the fluxes in Fig. 5-6 it is surmised that in case there is little or no rainfall between two consecutive weekly irrigations, the BI fluxes could be those measured either 1, 2, or 3 days before irrigation began.

**Figure 5-6 Mean hourly denitrification fluxes on Fridays vs fluxes on Mondays (BI) in 2012.**

On some occasions, the estimated denitrification fluxes (apart from those in August) were roughly similar to the fluxes measured elsewhere in effluent-irrigated surface soils. Ryden et al. (1981) measured denitrification fluxes between $0.07 \times 10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ and $3.1 \times 10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ in pasture grasses, whereas Barton et al. (1998) measured denitrification fluxes of $0.03 \times 10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ in an unfertilized forest. Hooda et al. (2003) measured denitrification fluxes in the range of $0.82 \times 10^{-2}$ to $9.1 \times 10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ on the first day after irrigation in a *Eucalyptus globulus* plantation in the summer in Australia. In the studies by Ryden et al. (1981) and Hooda et al. (2003) $NH_4$-dominated effluents were used, whereas the irrigation frequency and effluent

characteristics ($NO_3$-N dominated) in the study by Barton et al. (1998) were similar to those at the LF study site. Fedler et al. (2003) measured denitrification capacities of 1.2 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ , 1.7 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$, and 2.5 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ in sandy loam, loam, and clay loam soils, respectively, on the second day after saturating cores with effluent (from a Bermuda grass field). The denitrification flux for the loam soil of Fedler et al. (2003) was comparable to some of the fluxes measured in this study on 2 June 2011 (1.6 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$), 11 August 2011 (1.9 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ ), 27 September 2011 (1.8 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$ ), and 14 August 2012 (1.6 x $10^{-2}$ kg N $ha^{-1}$ $h^{-1}$). The 5 to 15-cm soil depth at the study site is predominantly loam (see chapter 3, Table 3-1). Although the denitrification fluxes were likely influenced by the UAN-30 fertilizer application, some of the fluxes were similar to those measured in other effluent irrigation studies (e.g. Ryden et al., 1981; Fedler et al., 2003).

### 5.5.2 *f*md estimates

Table 5-1 provides relevant data and calculated *f*md for twelve irrigation cycles, seven of the *f*md values were less than one (*f* values greater than one are unreasonable for design purpose). While all the *f*md values are not amenable to simple interpretation, some features of the data are noteworthy. For example, three *f*md estimates were in the range of 3 and 3.5 for three irrigation cycles (12 to 15 August 2011; 16 to 22 August 2011; and 7 to 13 August 2012) in August when UAN-30 fertilizer was applied to the grass field. Thus, it is likely that in August some of the measured denitrification N loss originated from the UAN-30 fertilizer and not from the applied effluent.

**Table 5-1 Measured denitrification and *f*md per irrigation cycle**

| Irrigation cycle[1] | Rain fall during irrigation cycle (cm) | Measured mean denitrification flux[2] (x $10^{-2}$) (kg N ha$^{-1}$ h$^{-1}$) | Denitrification calculated from y=ae$^{-bx}$ (kg N ha$^{-1}$/irrigation cycle) | a in y=ae$^{-bx}$ | b in y=ae$^{-bx}$ | MWE-TN (kg N ha$^{-1}$/irrigation cycle) | *f*md (fraction) |
|---|---|---|---|---|---|---|---|
| 2 to 6 June 2011 | 0.56 | AI: 1.63<br>BI: 1.10 | 1.66 | 0.42 | 0.08 | 4.22 | 0.40 |
| 12 to 18 July 2011 | 00.0 | **AI: 12.14**<br>**BI: 0.05** | 4.82 | 7.35 | 0.93 | 4.86 | 0.98 |
| 12 to 15 August 2011 | 1.47 | AI: 27.78<br>BI: 8.32 | 17.24 | 9.01 | 0.30 | 5.28 | 3.25 |
| 16 to 22 Aug. 2011 | 3.12 | **AI: 9.72**<br>**BI: 1.01** | 6.90 | 3.40 | 0.38 | 1.97 | 3.45 |
| 21 to 26 September 2011 | 0.45 | **AI: 4.54**<br>**BI: 0.81** | 3.25 | 1.45 | 0.29 | 6.51 | 0.50 |
| 27 September to 3 October 2011 | 3.91 | **AI: 1.80**<br>**BI: 0.23** | 1.35 | 0.61 | 0.35 | 6.29 | 0.21 |
| 25 to 31 October 2011 | 2.16 | **AI: 15.12**<br>**BI: 0.72** | 8.85 | 6.03 | 0.51 | 8.12 | 1.10 |
| 15 to 21 November 2011 | 5.59 | AI: 5.40<br>BI: 0.40 | 3.51 | 2.00 | 0.43 | 5.01 | 0.70 |
| 15 to 21 May 2012 | 2.36 | AI: 0.10<br>BI: 0.02 | 0.08 | 0.03 | 0.31 | 3.42 | 0.02 |
| 22 to 25 June 2012 | 1.14 | AI: 1.99<br>BI: 0.83 | 1.37 | 0.60 | 0.22 | 1.90 | 0.74 |
| 10 to 16 July 2012 | 0.64 | **AI: 1.05**<br>**BI: 0.16** | 0.84 | 0.34 | 0.31 | 4.21 | 0.19 |
| 7 to 13 August 2012 | 2.87 | **AI: 13.17**<br>**BI: 1.13** | 8.86 | 4.76 | 0.41 | 3.06 | 2.87 |

[1]AI and BI dates, respectively in an irrigation cycle.
[2]Bolded denitrification means are significantly different (α=0.05).

### 5.5.2.1 *f*md estimates in May

The *f*md of 0.03 estimated for the irrigation cycle between 15 and 21 May 2012 was due

to the low denitrification fluxes measured in May 2012 (see section 5.5.1) despite

possible anaerobic conditions due to the WFPS of 81.4 (see Appendix H) on 15 May

2012 (AI). The measured denitrification fluxes were small possibly due to a limitation in

the denitrification activity influencing factors such as dissolved organic carbon and soil

$NO_3$ or slow increase of the air-filled porosity to allow diffusion of the denitrification

products from the undisturbed cores. During the irrigation cycle between 15 and 21 May

2012, soil air-filled porosity probably limited the amount of denitrification productions

due to the 5 cm irrigation and 2.8 cm rainfall on 14 May and 1.9 cm rainfall on 21 May

(BI) (see Appendix 3A).

According to Letey et al. (1980) and Stegemann and Cammenga (1990) the fraction of

$N_2O$ and $N_2$ diffusing from soil increases as the air-filled porosity increases and the

adsorption between the gases and the soil or the clay decreases. Also despite the possible

effect of UAN-30 fertilizer application, denitrification fluxes were possibly small since

the highest N uptake in 2012 (53.1 kg N ha$^{-1}$) (see chapter 3, Table 3-4) occurred in May.

Thus, the *f*md value of 0.02 could probably be representative for the month of May for

the grass field. The *f*md estimates were not determined in May 2011 since the AI and BI

denitrification measurements were not within the same irrigation cycle.

### 5.5.2.2 *f*md estimates in June

The *f*md estimates of 0.40 (2 to 6 June 2011) and 0.74 (22 to 25 June 2012) would be

higher than the values reported in Table 5-1, since the calculated denitrification was for 5

days (June 2011)  and 4 days (June 2012) and not 7 days as  with the rest of the irrigation

cycles. The smaller MWE-TN application of 1.9 kg N ha$^{-1}$ in 2012, compared to 4.2 kg N

ha$^{-1}$ in 2011, contributed to the higher $f$md estimate in June 2012, since the calculated

weekly denitrification was 1.66 kg N ha$^{-1}$ for the irrigation cycle in 2011 and 1.37 kg N

ha$^{-1}$ for the irrigation cycle in June 2012. Both the $f$md estimates would probably be high

for design purposes, since the N uptake of 71.0 kg N ha$^{-1}$ measured for June 2011 was

even higher the crop N uptake of 59.2 kg N ha$^{-1}$ measured in April and May 2011 (see

chapter 3, Table 3-4). Since crop N uptake, tall fescue biomass yield, and air

temperatures in May and June are comparable, assuming similar $f$ values for May and

June seems appropriate.

### 5.5.2.3 $f$md estimates in July

The $f$md estimate of 0.98 for the irrigation cycle between 12 and 18 July 2011 was about

five times the $f$md estimate of 0.19 for the irrigation cycle between 10 and 16 July 2012,

although the MWE-TN application rate per irrigation cycle was roughly equal in both

years, 4.9 kg N ha$^{-1}$ (2011) and 4.2 kg N ha$^{-1}$ (2012). The $f$md estimate in 2011 was

higher than in 2012 due to the estimated AI denitrification flux of 2.7 kg N ha$^{-1}$ d$^{-1}$ on 12

July 2011, which was greater than 0.4 kg N ha$^{-1}$ d$^{-1}$ estimated on 10 July 2012. The

difference in the July $f$md estimates highlights the limitations of the method used in

estimating $f$ even for irrigation cycles occurring within the same month and year. The tall

fescue N uptake was roughly the same in July (2.8% DM in 2011 and 2.6% DM in 2012),

however, the measured aboveground biomass yield in July 2011 (716.8 kg ha$^{-1}$) was more

realistic for the grass field than in July 2012 (1187.2 kg ha$^{-1}$) (see chapter 3, Table 3-4).

Despite this fact an $f$ value of 0.99 in not realistic for design purposes, thus, the smaller

$f$md value of 0.2 estimated in July 2012 could be representative for the grass field in July.

**5.5.2.4 *f*md estimates in August**

The three *f*md estimates in August 2011 and 2012 were in the range of 3 and 3.5: 3.25 (12
to 15 August 2011), 3.45 (16 to August 2011), and 2.87 (7 to 13 August 2012), probably
due the UAN-30 fertilizer applications on 5 August 2011 and 3 August 2012. As in the
other months, in August the AI denitrification fluxes contributed more to the estimated
denitrification per irrigation cycle than the BI fluxes (Table 5-1). However, it is
suspected that N from the UAN-30 fertilizer applications, and not from the applied N,
contributed to the denitrification N losses. Thus, additional data without commercial
fertilizer are needed to estimate *f*md in August.

**5.5.2.5 *f*md estimates in September**

In 2011 the mean (n=2) *f*md was 0.35 for the two irrigation cycles: from 21 to 26
September 2011 (*f*md =0.5) and from 27 September to 3 October 2011 (*f*md=0.21).
Although the crop N uptake was roughly the same in September in both years (2.9% DM
in 2011 and 3.4% DM in 2012), the measured aboveground biomass yield of 1859.2 kg
ha$^{-1}$ in 2011 was more realistic for the grass field than 224.0 kg ha$^{-1}$ in 2012 (see chapter
3, Table 3-4). Thus considering that the measured crop N uptake in September 2011
(55.1 kg N ha$^{-1}$) was comparable to the N uptake in April and May 2011 (59.2 kg N ha$^{-1}$)
and May 2012 (53.1 kg N ha$^{-1}$) (see chapter 3, Table 3-4), the *f*md value of 0.35 may not
be representative for September. Thus, the *f*md estimate of 0.21 could be more realistic
for the month of September than 0.49. In September 2012 the *f*md estimates were not
determined since the AI and BI denitrification measurements were not within the same
irrigation cycle.

**5.2.2.6 *f*md estimates in October and November**

During the irrigation cycle between 25 and 31 October 2011 the *f*md estimate was 1.09 due to the high AI denitrification flux estimated on 25 October 2011 ($15.12 \times 10^{-2}$ kg N ha$^{-1}$ h$^{-1}$), which resulted in a high denitrification estimate for the irrigation cycle. The denitrification fluxes measured from 6 of the 8 soil cores collected on 25 October 2011 were similar to the AI fluxes measured in August in 2011 and 2012, when UAN-30 fertilizer was applied and generally greater than the fluxes from most of the soil cores in both years.

Although it was not clear why the denitrification fluxes measured on 25 October were very high compared to the other measurements in this study, the high fluxes were probably due to small crop N removal typical in October at the study site and environmental conditions. Although it is speculated that the WFPS of 91.4 % and soil $NO_3$ of 14.4 kg N ha$^{-1}$ on 25 October were comparable to what was measured on two other AI dates in October, 90.6 % (WFPS) and 18.1 kg N ha$^{-1}$ (soil nitrate) on 4 October 2011 and 91% (WFPS) and 15.1 kg N ha$^{-1}$ on 23 October 2012 (Appendix H), no conclusions could be made from the *f*md estimate in October, since *f* values > 1 are unreasonable for design purposes. Since the fraction of the annual aboveground biomass yield suggested for tall fescue in April (0.05) and October (0.06) are similar (see chapter 3, section 3.7), the same *f* value probably could be representative for the grass field during both months, however; additional data is needed. The *f*md of 0.7 in November 2011 is possible due to lack of vegetative growth and thus lack of N removal.

### 5.5.3 *f*md estimates, design *f* values, and *f* values from other MWE studies

Apart from May 2012 for which the *f*md estimate was 0.02, the rest of the *f*md estimates were generally higher than those estimated in other effluent-irrigated soils, probably because UAN-30 fertilizer application enhanced denitrification at the study site. In a study to determine the denitrification potential at the PSU LF, Brar et al. (1978) determined zero fractional denitrification N loss (as a fraction of $NO_3$-N) in the surface soil for four soil depths in the 0 to 60-cm depths of the surface soil horizon in reed canarygrass. Ryden et al. (1981) estimated the fractional atmospheric N losses (ammonia volatilization and denitrification) in the range of 0.07 to 0.09. Ryden et al. (1981) attributed low denitrification fluxes to low soil $NO_3$ and good aeration, since even after irrigation the WFPS was never above 82%, which was not the case on the AI dates in this study.

Using the weekly total denitrification and tertiary-treated MWE-TN data from Barton et al. (1998), the *f* value was determined to be 0.002 in one week and 0.011 in another week in unfertilized forest soils. Also in unfertilized soils irrigated with secondary-treated MWE in the Piedmont region of Georgia, Meding et al. (2001) estimated the fractional denitrification loss as 0.024.

Out of the 12 *f*md estimates only three values were in close proximity to design *f* values. The *f*md estimates of 0.2 in July 2012 and 0.21 in September/October 2011 (Table 5-1) were within the range of 0.15 to 0.25 (USEPA, 2006) for secondary-treated effluent and were equal to the *f* value of 0.2 suggested by (Crites and Tchobanoglous, 1998) for secondary-treated effluents in cold climates. The *f*md estimate of 0.02 in May 2012 was

smaller than the *f* value of 0.1 suggested by USEPA (2006) and Crites and

Tchobanoglous (1998) for tertiary-treated effluents (C:N ratio <1). The effluent C:N ratio

during the study period was in the range of 0.04 to 0.2 (see chapter 3, Fig. 3-5).

### 5.5.4 *f*md estimates vs ratio of the BI to AI mean hourly denitrification fluxes

The *f*md estimates decreased linearly with the ratio of the BI to AI mean hourly

denitrification fluxes measured within the same irrigation cycle when the AI and BI

fluxes were significantly different ($\alpha$=0.05) (Fig. 5-7) and when the AI and BI fluxes

were not significantly different ($\alpha$=0.05) (Fig. 5-8). In Figure 5-8, the *f*md estimate of

0.02 for the irrigation cycle between 15 May and 21 May 2012 was not plotted since it

was much smaller compared to the other *f*md values.



**Figure 5-7 *f*md estimate vs ratio of BI to AI mean hourly denitrification fluxes.** For AI and BI mean hourly denitrification fluxes that were significantly different ($\alpha$=0.05). See Table 5-1 (ratios for August not included).

**Figure 5-8** *f*md estimate vs ratio of BI to AI mean hourly denitrification fluxes. For AI and BI mean hourly denitrification fluxes that were not significantly different ($\alpha=0.05$). See Table 5-1 (ratios for August not included).

Using the BI/AI denitrification flux ratios of 0.19 and 0.17 in the linear equation in Figure 5-7, the *f*md estimates were 0.17 and 0.27, respectively, and for the BI/AI denitrification flux ratios of 0.10 and 0.22 the *f*md estimates were 0.61 and 0.03, respectively. A unit BI/AI ratio used in the linear equation in Figure 5-8 yielded an *f*md estimate of 0.3. Although BI/AI denitrification flux ratios of up to 1.6 resulted in *f*md estimates above zero the BI denitrification fluxes were always less than the AI fluxes within an irrigation cycle. However, additional data are needed to verify the relationship between *f*md and the ratio of the BI and AI denitrification fluxes measured continuously in the field.

### 5.6 Summary and conclusions

In 2011 and 2012, fractional denitrification N loss (*f*md) was estimated in a tall fescue field (15A) at the Penn State University Living Filter site. The grass field was irrigated with secondary-treated MWE at a rate of 5 cm wk$^{-1}$ and was also fertilized with urea ammonium nitrate (30%N). Denitrification was measured in intact soil cores (4.8 cm i.d. by 10.2 cm long) collected from the surface soil horizon of the grass field 4 to 5 h after irrigation ceased (AI) and 6 to 7 h before irrigation began in the next week (BI).

In both years the mean (n=8) AI denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$) were greater than the mean (n=8) BI denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$), and the denitrification fluxes in 2011 were generally higher than the fluxes in 2012. The AI fluxes were greater than the BI fluxes probably due to the temporary increase in WFPS, an increase in soil $NO_3$ on some occasions, and a possible increase in dissolved organic carbon on the AI dates. Also, in both years, the denitrification fluxes in August were greater than the fluxes in the other months probably due to increased nitrification and denitrification following UAN-30 fertilizer applications in August.

With the exception of August, the AI denitrification fluxes in both years were in the range $1 \times 10^{-3}$ to $15.12 \times 10^{-2}$ kg N ha$^{-1}$ h$^{-1}$ and the BI denitrification fluxes were in the range $2.0 \times 10^{-4}$ to $2.0 \times 10^{-2}$ kg N ha$^{-1}$ h$^{-1}$. Although the fluxes in this study were influenced by UAN-30 fertilizer application, some of the denitrification fluxes were similar to those measured in other MWE irrigation studies. In 2012, the mean (n=8) denitrification fluxes on Fridays (three days after irrigation ceased) and the BI fluxes on Mondays (6 days following irrigation) within an irrigation cycle had a linear correlation

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of determination ($R^2$) of 0.98 and slope of 0.68. This suggests the BI fluxes could be those measured either 1, 2, or 3 days before irrigation began. However, this needs to be verified with further research.

On average, the MWE-TN loading was 4 to 5 kg N ha$^{-1}$ per irrigation cycle. In 2011, the *f*md estimates were 0.40 (2 to 6 June), 0.98 (12 to 18 July), 3.25 (12 to 15 August), 3.45 (16 to 22 August), 0.50 (21 to 26 September), 0.21 (27 September to 3 October), 1.10 (25 to 31 October), and 0.7 (15 to 21 November). In 2012, the *f*md estimates were 0.03 (15 to 21 May), 0.72 (22 to 25 June), 0.19 (10 to 16 July), and 2.87 (7 to 13 August). Seven *f*md values were less than one. The *f*md estimates in September/October 2011 and July 2012 were equal to 0.2 as noted in Crites and Tchobanoglous (1998) for secondary-treated effluents in cold climates and were also in the range of 0.15 to 0.25 suggested by USEPA (2006) for secondary-treated effluents. In May 2012, the *f*md value of 0.02 was less than the design values and it is argued that the *f* values in May could even be lower in the absence of commercial fertilizer due to the high N uptake in May. The high *f*md estimate in November was probably due to lack of plant N uptake. The *f*md estimates in July and November were likely least affected by UAN-30 fertilizer applications on 22 April 2011, 5 August 2011, 6 April 2012 and 3 August 2012 and all the three *f*md estimates in August were in the range of 3 and 3.5; probably due to the UAN-30 fertilizer application. Since *f* values $\geq 1$ are not realistic for design purposes, the *f*md estimates of 0.2, 0.21, and 0.02 estimated in July 2011, September 2011, and May 2012, respectively, seemed to somewhat represent these months. The measured aboveground biomass yield and crop N removal during these months (see chapter 3, Table 3-4) was realistic for tall fescue.

The *f*md estimates and the ratio of the BI to AI mean denitrification fluxes

(kg ha$^{-1}$ h$^{-1}$) within the same irrigation cycle were fit to a linear relationship and the *f*md

estimates decreased as the ratio of the BI to AI mean denitrification fluxes increased,

irrespective of whether the BI and AI fluxes were significantly different ($\alpha=0.05$) or not.

The ratios (n=5) for the BI to AI denitrification fluxes were less than 0.2 when the BI and

AI denitrification fluxes were significantly different ($\alpha=0.05$).

For future research, additional data are needed in the absence of commercial fertilizer

applications to refine the *f*md values and the relationship between the *f*md values and the

ratios of the BI to AI denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$) within an irrigation cycle.

Additional data considerations might include continuous measurement of denitrification

on the BI and AI dates and between irrigations, especially around the two tall fescue

aboveground biomass growth peaks in May/June and August/September.

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**Chapter 6. FRACTIONAL DNDC-SIMULATED ATMOSPHERIC DENITRIFICATION NITROGEN LOSS FROM  TALL FESCUE HAY SPRAY-IRRIGATED WITH MUNICIPAL WASTEWATER EFFLUENT**

**Abstract**

The fraction of atmospheric nitrogen (N) losses and soil N storage of the total nitrogen in municipal wastewater effluent (MWE), usually denoted $f$ in the U.S., is used in the design of N-based MWE irrigation rates.  However, few scientific investigations have estimated $f$ values based on simulated atmospheric N outputs. The goal of this study was to conduct field-scale simulations for a crop field irrigated with MWE and estimate $f$ based on simulated atmospheric N losses ($N_2O$-N + $N_2$). Simulations using the DeNitrificationDeComposition (DNDC) biogeochemical model were completed for tall fescue at the Penn State University Living Filter; where secondary-treated (including biological nitrogen removal) MWE is irrigated at a rate of 5 cm $wk^{-1}$. In addition to MWE nitrogen, urea ammonium nitrate (UAN-30) fertilizer was applied to the grass field to supplement effluent N.

The DNDC Crop simulation model was parameterized in the site mode and simulations were completed using the DNDC default clay fraction (0.19 for loam soil and 0.4 for clay loam) and default saturated hydraulic conductivity, $K_{sat}$ (0.025 m $h^{-1}$ for loam soil and 0.009 m $h^{-1}$ for clay loam soil). These soil types were identified in the 5 to15-cm depth in the surface soil horizon at the study site.  Simulations were also completed using measured clay fractions of 0.26 (loam soil) and 0.31 (clay loam soil) and $K_{sat}$ measured for the 0 to 15-cm soil depth (0.017 m $h^{-1}$) in the surface soil. The simulations were named LD and CLD for the default soil properties for loam and clay soil, respectively,

and LM and CLM for the measured soil properties for loam and clay soil, respectively. The simulations were completed for the period 2004 to 2012 for latitude $40^\circ 49' 44.4''$ N. The $f$sd and the fractional denitrification N loss ($f$md), based on measured denitrification and MWE-TN, were compared.

The simulated and measured denitrification rates followed similar trends, with generally higher rates in the day after irrigation than on the day before irrigation. The model simulated before irrigation (BI) denitrification rates better than the after irrigation (AI) rates. All the mean absolute error (MAE) values, for all the four simulation types (before irrigation), were equal, 0.3 in 2011 and 0.15 in 2012 and smaller than the MAE values for the after irrigation rates, 0.98 to 5.2 in both years. For representation of the study site the average $f$sd for the LM and CLM simulations are discussed along with the $f$md and design $f$ values.

The average $f$sd (LM and CLM simulations)/ $f$md values were: 0.03/0.4 (2 to 6 June 2011), 0.01/0.98 (12 to 18 July 2011), 0.08/3.25 (12 to 15 August 2011), 0.16/3.45 (16 to 22 August 2011), 0.02/0.50 (21 to 27 September 2011), 0.01/0.21 (27 September to 3 October), 0.004/1.10 (25 to 31 October 2011), 0.02/0.70 (15 to 21 November 2011), 0.05/0.03 (15 to 21 May 2012), 0.03/0.74 (21 to 25 June 2012), 0.01/0.19 (10 to 16 July 2012), and 0.14/2.87 (7 to 13 August 2012). Due to UAN-30 fertilizer application, both the $f$sd and $f$md estimates were greatest in August. The measured and simulated denitrification rates and $f$md and $f$sd estimates in July and November were suspected to be least affected by the UAN-30 fertilizer applications in April and August in both years. The $f$sd values varied partly due to the variation in denitrification activity and effluent N application rates.

The average (n=24) $f$sd for the LM and CLM simulation for 12 irrigations in both years was 0.05. The $f$sd estimates were all smaller than the $f$md values except for irrigation cycle between 15 and 21 May 2012, when the $f$sd (0.05) and $f$md (0.03) were similar. The $f$sd estimates were also smaller than the design $f$ values; apart from August when they were near the lower boundary for design $f$ values for secondary-treated effluent (0.15 - 0.25). Based on the study findings $f$ values in the range of 0 to 0.1 and 0.1 to 0.2 could represent the months of May/June and August/September, respectively, and 0.2 could represent the month of July. However, further investigation is needed to refine the $f$sd and $f$md without commercial fertilizer application, especially during the months of May/June and August/September when the aboveground biomass of tall fescue peaks at the study site.

## 6.1  Introduction

In municipal wastewater effluent (MWE) irrigation, the effluent nitrogen (N) undergoes complex processes which are difficult to accurately assess from field measurements. Thus, simulation models provide an alternative option of assessing the fate and transport of N through the soil (Kunjikutty et al., 2007). Some of the existing models that integrate crop growth and hydrological and biogeochemical processes to simulate atmospheric N losses include: DeNitrificationDeComposition (DNDC), which simulates $NH_3$ (gas) (ammonia), NO (nitrogen monoxide), $N_2O$ (nitrous oxide), and $N_2$ (dinitrogen) emission; the Daily Century Model (DAYCENT), which simulates NO and $N_2O$ emission, and CERES and ExpertN which simulate $N_2O$ production. Model simulations in effluent irrigation (Kunjikutty et al., 2007; Sophocleous and Townsend, 2009) have been conducted to compare model estimates with reliable values.

Soil biogeochemical simulation models combine primary drivers of denitrification (soil aeration status, available organic C, and nitrate ($NO_3$) concentration) and environmental factors in mathematical relationships either to predict field denitrification rates or to investigate the influence of denitrification drivers on observed denitrification variability (Parkin and Robinson, 1989).  Due to the high variability of denitrification activity, stochastic models that generate hourly predictions distributed over the daily model output rather than a single daily prediction have been proposed as a more reliable approach to simulate denitrification rates (Parkin and Robinson, 1989). However, most denitrification models used in scientific literature are deterministic and range from simple to complex, such as those that simulate microbial growth (Heinen, 2006). Denitrification submodels are based mainly on three approaches: simple processes that do not consider microbial

growth or gaseous diffusion, microbial growth processes, or soil structure aspects (Heinen, 2006). The microbial growth models simulate the dynamics of microorganisms responsible for the N cycling processes (e.g. crop-DNDC, NLOSS, ECOSYS, and Root Zone Water Quality Model (RZWQM)), soil structural models consider the diffusion of gases into and out of soil aggregates, and simple models are based on easily measured parameters such as degree of soil saturation, soil temperature and nitrate content of the soil (Heinen, 2006). Todate, no model simulation investigations in MWE irrigation have been completed to determine the fractional atmospheric N loss in such systems. The DNDC model was used in this study because the simulated total denitrification could be estimated as the sum of the $N_2O$ and $N_2$ model outputs, and thus, the total denitrification field data gathered in chapter 5 could be compared against model predictions.

### 6.2 Research goal and questions

The goal of this study was to test the measured total denitrification against simulated atmospheric N ($N_2O$-N +$N_2$) losses predicted by the DNDC model and to determine the fractional simulated N ($N_2O$-N+$N_2$) losses from municipal wastewater-irrigated tall fescue hay (*f*sd). The following research questions were addressed:

1. How do the simulated denitrification N losses ($N_2O$-N+$N_2$) compare with the measured total denitrification N losses?

2. How do the fractional simulated N losses, (*f*sd) compare to the fractional measured denitrification N losses, (*f*md)?

3. How do the *f*sd estimates compare to the design *f* values specified by USEPA (2006) and noted in Crites and Tchobanoglous (1998)?

## 6.3  DNDC model components

The DNDC model was initially developed as a field scale, process-based, mechanistic model of nitrogen and carbon dynamics to determine $N_2O$ emissions from agricultural soils in the United States (Li et al., 1992a).  The model has been modified by integration with detailed crop growth algorithms (Zhang et al., 2002), hydrological processes to simulate $NO_3$ leaching in crop fields having a tile drainage system (Li et al., 2006), and recently, with inclusion of the curve number (SCS) runoff calculation and the revised universal soil loss equation (RUSLE) for erosion prediction (Deng et al., 2011).

The DNDC model consists of two major components (Fig. 6-1). The first component consists of the soil climate, plant growth and decomposition submodels, which predict the soil environmental factors using primary/ecological drivers as inputs (climate, soil properties, vegetation and anthropogenic activity) (Li et al., 1992a,1992b; Boyer et al., 2006). The soil climate submodel uses daily climate data to predict soil temperature and moisture profiles for the 50 cm surface soil horizon (Li et al., 1992a; DNDC, 2012b). In addition, the soil climate submodel calculates soil oxygen diffusion within the soil profile (Li et al., 2000). The plant (i.e. crop or forest) growth submodel simulates plant growth and is driven by solar radiation, temperature, water stress and N stress. The plant, soil climate and decomposition submodels are linked through litter production and water and N demands. The decomposition submodel tracks the turnover of organic matter in the soil, and provides soil solution $NH_4$, $NO_3$ and dissolved organic carbon (DOC) concentrations to the nitrification and/or denitrification submodels (Fig. 6-1) (Li et al., 1992a).

**Figure 6-1 DNDC model structure** (Li et al., 1992a).

The second component is the 'biogeochemical field', which plays a core role in the model, and consists of the nitrification, denitrification, and fermentation submodels. These submodels quantify production and consumption of $N_2O$, NO, $N_2$, $NH_3$ and $CH_4$ by tracking the kinetics of relevant biochemical or geochemical reactions, driven by the modeled soil environmental factors (Boyer et al., 2006). The nitrification submodel predicts $N_2O$ and NO production from nitrification regulated by soil temperature, moisture, ammonium, DOC concentration, growth and death of nitrifiers, and the nitrification rates. The denitrification submodel simulates denitrification and changes in the denitrifier biomass as a function of soil temperature and moisture, pH, and substrate

(e.g. DOC, $NO_3^-$, $NO_2^-$, NO and $N_2O$) concentrations. The denitrification-induced $N_2O$ and $N_2$ fluxes are determined based on substrate availability, air-filled porosity, and gas diffusion.

The fraction of $N_2O$ (Letey et al., 1980; Stegemann and Cammenga, 1990) and $N_2$ (Letey et al., 1980) diffusing from soil increases as the air-filled porosity increases and the adsorption between the gas and the soil or the clay content decreases. Table 6-1 includes highly sensitive factors for the DNDC model as a whole and the thermal-hydraulic, decomposition, and denitrification submodels, as noted by Li et al. (1992a).

**Table 6-1 Highly sensitive factors to denitrification substrates and products in the DNDC model** (Li et al., 1992a).

| Model | Item | Highly Sensitive Factors |
|---|---|---|
| DNDC model | $N_2O$ | (1) Soil clay content<br>(2) Soil organic C<br>(3) Mean annual temperature |
| | $N_2O+N_2$ | (1) Annual precipitation<br>(2) Soil $pH$<br>(3) Mean annual temperature<br>(4) Soil organic C |
| | $CO_2$ | (1) Soil organic C<br>(2) Soil clay content<br>(3) Mean annual temperature<br>(4) Annual precipitation |
| Thermal-hydraulic submodel | Soil moisture | (1) Rainfall patterns<br>(2) Soil texture |
| Decomposition submodel | Soluble C | (1) Initial organic C<br>(2) Soil temperature<br>(3) Soil moisture<br>(4) Dry period duration |
| | Nitrate | (1) Initial organic C<br>(2) Dry duration<br>(3) Soil temperature<br>(4) Soil moisture |
| Denitrification submodel | $N_2O$ | (1) Precipitation<br>(2) Soil soluble C<br>(3) Soil nitrate<br>(4) Soil texture |

In the DNDC model $N_2O$ plus $N_2$ emitted per day is the fraction of the total gas evolved in a day and is dependent on clay content and air-filled porosity (Eqs. [6-1] and [6-2]) (Li et al., 1992a).

$$P (N_2O) = (0.0006+0.0013*AD) + (0.013 - 0.005*AD)*PA \qquad [6-1]$$

$$P (N_2) = 0.017+ (0.025-0.0013*AD) *PA \qquad [6-2]$$

**where:**

     $P (N_2O)$ = emitted fraction of the total $N_2O$ evolved in a day.
     AD     = adsorption factor (0-2), which is selected depending on the soil clay
           fraction.
     PA     = air- filled fraction of total porosity (1-WFPS) $2^{Ts/20}$

     **where:**
           $T_s$     = soil daily temperature in a soil horizon (Zhang et al.,
               2002).
           WFPS = water-filled pore space.
           $P (N_2)$ = emitted fraction of the total $N_2$ evolved in a day.

The hydrological and other biogeochemical process equations are detailed by Li et al. (1992a), Li et al. (2000), Zhang et al. (2002), Li et al. (2006), Deng et al. (2011), and Li et al. (2012).

## 6.4 Model parameterization

The DNDC (crop) model was downloaded from http://www.dndc.sr.unh.edu/ and parameterized in the site mode, which has three major information input windows: climate, soil, and cropping (farming management practices). According to Shaffer and Delgado (2001) running a model for multiple years to dynamic steady-state conditions reduces the effects of the initial conditions and allows long-term trends to become more visible. Therefore, simulations were performed for the period of 2004 to 2012, when

irrigation data for the grass field were available from the farm operations and services unit, College of Agricultural Sciences. The simulations were completed for the loam and clay loam soil types at the study site (see chapter 3, Table 3-1), since $N_2O$ outputs in the denitrification submodel were found to be highly sensitive to the soil texture (Fig. 6-2). For each soil type, simulations were completed using default and measured clay fraction and saturated hydraulic conductivity ($K_{sat}$) (m h$^{-1}$), referred to as conductivity in DNDC. Simulations that were completed with default soil properties were named LD and CLD for loam and clay loam soil types, respectively, and simulations that were completed with measured clay fraction and $K_{sat}$ were named LM and CLM for loam and clay loam soil types, respectively.

## 6.4.1 Climate

The latitude 40 $^{o}$ 49 ' 44.4 '' N for lysimeter 8 was used in the model and simulations were completed for nine years (2004 - 2012). The climate text file for each year was created in the DNDC format as: day of year, maximum and minimum air temperature ($^{o}$C), rainfall (cm) and solar radiation (MJ m$^{-2}$ d$^{-1}$). The rainfall data for 2011 and 2012 were obtained from TR-525USW (Texas Electronic Inc.) rainfall sensor (as noted in chapter 3, section 3.8) and, for the rest of the years, rainfall data from a weather station at the Walker Building at the PSU University Park Campus (NOAA station ID 36844, approximately 4 km from the study site) was used. The mean air temperature at 2-m height and solar radiation data for all the years were obtained from http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV and http://power.larc.nasa.gov, respectively, as noted in chapter 3, section 3.9. Climate data for 2011 and 2012 are presented in Appendix B.

The air temperature and rainfall are used in the thermal-hydraulic submodel to simulate

soil heat flux and moisture flow and calculate hourly and daily mean soil temperature and

moisture profiles (Li et al., 1992a), whereas the predicted soil temperature and moisture

are used in the decomposition submodel to determine the carbon pool decomposition and

nitrification rates.

The rainfall N concentration of 1 mg $L^{-1}$ was used since the annual rainfall N (sum of

$NO_3$-N and $NH_4$-N) was determined as 0.93 mg $L^{-1}$ in 2011 and 0.76 mg $L^{-1}$ in 2012 (see

chapter 3, section 3.6). In DNDC, rainfall N is placed in the $NO_3$ pool in the

decomposition submodel. The annual atmospheric background $NH_3$ concentration of

0.33μg $m^{-3}$ was obtained from the Ammonia Monitoring Network (AMoN) PA29 site

(Kane Experimental Forest) located at latitude 41 $^o$ 35 ' 52.8 " N and longitude 78 $^o$ 46 '

1.2 " W and an elevation of 618 m for the period March 2011 to December 2012. The

mean annual atmospheric background $CO_2$ concentration of 377 ppm (2004) and $CO_2$

annual increase rate of 2 ppm $yr^{-1}$(2004 to 2012) were  used based on the annual mean

global $CO_2$ data (Ed Dlugokencky and Pieter Tans, NOAA/ESRL,

www.esrl.noaa.gov/gmd/ccgg/trends/)).  The atmospheric background $CO_2$ concentration

affects plant photosynthesis.  In free-air $CO_2$ enrichment (FACE) experiments, Ainsworth

and Long (2005) and Ainsworth and Rogers (2007) observed less enhancement of

photosynthesis and crop yield under low soil N conditions than with high soil N. For

illustration purposes, only the model input information for the loam soil default settings is

presented. Figure 6-2 shows an example of a completed climate input window.

**Figure 6-2 DNDC site mode climate input window.**

### 6.4.2 Soil properties

As noted in section 6.4 the simulations were completed with default and measured clay

fraction and $K_{sat}$ for loam and clay loam soil types. Otherwise the soil input information

was the same for all the four simulations.

*Land use and soil texture and initial SOC content*

Moist grassland/pasture was selected as the land-use type because of the humid climate in

central PA and also because the study site is irrigated weekly. Soil pH of 7.2 (see chapter

3, section 3.4.1) and a mean (n=2) bulk density of 1.25 g cm$^{-3}$ for the 0 to 6- cm and 6

to12-cm soil depths (see chapter 3, section 3.4.2) were used. Since the model

automatically computes the bulk density based on the SOC input, a SOC value of 0.0156

was used to give a bulk density of 1.25 g cm$^{-3}$. According to Li et al. (1992a), DOC and

$NO_3$ in the decomposition model were found to be highly sensitive to the initial SOC, and

$N_2O$ was highly sensitive to the input clay fraction. In the decomposition submodel, the

clay fraction affects ammonium adsorption, ammonia volatilization, and the carbon pool

decomposition rate through a logarithmic clay reduction factor relationship, while in the

denitrification submodel the clay fraction affects the fraction of $N_2O$ and $N_2$ emitted from

the soil through the adsorption factor (AD) (see equations [6-1] and [6-2]).

The calculated WFPS at field capacity and wilting point for loam and clay loam soils

used in all simulations are presented in Table 6-2.

**Table 6-2 Calculated WFPS at field capacity and wilting point for loam and clay
       loam soils.**

| Soil type | Silt (fraction)[a] | Clay (fraction)[1] | SOM (%)[2] | Volumetric water content at field capacity $(m^3\ m^{-3})^3$ | Volumetric water content at wilting point $(m^3\ m^{-3})^3$ | WFPS[4] at field capacity | WFPS[4] at wilting point |
|---|---|---|---|---|---|---|---|
| Loam | 0.34 | 0.26 | 3.8 | 0.33 | 0.17 | 0.61 | 0.33 |
| Clay loam | 0.36 | 0.31 | 3.8 | 0.34 | 0.20 | 0.64 | 0.37 |

[1]Mean from Table 3-2 in chapter 3 for 5 to15-cm soil depth
[2]Mean for 4.5 % (0 to5 cm) and 3.1% (5 to15-cm soil depth) (see chapter 3, section 3.4.1)
[3]Using equations from Saxton and Rawls (2006). Note: fractional silt and clay content, not %, is used in the equations.
[4]WFPS calculated based on porosity of 0.53. Porosity was calculated based on bulk density and particle density of 1.25 g cm$^{-3}$ and 2.65 g cm$^{-3}$, respectively.

*Soil structure*

A bypass flow rate in a range of 0-1 can be defined if the soil has macropores. Luo et al.

(2010) measured macro porosity of 0.06 m$^3$ m$^{-3}$ in pastured Hagerstown soil; however,

the value could not be modified in the model so the default value of 0 was used for the

simulations. The depth of the water retention layer was selected as 1.8 m since a suction-

cup lysimeter (LYS8) (see chapter 3, Fig. 3-3) at this depth usually yielded water samples

following an irrigation or rainfall event. The drainage efficiency is not clearly defined in

the DNDC (v9.3 and v9.5) manuals. However, in DNDC application studies, Tonitto et

al. (2007) define a DNDC default value of 0.4 as the proportion of water lost from the

freely available water pool. This value was used as the drainage efficiency for all

simulations.

*Initial SOC profile and partitioning and decomposition rates*

The mean (n=9) soil organic carbon measured at the study site decreased with each of the

three soil depths: 0 to 5-cm, 5 to 15-cm, and 15 to 30-cm. For this section an SOC input

value of 0.05 was used instead of a value of 0. The mean (n=8) rate of decrease of SOC

below the top soil was estimated as 2.16 using SOC data in Table 6-3 (courtesy of Dr.

Curtis. J. Dell, USDA/ARS/PSWMRU) measured in pastures at the PSU Haller farm

located less than 2 km from the study site. The Hagerstown silt loam soils at the Haller

Farm are similar to those at the study site. The SOC decrease rate below the top-soil

(assumed as 0 to 20 cm depth) was estimated as the SOC change between the 20 to 30 cm

depth and 30 to 60 cm depth with the measured SOC values considered to be in the

middle of the soil layer: thus soil depth used to calculate the SOC change rate was 20 cm.

**Table 6-3 Measured soil organic carbon (SOC, %) in pasture fields and SOC decrease rate below the top-soil (0 to 20-cm depth).**

| Soil depth | Pasture 1 | | | | Pasture 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Core 1 | Core 2 | Core 3 | Core 4 | Core 1 | Core 2 | Core 3 | Core 4 |
| 0 to 5 cm | 3.02 | 3.91 | 3.44 | 3.12 | 2.74 | 2.98 | 3.55 | 2.87 |
| 5 to 10 cm | 2.26 | 2.99 | 2.64 | 1.84 | 1.80 | 2.11 | 2.54 | 2.10 |
| 10 to 20 cm | 1.42 | 1.92 | 1.95 | 1.29 | 1.55 | 1.35 | 1.71 | 1.30 |
| 20 to 30 cm | 0.70 | 1.07 | 1.45 | 0.83 | 0.71 | 0.77 | 0.99 | 0.81 |
| 30 to 60 cm | 0.44 | 0.91 | 0.76 | 0.48 | 0.09 | 0.38 | 0.40 | 0.39 |
| SOC decrease rate below 0 to 20-cm soil depth | 1.29 | 0.77 | 3.46 | 1.72 | 3.09 | 1.95 | 2.98 | 2.07 |

The default SOC partitioning with a bulk C:N ratio of 10:1 was used. Li et al. (1992a) suggest a multiplicative factor of 1 for the decomposition rate of litter for loam soils and 0 for decomposition of resistant humads (active humus) to labile humads for no-till field management. Therefore, multiplication factors of 1 and 0 were used for litter and for humads and humus carbon pools, respectively.

*Initial NO$_3$-N and NH$_4$-N concentration at the soil surface, microbial activity, slope, soil salinity, rainwater collection index, and SCS and RUSLE parameters*

According to Li et al. (1992a) the initial NO$_3$-N and NH$_4$-N has little to no effect on the annual N$_2$O emissions, thus DNDC computes the initial NO$_3$-N concentration using the site latitude (Appendix I) and the initial NH$_4$-N concentration as a tenth of the initial NO$_3$-N concentration. Thus the initial NO$_3$-N and NH$_4$-N concentrations of 0.5 and 0.05 mg N kg$^{-1}$, respectively, were used.

Assuming baseline or enhanced microbial activity, a microbial activity index of 1 from a range of 0 to 1 was used. In enzyme activity studies, Chen et al. (2008) and Elifantz et al. (2011) found enhanced microbial activity in treated wastewater-irrigated soils. Enzyme activities can indicate the status of microbial activity and dependent soil biochemical processes (Bucher, 2002).

A slope of 2$^o$ was used based on an estimated slope of 3% for the area in the grass field where soil samples were collected. The 3% slope was based on the lowest (357.84 m) and highest (359.66 m) contours (see chapter 3, Fig. 3-2) and a distance of 30.5 m between the irrigation laterals (see chapter 3, Fig. 3-3).

Larson (2010) measured electrical conductivity of 0.821 dS m$^{-1}$ in the Ap horizon at the PSU LF, and Chen et al. (2008) measured electrical conductivity in the range of 0.8 to 1.9 dS m$^{-1}$ in wastewater-irrigated pasture in southern California.  The electrical conductivity of 0.821 dS m$^{-1}$ at the study site was assumed not to affect crop growth since the restriction on wastewater reuse is slight to moderate for wastewaters with electrical conductivity in the range of 0.7 to 3.0 (USEPA, 2012).   Thus a salinity index of 0 was used from the range of 0 to 100.

In DNDC, the rainwater collection index (0 to 1) is defined as how much water can be collected at the study site in addition to precipitation. For example, water from up-hill areas may flow into low lying areas/study sites. The DNDC addresses these phenomena as follows: if the rainwater collection index is set as 1 and precipitation is 2.0 cm in a rainfall event, 4.0 cm of precipitation will be input into the low-lying area/study site (Jia Deng, email communication April 2013). However since the study site has a perennial crop, runoff was considered to be minimal and a rainwater collection index of 0 was used.

The hydro-parameters of 58 (SCS curve number (CN)) and 0 (effect of land management on erosion) were used.  The CN was based on hydrologic soil group B for permanent meadow protected from grazing (Fangmeier et al., 2006). Novotny (2003) suggests a Manning's roughness coefficient in the range of 0.05 to 0.1 for grass and pasture; thus a coefficient of 0.12 (for no-till, 0.5 to 1 ton ha$^{-1}$ of residue) from the DNDC table was used for the simulations. Figure 6-3 is a completed soil information input window.

**Figure 6-3 DNDC site mode soil input window showing model default values for clay fraction and Ksat.**

The DNDC defaults for the clay fraction in loam and clay loam soils are 0.19 and 0.4,

respectively, and the defaults for the $K_{sat}$ values for loam and clay loam soils are 0.025 m

$h^{-1}$ and 0.009 m $h^{-1}$, respectively. The measured clay fraction was input as 0.26 and 0.31

for loam and clay loam soil (see chapter 3, Table 3-1 for the 5 to 15-cm soil depth),

respectively, and 0.017 m $h^{-1}$ was input as the measured $K_{sat}$ (Appendix J). The $K_{sat}$ was

measured in the laboratory using a permeameter designed by Walker (2006), in which the

inner flow and edge/boundary flow from intact soil cores were separated. According to

Walker (2006) the traditional constant-head soil core laboratory method has the potential

to overestimate $K_{sat}$, due to preferential flow of water between the soil core and the

cylindrical ring used to hold the core. Three intact soil cores (8.9 cm (i.d) and 15.24 cm

high) were collected about 4.5 m uphill from lateral 10-1 and opposite sprinklers SP-3,

SP-4, SP-5 and SP-6 (see chapter 3, Fig. 3-3) using a tractor-mounted hydraulic

Gidding's probe. The cores were saturated from the bottom for 24 h in a water bath in the

laboratory. Cheese cloth was wrapped on the bottom of the cores to prevent soil loss

during saturation. Walker (2006) determined 84 to 85 % and 93 to 94% mean water

saturation after saturating cores for 1 and 4, and 7 and 14 days, respectively. The author

found no significant difference in percent saturation between cores saturated for 1 and 4

days, 4 and 7 days, and 7 and 14 days. The $K_{sat}$ (Eq. [6-3]) was determined by

rearranging Darcy's equation as follows:

$$K_{sat} = \frac{VL}{AT(H_2 - H_1)} \qquad [6-3]$$

**where:**

$K_{sat}$ = Saturated hydraulic conductivity, cm $min^{-1}$
V = Steady-state volume of water flowing through the core, $cm^3$
L = Sample length, cm
A = Cross sectional area of the core, $cm^2$
T = Time, min
$H_2$ - $H_1$ = Hydraulic head difference, cm

Walker (2006) found that after removal of the boundary flow and using the inner flow

water volumes from the core, the laboratory determined saturated hydraulic

conductivities were much more comparable to the field determined $K_{sat}$. Therefore, the

inner flow water volume (V), which was measured in 10 min (T in Eq. [6-3] intervals was

used for the $K_{sat}$ calculations. The area (A) for the inner ring (8 cm dia.) was used. The

reference point was the bottom of the core, thus $H_1$ =0, whereas $H_2$ was the sum of h and

L, where L was the height of the soil core (15.24 cm) and h was the hydrostatic head

(Appendix J).

### 6.4.3 Farming management practices

### 6.4.3.1 Crop parameters

The number of cropping systems applied during the simulation years was equal to the

simulations years (9). Therefore, for each year, new crop parameter, fertilizer application,

and grass cutting information was put into the model.  Non-legume hay was selected as

the crop type (Crop_5) (DNDC, 2012a).  A single new crop was selected for each year

and the months of April and October were chosen as planting and harvest months,

respectively, based on the seasonal distribution of forage production in PA (see chapter 3,

Fig. 3-5). When the grass field was simulated as a perennial crop, with January and

December as the planting and harvest dates, respectively, the model simulated

aboveground biomass from January to March and for November and December, which is

not realistic for the grass field. The fraction of leaves and stems left in the field after

harvest was calculated as 0.07 based on the tall fescue height (6.4 to 7.6 cm)

(Undersander et al., 1996) and the 5.1 to 7.6 cm stubble heights to which the grass was

cut.

The input annual maximum grain biomass (kg C ha$^{-1}$ yr$^{-1}$) for each year (2004 to 2012)

for which the model computed the DNDC annual N demand (Assumed herein as N

measured in aboveground biomass) (Table 6-4) was arrived at through an iterative

process. The DNDC perennial and non-legume crop parameters include a fraction (0.01)

of N in grain biomass, which the model automatically computes as part of the annual N

demand.

**Table 6-4 DNDC model inputs: Crop N demand and maximum grain biomass from 2004 to 2012.**

| Year | Annual maximum grain biomass (kg C ha$^{-1}$ yr$^{-1}$) | Annual aboveground N removal (kg ha$^{-1}$ yr$^{-1}$)[1] |
|---|---|---|
| 2004 | 120.08 | 146.93 |
| 2005 | 117.24 | 143.46 |
| 2006 | 180.79 | 221.22 |
| 2007 | 195.92 | 239.74 |
| 2008 | 113.13 | 138.43 |
| 2009 | 162.91 | 199.34 |
| 2010 | 154.01 | 188.45 |
| 2011 | 202.68 | 248.2 |
| 2012 | 149.56 | 182.9 |

[1]2004 to 2010, N removal determined from two to three harvests (Source: James Loughran, Farm Operations and Services Unit, College of Agricultural Sciences (FOS-CAS), personal communication, 2014); Crop N removal in 2011 and 2012 was measured in this study.

The default biomass fractionation and C:N ratio for the grain, leaf and stem and root for non-legume hay were used for all simulations. Since the model accumulates thermal degree days based on the number of days with mean temperature above 0$^{o}$C, the annual thermal degree days were determined as 4000 based on the daily mean temperature measured at 2 m heights above the ground, as listed in Appendix B. The water demand was changed to 707.6 g water/g DM. The mean (n=2) water demand from April to October was estimated as 63.0 cm (25 inches) using the crop factors for pasture grasses (see chapter 7, section 7.3.1.2), reference evapotranspiration (ETo) (Appendix M), and the annual dry matter yield of about 8960 kg ha$^{-1}$ (4 tons ac$^{-1}$). An N fixation index of 1 suggested for non-legume crops (DNDC 2012b) was used. A mean air temperature of 18$^{o}$C in the months of May and June (Appendix B) was used as the optimum temperature since the greatest aboveground biomass yield occurred during these months. The default vascularity of 0 was used for the model simulations. Figure 6-4 is a completed crop parameters window for 2004.

**Figure 6-4 DNDC site mode crop parameters.**

### 6.4.3.2 Effluent and fertilizer nitrogen application rates and grass cutting grass dates

The irrigation depth (cm), effluent N (kg N ha$^{-1}$) and urea ammonium nitrate fertilizer (kg N ha$^{-1}$) data were used to create the fertigation file (.txt), which consists of 10 columns (Column 1: Julian day; 2: irrigated water (cm); 3: nitrate; 4: ammonium bicarbonate; 5: urea; 6: anhydrous ammonia; 7: ammonium nitrate; 8: ammonium sulfate; 9: ammonium phosphate (kg N/ha) dissolved in the irrigation water, and 10: Irrigation method). The input data for the fertigation files were: Irrigation water (cm) (see Appendices K (a and b) for input data from 2004 to 2010 and chapter 3, Table 3-2 for input data measured in 2011 and 2012) in column 2, MWE nitrate nitrogen (NO$_3$-N) (kg N ha$^{-1}$) (see Appendices K (a and b) for

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input data from 2004 to 2010 and chapter 3, Table 3-2 for input data measured in 2011 and 2012) in column 3, urea (kg N ha$^{-1}$) in column 5 (Table 6-5), ammonium nitrate (kg N ha$^{-1}$) in column 7 (Table 6-5), 1 in column 10 as defined in the model for sprinkler irrigation. Apart from column 1, zeros were entered in the rest of the columns.

The irrigation water was entered in the fertigation file on the day following the irrigation dates listed in Table 3-2 and Appendix K (a and b), since rainfall and irrigation in DNDC begins at midnight and irrigation at the study site was turned on at 6 PM on the irrigation dates. Nitrate fertilizer inputs are placed directly in the $NO_3$ pool in the decomposition submodel, whereas urea and ammonium fertilizers transfer to the $NO_3$ pool through hydrolysis and/or nitrification (Li et al., 1992a).

Table 6-5 includes effluent N and fertilizer application rates and grass cutting dates used in the simulations. Half of the fertilizer application rates were entered in column 5 and column 7 of the fertigation file on the fertilizer application dates, as noted in Table 6-5. Also the MWE-TN applied each year from 2004 to 2012 is noted in Table 6-5. The cut biomass parts were selected as grain, leaves and stem, and the cut fraction of 0.93 was used based on the stubble height to which the grass was clipped and the height for tall fescue (Undersander et al., 1996).

**Table 6-5 Effluent and fertilizer nitrogen application rates and grass cutting dates in 2011 and 2012.**

| Year | Effluent N application rate[12] (kg N ha$^{-1}$) | | Urea Ammonium Nitrate (30%N) fertilizer application[3] | | Fertilizer amount put in column 5 (Urea) and column 7 (Ammonium Nitrate) of the fertigation file (kg N ha$^{-1}$) | Grass cutting/harvest dates[3] |
|---|---|---|---|---|---|---|
| | Annual | April to October | Rate (kg N ha$^{-1}$) | Date | | |
| 2004 | 212.20 | 148.10 | 87.9 | 20 April | 44.0 | 5/25 and 9/2 |
| | | | 48.2 | 9 September | 24.1 | |
| 2005 | 231.14 | 138.20 | 76.2 | 15 April | 38.1 | 5/26; 7/29; 9/7; and 11/2 |
| 2006 | 368.70 | 218.90 | 70.6 | 18 April | 35.3 | 5/31; 7/25; and 9/27 |
| | | | 50.4 | 26 July | 25.2 | |
| 2007 | 287.60 | 182.30 | 35.8 | 5 April | 17.9 | 5/21; 7/10; 8/15; and 10/10 |
| | | | 47.0 | 17 July | 23.5 | |
| 2008 | 291.30 | 143.30 | 48.2 | 11 April | 24.1 | 2008 report could not be located so the cutting dates for 2009 were used. |
| | | | 33.6 | 11 August | 16.8 | |
| 2009 | 316.30 | 186.90 | 69.4 | 30 April | 34.7 | 6/3; 8/7; and 11/4 |
| 2010 | 302.50 | 181.20 | 68.3 | 9 April | 34.2 | 6/7; 8/7; and 11/3 |
| | | | 50.4 | 8 June | 25.2 | |
| 2011 | 220.01 | 164.30 | 66.1 | 22 April | 33.7 | 6/21; 8/11; and 9/19 |
| | | | 56.0 | 5 August | 27.3 | |
| 2012 | 152.90 | 139.80 | 56.0 | 6 April | 27.3 | 5/30; 7/20; and 9/14 |
| | | | 56.0 | 3 August | 27.3 | |

[1] Calculated using MWE-TN from PSU WWTP reports
[2] 2011 and 2012 data from chapter 3, Table 3-2.
[3] Personal communication from James Loughran (Farm Operations and Services-College of Agricultural Sciences, March 2014).

## 6.5 Model performance and estimation of *f*sd values

Since denitrification was measured in the 0 to10-cm depth in the surface soil horizon, which is the carbon-rich soil depth where the greatest activity of N cycling processes occur (Shaffer and Ma, 2001), and the model simulated $N_2O$, NO and $N_2$ in the 0 to 50-cm depth, simulated denitrification in the 0 to10-cm depth was estimated by multiplying the simulated denitrification (for the 0 to 50-cm soil depth) by a factor of 1.64. The factor was estimated as the ratio of the mean (n=2) SOC at 0 to 5-cm and 5 to 10-cm soil depths

and the mean (n=5) SOC for five soil depths (0 to 5, 5 to 10, 10 to 20, 20 to 30, and 30 to

60-cm) measured in the pasture fields at the PSU Haller farm.

The performance of the model was evaluated by comparing simulated and measured

denitrification in 2011 and 2012. The performance or predictive power of models can be

assessed using the following approaches: correlation measures or coefficients (correlation

coefficient, R, and coefficient of determination, $R^2$), descriptive statistics, difference

measures (root mean squared error (RMSE) and mean absolute error (MAE))(Willmott

and Matsuura, 2005; Willmott et al., 2012), indices such as the index of agreement

(Willmott et al., 2012) or the Nash-Sutcliffe model efficiency coefficient, t-tests, and use

of qualitative or visual approaches such as time series, and scatter or residual plots.

According to Willmott and Matsuura (2005) and Willmott et al. (2012) the MAE (Eq. 6-

3]) is, in general, preferable to the RMSE (Eq. 6-4]).

$$\text{MAE} = n^{-1}\sum_{i=1}^{n} |Pi - Oi| \qquad\qquad [6\text{-}3]$$

$$\text{RMSE} = [n^{-1}\sum_{i=1}^{n}(Pi - Oi)^2]^{0.5} \qquad\qquad [6\text{-}4]$$

**where:**

$P_i = i^{th}$ simulated value (estimated for the 0 to10-cm soil depth)

$O_i = i^{th}$ observed/measured value

The RMSE identifies unsystematic (RMSEu) and systematic (RMSEs) errors in the data,

and MAE values closer to zero suggest good model performance since the sum of errors

are small. A combination of time series plots and MAE and RMSE values were used to

evaluate the model performance for estimation of the BI and AI denitrification rates.

The fractional denitrification N losses (*f*sd) were estimated using the simulated N ($N_2O$-N

+ $N_2$) losses and the weekly MWE-TN loading for the irrigation cycles noted in chapter 5, Table 5-1.

## 6.6 Results and discussion

### 6.6.1 Simulated vs measured denitrification rates

The simulated and measured denitrification rates (kg N ha$^{-1}$ d$^{-1}$) followed similar trends with the AI rates being greater than BI rates (Fig. 6-5 and Fig. 6-6). In 2011, from 12 July (AI date) to November (except 27 September, AI date) and on 7 August 2012 (AI date), the order of magnitude of the denitrification rates generally followed the trend of: measured > CLD simulations > CLM simulations > LM simulations > LD simulations. The pattern of the denitrification rates could be explained in part by the difference in model inputs for clay content, which was 0.4 (CLD simulations) > 0.31 (CLM simulations) >0.26 (LM simulations) >0.19 (LD simulations).  From May to 11 June 2011 (BI date) and for all the dates in 2012 (except 7 August 2012) the CLD simulations were the greatest.

Notably, the measured denitrification rates were smaller than the simulated rates on the AI dates, especially in May and June (Fig. 6-5 and Fig. 6-6). This was probably due to low air-filled porosity and slow diffusion of $N_2O$ and $N_2$ from the soil cores during the 6 h incubation time. The fraction of $N_2O$ (Letey et al., 1980; Stegemann and Cammenga, 1990) and $N_2$ (Letey et al., 1980) diffusing from soil increases as the air-filled porosity increases.  Saturated soils were observed at the study site in May due to irrigation and rainfall. Notable rainfall events that occurred near the sampling dates were 1.98 cm on 15 May 2011, 0.76 cm on 17 May 2011, 0.94 cm on 13 May 2012, 4.83 cm on 14 May 2011, 1.93 cm on 21 May 2012, and 0.86 cm on 23 May 2012 (Appendix B).

**Figure 6-5 Simulated and measured daily denitrification rates (0 to 10-cm depth at soil surface) in 2011** (AI designates 4 to 5 h after irrigation ceased; soil samples were collected and denitrification measured immediately in the laboratory, otherwise denitrification 6 to 7 h before irrigation).

**Figure 6-6 Simulated and measured daily denitrification rates (0 to 10-cm depth at soil surface) in 2012** (AI designates 4 to 5 h after irrigation ceased; soil samples were collected and denitrification measured immediately in the laboratory, otherwise denitrification 6 to7 h before irrigation).

The clay content possibly affected the concentration of $NO_3$ in the soil solution and thus

the denitrification rates. In the DNDC model, partitioning between adsorbed and soil

solution $NH_4$ concentration is a function of the clay content (Li et al., 1992a).

The MAE values were smallest (0.30 for all the four simulation categories in 2011 and

0.15 for all simulations in 2012) for the BI denitrification rates (Table 6-6), compared to

the MAE values (0.98 to 5.2) for the AI denitrification rates (Table 6-7). The MAE

values suggest the measured and simulated denitrification BI rates were roughly the same

especially in 2012.

**Table 6-6 Model performance for BI denitrification fluxes** (kg N ha$^{-1}$ d$^{-1}$)

| Statistical measure | 2011 (n=15[1]) | | | | 2012 (n=10[1]) | | | |
|---|---|---|---|---|---|---|---|---|
| | LD | LM | CLD | CLM | LD | LM | CLD | CLM |
| MAE | 0.30 | 0.30 | 0.30 | 0.30 | 0.15 | 0.15 | 0.15 | 0.15 |
| RMSE | 0.54 | 0.54 | 0.54 | 0.55 | 0.39 | 0.39 | 0.38 | 0.39 |
| RMSEu | 0.16 | 0.21 | 0.32 | 0.16 | 0.34 | 0.35 | 0.33 | 0.33 |
| RMSEs | 0.52 | 0.50 | 0.44 | 0.52 | 0.18 | 0.18 | 0.20 | 0.21 |
| RMSEs/RMSE | 0.95 | 0.92 | 0.80 | 0.95 | 0.46 | 0.45 | 0.52 | 0.54 |
| RMSEu/RMSE | 0.30 | 0.39 | 0.60 | 0.30 | 0.89 | 0.89 | 0.85 | 0.84 |

[1]No data was collected on 1 June 2011 and data on 24 October 2012 was lost thus the no. of BI denitrification fluxes used for model performance were less by one than the number of AI denitrification fluxes used for model performance in Table 6-7.

**Table 6-7 Model performance for AI denitrification fluxes** (kg N ha$^{-1}$ d$^{-1}$)

| Statistical measure | 2011 (n=16) | | | | 2012 (n=10) | | | |
|---|---|---|---|---|---|---|---|---|
| | LD | LM | CLD | CLM | LD | LM | CLD | CLM |
| MAE | 5.20 | 5.13 | 4.97 | 5.00 | 0.98 | 0.98 | 0.98 | 0.99 |
| RMSE | 2.28 | 2.26 | 2.23 | 2.24 | 0.99 | 0.99 | 0.99 | 0.99 |
| RMSEu | 1.30 | 1.54 | 1.68 | 1.71 | 0.86 | 0.87 | 0.83 | 0.83 |
| RMSEs | 1.88 | 1.66 | 1.46 | 1.45 | 0.49 | 0.47 | 0.54 | 0.54 |
| RMSEs/RMSE | 0.82 | 0.73 | 0.66 | 0.65 | 0.50 | 0.48 | 0.55 | 0.54 |
| RMSEu/RMSE | 0.57 | 0.68 | 0.75 | 0.76 | 0.87 | 0.88 | 0.84 | 0.84 |

Randomness, which is often observed in the real world, accounted more to the total error

in the AI and BI denitrification rates in 2012 since the RMSEu errors were greater than

the RMSEs errors (Table 6-6 and Table 6-7). According to Willmott (1984), the

magnitude of RMSEu could be interpreted as a measure of a model's potential accuracy to estimate observations based on the ratio measures of $(RMSEs/RMSE)^2$ and $(RMSEu/RMSE)^2$. The greatest $(RMSEu/RMSE)^2$ values (0.7 to 0.80) were in 2012, however, if the model were to be calibrated, errors would be reduced mostly from the simulations for the BI denitrification rates in 2012, due to the small MAE values, than the errors that would be reduced for the AI denitrification rates in the same year.

### 6.6.2 *f*sd, *f*md, and design *f* values per irrigation cycle

Table 6-8 provides simulated denitrification N loss and *f*sd for twelve irrigation cycles in 2011 and 2012. The greatest denitrification was simulated for the CLD simulation type. The model uses the ratio of the average hydraulic conductivity per layer and Ksat to estimate WFPS per soil layer (Li et al., 1992a). Since denitrification may increase with anaerobic conditions (generally WFPS ≥ 60 to 70%), greater simulated denitrification occurred for the CLD simulations due to a small Ksat value of 0.009 m h$^{-1}$ put in the model compared to the Ksat values used for the other simulations types (0.025 m h$^{-1}$ for the LD simulations and 0.017 m h$^{-1}$ for the LM and CLM simulations). For better representation of the study site, denitrification rates and *f*sd values for the LM and CLM simulations are discussed in relation to the proportion of aboveground biomass N removal (see chapter 3, section 3.7). The *f*sd values varied as the *f*md values due to the variation in denitrification and effluent total N. Similar to the *f*md estimates (Table 5-1), the *f*sd estimates were greatest in August (0.16 in 2011 and 0.14 in 2012) (Table 6-8), due to increased denitrification following fertilizer application in August. The *f*sd values were smaller than the design *f* values and much smaller than the *f*md estimated values (Figure 6-7). The average (n=24) *f*sd value for the LM and CLM simulations of 0.05 is half the

design $f$ value suggested for tertiary-treated effleunts (USEPA, 2006; Crites and

Tchobanoglous, 1998).

**Table 6-8 Simulated denitrification and *f*sd per irrigation cycle**

| Irrigation Cycle[1] | Effluent Total N | Simulated denitrification (0 to 50-cm soil depth) | | | | | Estimated simulated denitrification[2] (0 to 10-cm soil depth) | | | | *f*sd based on estimated simulated denitrification (*f*sd) | | | | Average (*f*sd) for LM[3] and CLM[3] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Measured | LD[3] | LM[3] | CLD[3] | CLM[3] | LD[3] | LM[3] | CLD[3] | CLM[3] | LD[3] | LM[3] | CLD[3] | CLM[3] | |
| | kg N ha⁻¹wk⁻¹ | kg N ha⁻¹/irrigation cycle | | | | | | | | | Fraction | | | | |
| 2 to 6 June 2011 | 4.20 | 1.70 | 0.02 | 0.02 | 0.22 | 0.13 | 0.03 | 0.03 | 0.37 | 0.21 | 0.008 | 0.007 | 0.087 | 0.049 | 0.028 |
| 12 to 18 July | 4.90 | 4.80 | 0.03 | 0.03 | 0.09 | 0.03 | 0.05 | 0.05 | 0.15 | 0.05 | 0.011 | 0.011 | 0.030 | 0.010 | 0.010 |
| 12 to 15 August | 5.30 | 17.20 | 0.27 | 0.26 | 0.25 | 0.25 | 0.44 | 0.43 | 0.41 | 0.42 | 0.084 | 0.081 | 0.076 | 0.078 | 0.080 |
| 16 to 22 August | 2.00 | 6.90 | 0.10 | 0.18 | 0.22 | 0.20 | 0.17 | 0.29 | 0.35 | 0.34 | 0.084 | 0.145 | 0.176 | 0.168 | 0.156 |
| 21 to 26 September | 6.51 | 3.25 | 0.03 | 0.04 | 0.16 | 0.10 | 0.05 | 0.07 | 0.26 | 0.17 | 0.008 | 0.011 | 0.040 | 0.025 | 0.018 |
| 27 September to 3 October | 6.30 | 1.30 | 0.03 | 0.03 | 0.14 | 0.08 | 0.05 | 0.04 | 0.22 | 0.13 | 0.007 | 0.007 | 0.036 | 0.020 | 0.014 |
| 25 to 31 October | 8.10 | 8.90 | 0.02 | 0.02 | 0.05 | 0.02 | 0.04 | 0.04 | 0.09 | 0.04 | 0.005 | 0.005 | 0.011 | 0.004 | 0.004 |
| 15 to 21 November | 5.00 | 3.50 | 0.04 | 0.05 | 0.10 | 0.06 | 0.06 | 0.09 | 0.16 | 0.11 | 0.013 | 0.018 | 0.031 | 0.021 | 0.020 |
| 15 to 21 May 2012 | 3.40 | 0.10 | 0.02 | 0.05 | 0.28 | 0.16 | 0.03 | 0.08 | 0.45 | 0.26 | 0.008 | 0.024 | 0.133 | 0.077 | 0.050 |
| 22 to 25 June | 1.90 | 1.40 | 0.01 | 0.01 | 0.16 | 0.05 | 0.02 | 0.02 | 0.26 | 0.08 | 0.010 | 0.010 | 0.137 | 0.042 | 0.026 |
| 10 to 16 July | 4.20 | 0.80 | 0.02 | 0.02 | 0.06 | 0.02 | 0.04 | 0.04 | 0.09 | 0.04 | 0.009 | 0.009 | 0.022 | 0.008 | 0.009 |
| 7 to 13 August | 3.10 | 8.90 | 0.26 | 0.26 | 0.24 | 0.25 | 0.43 | 0.43 | 0.39 | 0.42 | 0.139 | 0.137 | 0.127 | 0.134 | 0.136 |

[1]AI and BI dates, respectively
[2]See section 6.5

**Figure 6-7** *f*sd, *f*md, and design *f* values. *f*sd values based on estimated simulated
denitrification (0 to 10 cm soil depth in the surface soil horizon) (see section
6.5).

### 6.6.2.1 *f*sd, *f*md, and design *f* values in May

The average *f*sd values of 0.05 for the LM and CLM simulations (Table 6-8) was similar

to the smallest *f*md value of 0.03 for the irrigation cycle from 15 to 21 May 2012 despite

the UAN-30 fertilizer application on April 6, 2012. The *f* values are half of the design *f*

value suggested for tertiary-treated effluents (USEPA, 2006; Crites and Tchobanoglous,

1998). The *f*sd and *f*md values could be reasonable in the month of May for design

purposes at the study site, since the largest proportion of the annual tall fescue

aboveground biomass N removal occurs in May (0.3) (see chapter 3, section 3.7).

### 6.6.2.2 *f*sd, *f*md, and design *f* values in June

In both June 2011 and 2012 the average *f*sd value for the LM and CLM simulations of

0.03 was similar to that estimated in May 2012 (0.05) and was much smaller than the

*f*md values estimated in both years (0.4 in 2011 and 0.74 in 2012). However, as in May 2012, the *f*sd value estimated in June in both years was half of the design *f* value suggested for tertiary-treated effluents (USEPA, 2006; Crites and Tchobanoglous, 1998). Given, that the proportion of the annual tall fescue aboveground biomass in June (0.2) (see chapter 3, section 3.7) is similar to the proportion in May (0.3) and thus N removal, the same *f* value can represent the months of May and June at the study site.

### 6.6.2.3 *f*sd, *f*md and design *f* values in July

Denitrification and thus the *f*md and *f*sd estimates were least affected by the UAN-30 fertilizer applications on 22 April 2011, 5 August 2011, 6 April 2012, and 3 August 2012. The average *f*sd estimates for the LM and CLM simulations in 2011 and 2012 were both 0.01 (Table 6-8). The July *f*sd values were much smaller than the *f*md estimates (0.98 in 2011 and 0.19 in 2012). Although the proportion of the annual tall fescue aboveground biomass in July is about half (0.12) of the greatest proportion of the annual tall fescue aboveground biomass in May (0.3) (see chapter 3, section 3.7), the *f*md estimate of 0.98 and *f*sd estimates would be unreasonable for design purposes. The *f*md estimate (0.19) in July 2012 was similar to the design *f* value for secondary-treated effluent in "cold" climates (Crites and Tchobanoglous, 1998), although the MWE C:N ratio for the effluent during the study period was ( 0.04 to 0.2), (chapter 3, section 3.5) (C:N <1, is classified for tertiary-treated effluents (Crites and Tchobanoglous, 1998; USEPA, 2006)).

### 6.6.2.4 *f*sd, *f*md and design *f* values in August

Denitrification rates and thus *f*sd and *f*md estimates were likely affected by the UAN-30 fertilizer applications in August in both years. The irrigation cycle between 16 and 22

August 2011 was assumed to be least affected by the fertilizer application on 5 August 2011 unlike the irrigation cycles, 12 to 15 August 2011 and 7 to 13 August 2012, which were close to the time of fertilizer application. The $f$md estimates were more than 20 times the $f$sd estimates. Unlike the $f$md values, the $f$sd estimates (0.08, 0.16, and 0.14) (Table 6-8) were similar to the design $f$ values: 0.15 to 0.25 for secondary-treated effluent (USEPA, 2006) and 0.1 for tertiary-treated effluents (Crites and Tchobanoglous, 1998; USEPA, 2006).

Due to the likely effect of UAN-30 fertilizer on denitrification and $f$sd, it was more difficult to draw conclusions about the $f$sd and $f$md estimates in August. However, it was surmised that since the proportion of the tall fescue aboveground biomass in August (0.15) is half of that in May (0.3), an $f$ value in August at the study could be greater than those used in May but less than those used in July. However, this assumption needs to be confirmed with studies at the study site without commercial fertilizer application.

### 6.6.2.5 $f$sd, $f$md and design $f$ values in September

The average $f$sd estimates for the LM and CLM simulations for the irrigation cycles between 21 and 26 September 2011 and 27 September and 3 October 2011 were approximately 0.02 and 0.01, respectively. This was because the simulated denitrification and the MWE-TN application rates (6.51 kg N ha$^{-1}$ (21 to 26 September 2011) and 6.30 kg N ha$^{-1}$ (27 September to 3 October 2011) were roughly equal (Table 6-8).

The $f$md value of 0.5 determined for the period between 21 and 26 September 2011 would be rather high for the month of September although the proportion of the annual tall fescue aboveground biomass for September is equal to the one in July (0.12). The fsd

and fmd values (except the *f*md of 0.21 estimated for the period from 27 September and 3 October 2011) were not in the range for design values.  Since the aboveground biomass in May (0.3) is about half of the one in September and because the mean monthly temperature (calculated using weather data from Appendix B) in June ($19.7 \pm 2.8\,^{\circ}C$ in June 2011 and $19.3 \pm 3.9\,^{\circ}C$ in June 2012) and September ($17.2 \pm 3.5\,^{\circ}C$ in 2011 and $16.2 \pm 4\,^{\circ}C$ in 2012) are similar, the *f*sd estimates in the range of 0.1 and 0.2 could represent the month of September.

**6.6.2.6 *f*sd, *f*md and design *f* values in October and November**

The average (LM and CLM simulations) *f*sd estimates for the irrigation cycles between 25 and 31 October 2011 (0.004) and 15 and 21 November 2011 (0.02) were smaller than both the *f*md (1.1 in October and 0.7 in November) and design *f* values. However the fsd values may not represent the months of October and November due to the small proportion of the annual tall fescue aboveground biomass in October (0.06) and lack of plant growth in November (see chapter 3, section 3.7).  It is also important to note that the greatest MWE-TN ($8.1$ kg N ha$^{-1}$) was applied during the irrigation cycle between 25 and 31 October 2011.  Due to the small proportion of aboveground biomass in October and the lack of it in November, the *f*md value of 0.7 estimated on November 2011 could represent the study site during these months. Although the simulated denitrification (0 to 50-cm depth) (Table 6-8) in November, 2011 was twice the one in October, 2011, the MWE-TN of 5 kg N ha$^{-1}$ in November was approximate to the mean MWE-TN (4.58 kg N ha$^{-1}$) applied for the 12 irrigation cycles. Additional studies are needed to elucidate further the *f* values in October.

**6.7 Data limitations**

Some of the rainfall and air temperature data collected near the study site was lost due to equipment failure. Although the missing data were replaced with data from a weather station near the study site (< 2 km), the accuracy of these data may have influenced the simulated atmospheric N losses through water-filled pore space (WFPS). Soil moisture is highly sensitive to wetting patterns (Li et al., 1992) due to rainfall and irrigation, which affect the DNDC-model simulated WFPS, the soil climate in general, and the model outputs, e.g. atmospheric N losses.

The initial organic C was fixed at 0.0156 which automatically computed a bulk density of 1.25 g cm$^{-3}$ measured in the 0 to12-cm soil depth in the surface soil horizon, thus the simulated atmospheric N losses might have been affected by the simulated soil nitrate concentration due to the initial organic C. The simulated denitrification (0 to 10-cm depth) used in calculating the $f$sd values was probably limited by the accuracy of the conversion factor of 1.64 (see section 6.5) used in estimating simulated denitrification in the 0 to 10-cm soil depth.

**6.8 Summary and conclusions**

The DNDC-Crop model was parameterized in the site mode and simulations were conducted from 2004 to 2012 using the default clay fraction (0.19 for loam soil and 0.4 for clay loam soil) and default K$_{sat}$ (0.0256 mh$^{-1}$ for loam soil and 0.009 m h$^{-1}$ for clay loam soil). The soil types were identified in the 0 to 15-cm soil depth at the study site. Simulations were also completed with measured clay fraction (0.26 for loam soil and 0.31 for clay loam soil) and measured K$_{sat}$ (0.017 mh$^{-1}$) for the 0 to 15-cm depth at the

soil surface. Simulations that were completed with default clay fraction and $K_{sat}$ were named LD (loam soil) and CLD (clay loam soil) and simulations completed with measured clay fraction and $K_{sat}$ were named LM (loam soil) and CLM (clay loam soil). Since the model simulates the 0 to 50-cm depth of the surface soil horizon, the simulated denitrification $(N_2O + N_2)$ $(kg\ N\ ha^{-1}d^{-1})$ in the 0 to 10-cm depth at the soil surface was estimated by multiplying the simulated denitrification (0 to 50-cm depth) by 1.64 (see section 6.5).

The estimated simulated denitrification (0 to 10-cm depth) was compared to denitrification measured in 0 to 10-cm deep undisturbed soil cores collected at the soil surface in 2011 and 2012. The soil cores were collected 6 to 7 h before irrigation began (BI) and 4 to 5 h after irrigation ceased (AI) (chapter 5). The USEPA (2006) fractional N loss design values suggested for secondary-treated effluents (0.15 to 0.25) and tertiary-treated effluents (0.1) and also those noted in Crites and Tchobanoglous (1998) (0.2 for secondary-treated effluent in "cold" climates and 0.1 for tertiary-treated effluent) were compared to the fractional simulated denitrification (*f*sd). The simulated and measured denitrification and the *f*sd and *f*md values were also compared.

The simulated and measured denitrification rates $(kg\ N\ ha^{-1}\ d^{-1})$ followed similar trends. The model simulated denitrification in 2012 better than in 2011 and the BI denitrification rates better than the AI rates. All the MAE values for the BI rates for all the four simulation types were equal, 0.3 in 2011 and 0.15 in 2012. The MAE values for the AI rates were in the range from 0.98 to 5.2 in both years. For representation of the study site,

the average $f$sd for the LM and CLM simulations were discussed along with the $f$md and

design $f$ values.

The average $f$sd (LM and CLM simulations)/ $f$md values were:  0.03/0.4 (2 to 6 June

2011), 0.01/0.98 (12 to 18 July 2011), 0.08/3.25 (12 to 15 August 2011), 0.16/3.45 (16 to

22 August 2011), 0.02/0.50 (21 to 27 September 2011), 0.01/0.21 (27 September to 3

October), 0.004/1.10 (25 to 31 October 2011), 0.02/0.70 (15 to 21 November 2011),

0.05/0.03 (15 to 21 May 2012), 0.03/0.74 (21 to 25 June 2012), 0.01/0.19 (10 to 16 July

2012), and 0.14/2.87 (7 to 13 August 2012). Due to UAN-30 fertilizer application, both

the $f$sd and $f$md estimates were greatest in August.

The average (n=24) $f$sd for the LM and CLM simulation for 12 irrigation events in both

years was 0.05. The $f$sd estimates were all smaller than the $f$md estimates except for

irrigation cycle between 15 and 21 May 2012 when the $f$sd (0.05) and $f$md (0.03) were

similar.  The $f$sd estimates were also smaller than the design $f$ values apart  from August

when they were near the lower boundary for design $f$ values for secondary-treated

effluent (0.15 - 0.25).

Based on the study results and the proportion of tall fescue aboveground biomass in

Pennsylvania: [0.05 (April), 0.3 (May), 0.2 (June), 0.12 (July), 0.15 (August), 0.12

(September), and 0.06 (October)] $f$ values in the range of 0 to 0.1 and 0.1 to 0.2 could

represent the months of May/June and August/September, respectively, and 0.2 could

represent the month of July at the study site. However, further investigation is needed to

refine the $f$sd and $f$md without commercial fertilizer application especially during the

months of May/June and August/September when the aboveground biomass tall fescue

peaks occur at the study site.

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## Chapter 7.  MONTHLY NITROGEN BALANCES TO ESTIMATE FRACTIONAL ATMOSPHERIC NITROGEN LOSSES FROM TALL FESCUE HAY SPRAY-IRRIGATED WITH MUNICIPAL WASTEWATER EFFLUENT

**Abstract**

Due to the potential of polluting groundwater, nitrogen (N) is often the most limiting design factor in determining irrigation depths for municipal wastewater effluent (MWE) irrigation systems. The irrigation depths are usually determined using a monthly or annual "source-sink" N mass-balance. The fraction ($f$) of the total N in the MWE (MWE-TN) estimated to be lost to the atmosphere and the change in soil N storage is included in the balance. However, few studies have quantified $f$ in existing MWE irrigation systems. The goal of this study was to determine $f$ values from monthly "source-sink" N mass balances ($f$nb) over the growing season in a crop field irrigated with MWE, compare the $f$ values to the US Environmental Protection Agency (USEPA) design $f$ values, and also determine relationships (if any) between the $f$nb values and effluent C:N, air temperatures,  and crop N removal.

The field study was conducted in 2011 and 2012 in a tall fescue (grass hay field) at the Penn State University Living Filter, which was irrigated at a rate of $\leq 5$ cm wk$^{-1}$ with secondary-treated (including biological nitrogen removal) effluent. During the study period the effluent characteristics were: C:N ratio (0.04 to 0.2); near neutral pH, and 70 to 85% of the effluent total N was $NO_3$-N. Urea-ammonium nitrate (30% N) (UAN-30) fertilizer was also applied to the grass field to supplement effluent-supplied N. The soil properties in the 0 to 30-cm depth at the study site are described in chapter 3, section 3.4.

The N balances were calculated for April to September in the surface soil horizon. The monthly MWE-TN was quantified using the irrigation depth and effluent total N in samples collected weekly from May to November. Between April and September, 132.5 kg N ha$^{-1}$ and 105.2 kg N ha$^{-1}$ from the MWE-TN was applied to the grass field in 2011 and 2012, respectively. The monthly crop N removal due to solely MWE-TN was estimated as the difference between the measured monthly N removal and crop N removal estimated to be due to UAN-30 fertilizer. Crop N removal due to UAN-30 fertilizer was estimated from the fraction of the measured crop N removal per month and the annual UAN-30 fertilizer N applications: 122 kg N ha$^{-1}$ in 2011 and 112 kg N ha$^{-1}$ in 2012. Leaching N was determined from $NO_3$-N levels in soil water collected from 35-cm deep suction cup lysimeters and the leachate volume was estimated from a monthly water balance for rainfall (cm), irrigation depth (cm), and crop evapotranspiration, $ET_c$ (cm). Monthly crop evapotranspiration was calculated as the product of the crop factor (Kc) and reference ETo). Rainfall was measured at an unirrigated field near (< 2 km) the study site. The monthly $ET_o$ (cm) was summed from the daily $ET_o$ (cm), which was calculated using the Penman-Monteith method.

The estimated *f*nb values were generally less than the USEPA design *f* values (0.15 to 0.25 for secondary-treated effluents and 0.1 for tertiary-treated effluents). The *f*nb values were 0.13 (April and May 2011), -1.35 (June, 2011), 0.22 (July, 2011), 0.09 (August, 2011), -0.40 (September, 2011), 0.23 (April, 2012), -0.13 (May, 2012), 0.05 (June, 2012), 0.13 (July, 2012), -0.44 (August, 2012), and 0.72 (September, 2012). Negative *f*nb estimates were obtained when the sum of the crop N removal and leaching N terms in the N balance exceeded the MWE-TN.

As would be expected, the *f*nb estimates decreased with an increase in N removal and increased with decrease in crop N removal. The positive *f*nb estimates in July and August, when monthly mean air temperatures were above 20$^o$C correlated better to logarithm of the measured monthly crop N removal (*f*nb = - 0.386 [Log (measured monthly crop N removal]+ 0.716; R$^2$ = 0.99) than during the months (April, May, June, and September) (*f*nb = - 0.276 [Log (measured monthly crop N removal]+ 0.644; R$^2$ =0.2) when monthly mean air temperatures were less than 20$^o$C. The *f*nb linear model developed in July and August could be useful in elucidating the *f* values over the growing season especially during months with high N removal at the study site.

A conclusion could not be drawn for the *f* value for April mainly due to the differences in field operations in both years. The *f* values of 0.05 and 0.1 seemed to appropriately represent the months of May and June, and August and September, respectively, since tall fescue at the study site had a greater aboveground biomass yield in May and June than in August and September. An *f* value of 0.2 seemed appropriate for the month of July at the study site. However, additional research, in the absence of commercial fertilizer addition, is needed to improve the *f*nb values.

## 7.1 Introduction

Nitrogen (N) is often the most limiting design factor for the land application of municipal wastewater effluent (MWE), especially when protection of potable groundwater is of major concern (Reed et al., 1995; O'Connor et al., 2008). Design professionals usually use a "source-sink" N mass-balance approach (Duan and Fedler, 2011) for the root zone plant-soil-water matrix to determine N-based MWE irrigation rates (Reed et al., 1995; Crites et al., 2006; Asano et al., 2007) for slow-rate MWE irrigation systems-the most common type of MWE land application systems (Crites et al, 2006; USEPA, 2006).

The N-based MWE irrigation depth ($L_n$) is determined by combining water and nitrogen balances usually on a monthly basis. The water balance is used to determine the volume of percolating water, which then allows calculation of N in leachate, using N concentration. The combined water and N balances yield equation [7-1] for the allowable irrigation depth (Crites et al., 2006; Asano et al., 2007):

$$L_n = \left( \frac{C_p[Pr - ETc] + 10\,U}{[C_n(1-f) - C_p]} \right) \qquad [7\text{-}1]$$

**where**:

| | | |
|---|---|---|
| $L_n$ | = | MWE irrigation, cm |
| $C_p$ | = | Leachate N concentration, mg $L^{-1}$ |
| $P_r$ | = | Rainfall, cm |
| $ET_c$ | = | Crop evapotranspiration, cm |
| $U$ | = | Crop N removal, kg N ha$^{-1}$ |
| $C_n$ | = | MWE total N concentration, mg $L^{-1}$ |
| | | (All the MWE nitrogen is assumed to be plant available) |
| 10 | = | unit conversion factor |
| $f$ | = | Fractional atmospheric N losses (Due to denitrification and ammonia volatilization) and change in soil N storage. |

The parameters in Eq. [7-1] can be quantified through measurements ($C_n$, $C_p$, $P_r$, U),

numerical estimations ($ET_c$), or obtained from literature (e.g. U, *f*); however, *f* is the most

uncertain. Table 1-1 in chapter 1 includes suggested design *f* values based on the effluent

C:N ratio and temperature. Reed and Crites (1984) suggest *f* values of 0.1 or less for

highly oxidized filtered effluents. However, to date there is little scientific evidence to

verify these *f* values.

There is no guidance offered on how to select an appropriate *f* value from a range if

primary or secondary-treated MWE is used for irrigation (see chapter 1, Table 1-1), or

how the values may vary throughout a growing season due to changes in crop N removal

or air temperate. According to Freney et al. (1983), interacting processes (e.g. plant N

removal and leaching) and environmental factors (e.g. water, temperature, wind, and

atmospheric $NH_3$ concentration) can influence ammonia volatilization from the air-soil

interface. Some fractional N losses reported in MWE irrigation scientific literature were

estimated from atmospheric N loss measurements (Ryden et al., 1981; Meding et al.,

2001) and others from annual or seasonal N balances (Lund et al., 1981; Schreffler and

Galeone, 2005). However, there are no investigations that used the "source-sink" N mass

balance in slow-rate MWE irrigation systems to determine monthly *f* values, how they

compare to design values and how they correlate with other driving factors such as

temperature and crop N removal.

## 7.2 Research goal and questions

The goal of the study was to determine *f* values from monthly "source-sink" N mass

balances (*f*nb) in a grass hay field irrigated with treated municipal wastewater effluent.

The research goal was achieved through measurement of effluent N, crop N removal, and N concentration in leachate. The following research questions were addressed:

- Do the $f$nb values vary over the growing season?

- How do the $f$nb estimates compare to those suggested by USEPA (2006) and those noted in Crites and Tchobanoglous (1998) for secondary and tertiary-treated effluent irrigation system design?

- Is there a correlation between the $f$nb estimates and, 1) the MWE C:N ratio, 2) air temperature measured at 2-m heights above the ground, and 3) crop N removal?

## 7.3 Materials and methods

The study was done in a grass hay field at the Penn State University (PSU) Living Filter (LF) where secondary-treated (including biological nitrogen removal) MWE is irrigated at a rate of 5 cm wk$^{-1}$. The site layout is described in chapter 3, section 3.3. The $f$nb values were estimated from monthly N balances for the 0.35-m soil depth in the surface soil horizon by rearranging Eq. [7-1] to make $f$ the unknown. The monthly N balances were done between April and September in 2011 and 2012. The N balance was not done in October, because an adequate quantity of grass could not be collected for the aboveground biomass (AGB) yield and plant tissue N analysis.

The $f$nb values were assumed to be mainly due to atmospheric N losses, since for design purposes USEPA (1981) suggests zero change in soil N storage. Furthermore, Duan and Fedler (2011) and Tsiknia et al. (2013) observed no change in total Kjeldahl nitrogen (TKN) in studies where MWE was applied to soil in field and pot experiments. Immobilization of MWE nitrogen was suspected to be negligible because, on average, the

MWE C:N ratio was in the range of 0.04 to 0.2 during the study period (see chapter 3, section 3.5). Nitrogen immobilization is expected to occur only when organic wastes with C:N ratios greater than 25 (Brady and Weil, 2008) are applied to soil. Allison (1955) noted the impracticality of accounting for all soil gains and losses in N balances including mineralization and immobilization. Apart from crop evapotranspiration, which was computed from meteorological data, all the parameters used in the N balance calculations were measured.

### 7.3.1 Parameters used in the monthly nitrogen balances

### 7.3.1.1 Effluent depth ($L_n$, cm), effluent N concentration ($C_n$, mg L$^{-1}$), and rainfall depth ($P_r$, cm)

The monthly MWE irrigation depth $L_n$ (cm) and the mean MWE-TN concentrations Cn (mg L$^{-1}$) were obtained from chapter 3, Table 3-2 and the monthly rainfall data (Appendix B) were obtained using Equations 3-1 and 3.2 (see chapter 3, section 3.8). The annual rainfall N deposition rates were 8.4 kg N ha$^{-1}$ in 2011 and 5.76 kg N ha$^{-1}$ in 2012 (see chapter 3, section 3.6). Rainfall N minimally affected the overall N balance in the grass field, compared to the annual total N from the effluent: 220 kg N ha$^{-1}$ in 2011 and 153 kg N ha$^{-1}$ in 2012 (see chapter 3, Table 3-2).

### 7.3.1.2 Water balance and surface runoff (Q, cm)

Asano et al. (2007) include an irrigation efficiency factor ($E_i$) to account for surface runoff and water drift in a water balance in Eq. [7-2]; however, the water balance in Eq. [7-1] does not include surface runoff due to either effluent or rainfall. The irrigation efficiency is the fraction of applied wastewater that corresponds to the crop evapotranspiration, thus lower efficiencies result in more water percolating through the

root zone (Crites et al., 2006). Although sprinkler irrigation systems have irrigation efficiencies in the range of 70 to 80% (Crites et al., 2006; Asano et al., 2007), Crites et al. (2006) assume 100% irrigation efficiency (i.e. $E_i = 1$) in Eq. [7-2].

$$Lw = \left( \frac{ET_c}{E_i} - P_r \right) + W_p \qquad \text{[7-2]}$$

**where:**

$L_w$ = Hydrologic-based MWE irrigation, cm
$E_i$ = Irrigation efficiency (0 - 1), fraction
$W_p$ = Allowable percolation, cm
$ET_c$ and $P_r$ are as specified for Eq. [7-1]

Surface runoff from effluent is specifically avoided in system design for MWE land application (USEPA, 2006), and thus not normally included in N balance in equation [7-1] (Crites et al., 2006; Asano et al., 2007). During studies at the LF between 1969 and 1970, Jarrett (1970) measured zero MWE runoff in irrigated reed canary grass between May and July with either, one, two, or four irrigation laterals turned on. However, during March and April, the author measured 11% (one irrigation lateral turned on) and 20% (four irrigation laterals turned on) of the MWE volume as runoff. Since surface runoff may occur due to antecedent soil moisture conditions (AMC) before an irrigation or rainfall event, surface runoff was included in the N balances.

The monthly surface runoff was summed from the daily surface runoff, which was estimated using the Natural Resources Conservation Service (NRCS) curve number method defined by equations [7-3] and [7-4] (USDA, 2004; Fangmeier et al., 2006).

$$Q = (P - I_a)^2/(P+0.8S) \quad P > I_a \qquad \text{[7-3]}$$

$$Q = 0 \qquad\qquad\qquad P \leq I_a \qquad \text{[7-4]}$$

**where:**

Q       =       Direct surface runoff, cm

P       =       Event rainfall, cm

$I_a$   =       0.2S is the initial abstraction or event rainfall required for initiation of runoff.

S       =       2540/CN - 25.4

CN      =       Curve number

The method is based on three (I, II, and III) antecedent moisture condition (AMC) categories and determined from the 5-day antecedent rainfall. The 5-day antecedent rainfall was determined as the sum of the irrigation and rainfall depths. The daily rainfall (Appendix B) was used as the event rainfall in equation [7-3]. The CN for AMC II was determined as 58 for the hydrologic soil group B and a factor of 0.66 and 1.32 were used to convert the CN of 58 to the curve numbers of 38.3 and 76.6 for the AMC I and AMC III antecedent rainfall conditions, respectively. Thus, the initial abstraction for the three antecedent rainfall conditions were determined as 8.19 cm (AMC I), 3.68 cm (AMC II), and 1.56 cm (AMC III).

### 7.3.1.3 Crop evapotranspiration ($ET_c$, cm)

Crop evapotranspiration ($ET_c$) was calculated using the Food and Agriculture Organization (FAO) Penman-Monteith method (Allen et. al., 1998) as the product of a crop factor ($K_c$) and potential or reference evapotranspiration ($ET_o$).

The monthly $ET_c$ was determined as the product of the average monthly $K_c$ values for pasture grasses (USDA, 1970) and the monthly $ET_o$ summed from the daily $ET_o$ values. The $K_c$ values used were 0.85 (April), 0.9 (May), 0.92 (June), 0.92 (July), 0.91 (August), and 0.87 (September). The daily $ET_o$ was calculated for an altitude of 358 m (approximate location for lysimeter 8 (LYS8), see Chapter 3, Fig. 3-3) using the visual basic (VB) code in Appendix L  (prepared by Dr. Armen R. Kemanian, Penn State

University, University Park ) to solve Eq. [7-5]. The names of the terms used in the VB

code are listed and bolded after the description of each term, and are also bolded in

Appendix L.

$$ETo = \left(\frac{1}{\lambda}\right)\left[\frac{\Delta(R_n - G) + \rho_a C_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left[1 + \dfrac{r_s}{r_a}\right]}\right] \qquad [7\text{-}5]$$

**where:**

| | |
|---|---|
| $ET_o$ | = Reference ET, cm day$^{-1}$; **ETref** |
| $\lambda$ | = Latent heat of vaporization, MJ kg$^{-1}$; **lamda** |
| $\Delta$ | = Slope of saturated vapor pressure vs temperature function, kPa $^o$C$^{-1}$; **delta** |
| $R_n$ | = Net radiation at the crop surface, MJ m$^{-2}$ day$^{-1}$; **NetRadiation** |

**where:**

| | |
|---|---|
| $R_n$ | = $R_{ns}$ - $R_{nl}$ |
| $R_{ns}$ | = (1-α) $R_s$ |
| $R_{ns}$ | = Shortwave solar radiation; **Rns** |
| α | = 0.23; **albedo** |
| $R_s$ | = Solar radiation; **Solar_Rad** |
| G | = 0, Daily heat soil flux density, MJ m$^{-2}$ day$^{-1}$ |
| $r_a$ | = Mean air density at constant pressure, kg m$^{-3}$; **AirDensity** |
| $C_p$ | = Specific heat of the air, J kg$^{-1}$; **CP** |
| ($e_s$ - $e_a$) | = Vapor pressure deficit of the air, kPa; **vpd** |
| $r_a$ | = Aerodynamic resistance, s m$^{-1}$; **rs** |
| γ | = Psychometric constant, kPa $^o$C$^{-1}$; **gamma** |
| $r_s$ | = Bulk surface resistance, s m$^{-1}$; **rs** |

The wind speed (m s$^{-1}$), maximum and minimum relative humidity (%), temperature ($^o$C),

and solar radiation (MJ m$^{-2}$ day$^{-1}$) used in the VB code are documented in Appendix B.

## 7.3.1.4 Crop nitrogen removal (U, kg ha$^{-1}$)

The monthly crop N removal due to solely MWE-TN was estimated as the difference

between the measured monthly crop N removal and the estimated N removal due to

UAN-30 fertilizer application.  If the difference was greater than MWE-TN, MWE-TN

was used in the N balance calculations. The monthly crop N removal due to UAN-30

fertilizer was estimated as the product of the monthly fraction of the measured annual N

removal in the AGB and the annual UAN-30 fertilizer applications, 122 kg N ha$^{-1}$ in 2011

and 112 kg N ha$^{-1}$ in 2012. In 2011, the  fractions of the monthly aboveground N removal

were 0.24, 0.29, 0.08, 0.17, and 0.22 in April & May (AGB yield and plant tissue N

content in the biomass were measured only in May 2011), June, July, August, and

September, respectively. In 2012, the fractions of the monthly aboveground N removal

were 0.26, 0.29, 0.05, 0.17, 0.19, and 0.04 in April, May, June, July, August, and

September , respectively (see Chapter 3, Table 3-4). The AGB yield and crop N removal

in June 2012 were not normal for the grass field (see Chapter 3, Table 3-4), probably due

to a lack of irrigation from 25 May to 21 June 2012 while the irrigation lateral 10-1 was

being repaired.

## 7.3.1.5 Leachate nitrogen concentration ($C_p$, mg L$^{-1}$)

Nitrogen concentration was measured in soil water collected in suction cup lysimeters

installed at 0.35-m depths.  Suction cup lysimeters were used in the study due to the

minimal disturbance they would cause to the soil structure in the perennial grass hay

field. Three lysimeters were installed at each of the four sampling positions (1 to 4) (see

chapter 3, Fig. 3-3). The lysimeter design was similar to the designs used in earlier

research at the LF. With a few minor modifications, the design, assembly, and installation

procedure of the lysimeters followed Wagner (1962) and Parizek and Lane (1970).

*Lysimeter design and assembly*

The lysimeters were assembled by cementing a ceramic porous cup (0653X01-B01M3; Soilmoisture Equipment Corp.), with an outside diameter of 4.83 cm and length of 6.05 cm, to a schedule-200 PVC pipe (4.46 cm i.d., 4.83 cm o.d., and 35.56 cm long). The cup had a connecting lip of 1.12 cm around the top to provide an air and watertight seal. The top of the PVC pipe was fit with a 5.08 cm male coupling adapter, to which a 91.44 cm PVC pipe was joined with a 5.08 cm female coupling adapter. The 91.44 cm PVC pipe was simply to enable visibility of the lysimeter locations during grass mowing operations. The top of the 91.44 cm PVC pipe was plugged with a two-hole rubber stopper and short (~30.48 cm) and long (~134.1 cm) 0.64 cm diameter hard plastic tubes were inserted through the holes in the stopper.    The short tube served as both the pressure and vacuum inlet and the long tube as the discharge tube. The long tube was attached to a 0.8 cm (5/16 inches) hardwood rod, in order to keep it straight within 1.27 cm of the ceramic cup bottom. A thumbscrew pinch clamp was tightened around each tube to maintain a vacuum inside the porous cup.  Two 0.64 cm flat plastic plates were cut into trapezoidal fins and welded 180$^{\circ}$ apart near the top of the 35.56 cm long PVC pipe in order to prevent movement of the lysimeter assembly in case there was need to remove the top PVC part (91.44 cm) once installed in the soil.

*Lysimeter installation*

A layer about 6-cm deep of a mixture of silica flour (sieve no. 200; Agsco Corporation, NJ) and water was placed at the bottom of a 35-cm deep hole dug with a 5.7 cm (2.25 inches) one-piece regular soil auger.  The silica flour helped to fill voids and provide a good seal (Parizek and Lane, 1970). The lysimeter assembly was inserted into the hole with the porous cup in the soil profile, and soil was backfilled into the hole up to about

5.08 cm below the ground level, where a plug of bentonite was deposited to prevent possible channeling of water down the lysimeter hole.

*Soil water sampling*

All the lysimeters were emptied 2 to 3 h before irrigation using a hand-held battery powered peristaltic pump to create a vacuum inside the porous cup. Thus the collected water samples were considered as to be primarily due to irrigation. Four to five hours after irrigation ceased, water samples were collected in acid-washed plastic bottles via the long discharge tube using the peristaltic pump. Composite samples were made using samples from the three lysimeters at each of the four sampling locations: 1, 2, 3, and 4 (see chapter 3, Figure 3-4), and the samples were analyzed for $NO_3$-N and $NO_2$-N at the PSU Agricultural Analytical Services laboratory (AASL). The $C_p$ used in the monthly N balance was the mean leachate N concentration (measured in the composite samples) per sampling event in the month. The water samples were collected after at least two irrigations per month from May to November in 2011 and 2012.

**7.4 Summary of nitrogen balance parameters and *f*nb data assessment**

The overall N mass balance expression in Eq. [7-1] was rearranged to include surface runoff (Q, cm) and express the *f*nb values in the terms of the measured and calculated system parameters, Eq. [7-6]. Descriptive statistics was used to assess the *f*nb values against design *f* values and monthly: effluent C:N ratio, air temperature measured at 2-m heights above ground, and crop N removal.

$$f_{nb} = \frac{\overbrace{L_nC_n}^{\text{MWE-TN}} - \overbrace{C_p\left(L_n + P_r - ET_c - Q\right)}^{\substack{\text{N Leaching}\\\text{term}}} - \overbrace{10U}^{\substack{\text{Crop N removal}\\\text{term}}}}{L_nC_n} \qquad [7\text{-}6]$$

**Where:**

> $f$nb and Q are as defined in section 7.2 and Eq. [7-3], respectively, and all other parameters are as specified for Eq. [7-1] in section 7.1.

Table 7-1 summarizes the parameters used in the N balances. Variations in the monthly irrigation depths were due to the number of irrigation events per month and the variation in runoff was due to the irrigation scheduling and antecedent natural rainfall and thus resulting AMC. The estimated daily reference evapotranspiration ($ET_o$) (Appendix M) was within the 0.05 to 0.89 cm day$^{-1}$ range for central Pennsylvania (Jarrett and Brandt, 2007).

**Table 7-1 Parameters used to calculate monthly *f*nb values in 2011 and 2012.**

| Months | Monthly mean $C_n$ (standard deviation) | $L_n$ | MWE-TN | $P_r$ | $ET_c$ | Surface runoff | N in AGB (A) (see chapter 3, Table 3-4) | Crop N removal due to fertilizer N (B) | U (A-B) | Mean $C_p$[1] | Leachate sampling date: mean leachate N concentration (mg L$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | mg L$^{-1}$ | cm | kg N ha$^{-1}$ | cm | cm | | kg N ha$^{-1}$ | | | mg L$^{-1}$ | |
| April & May 2011 | 15.4[2] | 97.4 (April) 195.2 (May) | 45.1 | 16.4[2] | 3.4[3] (April) 96.9 (May) | 0.0 (April) 1.7 | 59.2 | 29.3 | 29.9 | 2.87 (2.8) | 10 May:4.85 (1.9), n=11; 17 May: 0.89 (0.71), n=4 |
| June 2011 | 8.9[4] | 18.9 | 16.9 | 8.1 | 11.7 | 0.9 | 71.0 | 35.4 | 35.6 | 2.69 (0.31) | 2 June:3.01 (2.13), n=4; 7 June: 2.68 (1.42), n=4; and 28 June: 2.39 (1.97), n=12 |
| July 2011 | 10.0[4] | 19.5 | 19.5 | 1.7 | 14.1 | 0.0 | 19.7 | 9.8 | 9.9 | 7.50 (1.13) | 12 July: 8.30 (3.3), n=3; 19 July: 6.70 (1.35) |
| August 2011 | 11.7 (5.95) | 24.6 | 28.7 | 6.3 | 10.2 | 1.3 | 43.2 | 20.7 | 22.5 | 1.86 (1.70) | 12 Aug.: 3.71 (1.99), n=4;16 Aug.: 0.36 (0.17), n=4; and 23 Aug.: 1.51 |
| September 2011 | 14.0 (1.55) | 15.6 | 21.8 | 10.7 | 5.8 | 0.1 | 55.1 | 26.8 | 28.3 | 1.13 (0.02) | 21 Sept.: 1.11 (0.76), n=4; 27 Sept.: 1.14 (0.68), n=4 |
| April 2012 | 13.6 (3.21) | 19.4 | 26.3 | 2.7 | 7.6 | 0.0 | 48.3 | 29.6 | 18.7 | 1.16[5] | 24 April: 1.16 (1.02), n=4 |
| May 2012 | 10.4 (2.64) | 19.7 | 20.4 | 14.9 | 10.3 | 1.4 | 53.1 | 32.5 | 20.6 | 1.05 (0.65) | 15 May: 0.59 (0.27), n=4; 22 May: 1.51 (1.07), n=4 |
| June 2012 | 3.9 (0) | 9.82 | 3.8 | 7.2 | 11.9 | 1.1 | 8.3 | 5.0 | 3.3 | 0.87 (0.37) | 22 June:1.13 (0.66), n=7; 26 June: 0.61 (0.46), n=4 |
| July 2012 | 7.8 (3.32) | 19.4 | 15.1 | 6.5 | 13.2 | 0.0 | 31.5 | 19.3 | 12.2 | 0.69 (0.44) | 10 July 1.0 (0.26), n=4 ; 17 July: 0.38 (0.3), n=5 |
| August 2012 | 9.9 (2.76) | 19.4 | 19.2 | 7.8 | 10.6 | 0.0 | 34.4 | 21.1 | 13.3 | 8.65 (5.21) | 7 Aug.: 12.34 (4.3), n=4; 14 Aug.: 4.97 (3.0), n=4 |
| September 2012 | 13.8 (2.23) | 14.7 | 20.3 | 8.2 | 6.9 | 0.0 | 7.3 | 4.5 | 2.8 | 1.81[5] | 25 Sept.: 1.81 (2.02), n=4 |

[1]Computed using values in the last column (standard deviation in brackets); [2]Used the mean effluent total N data from 18 April to 31 May 2011 (from the PSU WWTP reports); [3]$ET_c$ for April 2011 calculated using Kc for April and $ET_o$ from 18 to 30 April 2011; [4]Monthly mean (n=7 to 9) MWE-TN from PSU WWTP reports (see chapter 3, Table 3-3); [5]Not a mean.

## 7.5 Results and discussion

The *f*nb estimates remained the same with or without inclusion of surface runoff in the N balance calculations (Table 7-2) due to the small surface runoff values (0 to 1.7 cm) compared to the ETc values (Table 7-1). Despite the small contribution of runoff to the N balance, the discussion focuses on the *f*nb estimates determined from N balances in which runoff was included.

**Table 7-2 Monthly *f*nb estimates in 2011 and 2012.**

| Month | *f*nb [1] | *f*nb [2] | MWE-TN $(L_nC_n)$ | N leaching term $C_p (L_n + P_r - ET_c - Q)$ | Crop N removal term (10U) |
|---|---|---|---|---|---|
| | | | | cm mg L$^{-1}$ | |
| April & May 2011 | 0.13 | 0.13 | 451.7 | 92.7 | 299.2 |
| June 2011 | -1.36 | -1.35 | 168.2 | 39.0 | 356.0 |
| July 2011 | 0.22 | 0.22 | 194.9 | 53.6 | 99.4 |
| August 2011 | 0.08 | 0.09 | 287.1 | 35.9 | 225.0 |
| September 2011 | -0.40 | -0.40 | 217.9 | 23.0 | 282.6 |
| April 2012 | 0.23 | 0.23 | 263.6 | 16.9 | 187.3 |
| May 2012 | -0.14 | -0.13 | 204.0 | 24.0 | 206.2 |
| June 2012 | 0.03 | 0.05 | 38.3 | 3.5 | 32.6 |
| July 2012 | 0.13 | 0.13 | 150.7 | 8.7 | 122.4 |
| August 2012 | -0.44 | -0.44 | 191.9 | 143.8 | 133.4 |
| September 2012 | 0.72 | 0.72 | 203.0 | 28.8 | 28.2 |

[1]Surface runoff not included in N balance; [2]Surface runoff included in N balance.

Negative *f*nb values were obtained in June 2011, September 2011, May 2012, and August 2012 (Table 7-2) when the sum of the leaching and crop N removal terms in Eq. [7-6] exceeded the total N in the effluent (MWE-TN). One challenge involved the difficulty in isolating the N removal due to only effluent N from the total measured crop N removal. sections 7.5.1 to 7.5.5 include discussions of the effect of the N balance terms and fertilizer on the *f*nb estimates.

**7.5.1 *f*nb estimates in April and May in 2011 and 2012**

In this section the results for April and May for both years are discussed since in 2011 the aboveground biomass yield and crop N removal were measured at the end of May and thus one *f*nb value (0.13) was estimated for both April and May. It was difficult to determine to what extent the *f*nb estimate in April and May 2011 was affected by the N application and removal pathways due to the differences in the monthly mean air temperatures in April (9.5 $\pm$5.1$^o$C in 2011 and 9.0 $\pm$4.2$^o$C in 2012) and May (16.4 $\pm$.4$^o$C in 2011 and 17.3$\pm$ 3.0$^o$C in 2012-calculated using weather data in Appendix B), and also because $C_p$ data was collected in May 2011. It was suspected that the leachate N concentration ($C_p$) in the N balances for April and May 2011 and April 2012 were minimally affected by the fertilizer applications made on 22 April 2011 and 6 April 2012 since nitrogen concentration in the leachate samples ($C_p$) was measured about 2 weeks from these dates (see Table 7-1). The relatively high *f*nb estimate in April 2012 (0.23) was due to the small leaching term (Table 7-2). In addition to climatic factors (e.g. low air temperatures), field management (e.g. time to begin effluent irrigation and different times of applying starter fertilizer) at the study site probably affected the *f*nb estimates in April.

In May 2012, a negative *f*nb estimate (-0.13) was obtained since the estimated crop N removal (20.6 kg N ha$^{-1}$) was nearly equal to the applied MWE-TN (20.4 kg N ha$^{-1}$), the sum of the crop N removal and leaching terms in Eq. [7-6] were greater than the effluent total N. In both years, the greatest fraction of crop N removal was in the range of 0.22 to 0.29 (see section 7.3.1.4). This fraction was 0.24 in April & May 2011, 0.26 in April 2012, and 0.29 in May 2012. The high N removal in May 2012, partly explains the

negative $f$nb estimate and probably the reason for a small $f$nb value estimated for April and May 2011. However, negative $f$ values cannot be used for design purposes and assuming zero $f$ values is not practical in field conditions. Since the greatest N removal at the study site occurs in May, it was surmised that an $f$ value greater than zero but less than 0.1 (suggested for tertiary-treated effluents) would be appropriate.

## 7.5.2 $f$nb estimates in June 2011 and 2012

In June 2011, the sum of the crop N removal and leaching terms (395 cm mg $L^{-1}$) was greater than the applied effluent N (168.2 cm mg $L^{-1}$) thus the $f$nb value was negative (-1.35), whereas in June 2012 the calculated $f$nb was 0.05 (Table 7-2). In June 2012, the estimated crop N removal (3.3 kg N $ha^{-1}$) was approximate to the applied MWE-TN (3.8 kg N $ha^{-1}$) (Table 7-1). However, it is important to note that the crop N removal in June 2011 more likely represented the month than in June 2012, since the grass field was irrigated only twice on 21 and 25 in June 2012 resulting in small aboveground biomass yield and crop N removal. Due to the similarities of the monthly mean air temperatures in May and June (16.4 $\pm.4^{o}$C (May 2011), 19.7 $\pm$ 2.8$^{o}$C (June 2011), 17.3$\pm$ 3.0$^{o}$C (May 2012) 19.3$\pm$ 3.9$^{o}$C (June 2012)-calculated using weather data from Appendix B) and the identical fraction of crop N removal, 0.29 in June 2011 and May 2012 (section 7.3.1.4), similar $f$ values are appropriate for the months of May and June. Like in May 2012, a negative $f$ value was calculated in June 2011, probably due to high N removal. Although the AGB yield was not typical for the study site in June 2012, the $f$nb estimate was small (0.05) suggesting high N removal. Thus, an $f$ value of 0.05 could represent the study site in May and June.

### 7.5.3 *f*nb estimates in July 2011 and 2012

The *f*nb value of 0.22 estimated in July 2011 was almost double the value of 0.13 estimated in July 2012 (Table 7-2) due to higher MWE-TN 19.5 kg N ha$^{-1}$ in July 2011 than 15.1 kg N ha$^{-1}$ in July 2012, in conjunction with similar estimated crop N removal rates of 10.0 kg N ha$^{-1}$ in 2011 and 12.2 kg N ha$^{-1}$ in 2012 (Table 7-1).

The mean (n=2) *f*nb value of 0.18 for the two years could be representative for the grass field in July since the fraction of 0.12 AGB yield and thus N removal in July is about half of the greatest fraction of 0.3 in May (see chapter 3, Fig. 3-6). From chapter 3, Table 3-4, these fractions were 0.17 in July 2012 and 0.34 in May 2012. Also the increase in soil microbial activity due to increased July mean air temperatures of $23.7 \pm 2.8^{o}$C (2011) and $22.9 \pm 2.5^{o}$C (2012) compared to the monthly mean air temperatures in May and June (see section 7.4.1 and 7.4.2) probably increased soil biochemical processes and thus atmospheric N losses and *f*. The *f*nb estimates in July were least affected by fertilizer additions in April and August.

### 7.5.4 *f*nb estimates in August 2011 and 2012

Unlike in August 2011 when an *f*nb value of 0.09 was calculated, a negative *f*nb estimate of -0.44 was obtained in 2012. This was due to the MWE-TN term of 287.1 cm mg L$^{-1}$ in August 2011 being large compared to 191.9 cm mg L$^{-1}$ in August 2012 (Table 7-2). The sum of the N leaching and crop N removal terms in August 2011 (260.9 cm mg L$^{-1}$) and August 2012 (277.2 cm mg L$^{-1}$) were similar in magnitude. Notably, the leachate N concentration ($C_p$) in August 2012 was likely affected by the UAN-30 fertilizer applied to the grass field on 3 August. The leachate N concentration ($C_p$) in samples collected on 7 August and 14 August were 12.34 mg L$^{-1}$ and 4.97 mg L$^{-1}$ (see Table 7-1), respectively.

Although the extent to which UAN-30 fertilizer affected the $f$nb estimates in August could not be explicitly determined, the $f$nb estimate in August 2011 was less affected by the fertilizer addition, since, $C_p$ value used in the August 2011 N balance was measured further (12 August) from the fertilizer application on 5 August than in 2012.

Since the AGB yield for the fescue hay in August and September were smaller than the yield in May and June (see chapter 3, Fig. 3-6), and the monthly mean air temperatures in August (20.2 ±1.9$^o$C in 2011 and 20.3 ±2.3$^o$C in 2012) were comparable to those in July (see section 7.4.3), the $f$nb value of 0.09 estimated in August 2011 is deemed representative of the study site. Lund et al. (1981) estimated the same $f$ value (0.09) in permanent pastures under a warm climate in Santa Maria, California.

### 7.5.5 $f$nb estimates in September 2011 and 2012

The dramatic difference in the $f$nb values of -0.4 in September 2011 and 0.72 in September 2012 was mainly due to the 10-fold difference in the estimated crop N removal, 28.3 kg N ha$^{-1}$ in 2011 and 2.8 kg N ha$^{-1}$ in 2012 (Table 7-1). However, from field observations the AGB yield and thus crop N removal were more normal for the study site in 2011 than in 2012. The effluent N (217.9 cm mg L$^{-1}$ in 2011 and 203 cm mg L$^{-1}$ in 2012) and leaching N terms (23.0 cm mg L$^{-1}$ in 2011 and 28.8 cm mg L$^{-1}$ in 2012) (Table 7-2) were comparable. The monthly mean air temperatures in September (17.2 ±3.5$^o$C in 2011 and 16.2 ±4$^o$C in 2012) were similar to temperatures in May and June (see section 7.4.2), and the fraction of crop N removal in September 2011 (0.22) was comparable to the N removal fractions in April and May 2011 (0.24), June 2011 (0.29), August 2011 (0.17), April (0.26), May 2012 (0.29), and in August 2012 (0.19) (see section 7.3.1.3). However, since the AGB yield in August and September is typically

smaller than the biomass yield in May and June, an *f* value used for August at the study site could also represent the month of September, rather than the *f* value used for the months of May and June.

### 7.5.6 *f*nb estimates vs design *f* values

The *f*nb estimates were approximate to the design *f* values in April and May 2011, July 2011, August 2011 (Fig. 7-1), April 2012, and July 2012 (Fig. 7-2). The average (n=2) *f*nb estimate for July 2011 (0.22) and July 2012 (0.13) was 0.18. Crites and Tchobanoglous (1998) suggest *f* values of 0.2 for secondary-treated effluents and 0.15 in "warm" climates and 0.1 in "cold" climates for tertiary-treated effluents. Tertiary-treated effluent (C:N ratio < 1) was applied at the study site.



**Figure 7-1 Monthly *f*nb estimates in 2011 and design *f* values.**

**Figure 7-2  Monthly *f*nb estimates in 2012 and design *f* values**.

Although 2011 was a more representative year (based on aboveground biomass yield) at

the study site than 2012, in June and August of both years, and in September 2011 and

May 2012 the estimated *f*nb values were less than or equal to 0.1, the design *f* value for

tertiary-treated effluent (USEPA, 2006).  The averages for the *f*nb estimates for the

months of June, August and September returned negative values.  This could partly be

explained by overestimation of nitrogen removal or actual high N removal during these

months hence the small *f* values. Since negative *f* values cannot be used for design

purposes, the positive *f*nb estimates were assessed against crop N removal and the

common factors considered in selecting design $f$ values-effluent C:N ratio and air temperature.

**7.5.7 $f$nb estimates, effluent C:N ratio, mean air temperature, and crop N removal**

Although the denitrification activity is affected by several factors, e.g. MWE characteristics and method of MWE application, design $f$ values in literature are selected based on the effluent's C:N ratio and climate (see chapter 1, Table 1-1). This is probably due to the wide availability of such data. Crites and Tchobanoglous (1998) suggest design $f$ values generally for "warm" and "cold" climates without specifying the corresponding temperature ranges. The effluent's C:N ratio, which is controlled by operational conditions at the wastewater plant, was in the range of 0.04 to 0.2 (Fig. 7-3 and 7-4) during the study period and, as evidenced in Figure 7-3 and Figure 7-4, the effluent's C:N did not affect the $f$nb estimates.

During the summer months (July and August) when the monthly mean air temperatures were $20^{o}$C or higher the $f$nb estimates were similar to the design $f$ values, except in August 2012 when $f$nb value was negative. The monthly mean air temperatures (calculated from the weather data in Appendix B) in July 2011, August 2011, July 2012, and August 2012 were: $23.6 \pm 2.8^{o}$C, $20.2 \pm 1.9^{o}$C, $22.9^{o}$C$\pm 2.5$, and $20.3 \pm 2.3^{o}$C, respectively.

**Figure 7-3 Monthly *f*nb estimates, effluent C:N ratio, mean air temperature, and crop nitrogen removal in 2011.** The mean air temperature and effluent C:N ratio for April and May are plotted as one value. Inset is a general growth curve for cool season grasses (Craig et al., 2009).

**Figure 7-4 Monthly *f*nb estimates, effluent C:N ratio, mean air temperature, and crop nitrogen removal in 2012.**

During the months (apart from April and May 2011 and April 2012) when the monthly mean air temperatures were less than 20$^{\circ}$C, the *f*nb estimates were: negative -1.35 in June 2011, -0.4 in September 2011, and -0.13 in May 2012), nearly zero (0.05 in June 2012), or large (0.72 in September 2012) (Figs. 7-3 and 7-4). The monthly mean air temperatures (calculated from the weather data in Appendix B) in April & May 2011, June 2011, September 2011, April 2012, May 2012, June 2012, and September 2012 were: 12.9 ± 5.8$^{\circ}$C, 19.7± 2.8$^{\circ}$C, 17.2 ± 3.5$^{\circ}$C, 9.1± 4.2$^{\circ}$C, 17.3± 3.0$^{\circ}$C, 19.3± 3.9$^{\circ}$C, and

16.2± 4.0$^o$C, respectively. In addition to the limitations of the N balance, negative and large $f$ values were probably due to increased field spatial and temporal variability as a result of slightly higher soil moisture content during these months than in the summer months when the soil dried faster as a result of high summer temperatures and smaller aboveground biomass coverage per unit area-especially in July.

As would be expected, the $f$nb estimates roughly decreased with an increase in crop N removal and vice versa especially in 2011 (Fig. 7-3) suggesting a negative correlation between the $f$nb estimates and crop N removal. The decline in crop N removal in the summer did not typically occur in August as typical for cool season grasses (inset, Fig. 7-3), since the smallest crop N removal occurred in July 2011 (Fig. 7-3) and September 2012 (Fig. 7-4). The crop N removal in September 2012 (7.3 kg N ha$^{-1}$) and June 2012 (8.3 kg N ha$^{-1}$) were about one-third the crop N removal in July 2012 (19.7 kg N ha$^{-1}$).

The positive $f$nb estimates were inversely correlated to the logarithm of the crop N removal as shown in Figures 7-5 (monthly mean air temperature was greater than or equal to 20$^o$C (July and August) and Figure 7-6 (monthly mean air temperature was less than 20$^o$C). The correlations of determination, 0.99 in Figure 7-5 and 0.2 in Figure 7-6 suggest there was better correlation between the $f$nb estimates and the crop N removal in July and August than the rest of the months.

**Figure 7-5 Monthly positive *f*nb estimates vs logarithm of measured monthly crop nitrogen removal in July and August, 2011 and July, 2012.** Measured monthly crop N removal (kg N ha$^{-1}$) was obtained from chapter 3, Table 3-4.

**Figure 7-6 Monthly positive *f*nb estimates vs logarithm of measured monthly crop nitrogen removal in April & May, 2011 and April, June, and September, 2012.** Measured monthly crop nitrogen removal (kg N ha$^{-1}$) was obtained from chapter 3, Table 3-4. The *f* values for April and May 2011 are plotted as one value.

Since crop N removal was better correlated to the *f*nb estimate in July and August (Fig. 7-5), the *f*nb linear model in Figure 7-5 was used to model *f* values for all the months in both years (Fig. 7-7). During the months with high crop N removal (e.g. May and June) the *f*nb linear model yielded small *f* values (between 0 and 0.1) as would be expected (Fig. 7-7) except for June 2012. Due to the small crop N removal in June 2012 and September 2012 the *f*nb linear model yielded higher *f* values (0.36 and 0.38 in June and September, respectively) than even the *f* values in July (Fig. 7-6) when crop N removal is

typically smallest at the study site. These $f$ values would probably be smaller if the measured crop N removal in these months was more representative for the study site.

In April & May 2011 and April 2012, the model yielded smaller values than the $f$nb estimates but similar to the $f$ values in May 2012 and September 2011. However, none of the $f$nb estimates in September, -0.4 in 2011 and 0.72 in 2012 and those determined using the $f$nb linear model, 0.04 for 2011 and 0.38 for 2012, seem plausible for the month at the study site. As noted in section 7.5.5, an $f$ value similar to the one used in August would probably be appropriate for September, however this assumption needs to be verified with further research.

**Figure 7-7 Monthly *f*nb estimates and *f* values modeled using monthly crop nitrogen removal.** The *f* values for April and May 2011 are plotted as one value.

## 7.6 Data limitations

The $f$nb estimates were mainly limited by the accuracy of the crop N removal term and the leaching term. Due to UAN-30 commercial fertilizer application at the study site it was difficult to isolate crop N removal due to solely effluent, which probably caused errors in estimation of the crop N removal term. The leaching term was limited by rainfall depth and leachate N concentration data. Due to data loss, some daily rainfall (Appendix B) at the study site was predicted using Equations 3-1 and 3.2 (see chapter 3, section 3.8). Also the N concentration in the leachate limited the accuracy of the leaching term especially in April 2012 and September 2012 when a single monthly $C_p$ value was used.

The monthly N removal fractions used to estimate N removal due to fertilizer addition were based on a six-month period (April to September) rather than seven months since N removal in October was not measured (see section 7.3). This implied the annual fertilizer applications influenced N removal only from April to September, which is not practical under field conditions.

The N balance assumes all effluent nitrogen is available to the crop. Although the effluent used at the study site on average was composed of $NO_3$-N (70% in 2011 and 87% in 2012- see chapter 3, Table 3-2), the availability of effluent-derived plant available nitrogen could not be entirely ascertained under field conditions.

## 7.7 Summary and conclusions

In 2011 and 2012, a monthly nitrogen (N) balance was conducted in a tall fescue hay field as part of a larger research study with a goal to estimate the fraction of MWE-total nitrogen lost to the atmosphere due to ammonia volatilization and denitrification. The

monthly fractional N loss in the N balance was termed $f$nb. The nitrogen balance is used to determine nitrogen-based MWE land application rates with crop N removal and assumes no change in soil N storage (see Eqn. 7-1).  The grass field was spray-irrigated with municipal wastewater effluent (MWE) and also fertilized with UAN-30.  Since the effluent's C:N ratio  was less than 1 and soil and effluent pH was near neutral,  it was assumed that the that the $f$nb values would be smaller than the design $f$ values and that $f$nb values varied during the growing season due to interacting environmental and land management factors. The study also sought to determine whether there is a relationship between $f$ values, effluent C:N, air temperatures measured at 2-m aboveground,  and crop N removal.

The $f$nb estimates using field data included 0.13 (April and May, 2011), -1.35 (June, 2011), 0.22 (July, 2011), 0.09 (August, 2011), -0.40 (September,  2011), 0.23 (April, 2012), -0.13 (May, 2012), 0.05 (June, 2012), 0.13 (July, 2012), -0.44 (August, 2012), and 0.72 (September, 2012). Except in September 2012, the $f$nb estimates were within or less than the range of design $f$ values 0.15 to 0.25 for secondary-treated effluent (USEPA, 2006) or comparable to 0.1 suggested for tertiary-treated effluents (Crites and Tchobanoglous, 1998; USEPA, 2006).  The N balance yielded negative values, whenever the sum of the crop N removal and the leaching N removal terms exceeded the applied effluent N.

The $f$nb estimates varied over the growing season and as would be expected the estimated N loss decreased with an increase in N removal and vice versa. During the study period, the effluent C:N ratio was in the range 0.04 to 0.2 and did not affect the $f$nb estimates. This supports using the same range of design $f$ values for effluents with C:N ratios that

are less than 1 (see chapter 1, Table 1-1). The assessment of the positive *f*nb estimates (since negative *f* values cannot be used for design purposes) against crop N removal and air temperature in this study helped to elucidate the *f* values in a cold climate.

The positive *f*nb estimates were inversely correlated with the logarithm of the measured monthly crop N removal. In July and August when the monthly mean air temperature was equal to or greater than $20^o$C, the *f*nb estimates were better correlated to the logarithm of the measured monthly crop N removal (*f*nb = - 0.386 [Log (measured monthly crop N removal] + 0.716; $R^2$ =0.99) than in April, May, June, and September, (*f*nb = - 0.276 [Log (measured monthly crop N removal] + 0.644; $R^2$ =0.2) when monthly mean air temperatures were less than $20^o$C. The *f*nb linear model generated using the July and August data yielded seemingly reasonable *f* values for the months of April, May, June, and September (except June and September 2012): 0.03 for April & May 2011, 0.001 for June 2011, 0.04 for September 2011, 0.07 for April 2012, and 0.05 for May 2012. Since the *f*nb estimates in July 2011, August 2011, and July 2012 were comparable to the design *f* values, the *f*nb linear model for the warm months at the study site could be useful in elucidating the *f* values, especially for the months with high N removal and when monthly mean air temperatures are less than $20^o$C.

A conclusion could not be drawn regarding the *f* value for April for several reasons: UAN-30 fertilizer applications were made on different dates in each year (22 April in 2011 and 6 April in 2012) and also because in 2011, the *f*nb estimate represented both April and May. Since tall fescue at the study site has two annual biomass yield peaks, with a greater peak in May and June than in August and September, *f* values of 0.05 and

0.1 seemed to appropriately represent the months of May and June, and August and September.   An $f$ value of 0.2 seemed appropriate for the month of July at the study site.

Despite the complexity of conducting nitrogen balances in the field, this study has demonstrated the possibility of using a "source-sink" N mass balance approach to elucidate $f$ values in MWE irrigated cropping systems.  However, additional research is needed to further improve the $f$ values in the absence of commercial fertilizer addition.

## 7.8 References

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**Chapter 8. SUMMARY, CONCLUSIONS, AND FUTURE WORK**

**8.1 Summary and conclusions**

The fractional nitrogen (N) loss due to atmospheric N losses (denitrification and ammonia volatilization) (*f*) in municipal wastewater effluent (MWE) irrigation was quantified in 2011 and 2012 at the Pennsylvania State University (PSU) Living Filter (LF) in a tall fescue hay field (8.4 ha). The field was irrigated with secondary-treated municipal wastewater effluent (MWE) at a rate of 5 cm wk$^{-1}$. Effluent N application rates to the grass field were 220 kg N ha$^{-1}$ in 2011 and 153 kg N ha$^{-1}$ in 2012. The grass field was also fertilized with urea-ammonium nitrate (UAN-30): 66 kg N ha$^{-1}$ on 22 April 2011, and 56 kg N ha$^{-1}$ on each of the dates, 5 August in 2011, 6 April 2012, and 3 August in 2012.

Following standard design procedures, zero N storage was assumed and atmospheric N losses were mainly attributed to denitrification, since on average the effluent total N was 70% and 87% $NO_3$-N in 2011 and 2012, respectively, and ammonia volatilization due to effluent irrigation was essentially zero apart from when UAN-30 fertilizer was applied. The maximum measured ammonia emission rate of $10^{-4}$ kg $NH_3$-N ha$^{-1}$ h$^{-1}$ was roughly equivalent to 1 kg N ha$^{-1}$ yr$^{-1}$, which was insignificant relative to the effluent N applied during the study period.

Denitrification gaseous fluxes (kg N ha$^{-1}$ h$^{-1}$) were measured from intact soil cores collected using 4.8 cm i.d. and 10.2 cm long aluminum cylinders. The soil cores were collected from the surface soil horizon 6 to 7 h before irrigation began (BI) and 4 to 5 h after irrigation ceased (AI). The daily denitrification fluxes were extrapolated from the hourly fluxes and the denitrification N loss per irrigation cycle (y) was estimated with the

exponential equation $y = ae^{-bx}$ where x was the number of days after irrigation ceased.

The constants a and b were determined using the AI and BI estimated daily denitrification

rates. Nitrogen losses to the atmosphere from denitrification N ($N_2O+N_2$) were also

simulated using the DeNitrificationDeComposition (DNDC) crop model, Version 9.5, in

the site mode. Tall fescue was simulated as a non-legume hay and simulations were

conducted from 2004 to 2012 with DNDC's default clay fraction and saturated hydraulic

conductivity ($K_{sat}$) for loam and clay loam soil types. The soil types were identified in the

5 to 15-cm depth in the surface soil horizon at the study site. The default clay fraction

values in DNDC for the 0 to 10-cm deep surface soil layer are 0.19 and 0.4 for loam and

clay loam soil types, respectively, and the DNDC default saturated hydraulic conductivity

($K_{sat}$) values are 0.025 m $h^{-1}$ and 0.009 m $h^{-1}$ for loam soil and clay loam soil types,

respectively.

Simulations were also completed with measured clay fraction of 0.26 (mean =5) and 0.31

(mean=4) for loam and clay loam soil types, respectively, in the 5 to15-cm depth of the

surface soil horizon, and mean (n=4) $K_{sat}$ of 0.017 m $h^{-1}$ was determined in the 0 to15-cm

depth of the surface soil horizon. The calculated water-filled pore space (WFPS) at field

capacity (0.61 (loam) and 0.64 (clay loam)), and WFPS at wilting point (0.33 (loam) and

0.37 (clay loam)), and porosity (0.53) were used in the simulations. The porosity was

calculated using bulk density of 1.25 g $cm^{-3}$ and assumed particle density of 2.65 g $cm^{-3}$.

The initial soil carbon was set at 0.0156 kg C (kg soil)$^{-1}$. Simulations that were completed

with default clay fraction and $K_{sat}$ were named LD (loam soil) and CLD (clay loam soil)

and simulations completed with measured clay fraction and $K_{sat}$ were named LM (loam

soil) and CLM (clay loam soil).

Effluent samples were collected in the field weekly and analyzed for TN and $NO_3$-N. The applied MWE-total nitrogen (MWE-TN) was in the range of 1.9 to 8.1 kg N ha$^{-1}$ per irrigation cycle (4 to 7 days). Twelve $f$ values were calculated based on MWE-TN applied per irrigation cycle and measured denitrification, (kg N ha$^{-1}$ per irrigation cycle), $f$md and simulated denitrification ($N_2O + N_2$), $f$sd. Monthly $f$ estimates ($f$nb) were also calculated from the "source-sink" N mass balance from April to September in both years. The monthly crop N removal due to only MWE-TN was estimated as the difference between the measured N removal in the aboveground biomass and the estimated N removal due to UAN-30 fertilizer application. Nitrogen removal due to fertilizer was estimated from the annual N removal, 248 kg N ha$^{-1}$ in 2011 and 183 kg N ha$^{-1}$ in 2012, and the monthly proportion of aboveground biomass in Pennsylvania:  0 (January, February, March, November, and December), 0.05 (April), 0.3 (May), 0.2 (June), 0.12 (July), 0.15 (August), 0.12 (September), and 0.06 (October)).  If the difference was greater than the applied effluent total N, the crop N removal was considered to be equal to the applied effluent N (see chapter 3, Table 3-2).  The measured and simulated denitrification rates were compared and the $f$md, $f$sd, and $f$nb values were compared to the design $f$ values: 0.15 to 0.25 suggested for secondary-treated effluents, and 0.1 suggested for tertiary-treated effluents (Crites and Tchobanoglous, 1998; USEPA, 2006).  The denitrification fluxes and $f$ estimates in July and November were likely least affected by UAN-30 fertilizer applications that occurred in April and August in both years.

The measured AI mean (n=8)  hourly denitrification fluxes were greater than measured BI mean (n=8) hourly denitrification fluxes, thereby suggesting soil conditions needed for denitrification such as anaerobicity, dissolved organic carbon and $NO_3$-N substrate

concentrations were provided by the irrigation event. The AI and BI WFPS was above 60% (0 to 6-cm soil depth at the soil surface), the threshold needed for denitrification (Nommik, 1956; Bremner and Shaw, 1958). Higher WFPS values (80% - 90%) were measured after irrigation.

A Tukey's pairwise comparison test indicated that the means (n=8) of the AI and BI hourly denitrification fluxes were statistically different ($\alpha$=0.05) for the irrigation cycles (AI and BI dates listed, respectively) 12 to 18 July 2011, 12 to 15 August 2011, 16 to 22 August 2011, 21 to 26 September 2011, 27 September to 3 October 2011, 10 to 16 July 2012, and 7 to 13 August 2012. However, the means of the AI and BI fluxes were not statistically  different ($\alpha$=0.05) for the irrigation cycles 2 to 6 June 2011, 15 to 21 November  2011, 15 to 21 May 2012, and 22 to 25 June 2012. This was probably due to rainfall received on the BI dates of 21 November 2011 (4.75 cm), 21 May 2012 (1.93 cm), 24 June 2012 (1.07 cm), and 25 June 2012 (0.08 cm) (Appendix B), resulting in similar soil conditions (e,g, soil moisture) and thus similar denitrification N losses on the AI and BI dates. The $f$md estimates and the ratio of the BI to AI denitrification fluxes (kg N ha$^{-1}$ h$^{-1}$) within an  irrigation cycle were fitted to a  linear relationship for two categories: BI and AI denitrification fluxes that were significantly different and fluxes that were not significantly different ($\alpha$=0.05).  The $f$md estimates were minimized as the ratio of the BI to AI denitrification fluxes within an irrigation cycle increased irrespective of whether the BI and AI denitrification fluxes were significantly different.

Both the measured and simulated denitrification fluxes followed similar trends, and the AI denitrification rates were generally greater than the BI rates.  The simulated and denitrification rates followed similar trends, with generally higher rates in the day after

irrigation than on the day before irrigation. The model simulated before irrigation denitrification rates better than the after irrigation rates. All the MAE values, for all the four simulation types, (before irrigation) were equal, 0.3 in 2011 and 0.15 in 2012 and smaller than the MAE values for the after irrigation rates, which were all 0.98 in 2012 and 5.2 (LD simulations), 5.13 (LM simulations), 4.97 (CLD simulations), and 5.0 (CLM simulations) in 2011. The average $f$sd estimates for the LM and CLM simulations were discussed along with the $f$md estimates and design $f$ values.

The average $f$sd (LM and CLM simulations)/ $f$md values were: 0.03/0.4 (2 to 6 June 2011), 0.01/0.98 (12 to 18 July 2011), 0.08/3.25 (12 to 15 August 2011), 0.16/3.45 (16 to 22 August 2011), 0.02/0.50 (21 to 27 September 2011), 0.01/0.21 (27 September to 3 October), 0.004/1.10 (25 to 31 October 2011), 0.02/0.70 (15 to 21 November 2011), 0.05/0.03 (15 to 21 May 2012), 0.03/0.74 (21 to 25 June 2012), 0.01/0.19 (10 to 16 July 2012), and 0.14/2.87 (7 to 13 August 2012). The high $f$md estimates in August ($\geq$3) were probably due to UAN-30 fertilizer application and the $f$md estimate of 0.7 in November was probably due to lack of plant N removal.

The average (n=24) $f$sd for the LM and CLM simulation for 12 irrigations in both years was 0.05. The $f$sd estimates were all smaller than the $f$md estimates except for irrigation cycle between 15 and 21 May 2012 when the $f$sd (0.05) and $f$md (0.03) were similar. All the $f$sd estimates were also smaller than the design $f$ values apart from August when they were near the lower boundary for design $f$ values for secondary-treated effluent (0.15 - 0.25).

The *f*nb estimates were 0.13 (April and May 2011), 0.22 (July 2011), 0.09 (August 2011), 0.23 (April 2012), 0.05 (June 2012), 0.13 (July 2012), and 0.72 (September 2012). Negative *f*nb estimates obtained in June 2011 (-1.35), September 2011 (-0.40), May 2012 (-0.13), and August 2012 (-0.44) were due to the sum of the crop N removal and leaching exceeding the applied effluent N in these months (see chapter 7, Table 7-2). Apart from September 2012, the *f*nb values were less than or within the range of the design *f* values.

The positive *f*nb estimates were negatively correlated to the logarithm of the measured monthly crop N removal with the correlation of determination of $R^2 = 0.99$ in the warmer months (monthly mean air temperature was equal to or greater than $20^o$C) of July and August being greater than the $R^2 = 0.2$ for the cooler months (monthly mean air temperatures were less than $20^o$C) of April, May, June, and September. Since the *f*nb linear model generated using the July and August data yielded reasonable *f* values for the months of April, May, June, and September (except June and September 2012): 0.03 for April & May 2011, 0.001 for June 2011, 0.04 for September 2011, 0.07 for April 2012, and 0.05 for May 2012, it could useful in elucidating the *f* values, in the months with the greatest N removal and aboveground biomass.

Due to the variability of denitrification, difficulty in isolating the applied effluent N from the large soil N pool and the impracticality of accounting for all soil gains and losses in N balances (Allison, 1955), the following conclusions were made based on measured and simulated denitrification fluxes, the three estimated *f*md, *f*sd, and *f*nb values and the growth curve for tall fescue (see chapter 3, section 3.7).

- The DNDC model simulated the BI fluxes better than the AI fluxes.

- The AI denitrification fluxes are more variable than BI fluxes and AI and BI fluxes within an irrigation cycle can be significantly different ($\alpha$=0.05) if no rainfall occurs within two days of the BI date.

- Measured AI denitrification rates were generally greater than the BI denitrification rates except if rainfall occurred within two days of the BI date. As such the $f$md estimates decreased linearly with the ratio of the BI to AI denitrification rates.

- $f$ estimates >1 and those <0 result from one or more of the interacting processes (e.g. crop N removal or leaching) being more predominant than other processes. However, these $f$ values are not usable for design purposes.

- Positive monthly $f$ estimates from the nitrogen mass balance were negatively correlated to the logarithm of the monthly N removal in the aboveground biomass, with a better correlation in the warmer months (monthly mean air temperature $\geq 20^oC$) than in the cooler months (monthly mean air temperature $<20^oC$). $f$ estimates in the warm months were similar to the design $f$ values.

- $f$ estimates ($f$sd, $f$md, and $f$nb) in the month of July (except $f$md in July 2011) are similar to the design $f$ values.

- For highly nitrified effluents with C:N ratios of < 0.9, lower design $f$ values could be used than those suggested for secondary and tertiary-treated effluents (Crites and Tchobanoglous,1998; USEPA, 2006). During the study period, the monthly mean effluent C:N ratio (0.04 to 0.2) was < 0.9 , typical for tertiary-treated effluents. The $f$ values in the ranges of 0 and 0.1 and 0.1 and 0.2 for the months of May/June and August/September, respectively, and 0.2 for July were deemed

appropriate for the study site. However, no clear conclusion could be drawn for the *f* values for the months of April and October.

## 8.2 Suggestions for future work

The *f* values varied due to the difference in the monthly MWE-TN application rates used in the N balance, environmental and other management factors. The *f* variation could be minimized by using a seasonal mean MWE-TN application rate per irrigation cycle or an annual mean MWE-TN application rate per irrigation cycle.  In this research the effluent N in samples from the treatment plant and the irrigation spigots were similar, thus similar studies may consider evaluating this scenario. The *f* values could further be refined by using monthly or annual mean MWE-TN values without any commercial fertilizer use especially during May/June and August/ September when the aboveground biomass and thus crop N removal is greatest at the study site.

Since about 70 to 80% of the total N in the effluent irrigated at the study site is $NO_3$-N, transferring *f* estimates from this study to design MWE irrigation application rates for $NH_4$-N dominated effluents needs to be done with caution. Further studies are needed especially during the months with the greatest and lowest crop N removal since negative *f*nb estimates resulted from the N balance whenever the sum of the crop N removal and leached N were greater than the effluent total N.

Continuous field measurements of denitrification between irrigations would provide better *f* estimation. Also a comparison of measured and simulated denitrification fluxes with more than one biogeochemical simulation model would also be good for future similar studies.

The *f*md values linearly decreased with the ratio of BI/AI mean denitrification fluxes (chapter 5). However, additional data are needed on the AI and BI dates and between irrigations to further understand the relationship between the *f* estimate and ratio of the mean BI/AI denitrification fluxes.  Plots of *f*sd vs the ratio of BI/AI mean denitrification fluxes (not done in this study) could be explored once model calibration and validation is completed.

Determining *f* values based on the climate categories: cool (relative humidity (RH) < 50% and mean maximum temperature < 21$^{\circ}$C), cool (RH > 50% and mean maximum temperature < 21$^{\circ}$C), moderate (mean maximum temperature: 21$^{\circ}$C to 27$^{\circ}$C), warm (mean maximum temperature: 27 $^{\circ}$C to 38$^{\circ}$C), and hot (mean maximum temperature >38$^{\circ}$C) suggested by Hardie (1986), as cited by Jarrett and Brandt (2007), as well as land management, would improve *f* design values. Based on these criteria, *f* values for other crop fields at the LF would improve knowledge of *f* values in cool/cold climates.

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## Appendix A: $NH_3$ volatilization and denitrification stoichiometry

**$NH_3$ volatilization**

$$\overset{K_a}{NH_4^+ \Leftrightarrow NH_3(aq) + H^+}$$ [2-1]

$$\overset{K_b}{NH_3 + H_2O \Leftrightarrow NH_4^+ + OH^-}$$ [2-2]

$$\overset{K_w}{H_2O \Leftrightarrow H^+ + OH^-}$$ [2-3]

$$K_a = \frac{[NH_3][H^+]}{[NH_4^+]}$$ [2-4]

$$K_b = \frac{[NH_4^+][OH^-]}{[NH_3]}$$ [2-5]

$$Kw = [OH^-][H^+]$$ [2-6]

$$K_a = \frac{K_w}{K_b}$$ [2-7]

$$(pK_w - pK_b) - pH = \log_{10}\frac{[NH_4^+]}{[NH_3]}$$ [2-8]

$$K_H = \frac{[NH_3]}{\rho(NH_3)}$$ [2-9]

$$[NH_3] = \frac{[NH_3 + NH_4^+]}{1 + 10^{(0.09018 + 2729.92/T - pH)}}$$ [2-10]

$$\rho(NH_3) = \frac{0.00488\,[NH_3]\,T}{10^{(1477.8/T - 1.69)}}$$ [2-11]

$$\log_{10}K_a = -0.09018 - \frac{2729.92}{T}$$ [2-12]

**Appendix A: NH₃ volatilization and denitrification stoichiometry continued.**

$$Log_{10}H = \frac{1477.7}{T} - 1.69 \qquad\qquad [2\text{-}13]$$

(Hales and Drewes, 1979 as cited by Freney et al. 1983).

$$K_H = \frac{H}{RT} \qquad\qquad [2\text{-}14]$$

$$F = k\,(\rho_o - \rho_z) \qquad\qquad [2\text{-}15]$$

**where:**

| | | |
|---|---|---|
| $K_w$ | = Water ionization coefficient* | mole m$^{-3}$ bar$^{-1}$ |
| $K_b$ | = NH₃ dissociation coefficient* | mole m$^{-3}$ bar$^{-1}$ |
| $K_H$ | = Henry's coefficient | mole m$^{-3}$ bar$^{-1}$ |
| $\rho\,(NH_3)$ | = partial pressure of NH₃ | bar |
| H | = ratio between the dissolved molar (M) concentration of NH₃ in pure water and the molar gaseous concentration | |
| T | = absolute temperature | °K |
| R | = ideal gas constant (0.0831) | liter bar °K |
| F | = NH₃ flux density | µg N m$^{-2}$ s$^{-1}$ |
| k | = exchange coefficient which is a function of wind speed at reference height, z (m) | |
| $\rho_o$ | = equilibrium NH₃ vapor pressure in the soil solution | bar |
| $\rho_z$ | = partial pressure of NH₃ at the reference height, z (m) | bar |

*$K_w$ and $K_b$ increase with temperature (Bates and Pinching, 1950 and Weast, 1971 as cited by Freney et al., 1983)

**Denitrification**

$$5CH_2O + 4NO_3^{-} \xrightarrow{N_2O} 2N_2(g) + 4HCO_3^{-} + CO_2(g) + 3H_2O \qquad [2\text{-}16]$$

Nitrous oxide loss during nitrification

$$NH_4^{+} + 2O_2 \xrightarrow{N_2O} NO_3^{-} + 2H^{+} + H_2O \qquad\qquad [2\text{-}17]$$

**Appendix B: Daily rainfall and weather data in 2011 and 2012 (See footnotes)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | ºC | | MJ m^{-2} | m s^{-1} | | % | kPa |
| 1/1/2011 | 0.08 | 7.4 | -1.3 | 2.8 | 4.2 | 1.4 | 79.1 | 42.8 | 0.4 |
| 1/2/2011 | 0.00 | 7.5 | -4.8 | 1.2 | 8.8 | 2.8 | 99.9 | 50.2 | 0.5 |
| 1/3/2011 | 0.00 | 0.6 | -8.4 | -3.9 | 9.1 | 2.2 | 99.9 | 56.4 | 0.4 |
| 1/4/2011 | 0.00 | 5.0 | -4.4 | -0.3 | 8.2 | 1.8 | 72.5 | 36.7 | 0.3 |
| 1/5/2011 | 0.00 | -0.1 | -6.5 | -3.0 | 7.5 | 1.9 | 95.9 | 59.4 | 0.4 |
| 1/6/2011 | 0.00 | -2.4 | -9.6 | -5.1 | 7.9 | 1.3 | 95.0 | 54.6 | 0.3 |
| 1/7/2011 | 0.10 | -2.6 | -7.6 | -5.2 | 6.3 | 1.8 | 81.2 | 55.6 | 0.3 |
| 1/8/2011 | 0.03 | -5.4 | -8.5 | -7.0 | 5.6 | 2.4 | 99.5 | 78.3 | 0.3 |
| 1/9/2011 | 0.05 | -3.5 | -8.8 | -6.2 | 7.2 | 3.6 | 99.9 | 67.8 | 0.3 |
| 1/10/2011 | 0.00 | -3.5 | -9.5 | -6.0 | 6.3 | 2.0 | 94.2 | 59.4 | 0.3 |
| 1/11/2011 | 0.00 | -4.2 | -11.7 | -7.3 | 4.4 | 1.3 | 96.4 | 53.7 | 0.2 |
| 1/12/2011 | 0.18 | -4.1 | -7.3 | -5.8 | 5.2 | 3.6 | 79.2 | 62.2 | 0.3 |
| 1/13/2011 | 0.08 | -3.1 | -8.3 | -5.9 | 8.1 | 3.2 | 97.8 | 65.9 | 0.3 |
| 1/14/2011 | 0.00 | -3.4 | -8.8 | -6.1 | 6.9 | 1.6 | 99.9 | 67.3 | 0.3 |
| 1/15/2011 | 0.00 | 1.7 | -8.7 | -2.9 | 4.3 | 2.0 | 99.9 | 46.3 | 0.3 |
| 1/16/2011 | 0.00 | -2.2 | -7.5 | -5.3 | 8.4 | 2.2 | 99.9 | 69.4 | 0.4 |
| 1/17/2011 | 0.00 | -4.5 | -10.3 | -6.7 | 4.1 | 1.7 | 99.9 | 64.0 | 0.3 |
| 1/18/2011 | 0.20 | 0.0 | -6.0 | -3.3 | 5.4 | 1.3 | 71.7 | 45.8 | 0.3 |
| 1/19/2011 | 0.20 | 2.0 | -2.5 | 0.5 | 3.5 | 2.1 | 78.7 | 56.7 | 0.4 |
| 1/20/2011 | 0.00 | -2.5 | -5.3 | -4.0 | 5.7 | 1.7 | 99.9 | 86.6 | 0.4 |
| 1/21/2011 | 0.53 | -5.2 | -13.6 | -8.0 | 7.6 | 3.5 | 99.9 | 86.9 | 0.4 |
| 1/22/2011 | 0.00 | -8.0 | -17.4 | -11.9 | 9.8 | 1.4 | 77.0 | 35.9 | 0.1 |
| 1/23/2011 | 0.00 | -6.7 | -13.9 | -9.5 | 9.0 | 2.4 | 57.5 | 32.5 | 0.1 |
| 1/24/2011 | 0.00 | -5.2 | -20.7 | -11.8 | 9.8 | 1.6 | 99.9 | 29.0 | 0.1 |
| 1/25/2011 | 0.03 | -1.6 | -6.0 | -3.9 | 5.9 | 1.3 | 30.7 | 22.1 | 0.1 |
| 1/26/2011 | 0.00 | 0.0 | -6.0 | -2.8 | 3.8 | 2.0 | 92.2 | 58.9 | 0.4 |
| 1/27/2011 | 0.25 | 0.0 | -3.4 | -2.2 | 6.2 | 2.4 | 92.5 | 72.0 | 0.4 |
| 1/28/2011 | 0.08 | -0.7 | -4.7 | -2.6 | 5.5 | 1.2 | 99.9 | 75.9 | 0.4 |
| 1/29/2011 | 0.00 | -0.8 | -6.0 | -3.5 | 3.5 | 1.3 | 92.2 | 62.4 | 0.4 |
| 1/30/2011 | 0.05 | 0.0 | -5.9 | -2.1 | 5.4 | 1.7 | 99.9 | 65.5 | 0.4 |
| 1/31/2011 | 0.00 | -3.8 | -13.5 | -6.7 | 10.7 | 1.6 | 92.8 | 43.3 | 0.2 |
| 2/1/2011 | 0.03 | -0.6 | -6.1 | -3.1 | 3.9 | 1.7 | 62.0 | 41.1 | 0.2 |
| 2/2/2011 | 0.71 | 3.4 | -5.1 | -0.7 | 7.4 | 3.3 | 99.9 | 56.5 | 0.4 |
| 2/3/2011 | 0.13 | -2.2 | -8.5 | -5.7 | 10.6 | 2.5 | 99.5 | 61.7 | 0.3 |
| 2/4/2011 | 0.00 | 0.4 | -9.5 | -4.5 | 10.5 | 1.4 | 67.3 | 31.8 | 0.2 |
| 2/5/2011 | 0.10 | 2.5 | -6.5 | -2.4 | 3.3 | 2.3 | 63.9 | 32.8 | 0.2 |
| 2/6/2011 | 0.05 | 1.5 | -1.3 | -0.2 | 9.6 | 1.9 | 79.1 | 64.6 | 0.4 |
| 2/7/2011 | 0.03 | 4.1 | -0.6 | 0.9 | 7.0 | 1.1 | 89.0 | 63.4 | 0.5 |
| 2/8/2011 | 0.13 | 0.1 | -12.8 | -5.5 | 9.6 | 4.0 | 99.9 | 71.5 | 0.4 |
| 2/9/2011 | 0.00 | -3.7 | -12.6 | -8.0 | 10.4 | 2.3 | 86.3 | 43.1 | 0.2 |
| 2/10/2011 | 0.00 | -6.2 | -12.6 | -9.2 | 13.2 | 2.6 | 86.3 | 52.1 | 0.2 |
| 2/11/2011 | 0.00 | 0.0 | -12.5 | -5.9 | 12.9 | 1.6 | 68.4 | 26.2 | 0.2 |
| 2/12/2011 | 0.00 | 0.2 | -3.8 | -1.9 | 9.8 | 3.2 | 43.3 | 32.2 | 0.2 |
| 2/13/2011 | 0.00 | 7.6 | -5.0 | 2.2 | 12.4 | 2.5 | 76.0 | 30.6 | 0.3 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 º 49 ' 44.4 " N and longitude 77 º 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 º 49 ' 44.4 " N and longitude 77 º 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 2/14/2011 | 0.00 | 9.0 | -0.7 | 4.9 | 9.7 | 4.3 | 75.9 | 38.3 | 0.4 |
| 2/15/2011 | 0.00 | 2.1 | -6.6 | -2.3 | 16.1 | 2.6 | 96.7 | 50.6 | 0.4 |
| 2/16/2011 | 0.00 | 8.8 | -4.1 | 2.8 | 13.7 | 2.2 | 79.9 | 31.8 | 0.4 |
| 2/17/2011 | 0.00 | 16.4 | 1.5 | 8.2 | 14.0 | 1.8 | 70.5 | 25.8 | 0.5 |
| 2/18/2011 | 0.00 | 18.8 | 5.0 | 11.9 | 12.6 | 3.3 | 73.4 | 29.5 | 0.6 |
| 2/19/2011 | 0.00 | 5.8 | -2.5 | 0.3 | 13.4 | 5.2 | 99.9 | 69.5 | 0.6 |
| 2/20/2011 | 0.00 | 3.9 | -5.5 | -0.8 | 14.2 | 2.3 | 98.7 | 49.6 | 0.4 |
| 2/21/2011 | 0.03 | 0.0 | -9.0 | -3.1 | 4.2 | 2.5 | 99.9 | 72.0 | 0.4 |
| 2/22/2011 | 0.28 | -2.1 | -11.0 | -7.2 | 12.6 | 1.6 | 99.9 | 53.5 | 0.3 |
| 2/23/2011 | 0.94 | 2.4 | -14.3 | -5.5 | 16.0 | 0.8 | 98.9 | 27.6 | 0.2 |
| 2/24/2011 | 0.81 | 2.2 | -8.9 | -2.2 | 5.7 | 1.4 | 64.1 | 27.9 | 0.2 |
| 2/25/2011 | 1.78 | 1.0 | -2.5 | 0.0 | 4.8 | 3.4 | 70.8 | 54.8 | 0.4 |
| 2/26/2011 | 0.00 | 1.7 | -6.1 | -1.4 | 15.0 | 1.8 | 99.9 | 57.8 | 0.4 |
| 2/27/2011 | 0.79 | 8.7 | 0.3 | 3.8 | 13.6 | 1.9 | 70.6 | 39.1 | 0.4 |
| 2/28/2011 | 0.41 | 12.7 | -1.1 | 5.5 | 4.8 | 3.6 | 99.9 | 40.8 | 0.6 |
| 3/1/2011 | 0.00 | 5.1 | -4.6 | -0.2 | 17.0 | 2.1 | 99.9 | 50.1 | 0.4 |
| 3/2/2011 | 0.00 | 6.5 | -7.2 | 0.8 | 16.6 | 3.2 | 99.9 | 37.2 | 0.4 |
| 3/3/2011 | 0.00 | 0.1 | -11.0 | -5.0 | 17.2 | 1.9 | 99.9 | 45.5 | 0.3 |
| 3/4/2011 | 0.00 | 5.9 | -2.3 | 1.7 | 13.5 | 3.1 | 61.9 | 34.5 | 0.3 |
| 3/5/2011 | 0.51 | 12.9 | 3.5 | 8.1 | 9.0 | 3.5 | 66.2 | 35.0 | 0.5 |
| 3/6/2011 | 0.84 | 10.5 | -2.5 | 4.6 | 4.0 | 3.5 | 99.9 | 63.0 | 0.8 |
| 3/7/2011 | 1.60 | 4.2 | -4.5 | -0.5 | 15.3 | 3.0 | 91.4 | 48.4 | 0.4 |
| 3/8/2011 | 0.00 | 5.0 | -7.1 | -0.9 | 12.1 | 1.2 | 89.3 | 36.7 | 0.3 |
| 3/9/2011 | 0.58 | 3.7 | -0.4 | 2.0 | 5.1 | 3.4 | 60.6 | 45.1 | 0.4 |
| 3/10/2011 | 1.50 | 10.0 | 3.1 | 6.2 | 5.1 | 3.8 | 83.8 | 52.1 | 0.6 |
| 3/11/2011 | 0.00 | 3.6 | 0.0 | 1.3 | 7.5 | 3.0 | 99.9 | 80.9 | 0.6 |
| 3/12/2011 | 0.03 | 13.7 | 0.0 | 6.1 | 13.7 | 2.7 | 98.2 | 38.2 | 0.6 |
| 3/13/2011 | 0.00 | 5.3 | 1.7 | 3.1 | 6.2 | 2.8 | 92.5 | 72.0 | 0.6 |
| 3/14/2011 | 0.00 | 7.0 | -0.7 | 2.6 | 14.0 | 1.5 | 99.9 | 63.9 | 0.6 |
| 3/15/2011 | 0.28 | 6.7 | -4.3 | 1.9 | 12.5 | 2.2 | 98.9 | 44.8 | 0.4 |
| 3/16/2011 | 0.00 | 9.0 | 1.5 | 4.8 | 9.4 | 1.9 | 64.6 | 38.3 | 0.4 |
| 3/17/2011 | 0.00 | 17.8 | 3.1 | 9.9 | 19.4 | 1.9 | 89.0 | 33.4 | 0.7 |
| 3/18/2011 | 0.00 | 22.9 | 10.7 | 16.7 | 17.8 | 2.8 | 62.1 | 28.7 | 0.8 |
| 3/19/2011 | 0.00 | 11.6 | 0.0 | 5.6 | 18.6 | 2.8 | 99.9 | 52.7 | 0.7 |
| 3/20/2011 | 0.31 | 9.3 | -4.6 | 2.9 | 19.9 | 1.9 | 99.9 | 37.6 | 0.4 |
| 3/21/2011 | 0.28 | 22.2 | 2.4 | 9.8 | 15.7 | 2.9 | 66.2 | 17.9 | 0.5 |
| 3/22/2011 | 0.18 | 10.8 | 1.3 | 6.5 | 16.7 | 2.2 | 99.9 | 58.8 | 0.8 |
| 3/23/2011 | 1.25 | 1.0 | 0.0 | 0.4 | 4.1 | 2.0 | 98.2 | 91.4 | 0.6 |
| 3/24/2011 | 0.10 | 1.9 | -3.2 | -0.2 | 9.3 | 2.4 | 99.9 | 85.7 | 0.6 |
| 3/25/2011 | 0.00 | 2.1 | -6.2 | -2.5 | 17.2 | 1.9 | 93.8 | 50.6 | 0.4 |
| 3/26/2011 | 0.00 | 2.0 | -6.6 | -2.5 | 22.0 | 1.9 | 96.7 | 51.0 | 0.4 |
| 3/27/2011 | 0.00 | 3.9 | -6.4 | -1.4 | 22.2 | 2.0 | 95.0 | 44.6 | 0.4 |
| 3/28/2011 | 0.00 | 5.1 | -7.5 | -1.4 | 22.4 | 2.2 | 92.1 | 36.4 | 0.3 |
| 3/29/2011 | 0.00 | 7.8 | -5.9 | 0.9 | 22.6 | 2.1 | 91.5 | 34.1 | 0.4 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | °C | | | MJ m$^{-2}$ | m s$^{-1}$ | % | | kPa |
| 3/30/2011 | 0.00 | 7.2 | -5.1 | 0.5 | 10.2 | 1.7 | 86.2 | 35.4 | 0.4 |
| 3/31/2011 | 0.58 | 2.5 | 0.0 | 1.1 | 6.4 | 0.8 | 72.0 | 60.2 | 0.4 |
| 4/1/2011 | 0.05 | 4.7 | 0.5 | 2.1 | 9.1 | 2.4 | 94.7 | 70.1 | 0.6 |
| 4/2/2011 | 0.00 | 9.0 | -1.2 | 3.7 | 14.1 | 2.2 | 85.9 | 41.8 | 0.5 |
| 4/3/2011 | 0.13 | 10.4 | 2.1 | 5.4 | 17.5 | 2.1 | 73.1 | 41.3 | 0.5 |
| 4/4/2011 | 1.91 | 17.3 | 4.0 | 9.9 | 10.8 | 2.8 | 88.5 | 36.5 | 0.7 |
| 4/5/2011 | 0.13 | 14.1 | 0.2 | 4.9 | 8.6 | 3.6 | 99.9 | 49.7 | 0.8 |
| 4/6/2011 | 0.20 | 6.1 | -2.1 | 2.6 | 7.5 | 1.9 | 99.4 | 55.2 | 0.5 |
| 4/7/2011 | 0.00 | 10.0 | 2.5 | 4.7 | 18.2 | 1.3 | 76.6 | 45.6 | 0.6 |
| 4/8/2011 | 1.96 | 5.3 | 2.7 | 4.0 | 3.6 | 2.1 | 96.9 | 81.0 | 0.7 |
| 4/9/2011 | 0.00 | 7.1 | 3.4 | 5.3 | 6.7 | 1.6 | 92.4 | 71.3 | 0.7 |
| 4/10/2011 | 0.00 | 15.7 | 6.2 | 10.0 | 11.6 | 1.8 | 84.2 | 44.8 | 0.8 |
| 4/11/2011 | 0.28 | 24.0 | 9.6 | 16.0 | 13.3 | 2.4 | 76.9 | 30.8 | 0.9 |
| 4/12/2011 | 1.19 | 15.0 | 7.2 | 9.5 | 7.7 | 2.7 | 98.3 | 58.6 | 1.0 |
| 4/13/2011 | 0.76 | 10.0 | 6.0 | 7.6 | 7.9 | 1.9 | 99.9 | 78.2 | 1.0 |
| 4/14/2011 | 0.00 | 19.0 | 3.0 | 11.5 | 24.3 | 1.6 | 95.0 | 32.8 | 0.7 |
| 4/15/2011 | 0.03 | 16.0 | 3.0 | 9.2 | 23.8 | 2.8 | 99.9 | 41.8 | 0.8 |
| 4/16/2011 | 1.75 | 11.0 | 5.0 | 7.1 | 3.9 | 4.3 | 91.7 | 60.9 | 0.8 |
| 4/17/2011 | 0.00 | 13.0 | 2.0 | 8.4 | 19.6 | 3.2 | 99.9 | 53.4 | 0.8 |
| 4/18/2011 | 0.00 | 17.0 | 3.0 | 9.5 | 12.9 | 1.8 | 89.7 | 35.1 | 0.7 |
| 4/19/2011 | 0.76 | 9.0 | 6.0 | 6.9 | 5.8 | 1.6 | 85.6 | 69.7 | 0.8 |
| 4/20/2011 | 0.08 | 23.0 | 8.0 | 14.0 | 13.4 | 2.9 | 89.5 | 34.2 | 1.0 |
| 4/21/2011 | 0.00 | 12.0 | 3.0 | 7.5 | 25.7 | 2.8 | 99.9 | 62.7 | 0.9 |
| 4/22/2011 | 0.51 | 5.0 | 1.0 | 3.1 | 6.4 | 2.4 | 97.5 | 73.4 | 0.6 |
| 4/23/2011 | 0.03 | 21.0 | 4.0 | 10.5 | 12.9 | 2.6 | 88.5 | 29.0 | 0.7 |
| 4/24/2011 | 0.00 | 21.0 | 14.0 | 16.7 | 11.4 | 1.8 | 57.6 | 37.0 | 0.9 |
| 4/25/2011 | 0.23 | 27.0 | 12.0 | 18.5 | 24.1 | 1.7 | 97.0 | 38.1 | 1.4 |
| 4/26/2011 | 0.76 | 27.0 | 13.0 | 19.0 | 21.1 | 2.5 | 96.1 | 40.4 | 1.4 |
| 4/27/2011 | 2.01 | 26.0 | 13.0 | 19.4 | 16.2 | 2.9 | 98.8 | 44.0 | 1.5 |
| 4/28/2011 | 0.00 | 22.0 | 11.0 | 17.3 | 20.8 | 3.1 | 99.9 | 60.5 | 1.6 |
| 4/29/2011 | 0.03 | 12.0 | 5.0 | 8.9 | 12.4 | 2.6 | 99.9 | 71.3 | 1.0 |
| 4/30/2011 | 0.00 | 19.0 | 5.0 | 10.6 | 26.6 | 1.4 | 99.9 | 40.0 | 0.9 |
| 5/1/2011 | 0.15 | 15.0 | 9.0 | 11.4 | 5.3 | 2.0 | 80.1 | 53.9 | 0.9 |
| 5/2/2011 | 0.00 | 19.0 | 10.0 | 14.1 | 14.4 | 1.6 | 94.5 | 52.8 | 1.2 |
| 5/3/2011 | 1.14 | 23.0 | 7.0 | 15.0 | 19.5 | 1.9 | 99.9 | 45.6 | 1.3 |
| 5/4/2011 | 0.05 | 11.0 | 6.0 | 7.4 | 11.8 | 2.6 | 98.4 | 70.1 | 0.9 |
| 5/5/2011 | 0.00 | 17.0 | 5.0 | 10.6 | 25.5 | 2.6 | 91.7 | 41.3 | 0.8 |
| 5/6/2011 | 0.00 | 19.0 | 4.0 | 12.2 | 22.9 | 1.4 | 93.5 | 34.6 | 0.8 |
| 5/7/2011 | 0.10 | 18.0 | 6.0 | 11.7 | 21.1 | 1.6 | 89.8 | 40.7 | 0.8 |
| 5/8/2011 | 0.00 | 20.0 | 5.0 | 13.0 | 25.1 | 1.3 | 99.9 | 37.6 | 0.9 |
| 5/9/2011 | 0.00 | 20.0 | 8.0 | 13.5 | 28 | 1.8 | 85.8 | 39.3 | 0.9 |
| 5/10/2011 | 0.00 | 23.0 | 5.0 | 14.3 | 27 | 1 | 96.3 | 29.9 | 0.8 |
| 5/11/2011 | 0.00 | 24.0 | 10.0 | 17.5 | 26.5 | 1.3 | 78.2 | 32.2 | 1.0 |
| 5/12/2011 | 0.00 | 25 | 9 | 17.8 | 24 | 1.6 | 94.1 | 34.1 | 1.1 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | °C | | | MJ m$^{-2}$ | m s$^{-1}$ | % | | kPa |
| 5/13/2011 | 0.00 | 19 | 16 | 17.1 | 9.7 | 2.1 | 68.2 | 56.4 | 1.2 |
| 5/14/2011 | 0.36 | 17 | 15 | 15.2 | 7.7 | 1.9 | 96.2 | 84.6 | 1.6 |
| 5/15/2011 | 1.98 | 20 | 14 | 15.1 | 12.2 | 1 | 99.9 | 68.4 | 1.6 |
| 5/16/2011 | 0.0 | 18 | 10 | 13.4 | 15.4 | 1.5 | 99.9 | 64 | 1.3 |
| 5/17/2011 | 0.76 | 16 | 10 | 12.6 | 6.7 | 2.6 | 99.9 | 72.6 | 1.3 |
| 5/18/2011 | 3.12 | 18 | 12 | 14.2 | 9.5 | 2 | 97 | 65.9 | 1.4 |
| 5/19/2011 | 0.46 | 19 | 10 | 13.3 | 12.2 | 0.9 | 99.9 | 61.9 | 1.4 |
| 5/20/2011 | 0.84 | 21 | 12 | 14.6 | 15.6 | 1.8 | 99.8 | 56.3 | 1.4 |
| 5/21/2011 | 0.04 | 24.0 | 11.0 | 17.4 | 25.2 | 1.1 | 97.5 | 42.9 | 1.3 |
| 5/22/2011 | 0.18 | 22.0 | 14.0 | 17.4 | 12.0 | 1.8 | 87.6 | 53.0 | 1.4 |
| 5/23/2011 | 0.64 | 23.0 | 16.0 | 18.6 | 16.0 | 2.1 | 90.2 | 58.4 | 1.6 |
| 5/24/2011 | 0.04 | 23.0 | 18.0 | 19.9 | 16.0 | 1.9 | 87.2 | 64.1 | 1.8 |
| 5/25/2011 | 0.03 | 26.0 | 13.0 | 19.8 | 23.9 | 1.3 | 99.9 | 47.6 | 1.6 |
| 5/26/2011 | 0.76 | 29.0 | 17.0 | 22.4 | 26.5 | 1.7 | 88.8 | 42.9 | 1.7 |
| 5/27/2011 | 1.22 | 24.0 | 15.0 | 18.5 | 19.2 | 1.6 | 99.9 | 59.0 | 1.8 |
| 5/28/2011 | 0.05 | 25.0 | 16.0 | 20.0 | 20.1 | 1.9 | 96.8 | 55.6 | 1.8 |
| 5/29/2011 | 0.03 | 29.0 | 19.0 | 23.3 | 26.7 | 1.6 | 85.6 | 46.9 | 1.9 |
| 5/30/2011 | 0.03 | 32.0 | 20.0 | 26.0 | 27.2 | 1.3 | 90.7 | 44.6 | 2.1 |
| 5/31/2011 | 0.03 | 32.0 | 19.0 | 25.8 | 27.2 | 0.8 | 94.7 | 43.7 | 2.1 |
| 6/1/2011 | 0.03 | 31.0 | 21.0 | 25.3 | 24.8 | 1.8 | 88.5 | 49.0 | 2.2 |
| 6/2/2011 | 0.03 | 22.0 | 13.0 | 18.6 | 29.9 | 2.7 | 99.9 | 65.1 | 1.7 |
| 6/3/2011 | 0.03 | 24.0 | 7.0 | 16.0 | 29.9 | 1.7 | 99.8 | 33.5 | 1.0 |
| 6/4/2011 | 0.46 | 23.0 | 9.0 | 15.0 | 16.8 | 0.9 | 90.6 | 37.0 | 1.0 |
| 6/5/2011 | 0.03 | 29.0 | 15.0 | 20.6 | 25.5 | 1.0 | 75.1 | 32.0 | 1.3 |
| 6/6/2011 | 0.03 | 27.0 | 12.0 | 19.6 | 28.7 | 1.0 | 94.1 | 37.0 | 1.3 |
| 6/7/2011 | 0.04 | 27.0 | 14.0 | 20.0 | 15.1 | 1.3 | 87.6 | 39.3 | 1.4 |
| 6/8/2011 | 0.03 | 33.0 | 16.0 | 24.5 | 28.2 | 1.3 | 88.0 | 31.8 | 1.6 |
| 6/9/2011 | 0.04 | 33.0 | 21.0 | 24.9 | 26.6 | 1.4 | 83.6 | 41.4 | 2.1 |
| 6/10/2011 | 3.83 | 28.0 | 18.0 | 21.9 | 25.7 | 1.1 | 93.0 | 50.8 | 1.9 |
| 6/11/2011 | 0.04 | 27.0 | 17.0 | 21.1 | 25.1 | 1.0 | 99.9 | 56.1 | 2.0 |
| 6/12/2011 | 0.16 | 27.0 | 15.0 | 20.5 | 20.6 | 1.3 | 99.9 | 53.9 | 1.9 |
| 6/13/2011 | 0.04 | 22.0 | 10.0 | 16.1 | 20.6 | 1.9 | 99.9 | 49.9 | 1.3 |
| 6/14/2011 | 0.03 | 21.0 | 12.0 | 15.4 | 17.5 | 1.9 | 94.1 | 53.1 | 1.3 |
| 6/15/2011 | 0.03 | 25.0 | 7.0 | 16.6 | 29.4 | 1.1 | 99.8 | 31.6 | 1.0 |
| 6/16/2011 | 0.28 | 21.0 | 13.0 | 16.0 | 15.2 | 1.8 | 82.8 | 49.9 | 1.2 |
| 6/17/2011 | 0.04 | 25.0 | 14.0 | 18.1 | 22.0 | 1.3 | 92.6 | 46.7 | 1.5 |
| 6/18/2011 | 0.03 | 27.0 | 15.0 | 20.6 | 24.8 | 0.9 | 93.8 | 44.9 | 1.6 |
| 6/19/2011 | 0.04 | 27.0 | 15.0 | 20.9 | 21.5 | 1.0 | 96.2 | 46.0 | 1.6 |
| 6/20/2011 | 1.95 | 26.0 | 17.0 | 20.7 | 18.7 | 1.3 | 92.9 | 53.5 | 1.8 |
| 6/21/2011 | 0.05 | 28.0 | 18.0 | 22.6 | 25.0 | 1.0 | 96.9 | 52.9 | 2.0 |
| 6/22/2011 | 0.04 | 28.0 | 21.0 | 23.6 | 23.7 | 1.3 | 88.5 | 58.2 | 2.2 |
| 6/23/2011 | 0.11 | 26.0 | 18.0 | 22.1 | 17.4 | 1.5 | 99.9 | 69.0 | 2.3 |
| 6/24/2011 | 0.20 | 22.0 | 17.0 | 18.6 | 15.8 | 1.6 | 97.0 | 71.1 | 1.9 |
| 6/25/2011 | 0.04 | 20.0 | 15.0 | 17.3 | 9.4 | 1.6 | 99.9 | 80.4 | 1.9 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 6/26/2011 | 0.03 | 21.0 | 14.0 | 17.3 | 15.6 | 1.0 | 99.9 | 64.3 | 1.6 |
| 6/27/2011 | 0.04 | 24.0 | 12.0 | 18.4 | 17.4 | 0.9 | 99.9 | 49.6 | 1.5 |
| 6/28/2011 | 0.46 | 28.0 | 18.0 | 21.5 | 21.2 | 1.3 | 79.5 | 43.4 | 1.6 |
| 6/29/2011 | 0.03 | 24.0 | 15.0 | 19.2 | 26.2 | 2.1 | 93.8 | 53.6 | 1.6 |
| 6/30/2011 | 0.03 | 26.0 | 12.0 | 19.1 | 29.1 | 1.3 | 97.0 | 40.5 | 1.4 |
| 7/1/2011 | 0.00 | 28.0 | 11.0 | 19.8 | 29.8 | 1.0 | 94.5 | 32.8 | 1.2 |
| 7/2/2011 | 0.00 | 29.0 | 11.0 | 21.2 | 27.9 | 0.8 | 97.5 | 32.0 | 1.3 |
| 7/3/2011 | 0.00 | 30.0 | 21.0 | 24.5 | 23.4 | 1.2 | 64.3 | 37.7 | 1.6 |
| 7/4/2011 | 0.00 | 28.0 | 17.0 | 22.2 | 18.7 | 0.9 | 88.8 | 45.5 | 1.7 |
| 7/5/2011 | 0.00 | 30.0 | 16.0 | 23.0 | 26.4 | 0.8 | 94.6 | 40.5 | 1.7 |
| 7/6/2011 | 0.00 | 32.0 | 15.0 | 23.6 | 28.2 | 0.8 | 91.5 | 32.8 | 1.6 |
| 7/7/2011 | 0.00 | 30.0 | 18.0 | 23.3 | 19.3 | 1.0 | 85.3 | 41.5 | 1.8 |
| 7/8/2011 | 0.00 | 24.0 | 18.0 | 20.8 | 8.0 | 1.0 | 99.9 | 69.7 | 2.1 |
| 7/9/2011 | 0.00 | 27.0 | 16.0 | 19.5 | 27.9 | 1.2 | 99.0 | 50.5 | 1.8 |
| 7/10/2011 | 0.08 | 31.0 | 21.0 | 25.9 | 27.6 | 0.9 | 64.3 | 35.6 | 1.6 |
| 7/11/2011 | 0.03 | 33.0 | 19.0 | 25.4 | 23.0 | 1.3 | 81.9 | 35.8 | 1.8 |
| 7/12/2011 | 0.00 | 32.0 | 21.0 | 25.4 | 25.6 | 2.0 | 91.7 | 48.0 | 2.3 |
| 7/13/2011 | 0.00 | 29.0 | 19.0 | 22.7 | 17.3 | 1.8 | 94.7 | 51.9 | 2.1 |
| 7/14/2011 | 0.00 | 28.0 | 13.0 | 20.6 | 28.7 | 1.6 | 93.5 | 37.0 | 1.4 |
| 7/15/2011 | 0.00 | 28.0 | 13.0 | 21.1 | 27.0 | 1.3 | 96.1 | 38.1 | 1.4 |
| 7/16/2011 | 0.00 | 29.0 | 14.0 | 22.0 | 28.1 | 1.5 | 87.6 | 35.0 | 1.4 |
| 7/17/2011 | 0.00 | 32.0 | 17.0 | 24.5 | 26.1 | 1.0 | 82.6 | 33.7 | 1.6 |
| 7/18/2011 | 0.00 | 34.0 | 19.0 | 25.3 | 24.4 | 1.1 | 87.4 | 36.1 | 1.9 |
| 7/19/2011 | 0.00 | 33.0 | 21.0 | 25.1 | 22.6 | 0.5 | 91.7 | 45.3 | 2.3 |
| 7/20/2011 | 0.00 | 35.0 | 19.0 | 26.2 | 25.5 | 0.9 | 99.9 | 40.6 | 2.3 |
| 7/21/2011 | 0.00 | 38.0 | 21.0 | 28.9 | 27.0 | 1.4 | 91.7 | 34.4 | 2.3 |
| 7/22/2011 | 0.00 | 39.0 | 26.0 | 31.5 | 25.1 | 1.3 | 78.5 | 37.8 | 2.6 |
| 7/23/2011 | 0.03 | 34.0 | 24.0 | 28.3 | 21.7 | 1.3 | 96.5 | 54.1 | 2.9 |
| 7/24/2011 | 0.56 | 33.0 | 21.0 | 26.6 | 16.7 | 1.0 | 99.9 | 57.3 | 2.9 |
| 7/25/2011 | 0.66 | 28.0 | 20.0 | 21.5 | 10.9 | 0.7 | 99.9 | 63.5 | 2.4 |
| 7/26/2011 | 0.00 | 31.0 | 17.0 | 23.7 | 24.8 | 1.6 | 99.1 | 42.7 | 1.9 |
| 7/27/2011 | 0.13 | 30.0 | 14.0 | 22.1 | 27.7 | 1.3 | 97.6 | 36.8 | 1.6 |
| 7/28/2011 | 0.08 | 23.0 | 18.0 | 20.1 | 8.1 | 0.8 | 83.3 | 61.2 | 1.7 |
| 7/29/2011 | 0.03 | 33.0 | 19.0 | 24.6 | 23.0 | 1.6 | 99.9 | 43.7 | 2.2 |
| 7/30/2011 | 0.03 | 32.0 | 19.0 | 25.1 | 27.1 | 1.6 | 99.9 | 46.3 | 2.2 |
| 7/31/2011 | 0.10 | 31.0 | 16.0 | 21.8 | 25.7 | 1.2 | 90.2 | 36.5 | 1.6 |
| 8/1/2011 | 0.20 | 33.0 | 17.0 | 22.1 | 23.4 | 1.4 | 92.9 | 35.8 | 1.8 |
| 8/2/2011 | 0.18 | 31.0 | 18.0 | 24.5 | 26.2 | 1.7 | 87.2 | 40.1 | 1.8 |
| 8/3/2011 | 0.08 | 24.0 | 19.0 | 21.1 | 7.7 | 1.0 | 91.0 | 67.0 | 2.0 |
| 8/4/2011 | 0.13 | 27.0 | 20.0 | 22.0 | 15.5 | 1.3 | 99.2 | 65.1 | 2.3 |
| 8/5/2011 | 0.25 | 26.0 | 18.0 | 21.4 | 15.5 | 1.7 | 99.9 | 65.4 | 2.2 |
| 8/6/2011 | 0.20 | 24.0 | 20.0 | 21.4 | 6.6 | 1.9 | 94.1 | 73.7 | 2.2 |
| 8/7/2011 | 0.05 | 29.0 | 20.0 | 23.7 | 16.4 | 1.4 | 99.2 | 57.9 | 2.3 |
| 8/8/2011 | 0.05 | 29.0 | 20.0 | 22.8 | 20.1 | 1.6 | 99.2 | 57.9 | 2.3 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 8/9/2011 | 0.15 | 27.0 | 18.0 | 21.0 | 17.6 | 1.4 | 99.9 | 59.5 | 2.1 |
| 8/10/2011 | 0.15 | 26.0 | 18.0 | 21.5 | 22.2 | 2.0 | 96.9 | 59.5 | 2.0 |
| 8/11/2011 | 0.08 | 25.0 | 13.0 | 19.1 | 22.8 | 1.6 | 96.1 | 45.5 | 1.4 |
| 8/12/2011 | 0.05 | 26.0 | 11.0 | 18.6 | 25.5 | 1.0 | 91.4 | 35.7 | 1.2 |
| 8/13/2011 | 0.25 | 25.0 | 14.0 | 19.2 | 11.9 | 1.6 | 85.1 | 42.9 | 1.4 |
| 8/14/2011 | 0.58 | 25.0 | 17.0 | 19.9 | 14.7 | 1.1 | 84.6 | 51.8 | 1.6 |
| 8/15/2011 | 0.58 | 23.0 | 17.0 | 18.0 | 9.9 | 1.6 | 99.1 | 68.3 | 1.9 |
| 8/16/2011 | 0.28 | 28.0 | 16.0 | 21.4 | 22.0 | 2.0 | 99.9 | 49.7 | 1.9 |
| 8/17/2011 | 0.03 | 28.0 | 13.0 | 20.4 | 24.2 | 1.0 | 96.1 | 38.1 | 1.4 |
| 8/18/2011 | 1.07 | 28.0 | 16.0 | 21.9 | 23.4 | 0.8 | 88.0 | 42.3 | 1.6 |
| 8/19/2011 | 0.00 | 25.0 | 15.0 | 18.3 | 14.3 | 0.4 | 99.9 | 54.3 | 1.7 |
| 8/20/2011 | 1.25 | 28.0 | 14.0 | 20.4 | 24.3 | 0.8 | 99.9 | 43.4 | 1.6 |
| 8/21/2011 | 0.23 | 26.0 | 17.0 | 20.0 | 14.7 | 1.2 | 90.8 | 52.4 | 1.8 |
| 8/22/2011 | 0.03 | 23.0 | 15.0 | 19.4 | 22.1 | 2.1 | 93.8 | 57.0 | 1.6 |
| 8/23/2011 | 0.25 | 24.0 | 10.0 | 17.1 | 24.4 | 1.0 | 94.5 | 38.9 | 1.2 |
| 8/24/2011 | 0.13 | 26.0 | 14.0 | 20.1 | 19.4 | 2.3 | 77.6 | 36.9 | 1.2 |
| 8/25/2011 | 0.03 | 26.0 | 19.0 | 21.9 | 14.5 | 1.7 | 72.8 | 47.6 | 1.6 |
| 8/26/2011 | 0.00 | 26.0 | 14.0 | 20.1 | 19.1 | 1.0 | 99.9 | 48.8 | 1.6 |
| 8/27/2011 | 0.03 | 25.0 | 17.0 | 20.0 | 12.0 | 2.0 | 84.6 | 51.8 | 1.6 |
| 8/28/2011 | 0.00 | 23.0 | 14.0 | 19.1 | 10.2 | 3.4 | 99.9 | 66.9 | 1.9 |
| 8/29/2011 | 0.00 | 22.0 | 10.0 | 15.6 | 22.2 | 1.0 | 91.2 | 42.4 | 1.1 |
| 8/30/2011 | 0.00 | 25.0 | 10.0 | 16.9 | 23.5 | 0.8 | 91.2 | 35.4 | 1.1 |
| 8/31/2011 | 0.00 | 25.0 | 11.0 | 17.9 | 19.6 | 1.1 | 91.4 | 37.9 | 1.2 |
| 9/1/2011 | 0.00 | 24.0 | 15.0 | 19.2 | 15.2 | 1.6 | 79.7 | 45.6 | 1.4 |
| 9/2/2011 | 0.00 | 23.0 | 19.0 | 20.9 | 11.4 | 1.6 | 78.3 | 61.2 | 1.7 |
| 9/3/2011 | 0.03 | 31.0 | 20.0 | 23.9 | 18.0 | 1.0 | 90.7 | 47.2 | 2.1 |
| 9/4/2011 | 0.00 | 29.0 | 19.0 | 22.6 | 16.5 | 1.2 | 99.9 | 54.9 | 2.2 |
| 9/5/2011 | 0.00 | 21.0 | 14.0 | 17.0 | 6.4 | 1.2 | 99.9 | 85.2 | 2.1 |
| 9/6/2011 | 0.00 | 15.0 | 13.0 | 13.8 | 5.4 | 2.2 | 99.9 | 93.8 | 1.6 |
| 9/7/2011 | 0.03 | 17.0 | 14.0 | 15.0 | 6.4 | 1.8 | 97.6 | 80.5 | 1.6 |
| 9/8/2011 | 0.03 | 21.0 | 16.0 | 17.8 | 6.6 | 1.9 | 90.2 | 65.9 | 1.6 |
| 9/9/2011 | 0.00 | 24.0 | 17.0 | 19.6 | 10.7 | 0.9 | 97.0 | 63.0 | 1.9 |
| 9/10/2011 | 0.03 | 25.0 | 18.0 | 20.1 | 17.1 | 1.0 | 93.0 | 60.6 | 1.9 |
| 9/11/2011 | 0.03 | 22.0 | 15.0 | 17.5 | 12.9 | 0.7 | 96.2 | 62.0 | 1.6 |
| 9/12/2011 | 0.00 | 23.0 | 13.0 | 17.7 | 17.8 | 1.2 | 99.9 | 55.5 | 1.6 |
| 9/13/2011 | 1.04 | 26.0 | 14.0 | 19.8 | 20.3 | 1.6 | 97.6 | 46.4 | 1.6 |
| 9/14/2011 | 0.03 | 25.0 | 17.0 | 19.8 | 17.3 | 1.2 | 84.6 | 51.8 | 1.6 |
| 9/15/2011 | 0.00 | 18.0 | 7.0 | 12.6 | 3.8 | 2.0 | 99.9 | 75.6 | 1.6 |
| 9/16/2011 | 0.00 | 16.0 | 5.0 | 10.1 | 18.0 | 1.0 | 91.7 | 44.0 | 0.8 |
| 9/17/2011 | 0.00 | 15.0 | 7.0 | 10.4 | 13.7 | 1.2 | 83.8 | 49.3 | 0.8 |
| 9/18/2011 | 0.73 | 18.0 | 6.0 | 11.8 | 20.3 | 1.1 | 98.4 | 44.6 | 0.9 |
| 9/19/2011 | 0.62 | 16.0 | 8.0 | 12.5 | 10.6 | 1.8 | 85.8 | 50.6 | 0.9 |
| 9/20/2011 | 0.00 | 21.0 | 14.0 | 16.5 | 12.1 | 1.2 | 72.6 | 46.6 | 1.2 |
| 9/21/2011 | 0.00 | 22.0 | 15.0 | 18.2 | 8.2 | 1.7 | 93.8 | 60.5 | 1.6 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2-m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 9/22/2011 | 0.00 | 23.0 | 17.0 | 19.7 | 11.2 | 1.1 | 92.9 | 64.1 | 1.8 |
| 9/23/2011 | 0.89 | 20.0 | 16.0 | 17.6 | 5.0 | 1.4 | 96.8 | 75.3 | 1.8 |
| 9/24/2011 | 0.00 | 22.0 | 14.0 | 17.2 | 16.3 | 1.0 | 99.9 | 60.5 | 1.6 |
| 9/25/2011 | 1.12 | 27.0 | 16.0 | 19.6 | 12.6 | 1.0 | 90.2 | 46.0 | 1.6 |
| 9/26/2011 | 2.64 | 25.0 | 18.0 | 20.4 | 12.7 | 1.4 | 91.1 | 59.3 | 1.9 |
| 9/27/2011 | 0.89 | 21.0 | 17.0 | 19.0 | 3.6 | 1.8 | 99.9 | 80.4 | 2.0 |
| 9/28/2011 | 0.03 | 22.0 | 17.0 | 18.7 | 7.7 | 1.4 | 99.1 | 72.6 | 1.9 |
| 9/29/2011 | 0.05 | 18.0 | 11.0 | 14.8 | 7.5 | 1.6 | 99.9 | 79.5 | 1.6 |
| 9/30/2011 | 2.52 | 15.0 | 10.0 | 12.9 | 7.2 | 1.9 | 99.9 | 77.4 | 1.3 |
| 10/1/2011 | 0.15 | 10.0 | 5.0 | 7.8 | 4.1 | 2.4 | 99.9 | 88.0 | 1.1 |
| 10/2/2011 | 0.28 | 7.0 | 3.0 | 5.0 | 6.4 | 2.2 | 95.0 | 71.9 | 0.7 |
| 10/3/2011 | 0.00 | 11.0 | 5.0 | 7.6 | 7.1 | 0.8 | 87.1 | 57.9 | 0.8 |
| 10/4/2011 | 0.00 | 16.0 | 7.0 | 11.1 | 9.3 | 1.8 | 91.8 | 50.6 | 0.9 |
| 10/5/2011 | 0.00 | 21.0 | 9.0 | 13.8 | 17.2 | 1.9 | 87.1 | 40.2 | 1.0 |
| 10/6/2011 | 0.00 | 18.0 | 3.0 | 10.3 | 17.7 | 0.6 | 95.0 | 34.9 | 0.7 |
| 10/7/2011 | 0.00 | 21.0 | 3.0 | 11.2 | 17.0 | 0.7 | 95.0 | 29.0 | 0.7 |
| 10/8/2011 | 0.00 | 23.0 | 6.0 | 13.9 | 16.8 | 0.8 | 85.6 | 28.5 | 0.8 |
| 10/9/2011 | 0.00 | 26.0 | 8.0 | 15.2 | 16.6 | 0.6 | 85.8 | 27.4 | 0.9 |
| 10/10/2011 | 0.41 | 22.0 | 9.0 | 14.9 | 11.4 | 0.7 | 90.6 | 39.3 | 1.0 |
| 10/11/2011 | 1.25 | 20.0 | 9.0 | 14.8 | 8.5 | 1.0 | 94.1 | 46.2 | 1.1 |
| 10/12/2011 | 0.43 | 12.0 | 11.0 | 11.6 | 4.2 | 2.2 | 91.4 | 85.6 | 1.2 |
| 10/13/2011 | 0.18 | 16.0 | 12.0 | 13.7 | 4.5 | 1.7 | 97.0 | 74.8 | 1.4 |
| 10/14/2011 | 0.05 | 16.0 | 9.0 | 13.1 | 4.9 | 2.3 | 99.9 | 77.0 | 1.4 |
| 10/15/2011 | 0.05 | 14.0 | 9.0 | 11.0 | 12.2 | 2.9 | 90.6 | 65.1 | 1.0 |
| 10/16/2011 | 0.05 | 17.0 | 9.0 | 11.9 | 11.1 | 2.5 | 90.6 | 53.7 | 1.0 |
| 10/17/2011 | 0.03 | 17.0 | 7.0 | 11.4 | 15.7 | 2.2 | 91.8 | 47.5 | 0.9 |
| 10/18/2011 | 0.03 | 19.0 | 10.0 | 13.6 | 14.6 | 1.2 | 74.9 | 41.9 | 0.9 |
| 10/19/2011 | 1.69 | 17.0 | 12.0 | 14.4 | 5.3 | 2.5 | 82.7 | 59.9 | 1.2 |
| 10/20/2011 | 0.13 | 14.0 | 7.0 | 8.8 | 6.0 | 2.8 | 99.9 | 72.6 | 1.2 |
| 10/21/2011 | 0.05 | 9.0 | 5.0 | 6.8 | 6.6 | 2.2 | 99.9 | 80.1 | 0.9 |
| 10/22/2011 | 0.03 | 10.0 | 4.0 | 7.6 | 4.3 | 1.0 | 99.9 | 74.9 | 0.9 |
| 10/23/2011 | 0.03 | 15.0 | 0.0 | 7.4 | 13.3 | 0.8 | 98.2 | 35.2 | 0.6 |
| 10/24/2011 | 0.05 | 14.0 | 6.0 | 9.6 | 7.1 | 1.5 | 68.4 | 40.0 | 0.6 |
| 10/25/2011 | 0.03 | 15.0 | 7.0 | 10.3 | 13.4 | 1.7 | 79.9 | 46.9 | 0.8 |
| 10/26/2011 | 0.69 | 18.0 | 4.0 | 11.1 | 8.2 | 1.6 | 98.4 | 38.8 | 0.8 |
| 10/27/2011 | 0.15 | 14.0 | 1.0 | 7.1 | 3.2 | 2.0 | 99.9 | 55.0 | 0.9 |
| 10/28/2011 | 0.56 | 6.0 | -2.0 | 2.4 | 8.5 | 1.3 | 98.6 | 55.6 | 0.5 |
| 10/29/2011 | 0.74 | 3.0 | 0.0 | 0.7 | 2.5 | 1.7 | 91.7 | 73.9 | 0.6 |
| 10/30/2011 | 0.00 | 6.0 | -3.0 | 0.9 | 12.3 | 1.3 | 98.0 | 51.3 | 0.5 |
| 10/31/2011 | 0.00 | 8.0 | -3.0 | 2.1 | 9.1 | 1.3 | 98.0 | 44.7 | 0.5 |
| 11/1/2011 | 0.00 | 12.0 | 0.0 | 5.7 | 12.7 | 0.6 | 85.1 | 37.1 | 0.5 |
| 11/2/2011 | 0.00 | 14.0 | 0.0 | 6.7 | 12.6 | 1.0 | 91.7 | 35.0 | 0.6 |
| 11/3/2011 | 0.00 | 17.0 | 2.0 | 8.4 | 10.1 | 0.9 | 79.4 | 28.9 | 0.6 |
| 11/4/2011 | 0.00 | 10.0 | 1.0 | 6.5 | 12.7 | 2.4 | 97.5 | 52.1 | 0.6 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 11/5/2011 | 0.03 | 10.0 | -2.0 | 4.0 | 12.8 | 1.5 | 83.4 | 35.8 | 0.4 |
| 11/6/2011 | 0.00 | 12.0 | 1.0 | 5.5 | 12.5 | 1.5 | 67.0 | 31.4 | 0.4 |
| 11/7/2011 | 0.00 | 19.0 | 0.0 | 9.0 | 12.1 | 1.0 | 78.6 | 21.8 | 0.5 |
| 11/8/2011 | 0.10 | 20.0 | 4.0 | 11.4 | 11.7 | 1.0 | 68.9 | 23.9 | 0.6 |
| 11/9/2011 | 0.00 | 18.0 | 2.0 | 10.5 | 12.0 | 1.8 | 85.0 | 29.1 | 0.6 |
| 11/10/2011 | 0.00 | 12.0 | 2.0 | 6.2 | 3.9 | 2.1 | 96.4 | 48.5 | 0.7 |
| 11/11/2011 | 0.00 | 5.0 | 0.0 | 1.6 | 7.1 | 2.8 | 98.2 | 68.8 | 0.6 |
| 11/12/2011 | 0.00 | 15.0 | -1.0 | 6.8 | 11.4 | 1.6 | 84.5 | 28.1 | 0.5 |
| 11/13/2011 | 0.31 | 19.0 | 6.0 | 11.5 | 7.7 | 1.9 | 55.6 | 23.7 | 0.5 |
| 11/14/2011 | 0.08 | 18.0 | 10.0 | 12.4 | 6.9 | 2.4 | 65.1 | 38.8 | 0.8 |
| 11/15/2011 | 0.00 | 13.0 | 10.0 | 11.3 | 3.2 | 1.6 | 94.5 | 77.4 | 1.2 |
| 11/16/2011 | 0.20 | 12.0 | 6.0 | 9.3 | 2.9 | 1.4 | 99.9 | 82.7 | 1.2 |
| 11/17/2011 | 0.43 | 5.0 | -1.0 | 2.1 | 4.5 | 2.5 | 99.9 | 82.5 | 0.7 |
| 11/18/2011 | 0.00 | 5.0 | -4.0 | 0.5 | 10.8 | 1.9 | 99.9 | 55.0 | 0.5 |
| 11/19/2011 | 0.13 | 10.0 | -2.0 | 4.4 | 10.3 | 1.9 | 83.4 | 35.8 | 0.4 |
| 11/20/2011 | 0.08 | 16.0 | 5.0 | 10.7 | 4.9 | 1.8 | 59.6 | 28.6 | 0.5 |
| 11/21/2011 | 4.75 | 12.0 | 4.0 | 6.3 | 3.2 | 1.3 | 99.9 | 62.7 | 0.9 |
| 11/22/2011 | 0.00 | 8.0 | 2.0 | 4.9 | 2.0 | 1.8 | 99.9 | 74.6 | 0.8 |
| 11/23/2011 | 0.00 | 9.0 | 2.0 | 5.8 | 3.2 | 2.7 | 99.9 | 69.7 | 0.8 |
| 11/24/2011 | 0.00 | 9.0 | 1.0 | 4.3 | 9.9 | 2.2 | 91.4 | 52.3 | 0.6 |
| 11/25/2011 | 0.00 | 15.0 | 2.0 | 8.0 | 9.9 | 1.8 | 85.0 | 35.2 | 0.6 |
| 11/26/2011 | 0.00 | 17.0 | 5.0 | 10.3 | 7.0 | 1.2 | 73.4 | 33.0 | 0.6 |
| 11/27/2011 | 0.03 | 15.0 | 4.0 | 10.5 | 6.4 | 1.9 | 83.6 | 39.9 | 0.7 |
| 11/28/2011 | 1.04 | 17.0 | 12.0 | 14.3 | 6.0 | 2.1 | 57.0 | 41.3 | 0.8 |
| 11/29/2011 | 0.00 | 16.0 | 3.0 | 12.4 | 2.4 | 2.8 | 99.9 | 68.2 | 1.2 |
| 11/30/2011 | 0.00 | 4.0 | 1.0 | 2.5 | 3.9 | 2.7 | 99.9 | 83.6 | 0.7 |
| 12/1/2011 | 0.00 | 7.0 | -1.0 | 2.0 | 9.4 | 1.6 | 98.6 | 55.9 | 0.6 |
| 12/2/2011 | 0.00 | 7.0 | -3.0 | 1.3 | 8.5 | 1.4 | 89.9 | 43.9 | 0.4 |
| 12/3/2011 | 0.00 | 6.0 | -4.0 | 0.8 | 9.3 | 1.3 | 96.9 | 47.1 | 0.4 |
| 12/4/2011 | 0.15 | 10.0 | 1.0 | 5.1 | 9.1 | 1.9 | 67.0 | 35.8 | 0.4 |
| 12/5/2011 | 1.04 | 12.0 | 3.0 | 6.8 | 5.4 | 1.7 | 73.9 | 39.9 | 0.6 |
| 12/6/2011 | 1.22 | 13.0 | 7.0 | 10.9 | 2.2 | 1.4 | 75.9 | 50.7 | 0.8 |
| 12/7/2011 | 0.41 | 7.0 | 0.0 | 3.6 | 1.5 | 2.4 | 99.9 | 91.8 | 0.9 |
| 12/8/2011 | 0.00 | 2.0 | -3.0 | -0.6 | 8.0 | 2.2 | 99.9 | 79.4 | 0.6 |
| 12/9/2011 | 0.00 | 5.0 | -4.0 | 0.6 | 8.9 | 1.2 | 96.9 | 50.4 | 0.4 |
| 12/10/2011 | 0.00 | 1.0 | -5.0 | -1.0 | 9.1 | 1.9 | 99.9 | 73.1 | 0.5 |
| 12/11/2011 | 0.00 | 2.0 | -8.0 | -3.3 | 9.1 | 0.9 | 95.7 | 45.3 | 0.3 |
| 12/12/2011 | 0.00 | 4.0 | -8.0 | -2.5 | 8.8 | 0.8 | 95.7 | 39.3 | 0.3 |
| 12/13/2011 | 0.03 | 8.0 | -7.0 | 0.0 | 8.8 | 1.2 | 88.6 | 29.8 | 0.3 |
| 12/14/2011 | 0.22 | 6.0 | 0.0 | 2.4 | 4.2 | 1.1 | 58.9 | 38.5 | 0.4 |
| 12/15/2011 | 0.60 | 14.0 | 3.0 | 7.9 | 1.8 | 2.8 | 84.5 | 40.0 | 0.6 |
| 12/16/2011 | 0.03 | 8.0 | 0.0 | 2.1 | 6.6 | 2.6 | 99.9 | 63.4 | 0.7 |
| 12/17/2011 | 0.07 | 1.0 | -3.0 | -0.5 | 3.9 | 1.6 | 99.9 | 91.4 | 0.6 |
| 12/18/2011 | 0.04 | 0.0 | -4.0 | -2.2 | 6.3 | 1.1 | 96.9 | 72.0 | 0.4 |

[1]Computed using equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 12/19/2011 | 0.11 | 7.0 | -4.0 | 2.2 | 5.8 | 2.2 | 88.1 | 39.9 | 0.4 |
| 12/20/2011 | 0.50 | 6.0 | 1.0 | 3.0 | 2.5 | 1.3 | 67.0 | 47.1 | 0.4 |
| 12/21/2011 | 0.90 | 9.0 | 2.0 | 5.2 | 2.2 | 2.3 | 96.4 | 59.2 | 0.7 |
| 12/22/2011 | 1.20 | 9.0 | 6.0 | 7.8 | 5.8 | 1.3 | 85.6 | 69.7 | 0.8 |
| 12/23/2011 | 0.04 | 6.0 | -1.0 | 3.0 | 4.2 | 2.3 | 99.9 | 85.6 | 0.8 |
| 12/24/2011 | 0.04 | 2.0 | -2.0 | -0.2 | 8.3 | 1.3 | 98.6 | 73.7 | 0.5 |
| 12/25/2011 | 0.07 | 8.0 | -3.0 | 2.3 | 8.7 | 1.9 | 89.9 | 41.0 | 0.4 |
| 12/26/2011 | 0.03 | 3.0 | -2.0 | 1.1 | 5.3 | 2.2 | 98.6 | 68.6 | 0.5 |
| 12/27/2011 | 1.69 | 4.0 | -1.0 | 1.8 | 1.7 | 2.6 | 84.5 | 59.0 | 0.5 |
| 12/28/2011 | 0.04 | 2.0 | -6.0 | -1.5 | 5.0 | 3.4 | 99.9 | 79.4 | 0.6 |
| 12/29/2011 | 0.04 | 0.0 | -8.0 | -3.9 | 4.6 | 1.6 | 95.7 | 52.4 | 0.3 |
| 12/30/2011 | 0.04 | 4.0 | -2.0 | 1.0 | 4.7 | 1.6 | 68.3 | 44.3 | 0.4 |
| 12/31/2011 | 0.04 | 7.0 | 0.0 | 4.1 | 3.7 | 1.8 | 91.7 | 55.9 | 0.6 |
| 1/1/2012 | 0.24 | 8.0 | 0.0 | 5.1 | 5.5 | 2.5 | 98.2 | 55.9 | 0.6 |
| 1/2/2012 | 0.06 | 1.0 | -4.0 | -1.5 | 5.5 | 3.1 | 99.9 | 79.2 | 0.5 |
| 1/3/2012 | 0.01 | 7.0 | -14.0 | -8.1 | 6.7 | 3.5 | 99.9 | 35.9 | 0.4 |
| 1/4/2012 | 0.00 | -4.0 | -15.0 | -8.2 | 4.8 | 1.9 | 99.9 | 44.0 | 0.2 |
| 1/5/2012 | 0.01 | 2.0 | -4.0 | -1.2 | 6.6 | 2.0 | 52.8 | 34.0 | 0.2 |
| 1/6/2012 | 0.00 | 13.0 | -2.0 | 5.7 | 8.8 | 2.1 | 83.4 | 29.4 | 0.4 |
| 1/7/2012 | 0.00 | 12.0 | 1.0 | 7.8 | 7.9 | 2.4 | 79.2 | 37.1 | 0.5 |
| 1/8/2012 | 0.00 | 2.0 | -3.0 | 0.2 | 7.8 | 1.6 | 99.9 | 73.7 | 0.5 |
| 1/9/2012 | 0.00 | 4.0 | -3.0 | -0.6 | 9.0 | 1.3 | 89.9 | 54.1 | 0.4 |
| 1/10/2012 | 0.00 | 7.0 | -3.0 | 1.5 | 8.2 | 1.9 | 89.9 | 43.9 | 0.4 |
| 1/11/2012 | 1.38 | 6.0 | -6.0 | 0.4 | 6.1 | 1.9 | 99.9 | 42.8 | 0.4 |
| 1/12/2012 | 0.91 | 5.0 | 1.0 | 3.5 | 4.2 | 1.5 | 67.0 | 50.4 | 0.4 |
| 1/13/2012 | 0.01 | 5.0 | -7.0 | -4.1 | 5.5 | 4.2 | 99.9 | 50.4 | 0.4 |
| 1/14/2012 | 0.01 | 0.0 | -7.0 | -5.5 | 8.8 | 2.9 | 99.6 | 58.9 | 0.4 |
| 1/15/2012 | 0.00 | -4.0 | -12.0 | -8.0 | 10.2 | 1.7 | 98.6 | 52.8 | 0.2 |
| 1/16/2012 | 0.06 | 1.0 | -12.0 | -4.4 | 9.4 | 2.5 | 98.6 | 36.5 | 0.2 |
| 1/17/2012 | 0.11 | 11.0 | 0.0 | 4.4 | 3.9 | 3.0 | 45.8 | 21.3 | 0.3 |
| 1/18/2012 | 0.01 | 4.0 | -8.0 | -2.7 | 8.9 | 3.1 | 99.9 | 63.9 | 0.5 |
| 1/19/2012 | 0.29 | -2.0 | -10.0 | -5.8 | 8.0 | 2.3 | 98.0 | 53.1 | 0.3 |
| 1/20/2012 | 0.78 | -4.0 | -11.0 | -7.4 | 9.4 | 1.9 | 91.0 | 52.8 | 0.2 |
| 1/21/2012 | 0.01 | -2.0 | -9.0 | -5.5 | 5.5 | 1.9 | 77.6 | 45.5 | 0.2 |
| 1/22/2012 | 0.01 | -2.0 | -9.0 | -5.6 | 3.9 | 1.9 | 77.6 | 45.5 | 0.2 |
| 1/23/2012 | 0.15 | 5.0 | -2.0 | 2.1 | 3.0 | 2.8 | 60.7 | 36.7 | 0.3 |
| 1/24/2012 | 0.00 | 5.0 | 0.0 | 3.6 | 6.4 | 2.4 | 98.2 | 68.8 | 0.6 |
| 1/25/2012 | 0.00 | 3.0 | -1.0 | 0.5 | 9.6 | 1.3 | 99.9 | 79.2 | 0.6 |
| 1/26/2012 | 1.19 | 1.0 | -1.0 | 0.8 | 3.3 | 1.6 | 99.9 | 91.4 | 0.6 |
| 1/27/2012 | 0.10 | 7.0 | 1.0 | 3.2 | 5.0 | 3.7 | 91.4 | 59.9 | 0.6 |
| 12/28/2012 | 0.04 | 2.0 | -6.0 | -1.5 | 5.0 | 3.4 | 99.9 | 79.4 | 0.6 |
| 12/29/2012 | 0.04 | 0.0 | -8.0 | -3.9 | 4.6 | 1.6 | 95.7 | 52.4 | 0.3 |
| 12/30/2012 | 0.04 | 4.0 | -2.0 | 1.0 | 4.7 | 1.6 | 68.3 | 44.3 | 0.4 |
| 12/31/2012 | 0.04 | 7.0 | 0.0 | 4.1 | 3.7 | 1.8 | 91.7 | 55.9 | 0.6 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | $^{o}$C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 2/1/2012 | 0.00 | 13.0 | 6.0 | 9.9 | 9.3 | 2.7 | 64.2 | 40.1 | 0.6 |
| 2/2/2012 | 0.00 | 5.0 | 1.0 | 1.9 | 4.6 | 2.2 | 91.4 | 68.8 | 0.6 |
| 2/3/2012 | 0.00 | 7.0 | -1.0 | 1.8 | 12.0 | 1.3 | 98.6 | 55.9 | 0.6 |
| 2/4/2012 | 0.00 | 3.0 | -3.0 | -0.2 | 6.1 | 0.7 | 89.9 | 58.1 | 0.4 |
| 2/5/2012 | 0.00 | 3.0 | -3.0 | 3.3 | 9.5 | 1.2 | 89.9 | 58.1 | 0.4 |
| 2/6/2012 | 0.00 | 10.0 | -3.0 | 2.4 | 12.8 | 1.8 | 89.9 | 35.8 | 0.4 |
| 2/7/2012 | 0.00 | 4.0 | 0.0 | 2.6 | 11.5 | 2.0 | 72.0 | 54.1 | 0.4 |
| 2/8/2012 | 0.20 | 1.0 | -2.0 | -0.8 | 3.9 | 1.2 | 98.6 | 79.2 | 0.5 |
| 2/9/2012 | 0.23 | 3.0 | -7.0 | -2.3 | 12.7 | 2.2 | 99.6 | 47.5 | 0.4 |
| 2/10/2012 | 0.00 | 2.0 | -4.0 | -0.7 | 8.2 | 1.2 | 88.1 | 56.7 | 0.4 |
| 2/11/2012 | 0.08 | 0.0 | -10.0 | -3.7 | 5.3 | 2.5 | 99.9 | 78.6 | 0.5 |
| 2/12/2012 | 0.00 | -5.0 | -11.0 | -7.0 | 7.6 | 4.3 | 99.9 | 66.5 | 0.3 |
| 2/13/2012 | 0.00 | 3.0 | -6.0 | -2.4 | 13.9 | 2.6 | 82.0 | 42.2 | 0.3 |
| 2/14/2012 | 0.03 | 4.0 | -2.0 | 0.6 | 9.8 | 1.1 | 75.8 | 49.2 | 0.4 |
| 2/15/2012 | 0.10 | 2.0 | -2.0 | 0.5 | 7.3 | 1.5 | 99.9 | 79.4 | 0.6 |
| 2/16/2012 | 0.43 | 2.0 | -3.0 | 0.8 | 3.4 | 1.9 | 99.9 | 73.7 | 0.5 |
| 2/17/2012 | 0.00 | 6.0 | 0.0 | 3.4 | 14.1 | 2.5 | 98.2 | 64.2 | 0.6 |
| 2/18/2012 | 0.00 | 7.0 | -2.0 | 1.3 | 10.4 | 2.3 | 91.0 | 47.9 | 0.5 |
| 2/19/2012 | 0.00 | 4.0 | -2.0 | -0.5 | 13.0 | 1.6 | 91.0 | 59.0 | 0.5 |
| 2/20/2012 | 0.00 | 5.0 | -4.0 | -1.4 | 15.4 | 1.9 | 96.9 | 50.4 | 0.4 |
| 2/21/2012 | 0.00 | 5.0 | -4.0 | 0.4 | 9.3 | 2.6 | 88.1 | 45.9 | 0.4 |
| 2/22/2012 | 0.00 | 12.0 | 1.0 | 6.3 | 14.3 | 2.4 | 67.0 | 31.4 | 0.4 |
| 2/23/2012 | 0.25 | 10.0 | 3.0 | 6.7 | 15.4 | 2.1 | 89.7 | 55.4 | 0.7 |
| 2/24/2012 | 0.10 | 6.0 | 1.0 | 3.5 | 4.6 | 2.9 | 99.9 | 77.0 | 0.7 |
| 2/25/2012 | 0.05 | 1.0 | -2.0 | -0.4 | 9.7 | 4.5 | 99.9 | 85.3 | 0.6 |
| 2/26/2012 | 0.00 | 3.0 | -3.0 | -0.4 | 14.0 | 1.9 | 99.9 | 68.6 | 0.5 |
| 2/27/2012 | 0.00 | 13.0 | -4.0 | 4.0 | 14.6 | 2.6 | 88.1 | 26.7 | 0.4 |
| 2/28/2012 | 0.03 | 8.0 | -2.0 | 2.7 | 16.6 | 1.9 | 75.8 | 37.3 | 0.4 |
| 2/29/2012 | 1.83 | 4.0 | 1.0 | 2.2 | 3.7 | 1.9 | 79.2 | 63.9 | 0.5 |
| 3/1/2012 | 0.00 | 6.0 | 2.0 | 3.6 | 4.6 | 2.8 | 90.7 | 68.4 | 0.6 |
| 3/2/2012 | 0.43 | 9.0 | -2.0 | 4.1 | 13.7 | 2.5 | 98.6 | 45.3 | 0.5 |
| 3/3/2012 | 0.03 | 9.0 | 0.0 | 5.7 | 17.1 | 3.5 | 91.7 | 48.8 | 0.6 |
| 3/4/2012 | 0.00 | 2.0 | -3.0 | -0.5 | 9.8 | 2.8 | 99.9 | 73.7 | 0.5 |
| 3/5/2012 | 0.00 | 4.0 | -5.0 | -1.8 | 14.5 | 2.2 | 95.0 | 49.2 | 0.4 |
| 3/6/2012 | 0.00 | 6.0 | -8.0 | -0.4 | 16.9 | 1.9 | 95.7 | 34.2 | 0.3 |
| 3/7/2012 | 0.00 | 19.0 | -2.0 | 9.3 | 17.1 | 2.5 | 68.3 | 16.4 | 0.4 |
| 3/8/2012 | 0.74 | 16.0 | 4.0 | 11.5 | 8.0 | 3.4 | 68.9 | 30.8 | 0.6 |
| 3/9/2012 | 0.00 | 4.0 | -2.0 | 1.7 | 12.5 | 3.7 | 99.9 | 73.8 | 0.6 |
| 3/10/2012 | 0.00 | 5.0 | -5.0 | -0.4 | 18.5 | 1.9 | 99.9 | 50.4 | 0.4 |
| 3/11/2012 | 0.00 | 18.0 | -2.0 | 7.4 | 18.6 | 1.5 | 75.8 | 19.4 | 0.4 |
| 3/12/2012 | 0.10 | 19.0 | 2.0 | 11.4 | 15.8 | 1.2 | 68.0 | 21.8 | 0.5 |
| 3/13/2012 | 0.00 | 22.0 | 10.0 | 16.3 | 14.0 | 2.2 | 52.1 | 24.2 | 0.6 |
| 3/14/2012 | 0.00 | 22.0 | 8.0 | 14.2 | 18.9 | 1.6 | 78.3 | 31.8 | 0.8 |
| 3/15/2012 | 0.00 | 23.0 | 7.0 | 15.4 | 15.3 | 1.3 | 79.9 | 28.5 | 0.8 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 $^{o}$ 49 ' 44.4 " N and longitude 77 $^{o}$ 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 $^{o}$ 49 ' 44.4 " N and longitude 77 $^{o}$ 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 3/16/2012 | 0.00 | 23.0 | 10.0 | 15.5 | 17.2 | 1.3 | 74.9 | 32.7 | 0.9 |
| 3/17/2012 | 0.00 | 24.0 | 7.0 | 14.3 | 19.2 | 1.4 | 91.8 | 30.8 | 0.9 |
| 3/18/2012 | 0.00 | 22.0 | 11.0 | 16.1 | 17.9 | 2.1 | 73.1 | 36.3 | 1.0 |
| 3/19/2012 | 0.03 | 20.0 | 11.0 | 15.6 | 11.6 | 1.3 | 85.3 | 47.9 | 1.1 |
| 3/20/2012 | 0.00 | 20.0 | 13.0 | 15.6 | 10.0 | 1.5 | 82.8 | 53.0 | 1.2 |
| 3/21/2012 | 0.00 | 18.0 | 9.0 | 14.5 | 7.5 | 1.4 | 99.9 | 56.2 | 1.2 |
| 3/22/2012 | 0.00 | 24.0 | 14.0 | 17.6 | 17.5 | 0.9 | 77.6 | 41.6 | 1.2 |
| 3/23/2012 | 0.86 | 24.0 | 9.0 | 18.0 | 19.6 | 1.3 | 99.9 | 38.9 | 1.2 |
| 3/24/2012 | 0.74 | 19.0 | 9.0 | 12.6 | 5.1 | 2.2 | 99.9 | 54.6 | 1.2 |
| 3/25/2012 | 0.03 | 15.0 | 7.0 | 11.4 | 13.8 | 1.7 | 99.9 | 61.0 | 1.0 |
| 3/26/2012 | 0.00 | 12.0 | -1.0 | 5.6 | 22.1 | 3.7 | 99.9 | 62.7 | 0.9 |
| 3/27/2012 | 0.00 | 10.0 | -4.0 | 3.2 | 22.5 | 1.6 | 96.9 | 35.8 | 0.4 |
| 3/28/2012 | 0.08 | 22.0 | 5.0 | 12.9 | 15.6 | 2.8 | 55.0 | 18.2 | 0.5 |
| 3/29/2012 | 0.00 | 12.0 | 2.0 | 6.1 | 15.3 | 3.1 | 99.9 | 51.3 | 0.7 |
| 3/30/2012 | 0.43 | 12.0 | -2.0 | 6.0 | 21.8 | 1.6 | 98.6 | 37.1 | 0.5 |
| 3/31/2012 | 0.08 | 7.0 | 5.0 | 6.7 | 6.3 | 1.6 | 64.2 | 55.9 | 0.6 |
| 4/1/2012 | 0.03 | 13.0 | 4.0 | 8.2 | 18.4 | 1.3 | 99.9 | 61.4 | 0.9 |
| 4/2/2012 | 0.00 | 14.0 | 3.0 | 6.9 | 20.0 | 2.8 | 99.9 | 50.0 | 0.8 |
| 4/3/2012 | 0.00 | 19.0 | 2.0 | 9.4 | 22.8 | 1.3 | 79.4 | 25.5 | 0.6 |
| 4/4/2012 | 0.00 | 19.0 | 7.0 | 12.4 | 21.6 | 2.6 | 59.9 | 27.3 | 0.6 |
| 4/5/2012 | 0.00 | 12.0 | 2.0 | 7.1 | 23.1 | 1.9 | 85.0 | 42.8 | 0.6 |
| 4/6/2012 | 0.00 | 14.0 | -1.0 | 5.9 | 24.1 | 2.5 | 91.6 | 32.5 | 0.5 |
| 4/7/2012 | 0.00 | 16.0 | 2.0 | 8.2 | 24.2 | 2.5 | 73.7 | 28.6 | 0.5 |
| 4/8/2012 | 0.00 | 17.0 | 3.0 | 9.7 | 22.6 | 2.8 | 73.9 | 28.9 | 0.6 |
| 4/9/2012 | 0.00 | 12.0 | 6.0 | 8.3 | 17.8 | 3.1 | 77.0 | 51.3 | 0.7 |
| 4/10/2012 | 0.00 | 9.0 | 2.0 | 5.0 | 13.2 | 2.6 | 99.9 | 62.7 | 0.7 |
| 4/11/2012 | 0.05 | 6.0 | 1.0 | 3.5 | 15.7 | 2.5 | 99.9 | 72.7 | 0.7 |
| 4/12/2012 | 0.00 | 11.0 | 2.0 | 6.3 | 15.3 | 2.2 | 90.7 | 48.8 | 0.6 |
| 4/13/2012 | 0.00 | 16.0 | -1.0 | 7.8 | 24.8 | 1.2 | 91.6 | 28.6 | 0.5 |
| 4/14/2012 | 0.03 | 19.0 | 1.0 | 10.8 | 16.4 | 1.3 | 79.2 | 23.7 | 0.5 |
| 4/15/2012 | 0.00 | 23.0 | 11.0 | 17.1 | 16.3 | 2.1 | 51.8 | 24.2 | 0.7 |
| 4/16/2012 | 0.00 | 30.0 | 13.0 | 20.0 | 23.5 | 2.2 | 69.4 | 24.5 | 1.0 |
| 4/17/2012 | 0.00 | 21.0 | 10.0 | 12.6 | 19.0 | 2.5 | 78.2 | 38.6 | 1.0 |
| 4/18/2012 | 0.00 | 14.0 | 6.0 | 9.3 | 13.7 | 1.2 | 94.1 | 55.0 | 0.9 |
| 4/19/2012 | 0.00 | 21.0 | 4.0 | 13.5 | 24.5 | 1.1 | 93.5 | 30.6 | 0.8 |
| 4/20/2012 | 0.00 | 22.0 | 8.0 | 15.9 | 24.6 | 1.9 | 67.1 | 27.2 | 0.7 |
| 4/21/2012 | 0.31 | 19.0 | 8.0 | 13.4 | 13.7 | 1.9 | 82.0 | 40.0 | 0.9 |
| 4/22/2012 | 1.30 | 8.0 | 2.0 | 4.7 | 6.3 | 2.8 | 99.9 | 82.0 | 0.9 |
| 4/23/2012 | 0.66 | 3.0 | 1.0 | 1.7 | 10.8 | 3.2 | 99.9 | 89.7 | 0.7 |
| 4/24/2012 | 0.00 | 8.0 | 2.0 | 4.5 | 16.9 | 2.5 | 96.4 | 63.4 | 0.7 |
| 4/25/2012 | 0.00 | 16.0 | 0.0 | 8.2 | 25.8 | 1.3 | 98.2 | 33.0 | 0.6 |
| 4/26/2012 | 0.20 | 19.0 | 5.0 | 10.6 | 17.2 | 1.9 | 78.0 | 30.9 | 0.7 |
| 4/27/2012 | 0.00 | 11.0 | 3.0 | 6.1 | 21.4 | 3.0 | 99.9 | 57.9 | 0.8 |
| 4/28/2012 | 0.00 | 8.0 | 0.0 | 4.6 | 10.6 | 0.7 | 85.1 | 48.5 | 0.5 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m^{-2} | m s^{-1} | | % | kPa |
| 4/29/2012 | 0.00 | 18.0 | -1.0 | 9.3 | 27.5 | 1.4 | 91.6 | 25.2 | 0.5 |
| 4/30/2012 | 0.15 | 19.0 | 1.0 | 10.7 | 22.9 | 2.0 | 73.1 | 21.8 | 0.5 |
| 5/1/2012 | 0.13 | 23.0 | 11.0 | 17.0 | 20.1 | 1.7 | 54.8 | 25.6 | 0.7 |
| 5/2/2012 | 0.79 | 23.0 | 12.0 | 16.7 | 12.3 | 1.2 | 85.6 | 42.7 | 1.2 |
| 5/3/2012 | 0.03 | 30.0 | 14.0 | 19.9 | 23.0 | 1.3 | 92.6 | 34.9 | 1.5 |
| 5/4/2012 | 0.25 | 28.0 | 17.0 | 20.8 | 21.6 | 1.1 | 74.3 | 38.1 | 1.4 |
| 5/5/2012 | 0.00 | 22.0 | 15.0 | 17.3 | 17.8 | 1.5 | 96.2 | 62.0 | 1.6 |
| 5/6/2012 | 0.00 | 21.0 | 12.0 | 15.3 | 10.5 | 1.4 | 97.0 | 54.7 | 1.4 |
| 5/7/2012 | 0.78 | 16.0 | 13.0 | 14.2 | 5.8 | 2.5 | 96.1 | 79.2 | 1.4 |
| 5/8/2012 | 1.73 | 17.0 | 11.0 | 13.8 | 5.5 | 2.2 | 99.9 | 70.2 | 1.4 |
| 5/9/2012 | 0.00 | 20.0 | 11.0 | 15.0 | 12.3 | 1.5 | 99.9 | 58.2 | 1.4 |
| 5/10/2012 | 0.00 | 14.0 | 8.0 | 11.0 | 19.0 | 2.8 | 99.9 | 67.6 | 1.1 |
| 5/11/2012 | 0.00 | 20.0 | 3.0 | 13.1 | 25.9 | 2.2 | 99.9 | 34.2 | 0.8 |
| 5/12/2012 | 0.00 | 24.0 | 8.0 | 16.7 | 26.9 | 1.3 | 74.6 | 26.8 | 0.8 |
| 5/13/2012 | 0.94 | 22.0 | 10.0 | 14.9 | 13.8 | 0.7 | 74.9 | 34.8 | 0.9 |
| 5/14/2012 | 4.83 | 15.0 | 12.0 | 13.6 | 6.8 | 1.4 | 94.1 | 77.4 | 1.3 |
| 5/15/2012 | 0.05 | 22.0 | 15.0 | 17.1 | 18.1 | 1.0 | 86.8 | 56.0 | 1.5 |
| 5/16/2012 | 0.38 | 26.0 | 12.0 | 17.5 | 26.1 | 1.5 | 99.8 | 41.6 | 1.4 |
| 5/17/2012 | 0.00 | 20.0 | 5.0 | 12.6 | 29.4 | 1.6 | 96.3 | 35.9 | 0.8 |
| 5/18/2012 | 0.00 | 23.0 | 6.0 | 14.8 | 29.1 | 1.0 | 89.8 | 29.9 | 0.8 |
| 5/19/2012 | 0.00 | 27.0 | 8.0 | 17.8 | 27.9 | 0.7 | 85.8 | 25.8 | 0.9 |
| 5/20/2012 | 0.00 | 27.0 | 11.0 | 20.1 | 28.1 | 1.3 | 85.3 | 31.4 | 1.1 |
| 5/21/2012 | 1.93 | 19.0 | 15.0 | 16.1 | 8.0 | 1.8 | 82.1 | 63.7 | 1.4 |
| 5/22/2012 | 0.36 | 23.0 | 16.0 | 17.5 | 17.5 | 1.0 | 94.6 | 61.2 | 1.7 |
| 5/23/2012 | 0.86 | 32.0 | 15.0 | 18.2 | 15.8 | 1.0 | 99.9 | 36.2 | 1.7 |
| 5/24/2012 | 0.03 | 25.0 | 15.0 | 19.8 | 22.3 | 1.9 | 99.9 | 54.3 | 1.7 |
| 5/25/2012 | 0.00 | 27.0 | 19.0 | 22.1 | 24.2 | 1.7 | 87.4 | 53.9 | 1.9 |
| 5/26/2012 | 0.58 | 28.0 | 19.0 | 21.2 | 20.3 | 0.8 | 91.0 | 52.9 | 2.0 |
| 5/27/2012 | 0.58 | 26.0 | 17.0 | 19.8 | 21.1 | 0.8 | 99.9 | 59.5 | 2.0 |
| 5/28/2012 | 0.00 | 30.0 | 15.0 | 22.6 | 27.4 | 1.3 | 99.9 | 42.4 | 1.8 |
| 5/29/2012 | 0.66 | 29.0 | 18.0 | 22.0 | 18.9 | 1.5 | 96.9 | 49.9 | 2.0 |
| 5/30/2012 | 0.00 | 26.0 | 14.0 | 19.2 | 26.7 | 1.2 | 99.9 | 51.2 | 1.7 |
| 5/31/2012 | 0.00 | 23.0 | 12.0 | 17.7 | 24.3 | 1.3 | 88.4 | 44.1 | 1.2 |
| 6/1/2012 | 2.57 | 19.0 | 14.0 | 16.2 | 10.0 | 2.5 | 90.1 | 65.5 | 1.4 |
| 6/2/2012 | 0.05 | 18.0 | 10.0 | 13.7 | 22.4 | 2.1 | 99.9 | 65.9 | 1.4 |
| 6/3/2012 | 0.53 | 20.0 | 9.0 | 13.5 | 17.8 | 2.0 | 99.9 | 51.3 | 1.2 |
| 6/4/2012 | 0.18 | 17.0 | 11.0 | 13.6 | 16.2 | 2.1 | 97.5 | 66.1 | 1.3 |
| 6/5/2012 | 0.03 | 18.0 | 10.0 | 13.1 | 16.7 | 1.2 | 99.9 | 62.0 | 1.3 |
| 6/6/2012 | 0.00 | 21.0 | 10.0 | 15.3 | 19.6 | 0.7 | 94.5 | 46.6 | 1.2 |
| 6/7/2012 | 0.74 | 23.0 | 10.0 | 15.1 | 24.2 | 1.4 | 99.9 | 44.1 | 1.2 |
| 6/8/2012 | 0.00 | 24.0 | 10.0 | 18.0 | 27.0 | 1.6 | 99.9 | 41.6 | 1.2 |
| 6/9/2012 | 0.00 | 28.0 | 14.0 | 20.9 | 26.9 | 1.7 | 85.1 | 36.0 | 1.4 |
| 6/10/2012 | 0.00 | 30.0 | 17.0 | 23.5 | 28.8 | 1.0 | 84.6 | 38.7 | 1.6 |
| 6/11/2012 | 0.05 | 27.0 | 14.0 | 22.1 | 23.6 | 1.8 | 99.9 | 50.5 | 1.8 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 6/12/2012 | 1.12 | 24.0 | 17.0 | 19.5 | 9.5 | 1.6 | 99.9 | 67.0 | 2.0 |
| 6/13/2012 | 0.00 | 23.0 | 14.0 | 17.5 | 29.8 | 2.4 | 92.6 | 52.7 | 1.5 |
| 6/14/2012 | 0.00 | 24.0 | 10.0 | 17.4 | 24.5 | 1.5 | 99.9 | 42.9 | 1.3 |
| 6/15/2012 | 0.00 | 25.0 | 13.0 | 19.2 | 25.8 | 1.1 | 93.5 | 44.2 | 1.4 |
| 6/16/2012 | 0.00 | 25.0 | 12.0 | 18.3 | 25.8 | 1.3 | 99.9 | 45.5 | 1.4 |
| 6/17/2012 | 0.25 | 24.0 | 15.0 | 19.4 | 27.5 | 2.1 | 93.8 | 53.6 | 1.6 |
| 6/18/2012 | 0.03 | 18.0 | 15.0 | 16.4 | 7.2 | 1.9 | 96.2 | 79.5 | 1.6 |
| 6/19/2012 | 0.00 | 29.0 | 17.0 | 21.5 | 24.4 | 1.2 | 92.9 | 44.9 | 1.8 |
| 6/20/2012 | 0.00 | 32.0 | 20.0 | 25.6 | 28.4 | 1.3 | 85.5 | 42.1 | 2.0 |
| 6/21/2012 | 0.00 | 32.0 | 20.0 | 25.6 | 27.3 | 1.4 | 94.1 | 46.3 | 2.2 |
| 6/22/2012 | 0.00 | 28.0 | 21.0 | 23.7 | 24.2 | 1.4 | 93.3 | 61.4 | 2.3 |
| 6/23/2012 | 0.00 | 27.0 | 15.0 | 21.2 | 26.2 | 1.5 | 99.9 | 48.2 | 1.7 |
| 6/24/2012 | 1.07 | 26.0 | 12.0 | 19.2 | 24.1 | 0.9 | 99.9 | 42.8 | 1.4 |
| 6/25/2012 | 0.08 | 23.0 | 14.0 | 18.2 | 24.7 | 2.1 | 99.9 | 58.4 | 1.6 |
| 6/26/2012 | 0.00 | 23.0 | 12.0 | 17.0 | 25.6 | 2.6 | 88.4 | 44.1 | 1.2 |
| 6/27/2012 | 0.00 | 26.0 | 13.0 | 20.0 | 27.2 | 2.2 | 90.8 | 40.5 | 1.4 |
| 6/28/2012 | 0.53 | 31.0 | 15.0 | 23.7 | 27.7 | 1.5 | 91.5 | 34.7 | 1.6 |
| 6/29/2012 | 0.00 | 33.0 | 19.0 | 27.6 | 27.9 | 1.8 | 85.6 | 37.4 | 1.9 |
| 6/30/2012 | 0.00 | 28.0 | 20.0 | 24.2 | 12.3 | 1.4 | 90.7 | 56.1 | 2.1 |
| 7/1/2012 | 0.00 | 31.0 | 19.0 | 26.7 | 27.5 | 1.4 | 94.7 | 46.3 | 2.1 |
| 7/2/2012 | 0.00 | 30.0 | 17.0 | 25.1 | 27.9 | 1.6 | 90.8 | 41.5 | 1.8 |
| 7/3/2012 | 0.27 | 30.0 | 15.0 | 22.7 | 25.9 | 1.2 | 96.2 | 38.7 | 1.6 |
| 7/4/2012 | 0.00 | 31.0 | 18.0 | 24.5 | 27.0 | 1.8 | 91.1 | 41.8 | 1.9 |
| 7/5/2012 | 0.00 | 32.0 | 22.0 | 26.3 | 24.4 | 1.8 | 86.2 | 48.0 | 2.3 |
| 7/6/2012 | 0.00 | 34.0 | 19.0 | 26.2 | 28.1 | 1.3 | 99.9 | 41.4 | 2.2 |
| 7/7/2012 | 0.15 | 36.0 | 20.0 | 26.2 | 26.9 | 1.4 | 97.5 | 38.4 | 2.3 |
| 7/8/2012 | 0.01 | 30.0 | 21.0 | 24.7 | 22.2 | 1.4 | 96.5 | 56.6 | 2.4 |
| 7/9/2012 | 0.00 | 28.0 | 18.0 | 22.7 | 23.4 | 1.3 | 99.9 | 55.0 | 2.1 |
| 7/10/2012 | 0.00 | 29.0 | 14.0 | 20.9 | 25.9 | 1.0 | 99.9 | 39.9 | 1.6 |
| 7/11/2012 | 0.00 | 29.0 | 16.0 | 19.6 | 23.3 | 1.0 | 94.6 | 42.9 | 1.7 |
| 7/12/2012 | 0.00 | 30.0 | 16.0 | 23.8 | 26.6 | 1.3 | 99.0 | 42.4 | 1.8 |
| 7/13/2012 | 0.02 | 27.0 | 19.0 | 22.0 | 11.2 | 1.2 | 91.0 | 56.1 | 2.0 |
| 7/14/2012 | 0.02 | 26.0 | 18.0 | 21.5 | 15.3 | 1.0 | 99.9 | 61.9 | 2.1 |
| 7/15/2012 | 0.58 | 29.0 | 19.0 | 22.0 | 17.1 | 1.3 | 99.9 | 56.9 | 2.3 |
| 7/16/2012 | 0.00 | 31.0 | 19.0 | 24.0 | 24.2 | 1.5 | 99.9 | 50.8 | 2.3 |
| 7/17/2012 | 0.00 | 35.0 | 18.0 | 26.4 | 26.8 | 1.6 | 99.9 | 37.0 | 2.1 |
| 7/18/2012 | 0.15 | 32.0 | 23.0 | 25.9 | 13.3 | 1.3 | 81.2 | 48.0 | 2.3 |
| 7/19/2012 | 1.23 | 28.0 | 19.0 | 22.5 | 17.5 | 1.0 | 99.9 | 63.5 | 2.4 |
| 7/20/2012 | 1.87 | 19.0 | 16.0 | 17.2 | 6.5 | 1.3 | 99.9 | 94.7 | 2.1 |
| 7/21/2012 | 0.01 | 20.0 | 15.0 | 17.3 | 13.4 | 1.0 | 99.9 | 75.3 | 1.8 |
| 7/22/2012 | 0.00 | 27.0 | 16.0 | 21.5 | 25.2 | 0.9 | 96.8 | 49.4 | 1.8 |
| 7/23/2012 | 0.00 | 29.0 | 19.0 | 24.0 | 19.9 | 1.3 | 91.0 | 49.9 | 2.0 |
| 7/24/2012 | 0.00 | 32.0 | 22.0 | 26.0 | 22.6 | 2.3 | 87.7 | 48.8 | 2.3 |
| 7/25/2012 | 0.01 | 27.0 | 15.0 | 21.2 | 28.1 | 1.4 | 91.5 | 43.8 | 1.6 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 7/26/2012 | 1.63 | 34.0 | 19.0 | 22.9 | 25.3 | 1.9 | 80.1 | 33.1 | 1.8 |
| 7/27/2012 | 0.04 | 29.0 | 19.0 | 22.3 | 20.5 | 1.3 | 99.9 | 54.9 | 2.2 |
| 7/28/2012 | 0.10 | 26.0 | 18.0 | 20.5 | 19.2 | 0.9 | 99.9 | 63.1 | 2.1 |
| 7/29/2012 | 0.00 | 28.0 | 17.0 | 22.1 | 24.3 | 1.5 | 99.9 | 52.9 | 2.0 |
| 7/30/2012 | 0.00 | 29.0 | 14.0 | 21.5 | 23.3 | 1.3 | 99.9 | 39.9 | 1.6 |
| 7/31/2012 | 0.41 | 28.0 | 18.0 | 22.2 | 20.4 | 1.6 | 87.2 | 47.6 | 1.8 |
| 8/1/2012 | 0.00 | 29.0 | 17.0 | 21.9 | 22.6 | 0.6 | 99.9 | 49.9 | 2.0 |
| 8/2/2012 | 0.00 | 31.0 | 16.0 | 22.9 | 26.0 | 0.7 | 99.0 | 40.1 | 1.8 |
| 8/3/2012 | 0.00 | 30.0 | 17.0 | 23.8 | 18.5 | 1.0 | 99.1 | 45.3 | 1.9 |
| 8/4/2012 | 1.52 | 30.0 | 21.0 | 24.3 | 19.4 | 1.7 | 85.2 | 50.0 | 2.1 |
| 8/5/2012 | 0.05 | 28.0 | 22.0 | 24.1 | 17.6 | 2.1 | 93.8 | 65.6 | 2.5 |
| 8/6/2012 | 0.00 | 31.0 | 18.0 | 22.9 | 25.6 | 1.3 | 99.9 | 50.8 | 2.3 |
| 8/7/2012 | 0.00 | 28.0 | 14.0 | 20.7 | 24.3 | 0.8 | 97.6 | 41.3 | 1.6 |
| 8/8/2012 | 0.00 | 30.0 | 15.0 | 23.0 | 25.3 | 0.9 | 96.2 | 38.7 | 1.6 |
| 8/9/2012 | 1.65 | 30.0 | 17.0 | 22.3 | 11.0 | 1.1 | 97.0 | 44.3 | 1.9 |
| 8/10/2012 | 0.23 | 25.0 | 17.7 | 19.9 | 11.2 | 1.5 | 98.6 | 63.1 | 2.0 |
| 8/11/2012 | 0.00 | 25.0 | 16.1 | 19.8 | 23.7 | 1.6 | 99.9 | 59.3 | 1.9 |
| 8/12/2012 | 0.00 | 23.0 | 14.7 | 18.6 | 16.6 | 1.4 | 99.9 | 61.2 | 1.7 |
| 8/13/2012 | 0.99 | 26.0 | 13.6 | 19.8 | 22.2 | 1.0 | 99.9 | 46.4 | 1.6 |
| 8/14/2012 | 1.91 | 26.0 | 16.8 | 19.4 | 17.9 | 1.0 | 90.0 | 51.2 | 1.7 |
| 8/15/2012 | 0.03 | 24.0 | 15.6 | 18.7 | 15.3 | 1.0 | 99.9 | 64.3 | 1.9 |
| 8/16/2012 | 0.00 | 27.0 | 13.0 | 19.5 | 23.9 | 1.3 | 99.9 | 44.9 | 1.6 |
| 8/17/2012 | 0.05 | 23.0 | 17.2 | 19.4 | 10.8 | 1.4 | 87.5 | 61.2 | 1.7 |
| 8/18/2012 | 0.03 | 24.0 | 14.0 | 18.3 | 24.0 | 1.4 | 97.6 | 52.3 | 1.6 |
| 8/19/2012 | 0.10 | 19.0 | 10.0 | 14.9 | 10.7 | 1.1 | 99.9 | 60.1 | 1.3 |
| 8/20/2012 | 0.05 | 22.0 | 13.1 | 16.8 | 13.0 | 0.7 | 90.1 | 51.4 | 1.4 |
| 8/21/2012 | 0.00 | 24.0 | 12.0 | 16.7 | 23.9 | 0.8 | 99.8 | 46.9 | 1.4 |
| 8/22/2012 | 0.00 | 25.0 | 12.8 | 18.8 | 22.1 | 0.7 | 94.8 | 44.2 | 1.4 |
| 8/23/2012 | 0.00 | 26.0 | 13.0 | 19.5 | 23.3 | 0.7 | 98.8 | 44.0 | 1.5 |
| 8/24/2012 | 0.00 | 27.0 | 14.0 | 20.4 | 21.0 | 1.0 | 92.6 | 41.5 | 1.5 |
| 8/25/2012 | 0.00 | 26.0 | 15.0 | 20.2 | 19.7 | 1.4 | 96.2 | 48.8 | 1.6 |
| 8/26/2012 | 0.38 | 25.0 | 18.0 | 20.1 | 13.8 | 2.1 | 91.1 | 59.3 | 1.9 |
| 8/27/2012 | 0.81 | 27.0 | 19.0 | 21.7 | 21.7 | 1.6 | 94.7 | 58.3 | 2.1 |
| 8/28/2012 | 0.00 | 27.0 | 17.7 | 22.2 | 21.4 | 1.9 | 99.9 | 61.7 | 2.2 |
| 8/29/2012 | 0.00 | 25.0 | 13.0 | 18.3 | 22.0 | 1.3 | 98.8 | 46.7 | 1.5 |
| 8/30/2012 | 0.00 | 26.0 | 10.0 | 18.2 | 23.7 | 0.9 | 99.9 | 36.9 | 1.2 |
| 8/31/2012 | 0.00 | 31.0 | 13.0 | 22.2 | 23.3 | 1.7 | 90.8 | 30.3 | 1.4 |
| 9/1/2012 | 0.00 | 28.0 | 20.4 | 23.7 | 17.5 | 1.6 | 66.8 | 42.3 | 1.6 |
| 9/2/2012 | 0.00 | 24.0 | 19.0 | 20.8 | 10.2 | 0.8 | 96.5 | 71.0 | 2.1 |
| 9/3/2012 | 0.15 | 24.0 | 20.7 | 21.4 | 8.4 | 1.7 | 90.0 | 73.7 | 2.2 |
| 9/4/2012 | 0.64 | 26.0 | 21.0 | 22.4 | 10.8 | 1.7 | 96.5 | 71.4 | 2.4 |
| 9/5/2012 | 0.00 | 26.0 | 18.1 | 21.4 | 17.8 | 1.2 | 99.9 | 69.0 | 2.3 |
| 9/6/2012 | 0.76 | 29.0 | 17.0 | 22.0 | 19.6 | 0.8 | 99.9 | 51.9 | 2.1 |
| 9/7/2012 | 0.04 | 29.0 | 17.0 | 21.9 | 20.7 | 1.3 | 99.1 | 47.9 | 1.9 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 9/8/2012 | 0.58 | 22.0 | 12.1 | 18.4 | 6.4 | 2.3 | 99.9 | 75.6 | 2.0 |
| 9/9/2012 | 0.13 | 22.0 | 10.0 | 14.7 | 18.9 | 1.5 | 99.9 | 49.9 | 1.3 |
| 9/10/2012 | 0.00 | 20.0 | 8.0 | 13.7 | 18.3 | 1.9 | 99.9 | 47.9 | 1.1 |
| 9/11/2012 | 0.00 | 21.0 | 6.0 | 13.2 | 20.7 | 0.8 | 98.4 | 37.0 | 0.9 |
| 9/12/2012 | 0.00 | 25.0 | 8.0 | 16.3 | 21.2 | 1.1 | 89.5 | 30.3 | 1.0 |
| 9/13/2012 | 0.00 | 26.0 | 10.0 | 18.1 | 21.0 | 1.3 | 91.2 | 33.3 | 1.1 |
| 9/14/2012 | 0.09 | 26.0 | 12.0 | 18.5 | 18.4 | 1.3 | 94.1 | 39.3 | 1.3 |
| 9/15/2012 | 0.00 | 21.0 | 10.0 | 15.3 | 19.5 | 1.9 | 97.7 | 48.3 | 1.2 |
| 9/16/2012 | 0.00 | 22.0 | 7.0 | 14.1 | 19.3 | 1.0 | 95.8 | 36.3 | 1.0 |
| 9/17/2012 | 1.36 | 23.0 | 7.0 | 15.3 | 19.6 | 1.5 | 99.8 | 35.6 | 1.0 |
| 9/18/2012 | 1.18 | 21.0 | 12.5 | 17.6 | 7.6 | 2.6 | 77.3 | 45.0 | 1.1 |
| 9/19/2012 | 0.00 | 17.0 | 6.8 | 12.0 | 19.9 | 1.6 | 99.9 | 57.8 | 1.1 |
| 9/20/2012 | 0.00 | 20.0 | 3.0 | 11.5 | 19.0 | 1.5 | 99.9 | 34.2 | 0.8 |
| 9/21/2012 | 0.06 | 22.0 | 11.8 | 16.8 | 13.0 | 1.9 | 63.7 | 33.3 | 0.9 |
| 9/22/2012 | 0.04 | 22.0 | 10.3 | 16.9 | 13.7 | 2.5 | 99.9 | 51.4 | 1.4 |
| 9/23/2012 | 0.00 | 16.0 | 7.0 | 10.6 | 14.8 | 1.7 | 99.9 | 61.6 | 1.1 |
| 9/24/2012 | 0.00 | 15.0 | 4.9 | 9.8 | 16.1 | 1.4 | 99.9 | 51.6 | 0.9 |
| 9/25/2012 | 0.42 | 17.0 | 4.0 | 11.3 | 12.6 | 1.8 | 88.5 | 37.2 | 0.7 |
| 9/26/2012 | 0.49 | 19.0 | 12.1 | 15.4 | 7.5 | 1.6 | 62.3 | 40.0 | 0.9 |
| 9/27/2012 | 2.16 | 18.0 | 14.0 | 15.8 | 8.7 | 1.2 | 99.9 | 77.5 | 1.6 |
| 9/28/2012 | 0.02 | 18.0 | 11.8 | 13.9 | 12.3 | 1.6 | 99.9 | 77.5 | 1.6 |
| 9/29/2012 | 0.06 | 16.0 | 7.0 | 11.3 | 10.1 | 1.3 | 99.9 | 57.2 | 1.0 |
| 9/30/2012 | 0.01 | 17.0 | 6.7 | 10.6 | 10.2 | 1.0 | 99.9 | 53.7 | 1.0 |
| 10/1/2012 | 0.46 | 19.0 | 5.4 | 12.0 | 17.7 | 1.2 | 98.2 | 40.0 | 0.9 |
| 10/2/2012 | 0.20 | 17.0 | 14.0 | 15.0 | 5.5 | 1.4 | 62.6 | 51.6 | 1.0 |
| 10/3/2012 | 0.00 | 25.0 | 15.5 | 18.7 | 11.8 | 0.9 | 90.9 | 50.5 | 1.6 |
| 10/4/2012 | 0.00 | 23.0 | 13.3 | 18.0 | 11.6 | 1.3 | 99.9 | 62.6 | 1.8 |
| 10/5/2012 | 0.03 | 24.0 | 11.8 | 17.0 | 15.8 | 1.5 | 89.7 | 41.6 | 1.2 |
| 10/6/2012 | 0.03 | 15.9 | 8.5 | 12.0 | 9.0 | 2.2 | 99.9 | 68.7 | 1.2 |
| 10/7/2012 | 0.10 | 10.0 | 4.3 | 7.1 | 6.1 | 1.3 | 99.9 | 74.9 | 0.9 |
| 10/8/2012 | 0.00 | 9.0 | 1.8 | 5.3 | 7.6 | 1.0 | 99.9 | 62.7 | 0.7 |
| 10/9/2012 | 0.00 | 15.0 | 5.5 | 9.5 | 14.8 | 0.7 | 88.6 | 46.9 | 0.8 |
| 10/10/2012 | 0.00 | 15.0 | 5.0 | 9.0 | 11.2 | 2.0 | 99.9 | 51.6 | 0.9 |
| 10/11/2012 | 0.00 | 13.0 | 3.0 | 7.9 | 16.3 | 1.7 | 99.9 | 53.4 | 0.8 |
| 10/12/2012 | 0.00 | 11.0 | 1.9 | 6.7 | 14.5 | 2.1 | 97.1 | 51.8 | 0.7 |
| 10/13/2012 | 0.00 | 12.0 | -3.0 | 5.4 | 15.7 | 1.6 | 98.0 | 34.2 | 0.5 |
| 10/14/2012 | 0.00 | 22.0 | 10.0 | 15.1 | 13.4 | 2.4 | 42.3 | 19.7 | 0.5 |
| 10/15/2012 | 0.00 | 17.2 | 10.0 | 14.4 | 5.6 | 2.5 | 99.9 | 65.1 | 1.3 |
| 10/16/2012 | 0.00 | 12.0 | 4.8 | 8.4 | 12.3 | 1.8 | 99.9 | 74.1 | 1.0 |
| 10/17/2012 | 0.00 | 17.0 | 1.0 | 9.0 | 14.5 | 1.1 | 97.5 | 33.0 | 0.6 |
| 10/18/2012 | 1.14 | 17.0 | 8.5 | 12.6 | 9.4 | 2.8 | 61.3 | 35.1 | 0.7 |
| 10/19/2012 | 0.00 | 15.0 | 9.0 | 10.9 | 6.6 | 1.0 | 97.6 | 65.7 | 1.1 |
| 10/20/2012 | 0.00 | 12.0 | 5.0 | 8.3 | 9.7 | 1.8 | 99.9 | 68.4 | 1.0 |
| 10/21/2012 | 0.00 | 14.0 | 4.8 | 9.6 | 12.5 | 1.9 | 99.9 | 55.0 | 0.9 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
|  | cm | | $^o$C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 10/22/2012 | 0.08 | 20.0 | 4.6 | 12.2 | 14.2 | 1.2 | 84.8 | 30.8 | 0.7 |
| 10/23/2012 | 0.00 | 22.0 | 9.5 | 14.8 | 8.8 | 0.9 | 67.4 | 30.3 | 0.8 |
| 10/24/2012 | 0.00 | 24.0 | 12.0 | 17.4 | 13.2 | 0.8 | 91.3 | 42.9 | 1.3 |
| 10/25/2012 | 0.00 | 21.0 | 11.0 | 15.7 | 8.7 | 1.5 | 97.5 | 51.5 | 1.3 |
| 10/26/2012 | 0.00 | 17.0 | 14.0 | 15.3 | 4.8 | 1.5 | 82.6 | 68.1 | 1.3 |
| 10/27/2012 | 0.03 | 15.0 | 12.8 | 14.1 | 3.7 | 1.2 | 99.9 | 93.8 | 1.6 |
| 10/28/2012 | 0.25 | 13.3 | 7.2 | 8.8 | 3.7 | 2.0 | 99.9 | 76.1 | 1.2 |
| 10/29/2012 | 5.92 | 8.7 | 7.0 | 7.4 | 2.4 | 4.3 | 99.8 | 88.8 | 1.0 |
| 10/30/2012 | 0.36 | 11.1 | 2.1 | 5.0 | 3.2 | 2.8 | 99.9 | 69.6 | 0.9 |
| 10/31/2012 | 0.08 | 4.5 | 1.0 | 3.0 | 3.6 | 1.9 | 99.9 | 80.7 | 0.7 |
| 11/1/2012 | 0.00 | 6.0 | 3.8 | 4.9 | 5.1 | 2.3 | 89.9 | 77.0 | 0.7 |
| 11/2/2012 | 0.08 | 6.0 | 2.0 | 3.8 | 7.1 | 2.5 | 99.9 | 81.3 | 0.8 |
| 11/3/2012 | 0.00 | 5.0 | 1.9 | 3.1 | 5.9 | 2.5 | 97.1 | 78.0 | 0.7 |
| 11/4/2012 | 0.00 | 3.5 | 1.2 | 2.6 | 6.3 | 1.5 | 99.9 | 91.7 | 0.7 |
| 11/5/2012 | 0.00 | 4.0 | 0.0 | 1.4 | 9.0 | 1.6 | 99.9 | 78.7 | 0.6 |
| 11/6/2012 | 0.00 | 4.0 | -3.0 | 0.5 | 11.0 | 1.0 | 99.9 | 68.9 | 0.6 |
| 11/7/2012 | 0.00 | 5.0 | -4.0 | 0.3 | 7.8 | 1.7 | 96.9 | 50.4 | 0.4 |
| 11/8/2012 | 0.00 | 8.0 | -1.0 | 2.8 | 12.0 | 2.8 | 84.5 | 44.7 | 0.5 |
| 11/9/2012 | 0.00 | 11.0 | 0.0 | 5.4 | 11.1 | 1.7 | 91.7 | 42.7 | 0.6 |
| 11/10/2012 | 0.00 | 12.0 | 2.0 | 6.5 | 7.2 | 1.0 | 85.0 | 42.8 | 0.6 |
| 11/11/2012 | 0.00 | 18.0 | 2.0 | 9.8 | 11.2 | 1.5 | 90.7 | 31.0 | 0.6 |
| 11/12/2012 | 0.53 | 17.1 | 5.9 | 13.6 | 4.8 | 2.8 | 73.3 | 34.8 | 0.7 |
| 11/13/2012 | 0.00 | 5.2 | 0.0 | 2.4 | 10.4 | 2.3 | 99.9 | 72.2 | 0.6 |
| 11/14/2012 | 0.00 | 5.0 | -0.8 | 1.3 | 11.1 | 1.3 | 99.9 | 68.8 | 0.6 |
| 11/15/2012 | 0.00 | 6.0 | -3.0 | 0.8 | 8.6 | 0.6 | 98.0 | 51.3 | 0.5 |
| 11/16/2012 | 0.00 | 8.0 | -3.0 | 2.1 | 10.8 | 1.2 | 98.0 | 44.7 | 0.5 |
| 11/17/2012 | 0.00 | 10.0 | -4.0 | 2.6 | 10.8 | 1.1 | 96.9 | 35.8 | 0.4 |
| 11/18/2012 | 0.00 | 9.0 | -3.0 | 2.1 | 10.6 | 1.0 | 89.9 | 38.3 | 0.4 |
| 11/19/2012 | 0.00 | 7.0 | -3.0 | 1.4 | 9.0 | 0.7 | 89.9 | 43.9 | 0.4 |
| 11/20/2012 | 0.00 | 8.0 | -2.0 | 2.7 | 7.2 | 0.3 | 98.6 | 48.5 | 0.5 |
| 11/21/2012 | 0.00 | 11.0 | -3.0 | 3.7 | 10.1 | 0.6 | 98.0 | 36.6 | 0.5 |
| 11/22/2012 | 0.00 | 14.0 | -3.0 | 5.0 | 10.1 | 0.7 | 89.9 | 27.5 | 0.4 |
| 11/23/2012 | 0.02 | 12.0 | 0.0 | 5.3 | 6.4 | 2.0 | 78.6 | 34.2 | 0.5 |
| 11/24/2012 | 0.01 | 2.0 | -1.0 | 0.0 | 5.3 | 3.3 | 91.6 | 73.7 | 0.5 |
| 11/25/2012 | 0.01 | 2.0 | -2.0 | -0.6 | 5.7 | 1.9 | 99.9 | 79.4 | 0.6 |
| 11/26/2012 | 0.06 | 6.0 | -0.5 | 2.1 | 9.1 | 1.3 | 81.5 | 51.3 | 0.5 |
| 11/27/2012 | 0.11 | 2.0 | -1.0 | 0.3 | 3.5 | 1.0 | 91.6 | 73.7 | 0.5 |
| 11/28/2012 | 0.00 | 4.0 | -2.0 | 0.4 | 7.9 | 1.6 | 91.0 | 59.0 | 0.5 |
| 11/29/2012 | 0.00 | 7.0 | -3.0 | 1.2 | 8.6 | 1.3 | 98.0 | 47.9 | 0.5 |
| 11/30/2012 | 0.00 | 7.0 | -4.2 | 1.5 | 7.4 | 1.0 | 98.5 | 43.9 | 0.4 |
| 12/1/2012 | 0.00 | 6.0 | 0.0 | 2.9 | 5.3 | 1.1 | 78.6 | 51.3 | 0.5 |
| 12/2/2012 | 0.10 | 10.5 | 2.1 | 5.9 | 6.3 | 1.8 | 84.4 | 47.3 | 0.6 |
| 12/3/2012 | 0.05 | 16.0 | 10.0 | 12.5 | 6.8 | 1.0 | 65.1 | 44.0 | 0.8 |
| 12/4/2012 | 0.10 | 20.0 | 9.2 | 14.6 | 8.6 | 1.9 | 89.2 | 44.5 | 1.0 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 $^o$ 49 ' 44.4 " N and longitude 77 $^o$ 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 $^o$ 49 ' 44.4 " N and longitude 77 $^o$ 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix B Daily rainfall and weather data in 2011 and 2012 (Continued)**

| Day of year | Rain fall[1] | Max. temp.[2] | Min. temp.[2] | Mean temp.[2] | Solar radiation[3] | Wind speed[3] at 2 m height | Max. RH[4] | Min. RH[4] | Vapor pressure[5] |
|---|---|---|---|---|---|---|---|---|---|
| | cm | | °C | | MJ m$^{-2}$ | m s$^{-1}$ | | % | kPa |
| 12/5/2012 | 0.03 | 8.9 | -1.7 | 3.8 | 6.7 | 2.8 | 99.9 | 73.7 | 0.8 |
| 12/6/2012 | 0.08 | 3.0 | -5.0 | -0.9 | 9.3 | 1.4 | 95.0 | 52.8 | 0.4 |
| 12/7/2012 | 0.66 | 2.1 | 0.0 | 1.2 | 2.0 | 1.5 | 72.0 | 61.9 | 0.4 |
| 12/8/2012 | 0.03 | 12.0 | 1.6 | 7.1 | 5.8 | 1.3 | 93.3 | 45.6 | 0.6 |
| 12/9/2012 | 0.51 | 8.7 | 2.0 | 3.9 | 2.1 | 1.9 | 99.9 | 63.9 | 0.7 |
| 12/10/2012 | 0.69 | 11.0 | 3.9 | 7.6 | 2.0 | 2.4 | 89.2 | 54.8 | 0.7 |
| 12/11/2012 | 0.00 | 3.6 | 0.0 | 2.0 | 5.6 | 1.9 | 99.9 | 91.0 | 0.7 |
| 12/12/2012 | 0.03 | 5.0 | -3.5 | 0.9 | 8.8 | 1.0 | 99.9 | 64.2 | 0.6 |
| 12/13/2012 | 0.00 | 5.0 | -7.0 | -1.3 | 9.0 | 0.7 | 99.6 | 41.3 | 0.4 |
| 12/14/2012 | 0.00 | 9.0 | -5.0 | 1.5 | 8.9 | 1.3 | 85.5 | 31.4 | 0.4 |
| 12/15/2012 | 0.03 | 6.0 | -3.0 | 1.8 | 7.1 | 1.5 | 81.7 | 42.8 | 0.4 |
| 12/16/2012 | 0.00 | 7.0 | 4.0 | 5.5 | 3.5 | 1.9 | 59.0 | 47.9 | 0.5 |
| 12/17/2012 | 1.30 | 10.0 | 5.5 | 6.6 | 4.2 | 1.5 | 93.0 | 68.4 | 0.8 |
| 12/18/2012 | 0.03 | 7.0 | 1.5 | 4.3 | 4.0 | 2.7 | 99.9 | 87.8 | 0.9 |
| 12/19/2012 | 0.00 | 5.0 | 0.0 | 2.6 | 4.7 | 1.9 | 99.9 | 73.4 | 0.6 |
| 12/20/2012 | 2.57 | 4.1 | -2.0 | 1.0 | 3.8 | 2.5 | 98.6 | 63.4 | 0.5 |
| 12/21/2012 | 0.00 | 4.7 | -1.0 | 0.7 | 2.7 | 3.4 | 98.6 | 65.5 | 0.6 |
| 12/22/2012 | 0.03 | 0.0 | -2.0 | -0.7 | 5.2 | 4.2 | 99.9 | 91.7 | 0.6 |
| 12/23/2012 | 0.00 | 5.0 | -5.0 | -0.5 | 8.8 | 1.9 | 99.9 | 50.4 | 0.4 |
| 12/24/2012 | 0.00 | 2.0 | -6.0 | -2.0 | 5.8 | 1.4 | 92.2 | 51.0 | 0.4 |
| 12/25/2012 | 0.31 | 1.0 | -2.5 | -0.1 | 3.5 | 1.6 | 78.7 | 60.9 | 0.4 |
| 12/26/2012 | 0.00 | -2.5 | -5.0 | -3.7 | 1.5 | 2.6 | 99.9 | 94.4 | 0.5 |
| 12/27/2012 | 0.00 | -1.0 | -3.0 | -2.1 | 3.2 | 3.5 | 89.9 | 77.5 | 0.4 |
| 12/28/2012 | 0.00 | -1.0 | -6.4 | -2.5 | 5.5 | 1.3 | 99.9 | 84.5 | 0.5 |
| 12/29/2012 | 0.03 | -1.0 | -6.7 | -3.0 | 2.3 | 2.1 | 99.9 | 70.5 | 0.4 |
| 12/30/2012 | 0.02 | -1.0 | -5.0 | -2.4 | 4.0 | 3.4 | 99.9 | 77.5 | 0.4 |
| 12/31/2012 | 0.01 | 3.0 | -6.0 | -1.4 | 5.6 | 2.3 | 99.9 | 0.0 | 0.4 |

[1]Equations 3-1 and 3.2 (see chapter 3, section 3.8)

[2]Available at http://climate.psu.edu/data/ida/index.php?t=3&x=faa_daily&id=KUNV, for AWOS III weather station (see chapter 3, Figure 3-7)

[3]Available at http://power.larc.nasa.gov, for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W. Multiplied wind speed at 10 m by 0.748 to obtain wind speed at 2 m (Allen et al., 1998)

[4]99.9% was used for all values that were > 100%

[5]Available at http://Daymet.ornl.gov/ for latitude 40 ° 49 ' 44.4 " N and longitude 77 ° 52 ' 12 " W and used to compute maximum and minimum relative humidity.

**Appendix C: Assembly of the C and L-type passive diffusion samplers (PDS).**

**a, b and c are top, middle and bottom PDS assembly parts, respectively.**



L-type PDS

C-type PDS

Acidified filter paper (8-µm pore, 2.4 cm dia.)

Acidified filter paper

Rubber band

Assembled PDSs

Membrane filter (1.0-µm pore and 2.5 cm dia.)

**Appendix D: Rainfall and weather data during field ammonia measurement.**

| Date | Solar Radiation | Maximum air temperature | Minimum air temperature | Rainfall | Mean relative humidity | Est. surface soil temperature |
|---|---|---|---|---|---|---|
| | MJ m$^{-2}$ | $^o$C | $^o$C | cm | % | $^o$C |
| | From Appendix B | | | | Using Eq. [3-4] in chapter 3. | Mean for Eq. [4-9] and Eq. [4-10] in chapter 4 |
| 22 April 2011[1] | 6.4 | 5.0 | 1.0 | 0.51 | 72.1 | 4.5 |
| 23 | 12.9 | 21.0 | 4.0 | 0.03 | 83.4 | 17.2 |
| 24 | 11.4 | 21.0 | 14.0 | 0.00 | 77.6 | 22.0 |
| 25 | 24.1 | 27.0 | 12.0 | 0.23 | 72.2 | 26.6 |
| 26 | 21.1 | 27.0 | 13.0 | 0.76 | 80.6 | 26.7 |
| 27 | 16.2 | 26.0 | 13.0 | 2.01 | 79.8 | 25.4 |
| 28 | 20.8 | 22.0 | 11.0 | 0.00 | 58.9 | 22.6 |
| 29 | 12.4 | 12.0 | 5.0 | 0.03 | 67.4 | 12.1 |
| 5 August 2011[1] | 15.5 | 26.0 | 18.0 | 0.25 | 83.4 | 25.3 |
| 6 | 6.6 | 24.0 | 20.0 | 0.20 | 91.3 | 24.1 |
| 7 | 16.4 | 29.0 | 20.0 | 0.05 | 84.4 | 28.1 |
| 8 | 20.1 | 29.0 | 20.0 | 0.05 | 75.6 | 28.4 |
| 9 | 17.6 | 27.0 | 18.0 | 0.15 | 83.4 | 26.1 |
| 10 | 22.2 | 26.0 | 18.0 | 0.15 | 63.1 | 25.9 |
| 11 | 22.8 | 25.0 | 13.0 | 0.08 | 57.0 | 22.9 |
| 12 | 25.5 | 26.0 | 11.0 | 0.05 | 63.2 | 22.6 |
| 6 April 2012[1] | 24.1 | 14.0 | -1.0 | 0.00 | 35.6 | 9.2 |
| 7 | 24.2 | 16.0 | 2.0 | 0.00 | 29.7 | 11.8 |
| 8 | 22.6 | 17.0 | 3.0 | 0.00 | 35.0 | 12.7 |
| 9 | 17.8 | 12.0 | 6.0 | 0.00 | 40.6 | 11.1 |
| 10 | 13.2 | 9.0 | 2.0 | 0.00 | 61.5 | 7.1 |
| 11 | 15.7 | 6.0 | 1.0 | 0.05 | 71.9 | 5.1 |
| 12 | 15.3 | 11.0 | 2.0 | 0.00 | 54.5 | 8.4 |
| 13 | 24.8 | 16.0 | -1.0 | 0.00 | 45.4 | 10.3 |

[1]Urea Ammonium Nitrate (UAN) (30%N) fertilizer application dates.

# Appendix E: Ammonia flux calculations in April 2011

| Day after UAN-30 application | Chamber no. | Tc | Tk | D (x 10⁻⁵) | t exp, ch | t exp,a | C C, ch | C L,ch | C C,a | C L,a | Mean Ka | L lbl,ch,real | K ch,real | C ch,real | L lbl,a* | Ka* | Ca* | Mean Ca | C eq,ch | NH₃-N flux |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | °C | K | m²/s | min | min | mg/L | mg/L | mg/L | mg/L | m/s | m | m/s | µg/m³ | m | m/s | µg/m³ | µg/m³ | µg/m³ | Kg/ha/h |
| | | | | Eq. [4-8] | | | | | | | | Eq. [4-7] | Eq. [4-6] | Eq. [4-5] | Eq. [4-7] | Eq. [4-6] | Eq. [4-5] | | Eq. [4-4] | Eq. [4-1] |
| 1 | 1 | 17.2 | 290.4 | 2.3 | 1490 | 1490 | 6.7 | 16.1 | 0.5 | 1.8 | 0.006 | 0.007 | 0.003 | 3138.4 | 0.004 | 0.006 | 176.4 | 176.4 | 4052.2 | 0.85 |
| | 2 | 17.2 | 290.4 | 2.3 | 1490 | 1490 | 8.0 | 24.5 | | | 0.006 | 0.005 | 0.005 | 3282.1 | | | | 176.4 | 3939.9 | 0.83 |
| | 3 | 17.2 | 290.4 | 2.3 | 1490 | 1490 | 7.9 | 19.5 | | | 0.006 | 0.007 | 0.003 | 3622.5 | | | | 176.4 | 4636.4 | 0.98 |
| 2 | 1 | 22.0 | 295.1 | 2.3 | 1440 | 1440 | 2.0 | 13.9 | 0.2 | 0.6 | 0.006 | 0.002 | 0.014 | 645.0 | 0.004 | 0.006 | 59.7 | 59.7 | 686.5 | 0.13 |
| | 2 | 22.0 | 295.1 | 2.3 | 1440 | 1440 | 1.0 | 5.8 | | | 0.006 | 0.002 | 0.011 | 331.1 | | | | 59.7 | 355.0 | 0.06 |
| | 3 | 22.0 | 295.1 | 2.3 | 1440 | 1440 | 1.6 | 7.5 | | | 0.006 | 0.003 | 0.009 | 532.2 | | | | 59.7 | 584.0 | 0.11 |
| 3 | 1 | 26.6 | 299.8 | 2.4 | 1440 | 1440 | 0.6 | 4.2 | 0.1 | 0.2 | 0.011 | 0.001 | 0.017 | 155.3 | 0.002 | 0.012 | 7.0 | 10.6 | 163.6 | 0.06 |
| | 2 | 26.6 | 299.8 | 2.4 | 1440 | 1440 | 0.6 | 2.8 | 0.1 | 0.3 | 0.011 | 0.002 | 0.011 | 164.4 | 0.002 | 0.010 | 14.1 | 10.6 | 178.5 | 0.06 |
| | 3 | 26.6 | 299.8 | 2.4 | 1440 | 1440 | 0.3 | 1.9 | | | 0.011 | 0.001 | 0.017 | 69.3 | | | | 10.6 | 72.7 | 0.02 |
| 4 | 1 | 26.7 | 299.9 | 2.4 | 1440 | 1440 | 0.2 | 1.0 | 0.1 | 0.3 | 0.010 | 0.002 | 0.010 | 59.7 | 0.002 | 0.014 | 10.0 | 16.9 | 63.8 | 0.02 |
| | 2 | 26.7 | 299.9 | 2.4 | 1440 | 1440 | 0.4 | 1.7 | 0.1 | 0.3 | 0.010 | 0.002 | 0.010 | 106.3 | 0.003 | 0.008 | 23.8 | 16.9 | 115.3 | 0.04 |
| | 3 | 26.7 | 299.9 | 2.4 | 1440 | 1440 | 0.2 | 1.0 | | | 0.010 | 0.002 | 0.011 | 57.0 | | | | 16.9 | 60.6 | 0.02 |
| 5 | 1 | 25.4 | 298.5 | 2.4 | 1465 | 1465 | 0.1 | 0.2 | 0.1 | 0.1 | 0.001 | 0.001 | 0.016 | 6.6 | 0.004 | 0.006 | 8.0 | 44.7 | 4.3 | 0.00 |
| | 2 | 25.4 | 298.5 | 2.4 | 1465 | 1465 | 0.2 | 0.5 | 0.1 | 0.1 | 0.001 | 0.003 | 0.009 | 31.1 | 0.073 | 0.000 | 81.3 | 44.7 | 29.7 | 0.00 |
| | 3 | 25.4 | 298.5 | 2.4 | 1465 | 1465 | 0.1 | 0.3 | | | 0.001 | 0.004 | 0.007 | 26.3 | | | | 44.7 | 23.5 | 0.00 |
| 6 | 1 | 22.6 | 295.8 | 2.3 | 1410 | 1410 | 0.1 | 0.1 | 0.1 | 0.1 | 0.003 | 0.004 | 0.007 | 8.2 | 0.011 | 0.002 | 12.6 | 11.2 | 7.8 | 0.00 |
| | 2 | 22.6 | 295.8 | 2.3 | 1410 | 1410 | 0.1 | 0.3 | 0.1 | 0.1 | 0.003 | 0.002 | 0.013 | 12.2 | 0.006 | 0.004 | 9.8 | 11.2 | 12.3 | 0.00 |
| | 3 | 22.6 | 295.8 | 2.3 | 1410 | 1410 | 0.1 | 0.3 | | | 0.003 | 0.001 | 0.019 | 6.8 | | | | 11.2 | 6.6 | 0.00 |
| 7 | 1 | 12.1 | 285.3 | 2.2 | 1410 | 1410 | 0.1 | 0.1 | 0.1 | 0.1 | 0.002 | 0.011 | 0.002 | 13.3 | 0.011 | 0.002 | 13.3 | 13.3 | 13.3 | 0.00 |
| | 2 | 12.1 | 285.3 | 2.2 | 1410 | 1410 | 0.1 | 0.2 | 0.1 | 0.1 | 0.002 | 0.002 | 0.010 | 7.8 | 0.011 | 0.002 | 13.3 | 13.3 | 7.3 | 0.00 |
| | 3 | 12.1 | 285.3 | 2.2 | 1410 | 1410 | 0.1 | 0.1 | | | 0.002 | 0.005 | 0.004 | 9.8 | | | | 13.3 | 9.0 | 0.00 |

*Blanks (Calculations returned errors)

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## Appendix F: Ammonia flux calculations in August 2011.

| Day after UAN application | Chamber no. | Tc | Tk | D (x 10-5) | t exp, ch | t exp,a | C C, ch | C L, ch | C C,a | C L,a | Mean Ka | L lbl,ch, real | K ch, real | C ch, eal | L lbl,a* | Ka* | Ca* | Mean Ca | C eq,ch | NH$_3$-N flux |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | °C | K | m²/s | min | min | mg/L | mg/L | mg/L | mg/L | m/s | m | m/s | µg/m³ | m | m/s | µg/m³ | µg/m³ | µg/m³ | Kg/ha/h |
| | | Eq. [4-8] | | | | | | | | | | Eq. [4-7] | Eq. [4-6] | Eq. [4-5] | Eq. [4-7] | Eq. [4-6] | Eq. [4-5] | | Eq. [4-4] | Eq. [4-1] |
| 1 | 1 | 24.1 | 297.3 | 2.4 | 1480 | 1480 | 3.1 | 14.3 | 1.4 | 3.5 | 0.004 | 0.003 | 0.009 | 1037.4 | 0.007 | 0.004 | 604.8 | 604.8 | 1087.2 | 0.06 |
| | 2 | 24.1 | 297.3 | 2.4 | 1480 | 1480 | 6.2 | 25.2 | | | 0.004 | 0.003 | 0.007 | 2197.8 | | | | 604.8 | 2416.5 | 0.24 |
| | 3 | 24.1 | 297.3 | 2.4 | 1480 | 1480 | 5.0 | 20.7 | | | 0.004 | 0.003 | 0.008 | 1740.6 | | | | 604.8 | 1891.5 | 0.17 |
| 2 | 1 | 28.1 | 301.2 | 2.4 | 1435 | 1435 | 1.4 | 3.2 | 0.5 | 1.0 | 0.003 | 0.008 | 0.003 | 652.6 | 0.009 | 0.003 | 212.7 | 212.7 | 794.4 | 0.06 |
| | 2 | 28.1 | 301.2 | 2.4 | 1435 | 1435 | 4.4 | 9.3 | | | 0.003 | 0.009 | 0.003 | 2189.5 | | | | 212.7 | 2902.2 | 0.26 |
| | 3 | 28.1 | 301.2 | 2.4 | 1435 | 1435 | 4.2 | 9.4 | | | 0.003 | 0.008 | 0.003 | 1998.0 | | | | 212.7 | 2583.4 | 0.23 |
| 3 | 1 | 28.4 | 301.6 | 2.4 | 1450 | 1450 | 0.8 | 2.5 | 0.2 | 3.2 | 0.005 | 0.004 | 0.006 | 256.0 | 0.000 | 0.061 | 33.4 | 170.3 | 270.3 | 0.02 |
| | 2 | 28.4 | 301.6 | 2.4 | 1450 | 1450 | 1.9 | 5.8 | 0.7 | 1.4 | 0.005 | 0.005 | 0.005 | 721.2 | 0.008 | 0.003 | 307.3 | 170.3 | 827.8 | 0.13 |
| | 3 | 28.4 | 301.6 | 2.4 | 1450 | 1450 | 1.7 | 5.7 | | | 0.005 | 0.004 | 0.006 | 595.4 | | | | 170.3 | 664.3 | 0.10 |
| 4 | 1 | 26.1 | 299.2 | 2.4 | 1439 | 1439 | 0.4 | 1.6 | 0.2 | 0.3 | 0.002 | 0.003 | 0.009 | 105.4 | 0.010 | 0.002 | 55.7 | 184.5 | 96.8 | -0.01 |
| | 2 | 26.1 | 299.2 | 2.4 | 1439 | 1439 | 0.7 | 5.5 | 0.5 | 0.9 | 0.002 | 0.001 | 0.019 | 190.9 | 0.015 | 0.002 | 313.3 | 184.5 | 191.2 | 0.00 |
| | 3 | 26.1 | 299.2 | 2.4 | 1439 | 1439 | 0.7 | 4.9 | | | 0.002 | 0.001 | 0.017 | 185.2 | | | | 184.5 | 185.3 | 0.00 |
| 5 | 1 | 25.9 | 299.0 | 2.4 | 1424 | 1424 | 0.2 | 0.8 | 0.1 | 0.2 | 0.004 | 0.001 | 0.017 | 26.4 | 0.008 | 0.003 | 22.8 | 48.8 | 25.2 | 0.00 |
| | 2 | 25.9 | 299.0 | 2.4 | 1424 | 1424 | 0.4 | 2.8 | 0.3 | 1.0 | 0.004 | 0.001 | 0.017 | 106.7 | 0.003 | 0.008 | 74.7 | 48.8 | 110.2 | 0.01 |
| | 3 | 25.9 | 299.0 | 2.4 | 1424 | 1424 | 0.4 | 2.9 | | | 0.004 | 0.001 | 0.018 | 101.4 | | | | 48.8 | 104.3 | 0.01 |
| 6 | 1 | 22.9 | 296.0 | 2.3 | 1440 | 1440 | 0.2 | 0.6 | 0.1 | 0.2 | 0.012 | 0.002 | 0.015 | 22.7 | 0.002 | 0.013 | 5.2 | 20.6 | 22.8 | 0.00 |
| | 2 | 22.9 | 296.0 | 2.3 | 1440 | 1440 | 0.3 | 1.4 | 0.2 | 0.7 | 0.012 | 0.002 | 0.013 | 65.5 | 0.002 | 0.010 | 36.0 | 20.6 | 68.9 | 0.02 |
| | 3 | 22.9 | 296.0 | 2.3 | 1440 | 1440 | 0.3 | 1.7 | | | 0.012 | 0.001 | 0.020 | 53.4 | | | | 20.6 | 55.0 | 0.01 |
| 7 | 1 | 22.6 | 295.8 | 2.3 | 1442 | 1442 | 0.2 | 0.5 | 0.2 | 0.4 | 0.004 | 0.002 | 0.014 | 20.6 | 0.003 | 0.008 | 24.1 | 24.1 | 20.4 | 0.00 |
| | 2 | 22.6 | 295.8 | 2.3 | 1442 | 1442 | 0.3 | 1.2 | 0.3 | 0.6 | 0.004 | 0.002 | 0.012 | 62.4 | 0.008 | 0.003 | | 24.1 | 65.8 | 0.01 |
| | 3 | 22.6 | 295.8 | 2.3 | 1442 | 1442 | 0.2 | 1.1 | | | 0.004 | 0.001 | 0.016 | 40.2 | | | | 24.1 | 41.2 | 0.00 |

*Blanks (Calculations returned errors)

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# Appendix G: Ammonia flux calculations in April 2012.

| Day after UAN application | Chamber no. | Tc | Tk | D (x 10⁻⁵) | t exp, ch | t exp,a | C C,ch | C L,ch | C C,a | C L,a | Mean Ka | L lbl,ch,real | K ch, real | C ch, real | L lbl, a* | Ka* | Ca* | Mean Ca | C eq,ch | NH₃-N flux |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | °C | K | m²/s | min | min | mg/L | mg/L | mg/L | mg/L | m/s | m | m/s | µg/m³ | m | m/s | µg/m³ | µg/m³ | µg/m³ | Kg/ha/h |
| | | | | Eq. [4-8] | | | | | | | Eq. [4-7] | Eq. [4-6] | Eq. [4-5] | Eq. [4-7] | Eq. [4-6] | Eq. [4-5] | | Eq. [4-4] | Eq. [4-1] |
| 1 | 1 | 11.8 | 284.9 | 2.2 | 1444 | 1444 | 0.6 | 3.9 | 0.2 | 0.6 | 0.004 | 0.002 | 0.014 | 179.0 | 0.004 | 0.005 | 64.0 | 99.7 | 184.7 | 0.01 |
| | 2 | 11.8 | 284.9 | 2.2 | 1444 | 1444 | 0.7 | 5.6 | 0.3 | 0.8 | 0.004 | 0.001 | 0.018 | 205.0 | 0.006 | 0.003 | 135.4 | 99.7 | 211.0 | 0.02 |
| | 3 | 11.8 | 284.9 | 2.2 | 1444 | 1444 | 0.6 | 4.9 | | | 0.004 | 0.001 | 0.017 | 181.7 | | | | 99.7 | 186.4 | 0.01 |
| 2 | 1 | 12.7 | 285.9 | 2.2 | 1428 | 1428 | 0.3 | 2.1 | 0.1 | 0.4 | 0.008 | 0.001 | 0.015 | 88.8 | 0.003 | 0.008 | 26.5 | 34.3 | 92.3 | 0.02 |
| | 2 | 12.7 | 285.9 | 2.2 | 1428 | 1428 | 0.2 | 1.1 | 0.2 | 0.6 | 0.008 | 0.001 | 0.020 | 32.8 | 0.003 | 0.008 | 42.1 | 34.3 | 32.7 | 0.00 |
| | 3 | 12.7 | 285.9 | 2.2 | 1428 | 1428 | 0.3 | 2.1 | | | 0.008 | 0.001 | 0.017 | 81.0 | | | | 34.3 | 83.7 | 0.01 |
| 3 | 1 | 11.1 | 284.3 | 2.2 | 1440 | 1440 | 0.2 | 1.4 | 0.1 | 0.3 | 0.006 | 0.001 | 0.016 | 53.1 | 0.002 | 0.010 | 14.7 | 28.5 | 54.6 | 0.01 |
| | 2 | 11.1 | 284.3 | 2.2 | 1440 | 1440 | 0.1 | 0.5 | 0.2 | 0.4 | 0.006 | 0.002 | 0.013 | 23.0 | 0.005 | 0.005 | 42.2 | 28.5 | 22.6 | 0.00 |
| | 3 | 11.1 | 284.3 | 2.2 | 1440 | 1440 | 0.2 | 1.8 | | | 0.006 | 0.001 | 0.018 | 62.8 | | | | 28.5 | 64.7 | 0.01 |
| 4 | 1 | 7.1 | 280.2 | 2.2 | 1443 | 1443 | 0.2 | 0.9 | 0.1 | 0.4 | 0.005 | 0.002 | 0.011 | 50.3 | 0.004 | 0.005 | 38.5 | 45.6 | 50.8 | 0.00 |
| | 2 | 7.1 | 280.2 | 2.2 | 1443 | 1443 | 0.3 | 1.7 | 0.2 | 0.4 | 0.005 | 0.001 | 0.014 | 75.4 | 0.005 | 0.004 | 52.7 | 45.6 | 77.4 | 0.01 |
| | 3 | 7.1 | 280.2 | 2.2 | 1443 | 1443 | 0.3 | 1.6 | | | 0.005 | 0.001 | 0.014 | 70.7 | | | | 45.6 | 72.4 | 0.00 |
| 5 | 1 | 5.1 | 278.3 | 2.1 | 1456 | 1456 | 0.2 | 0.6 | 0.1 | 0.1 | 0.011 | 0.002 | 0.009 | 42.7 | 0.003 | 0.008 | 4.7 | 4.4 | 47.1 | 0.02 |
| | 2 | 5.1 | 278.3 | 2.1 | 1456 | 1456 | 0.2 | 1.2 | 0.1 | 0.2 | 0.011 | 0.002 | 0.013 | 55.6 | 0.001 | 0.017 | 4.2 | 4.4 | 59.6 | 0.02 |
| | 3 | 5.1 | 278.3 | 2.1 | 1456 | 1456 | 0.2 | 1.5 | | | 0.011 | 0.001 | 0.017 | 54.4 | | | | 4.4 | 57.5 | 0.02 |
| 6 | 1 | 8.4 | 281.5 | 2.2 | 1434 | 1434 | 0.1 | 0.6 | 0.1 | 0.1 | 0.008 | 0.002 | 0.013 | 29.0 | 0.004 | 0.006 | 5.1 | 4.7 | 30.9 | 0.01 |
| | 2 | 8.4 | 281.5 | 2.2 | 1434 | 1434 | 0.1 | 0.8 | 0.1 | 0.2 | 0.008 | 0.001 | 0.018 | 28.2 | 0.001 | 0.016 | 4.2 | 4.7 | 29.5 | 0.01 |
| | 3 | 8.4 | 281.5 | 2.2 | 1434 | 1434 | 0.1 | 0.9 | | | 0.008 | 0.001 | 0.031 | 18.7 | | | | 4.7 | 19.2 | 0.00 |
| 7 | 1 | 10.3 | 283.5 | 2.2 | 1422 | 1422 | 0.1 | 0.5 | 0.1 | 0.1 | 0.006 | 0.002 | 0.014 | 19.1 | 0.006 | 0.004 | 5.9 | 5.1 | 20.1 | 0.00 |
| | 2 | 10.3 | 283.5 | 2.2 | 1422 | 1422 | 0.1 | 0.5 | 0.1 | 0.1 | 0.006 | 0.000 | 0.071 | 3.8 | 0.002 | 0.014 | 4.3 | 5.1 | 3.8 | 0.00 |
| | 3 | 10.3 | 283.5 | 2.2 | 1422 | 1422 | 0.1 | 0.6 | | | 0.006 | 0.001 | 0.043 | 8.5 | | | | 5.1 | 8.6 | 0.00 |

*Blanks (Calculations returned errors)

**Appendix H: Normality test p-values, denitrification fluxes, rainfall, WFPS, soil mineral N, and MWE N on sampling dates in 2011 and 2012.**

| Sampling Date[1] | Anderson-Darling p-values for the normality test | Denitrification flux (x $10^{-2}$) Mean (n=8) | Min. | Max. | Coefficient of variation (CV) | Rain fall | Water-filled pore space (WFPS) | Soil $NO_3$-N[2] | Soil $NH_4$-N[2] | Soil temp. | MWE-(TN/$NO_3$-N) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg N ha$^{-1}$ h$^{-1}$ | | | % | cm | % | kg N ha$^{-1}$ | | (°C) | kg N ha$^{-1}$ |
| 16 May 2011 (BI) | 0.455 | 0.18[3] | 0.07 | 0.28 | 53.83 | 0.00 | 87.21 | | | 11.75 | 6.63[4]/4.47 |
| 17 May 2011 (AI) | 0.138 | 0.11 | -0.01 | 0.30 | 105.01 | 0.76 | 96.67 | | | 11.75 | |
| 27 May 2011 | 0.007 | 2.46 | -0.05 | 11.19 | 155.88 | 1.22 | 86.38 | 24.09 (42.63) | | 14.71 | |
| 14 May 2012 (BI) | 0.056 | 0.19 | -0.16 | 0.75 | 169.10 | 4.83 | 88.06 | 14.79 (26.18) | 8.35 (14.78) | 13.60 | 3.42[4]/2.98 |
| 15 May 2012 (AI) | 0.466 | 0.10 | -0.33 | 0.56 | 264.45 | 0.05 | 81.44 | 15.78 (27.93) | 7.98 (14.13) | 14.41 | |
| 18 May 2012 | <0.005 | 0.12 | 0.00 | 0.50 | 144.22 | 0.00 | 81.75 | 7.46 (13.2) | 8.35 (15.08) | 13.76 | |
| 21 May 2012 (BI) | <0.005 | 0.02 | -0.03 | 0.15 | 359.07 | 1.93 | 67.22 | 22.01 (38.95) | 9.19 (16.28) | 15.41 | 6.59[4]/5.46 |
| 22 May 2012 (AI) | 0.219 | 0.35 | -0.03 | 0.99 | 90.31 | 0.36 | 90.96 | 24.92 (44.10) | 8.63 (14.63) | 15.61 | |
| 25 May 2012 | 0.197 | 0.23 | 0.01 | 0.62 | 85.12 | 0.00 | 81.16 | 19.75 (34.95) | 8.21 (14.56) | 17.10 | |
| 2 June 2011 (AI) | 0.043 | 1.63 | 0.07 | 5.47 | 105.03 | 0.03 | 85.95 | | | 16.50 | |
| 6 June 2011 (BI) | 0.047 | 1.10 | 0.19 | 2.75 | 91.52 | 0.03 | 73.54 | | | 14.75 | 3.96[4]/2.80 |
| 7 June 2011 (AI) | 0.008 | 0.24[3] | 0.11 | 0.63 | 105.55 | 0.35 | 68.05 | | | 15.00 | |
| 27 June 2011 (BI) | <0.005 | 0.05 | 0.00 | 0.22 | 150.13 | 0.04 | 63.52 | | | 16.38 | 4.32[4]/6.97 |
| 28 June 2011 (AI) | 0.032 | 0.83 | 0.16 | 2.66 | 104.30 | 0.46 | 88.97 | 14.69 (26.00) | 6.16 (10.90) | 17.38 | |
| 21 June 2012 (BI) | 0.849 | 0.04 | 0.01 | 0.07 | 55.25 | 0.00 | 65.24 | 24.40 (39.80) | 9.22 (16.3) | 22.31 | 1.90[4]/1.77 |
| 22 June 2012 (AI) | 0.007 | 1.99 | -0.24 | 8.37 | 136.94 | 0.00 | 67.46 | 22.79 (41.15) | 7.70 | 23.41 | |
| 25 June 2012 (BI) | 0.02 | 0.83 | 0.23 | 2.65 | 95.68 | 0.08 | 75.76 | 21.13 (37.50) | 4.79 (8.5) | 21.99 | 1.95[4]/1.89 |
| 26 June 2012 (AI) | 0.781 | 1.55 | 0.39 | 2.63 | 54.15 | 0.00 | 84.19 | 28.36 (46.3) | 5.04 (8.9) | 19.60 | |
| 29 June 2012 | 0.049 | 0.40 | 0.07 | 0.85 | 82.07 | 0.00 | 71.16 | 32.85 (60.9) | 5.41 (9.6) | 22.19 | |
| 11 July 2011 (BI) | 0.901 | 0.23 | -0.06 | 0.61 | 92.44 | 0.03 | 69.80 | 18.93 (33.50) | 4.40 (7.78) | 19.25 | 4.86[4]/5.27 |
| 12 July 2011 (AI) | 0.107 | 12.14[5] | 0.06 | 31.29 | 108.27 | 0.00 | 79.93 | 8.80 (15.58) | 34.09 (60.35)[6] | 20.25 | |
| 18 July 2011 (BI) | 0.219 | 0.05 | 0.00 | 0.10 | 85.52 | 0.00 | 62.69 | 13.08 (23.15) | 3.67 (6.5) | 21.00 | 4.84[4]/5.02 |
| 19 July 2011 (AI) | 0.211 | 8.81 | 0.77 | 26.31 | 96.75 | 0.00 | 78.62 | 11.68 (20.68) | 8.0 (14.15) | 20.25 | |
| 9 July 2012 (BI) | 0.469 | 0.02 | -0.02 | 0.07 | 185.67 | 0.00 | 66.46 | 28.11 (49.80) | 7.56 (13.4) | 24.44 | 4.21/3.80 |
| 10 July 2012 (AI) | 0.259 | 1.05 | -0.08 | 2.95 | 100.18 | 0.03 | 76.95 | 30.65 (54.25) | 5.65 (10) | 22.21 | |
| 13 July 2012 | <0.005 | 0.16 | 0.00 | 0.78 | 164.34 | 0.02 | 68.29 | 28.17 (49.85) | 3.5 (6.61) | 23.14 | |
| 16 July 2012 (BI) | 0.376 | 0.16[5] | 0.00 | 0.46 | 99.02 | 0.00 | 68.49 | 38.39 (68.0) | 11.60 (20.55) | 22.76 | 2.88/2.83 |
| 17 July 2012 (AI) | 0.076 | 0.25 | -3.13 | 1.96 | 626.25 | 0.00 | 79.47 | 49.09 (86.9) | 10.72 (19) | 22.73 | |
| 20 July 2012 | 0.045 | 0.49 | -0.19 | 0.88 | 85.19 | 1.87 | 81.89 | 50.09 (88.70) | 8.34 (14.8) | 23.09 | |

[1]BI = 6 to 7 h before irrigation began and AI = 4 to 5 h after irrigation ceased; [2]Calculated based on a bulk density (0 to 6-cm depth) = 1.13 g cm$^{-3}$ and 0 to 5-cm soil depth. Units in brackets are in ppm; [3] n=4; [4]Mean (n=7 to 9) monthly MWE-TN from PSU wastewater treatment plant monthly reports; [5]n=7; [6]Soil samples were oven dried, hence increasing the ammonium N and probably nitrate N concentration in the samples.

# Appendix H: Normality test p-values, denitrification fluxes, rainfall, WFPS, soil mineral N, and MWE N on sampling dates in 2011 and 2012 (Continued).

| Sampling Date[1] | Anderson-Darling p-values for the normality test | Denitrification flux (x 10^-2) | | | Coefficient of variation (CV) | Rain fall | Water-filled pore space (WFPS) | Soil NO$_3$-N[2] | Soil NH$_4$-N[2] | Soil temp. | MWE-(TN/NO$_3$-N) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean (n=8) | Min. | Max. | | | | | | | |
| | | kg N ha$^{-1}$ h$^{-1}$ | | | % | cm | % | kg N ha$^{-1}$ | | (°C) | kg N ha$^{-1}$ |
| 11 August 2011 (BI) | 0.116 | 1.90 | 0.06 | 4.94 | 101.72 | 0.08 | 74.70 | 24.06 (42.58) | 7.37 (13.05) | 20.00 | 5.20/3.60 |
| 12 August 2011 (AI) | 0.064 | 27.78 | -0.28 | 101.29 | 128.29 | 0.05 | 79.47 | 18.75 (43.05) | 9.46 (16.75) | 24.32 | |
| 15 August 2011 (BI) | 0.274 | 8.32 | 0.92 | 23.73 | 89.93 | 0.58 | 89.19 | 18.39 (32.55) | 6.02 (10.65) | 19.25 | 1.97/1.71 |
| 16 August 2011 (AI) | 0.552 | 9.72 | 1.98 | 17.08 | 44.45 | 0.28 | 90.54 | 10.68 (18.90) | 7.18 (12.71) | 19.50 | |
| 22 August 2011 (BI) | 0.660 | 1.01 | 0.28 | 1.84 | 47.73 | 0.03 | 78.90 | 11.37 (20.13) | 8.21 (14.53) | 21.06 | 6.11/5.22 |
| 23 August 2011 (AI) | 0.188 | 3.68 | 0.23 | 10.42 | 88.04 | 0.25 | 92.32 | 17.29 (30.60) | 9.11 (16.13) | 19.61 | |
| 6 August 2012 (BI) | 0.115 | 4.99 | 0.90 | 14.69 | 89.72 | 0.00 | 73.76 | 74.13 (131.2) | 3.75 (6.6) | 24.18 | 3.06/2.88 |
| 7 August 2012 (AI) | 0.013 | 13.17 | 2.32 | 45.24 | 105.03 | 0.00 | 84.40 | 45.93 (81.3) | 3.73 (6.6) | 22.95 | |
| 10 August 2012 | 0.156 | 2.73 | 1.14 | 4.82 | 61.99 | 0.23 | 87.21 | 32.71 (57.9) | 3.50 (6.2) | 23.6 | |
| 13 August 2012 (BI) | 0.759 | 1.13 | 0.03 | 2.42 | 79.10 | 0.99 | 73.30 | 39.58 (70.1) | 2.34 (4.2) | 22.2 | 4.76/4.57 |
| 14 August 2012 (AI) | 0.339 | 1.63 | 0.23 | 3.18 | 69.82 | 1.91 | 87.97 | 40.23 (71.2) | 2.51 (4.45) | 22.03 | |
| 17 August 2012 | 0.006 | 0.89 | 0.15 | 2.79 | 91.71 | 0.05 | 73.77 | 49.09 (77.3) | 2.41 (4.3) | 22.4625 | |
| 20 September 2011 (BI) | 0.129 | 0.91 | 0.16 | 2.39 | 75.66 | 0.00 | 77.56 | 13.28 (23.50) | 4.41 (7.80) | 15.85 | 6.51/5.56 |
| 21 September 2011 (AI) | 0.085 | 4.54 | 0.82 | 11.36 | 87.32 | 0.00 | 89.41 | 21.60 (38.23) | 5.71 (10.11) | 16.723 | |
| 26 September 2011 | 0.016 | 0.81 | 0.04 | 3.12 | 124.67 | 2.64 | 68.92 | 9.68 (17.13) | 7.92 (14.03) | 18.39 | 6.29/4.77 |
| 27 September 2011 (AI) | <0.005 | 1.80 | -1.86 | 2.82 | 84.78 | 0.89 | 91.44 | 23.11 (40.90) | 5.18 (9.18) | 18.58 | |
| 25 September 2012 (AI) | 0.601 | 0.28 | 0.08 | 0.55 | 57.23 | 0.42 | 80.68 | 21.39 (37.85) | 5.29 (9.38) | 15.10 | 7.44/6.05 |
| 28 September 2012 | 0.940 | 0.51 | 0.18 | 0.87 | 41.85 | 0.02 | 86.31 | 14.72 (26.05) | 3.75 (6.64) | 17.30 | |
| 3 October 2011 (BI) | 0.066 | 0.23 | -0.34 | 0.80 | 190.22 | 0.00 | 86.20 | 16.03 (28.38) | 6.8 (12.02) | 13.63 | 6.64/4.88 |
| 4 October 2011 (AI) | 0.014 | 4.80 | 1.37 | 11.84 | 90.57 | 0.00 | 90.56 | 18.07 (31.98) | 4.92 (8.71) | 13.43 | |
| 24 October 2011 (BI) | 0.016 | 0.92 | -0.03 | 3.67 | 130.75 | 0.05 | 80.53 | 15.65 (27.70) | 6.01 (10.64) | 11.163 | 8.12/4.17 |
| 25 October 2011 (AI) | 0.751 | 15.12 | 1.52 | 32.31 | 69.13 | 0.03 | 91.49 | 14.41 (25.50) | 4.15 (7.35) | 10.84 | |
| 31 October 2011 | 0.176 | 0.72 | 0.30 | 1.64 | 62.22 | 0.00 | 85.51 | 12.79 (22.65) | 3.86 (6.84) | 7.25 | 9.41/4.93 |
| 22 October 2012 (BI) | 0.010 | 0.07 | -0.01 | 0.31 | 136.77 | 0.07 | 78.69 | 11.60 (20.53) | 3.55 (6.29) | 12.85 | 7.12/5.55 |
| 23 October 2012 (AI) | 0.395 | 0.89 | 0.37 | 1.53 | 49.15 | 0.00 | 91.00 | 15.09 (26.7) | 3.31 (5.86) | 12.36 | |
| 26 October 2012 | 0.030 | 0.13 | -0.01 | 0.49 | 126.30 | 0.00 | 81.52 | 14.20 (25.13) | 5.62 (9.94) | 14.74 | |
| 1 November 2011 (AI) | <0.005 | 7.49 | 0.67 | 33.69 | 149.85 | 0.00 | 95.76 | 18.05 (31.95) | 2.26 (4.0) | 7.74 | |
| 14 November 2011 (BI) | 0.787 | 0.23 | 0.07 | 0.40 | 52.02 | 0.08 | 86.58 | 11.23 (19.88) | 4.23 (7.5) | 8.36 | 10.50/4.79 |
| 15 November 2011 (AI) | <0.005 | 5.40 | -0.45 | 31.41 | 201.50 | 0.00 | 95.64 | 12.67 (22.43) | 4.13 (7.31) | 10.09 | |
| 21 November 2011 (BI) | 0.044 | 0.40 | -0.18 | 1.65 | 150.92 | 4.75 | 90.33 | 16.94 (29.98) | 33.47 (59.25)[6] | 8.41 | 5.01/4.52 |
| 22 November 2011 (AI) | 0.007 | 3.27 | 0.26 | 13.19 | 136.07 | 0.00 | 95.70 | 21.71 (38.43) | 39.56 (70.03)[6] | 7.68 | |
| 2 November 2012 | 0.272 | 0.07 | 0.01 | 0.18 | 88.91 | 0.08 | 90.43 | 11.33 (20.05) | 5.98 (1059) | 9.95 | |
| 5 November 2012 (BI) | 0.021 | 0.06 | 0.02 | 0.19 | 85.71 | 0.00 | 91.59 | 10.44 (18.48) | 4.33 (7.68) | 8.21 | 7.32/6.70 |
| 6 November 2012 (AI) | <0.005 | 2.07 | 0.04 | 14.11 | 235.03 | 0.00 | 93.25 | 13.41 (23.74) | 3.69 (6.53) | 6.79 | |

[1]BI= 6 to7 h before irrigation and AI = 4 to 5 h after irrigation ceased; [2]Calculated based on a bulk density (0 to 6-cm depth) = 1.13 g cm$^{-3}$ and 0 to 5-cm soil depth. Units in brackets are in ppm; [3] n=4; [4]Mean (n=7 to 9) monthly MWE-TN from PSU wastewater treatment plant monthly reports; [5]n=7; [6]Soil samples were oven dried, hence increasing the ammonium N and probably nitrate N concentration in the samples.

**Appendix I: DNDC code used to determine initial NO$_3$-N for site mode simulations.** (Jia Deng, DNDC model team member, Email communication, 26 September 2013).

```
float S_NO3 = 3.0 * (float)log(SOC) + 10.0;
if (latitude<0.0) latitude *= -1.0;
S_NO3 = S_NO3 / (90.0 - latitude);
S_NO3 = max (0.5, S_NO3).
```

# Appendix J: Saturated hydraulicconductivity ($K_{sat}$) measured in the laboratory

| Sampling location[1] | r[2] | h[3] | Steady-state volume of water, V through the core every 10 min. | | | | | | | $K_{sat}$ (K1-K7) based on steady-state volumes V1- V7 | | | | | | | $K_{sat}$[4] | Std | CV | $K_{sat}$[5] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | V1 | V2 | V3 | V4 | V5 | V6 | V7 | K1 | K2 | K3 | K4 | K5 | K6 | K7 | | | | |
| | | cm | cm³ | | | | | | | cm min⁻¹ | | | | | | | cm min⁻¹ | | | cm min⁻¹ |
| SP-3 | 1 | 4.85 | 2.21 | 1.70 | 1.86 | 1.87 | 1.57 | 1.75 | 2.98 | 0.003 | 0.003 | 0.003 | 0.003 | 0.002 | 0.003 | 0.004 | 0.003 | 0.001 | 0.24 | 0.01 |
| | 2 | 4.95 | 7.45 | 6.76 | 6.64 | 7.38 | 6.92 | 7.76 | 6.60 | 0.011 | 0.010 | 0.010 | 0.011 | 0.010 | 0.012 | 0.010 | 0.011 | 0.001 | 0.06 | |
| | 3 | 4.91 | 5.46 | 7.37 | 8.29 | 9.07 | 8.52 | 9.89 | 8.22 | 0.008 | 0.011 | 0.012 | 0.014 | 0.013 | 0.015 | 0.012 | 0.012 | 0.002 | 0.17 | |
| SP-4 | 1 | 4.84 | 49.50 | 46.61 | 48.90 | 56.81 | 55.00 | 63.58 | 55.44 | 0.075 | 0.070 | 0.074 | 0.086 | 0.083 | 0.096 | 0.084 | 0.081 | 0.009 | 0.11 | 0.04 |
| | 2 | 4.77 | 18.97 | 17.17 | 17.66 | 19.87 | 18.76 | 21.85 | 18.66 | 0.029 | 0.026 | 0.027 | 0.030 | 0.028 | 0.033 | 0.028 | 0.029 | 0.002 | 0.08 | |
| | 3 | 4.92 | 15.23 | 14.34 | 14.56 | 16.43 | 15.37 | 17.84 | 15.04 | 0.023 | 0.022 | 0.022 | 0.025 | 0.023 | 0.027 | 0.023 | 0.023 | 0.002 | 0.08 | |
| SP-5 | 1 | 4.83 | 4.16 | 4.62 | 4.50 | 5.05 | 4.79 | 3.95 | | 0.006 | 0.007 | 0.007 | 0.008 | 0.007 | 0.006 | | 0.007 | 0.001 | 0.09 | 0.01 |
| | 2 | 4.61 | 8.00 | 9.58 | 9.68 | 10.54 | 10.82 | 9.09 | | 0.012 | 0.015 | 0.015 | 0.016 | 0.017 | 0.014 | | 0.015 | 0.002 | 0.11 | |
| | 3 | 4.80 | 2.63 | 3.03 | 2.90 | 3.43 | 3.32 | 2.83 | | 0.004 | 0.005 | 0.004 | 0.005 | 0.005 | 0.004 | | 0.005 | 0.000 | 0.10 | |
| SP-6 | 1 | 4.91 | 32.95 | 36.44 | 36.94 | 41.49 | 41.20 | 36.11 | | 0.050 | 0.055 | 0.056 | 0.062 | 0.062 | 0.054 | | 0.056 | 0.005 | 0.09 | 0.05 |
| | 2 | 4.80 | 16.10 | 17.80 | 18.37 | 21.09 | 21.10 | 17.49 | | 0.024 | 0.027 | 0.028 | 0.032 | 0.032 | 0.026 | | 0.028 | 0.003 | 0.11 | |
| | 3 | 4.58 | 32.10 | 35.36 | 36.23 | 41.13 | 41.67 | 34.82 | | 0.049 | 0.054 | 0.055 | 0.063 | 0.064 | 0.053 | | 0.056 | 0.006 | 0.10 | |

[1] 4.5 m on the up-hill side of lateral 10-1 and opposite sprinklers (SP-3, SP-4, SP-5, and SP-6) (see chapter 3, Fig. 3-3)
[2] Replicate
[3] Hydrostatic head
[4] Mean (n=7) $K_{sat}$ per replicate
[5] Mean (n=3) $K_{sat}$ per sampling location

**Appendix K (a): Municipal wastewater effluent irrigation depth and nitrate nitrogen used in DNDC model fertigation files for 2004 and 2005.**

| Day of year[1] | 2004 | | | 2005 | | |
|---|---|---|---|---|---|---|
| | Effluent depth (Ln)[2] | NO$_3$-N[3] | NO$_3$-N | Effluent depth (Ln)[1] | NO$_3$-N[2] | NO$_3$-N |
| | cm | mg L$^{-1}$ | kg ha$^{-1}$ | cm | mg L$^{-1}$ | kg ha$^{-1}$ |
| 5 | 4.9 | 7.4 | 3.6 | 4.9 | 13.3 | 6.5 |
| 40 | 4.9 | 6.6 | 3.2 | 4.9 | 7.5 | 3.6 |
| 47 | 3.9 | 11.7 | 4.5 | 3.9 | 11.2 | 4.3 |
| 54 | 4.9 | 9.6 | 4.7 | 4.9 | 9.4 | 4.6 |
| 61 | 4.9 | 8.8 | 4.3 | 4.9 | 7.5 | 3.6 |
| 67 | | | | 2.3 | 11.4 | 2.3 |
| 68 | 2.3 | 4.5 | 0.9 | | | |
| 74 | | | | 4.9 | 8.4 | 4.9 |
| 75 | 4.9 | 14.1 | 6.9 | | | |
| 81 | | | | 4.9 | 9.9 | 4.8 |
| 82 | 4.9 | 11.4 | 5.5 | | | |
| 88 | | | | 4.9 | 8.0 | 3.9 |
| 89 | 4.9 | 11.8 | 5.7 | | | |
| 95 | | | | 4.9 | 1.2 | 5.0 |
| 96 | 4.9 | 9.7 | 4.7 | | | |
| 102 | | | | 4.9 | 5.8 | 2.8 |
| 103 | 4.9 | 11.7 | 5.7 | | | |
| 109 | | | | 4.9 | 7.4 | 3.6 |
| 110 | 4.9 | 9.5 | 4.6 | | | |
| 116 | | | | 4.9 | 7.8 | 3.8 |
| 117 | 4.9 | 11.9 | 5.8 | | | |
| 123 | | | | 4.9 | 5.7 | 2.8 |
| 124 | 4.9 | 11.2 | 5.5 | | | |
| 151 | | | | 4.9 | 11.5 | 5.6 |
| 152 | 4.9 | 6.9 | 3.4 | | | |
| 158 | | | | 4.9 | 5.2 | 2.5 |
| 159 | 4.9 | 5.7 | 2.8 | | | |
| 165 | | | | 4.9 | 6.3 | 3.7 |
| 166 | 4.9 | 9.0 | 4.4 | | | |
| 172 | | | | 4.9 | 8.9 | 4.3 |
| 173 | 4.9 | 6.2 | 3.2 | | | |
| 179 | | | | 4.9 | 6.2 | 3.2 |
| 180 | 4.9 | 8.0 | 3.9 | | | |
| 186 | | | | 4.9 | 11.3 | 5.5 |
| 187 | 4.9 | 6.7 | 3.3 | | | |
| 193 | | | | 4.9 | 5.2 | 2.5 |
| 194 | 4.9 | 2.2 | 1.8 | | | |
| 200 | | | | 4.9 | 7.4 | 3.6 |
| 201 | 4.9 | 13.0 | 6.3 | | | |
| 207 | | | | 4.9 | 5.9 | 2.9 |
| 208 | 4.9 | 8.9 | 4.3 | | | |
| 214 | | | | 4.9 | 7.3 | 3.6 |
| 215 | 4.9 | 1.1 | 4.9 | | | |
| 221 | | | | 4.9 | 5.3 | 2.6 |
| 222 | 4.9 | 8.3 | 4.4 | | | |
| 242 | | | | 4.9 | 3.5 | 1.7 |
| 243 | 4.9 | 6.8 | 3.4 | | | |
| 249 | | | | 2.4 | 3.3 | 0.8 |
| 250 | 2.4 | 8.7 | 2.1 | | | |
| 256 | | | | 4.9 | 4.8 | 2.3 |
| 257 | 4.9 | 9.7 | 4.7 | | | |
| 263 | | | | 4.9 | 6.6 | 3.2 |
| 264 | 4.9 | 11.1 | 5.4 | | | |
| 270 | | | | 4.9 | 7.6 | 3.7 |
| 271 | 4.9 | 12.6 | 6.1 | | | |
| 277 | | | | 4.9 | 4.7 | 2.3 |
| 278 | 4.9 | 1.9 | 5.3 | | | |
| 284 | | | | 4.9 | 7.9 | 3.8 |
| 285 | 4.9 | 12.1 | 5.9 | | | |
| 291 | | | | 4.9 | 7.2 | 3.5 |
| 292 | 4.9 | 13.7 | 6.7 | | | |
| 298 | | | | 4.9 | 6.9 | 3.4 |
| 299 | 4.9 | 9.2 | 4.5 | | | |
| 305 | | | | 4.9 | 12.2 | 5.9 |
| 306 | 4.9 | 1.2 | 5.0 | | | |
| 312 | | | | 4.9 | 8.9 | 4.3 |
| 313 | 4.9 | 1.3 | 5.1 | | | |

[1]Obtained from weekly irrigation logs for grass field. [2]Calculated using irrigation rate of 0.42 cm h$^{-1}$ and durations from turn-ON/OFF times for lateral 10-BR2 (see Figure 3-3). [3]Obtained from PSU WWTP monthly reports.

**Appendix K (b): Municipal wastewater effluent irrigation depth and nitrate nitrogen used in DNDC model fertigation files from 2006 to 2010.**

| | 2006 | | | | 2007 | | | | 2008 | | | | 2009 | | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day of year [1] | Effluent depth (Ln)[2] | $NO_3$-$N$[3] | $NO_3$-$N$ | Day of year [1] | Effluent depth (Ln)[2] | $NO_3$-$N$[3] | $NO_3$-$N$ | Day of year [1] | Effluent depth (Ln)[2] | $NO_3$-$N$[3] | $NO_3$-$N$ | Day of year [1] | Effluent depth (Ln)[2] | $NO_3$-$N$[3] | $NO_3$-$N$ | Day of year [1] | Effluent depth (Ln)[2] | $NO_3$-$N$[3] | $NO_3$-$N$ |
| | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ |
| 9 | 4.9 | 12.40 | 6.35 | 8 | 4.9 | 10.0 | 4.9 | 14 | 4.9 | 15.2 | 7.4 | 12 | 3.3 | 16.5 | 5.4 | 18 | 4.9 | 1.6 | 5.2 |
| 16 | 4.9 | 6.6 | 3.2 | 15 | 4.9 | 11.6 | 5.6 | 21 | 4.9 | 16.4 | 8.0 | 19 | 4.9 | 8.4 | 4.7 | 25 | 4.9 | 12.6 | 6.1 |
| 23 | 4.9 | 12.3 | 6.0 | 22 | 4.9 | 13.5 | 6.6 | 28 | 4.9 | 1.4 | 5.6 | 26 | 4.9 | 5.0 | 2.4 | 32 | 4.9 | 1.6 | 5.2 |
| 30 | 4.9 | 1.9 | 5.3 | 29 | 4.9 | 11.2 | 5.5 | 35 | 4.9 | 9.3 | 4.5 | 33 | 4.9 | 7.4 | 3.6 | 39 | 4.9 | 11.9 | 5.8 |
| 37 | 4.9 | 13.1 | 6.4 | 35 | 4.9 | 1.7 | 5.3 | 42 | 4.9 | 12.5 | 6.8 | 47 | 4.9 | 11.3 | 5.5 | 46 | 4.9 | 13.4 | 6.5 |
| 44 | 4.9 | 11.8 | 5.7 | 42 | 4.9 | 11.7 | 5.7 | 49 | 4.9 | 8.8 | 4.3 | 54 | 4.9 | 11.3 | 5.5 | 53 | 3.3 | 15.3 | 5.0 |
| 51 | 4.9 | 11.7 | 5.7 | 49 | 4.9 | 15.3 | 7.4 | 56 | 4.9 | 8.4 | 5.0 | 61 | 4.9 | 1.5 | 5.2 | 60 | 4.9 | 12.5 | 6.8 |
| 58 | 4.9 | 13.8 | 6.7 | 56 | 4.9 | 13.0 | 6.3 | 63 | 4.9 | 12.3 | 6.0 | 75 | 4.9 | 1.7 | 5.3 | 67 | 4.9 | 11.7 | 5.7 |
| 72 | 4.9 | 13.1 | 6.4 | 84 | 4.9 | 13.5 | 6.6 | 70 | 4.9 | 7.7 | 3.7 | 82 | 4.9 | 9.9 | 4.8 | 74 | 4.9 | 13.4 | 6.5 |
| 79 | 4.9 | 13.3 | 6.5 | 92 | 4.9 | 1.5 | 5.2 | 77 | 4.9 | 13.7 | 6.7 | 89 | 4.9 | 14.1 | 6.9 | 81 | 4.9 | 1.3 | 5.1 |
| 86 | 4.9 | 15.6 | 7.6 | 99 | 4.9 | 14.6 | 7.2 | 84 | 4.9 | 19.0 | 9.2 | 96 | 4.9 | 11.6 | 5.6 | 88 | 4.9 | 9.6 | 4.7 |
| 93 | 4.9 | 16.5 | 8.3 | 106 | 4.9 | 14.7 | 7.2 | 91 | 4.9 | 11.2 | 5.5 | 103 | 4.9 | 11.2 | 5.5 | 95 | 4.9 | 12.4 | 6.3 |
| 100 | 4.9 | 16.5 | 8.3 | 113 | 4.9 | 12.1 | 5.9 | 98 | 4.9 | 7.8 | 3.8 | 110 | 4.9 | 9.8 | 4.8 | 102 | 4.9 | 13.5 | 6.6 |
| 107 | 4.9 | 16.5 | 8.3 | 120 | 4.9 | 13.2 | 6.4 | 105 | 4.9 | 11.4 | 5.5 | 117 | 4.9 | 19.3 | 9.4 | 109 | 4.9 | 8.9 | 4.3 |
| 114 | 4.9 | 16.5 | 8.3 | 127 | 4.9 | 18.3 | 9.0 | 112 | 4.9 | 6.6 | 3.2 | 124 | 4.9 | 14.0 | 6.8 | 116 | 4.9 | 9.5 | 4.6 |
| 121 | 4.9 | 12.7 | 6.2 | 134 | 4.9 | 4.3 | 2.8 | 119 | 4.9 | 7.3 | 3.5 | 131 | 4.9 | 4.8 | 2.0 | 123 | 4.9 | 11.1 | 5.4 |
| 128 | 4.9 | 16.8 | 8.2 | 148 | 4.9 | 9.5 | 4.6 | 168 | 4.9 | 4.6 | 2.2 | 138 | 4.9 | 13.8 | 6.7 | 130 | 4.9 | 14.1 | 6.9 |
| 135 | 4.9 | 11.8 | 5.7 | 155 | 0.8 | 18.1 | 1.5 | 182 | 4.9 | 6.1 | 3.0 | 145 | 4.9 | 11.5 | 5.6 | 137 | 4.9 | 11.4 | 5.5 |
| 156 | 4.9 | 8.6 | 4.2 | 162 | 4.9 | 9.5 | 4.6 | 189 | 4.9 | 4.8 | 2.3 | 152 | 4.9 | 14.7 | 7.2 | 144 | 4.9 | 7.9 | 3.5 |
| 163 | 4.9 | 7.8 | 3.8 | 169 | 4.9 | 6.7 | 3.2 | 196 | 4.9 | 9.3 | 4.6 | 166 | 3.3 | 9.4 | 3.4 | 165 | 4.9 | 19.5 | 9.5 |
| 170 | 4.9 | 8.5 | 4.1 | 176 | 4.9 | 7.5 | 3.6 | 203 | 4.9 | 1.9 | 5.3 | 180 | 4.9 | 1.8 | 5.3 | 172 | 4.9 | 5.0 | 2.5 |
| 177 | 4.9 | 6.8 | 3.3 | 190 | 4.9 | 8.9 | 4.3 | 210 | 4.9 | 4.2 | 2.6 | 187 | 4.9 | 1.0 | 4.9 | 179 | 4.9 | 5.4 | 2.6 |
| 184 | 4.9 | 7.5 | 3.7 | 197 | 4.9 | 4.3 | 2.8 | 224 | 4.9 | 7.4 | 3.6 | 194 | 4.9 | 7.4 | 3.6 | 186 | 4.9 | 8.1 | 4.0 |
| 191 | 4.9 | 7.4 | 3.6 | 204 | 4.9 | 7.7 | 3.8 | 231 | 2.3 | 9.9 | 2.4 | 201 | 4.9 | 12.4 | 6.3 | 193 | 4.9 | 3.5 | 1.7 |
| 198 | 4.9 | 7.9 | 3.8 | 211 | 4.9 | 19.4 | 9.4 | 238 | 4.9 | 6.4 | 3.1 | 208 | 4.9 | 8.9 | 4.3 | 200 | 4.9 | 3.7 | 1.8 |

[1]Obtained from weekly irrigation logs for grass field.
[2]Calculated using irrigation rate of 0.42 cm h$^{-1}$ and durations from turn-ON/OFF times for lateral 10-BR2 (see Figure 3-3).
[3]Obtained from PSU WWTP monthly reports.

**Appendix K (b): Municipal wastewater effluent irrigation depth and nitrate nitrogen used in DNDC model fertigation files from 2006 to 2010 (Continued).**

| | 2006 | | | | 2007 | | | | 2008 | | | | 2009 | | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day of year[1] | Effluent depth (Ln)[2] | $NO_3$-N[3] | $NO_3$-N | Day of year[1] | Effluent depth (Ln)[2] | $NO_3$-N[3] | $NO_3$-N | Day of year[1] | Effluent depth (Ln)[2] | $NO_3$-N[3] | $NO_3$-N | Day of year[1] | Effluent depth (Ln)[2] | $NO_3$-N[3] | $NO_3$-N | Day of year[1] | Effluent depth (Ln)[2] | $NO_3$-N[3] | $NO_3$-N |
| | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ | | cm | mg $L^{-1}$ | kg $ha^{-1}$ |
| 205 | 4.9 | 1.1 | 4.9 | 221 | 4.9 | 9.1 | 4.4 | 245 | 4.9 | 4.9 | 2.4 | 215 | 4.9 | 7.7 | 3.8 | 214 | 4.9 | 7.8 | 3.9 |
| 212 | 4.9 | 11.0 | 5.4 | 228 | 4.9 | 5.7 | 2.8 | 252 | 4.9 | 5.9 | 2.9 | 222 | 4.9 | 5.6 | 2.7 | 221 | 4.9 | 6.6 | 3.3 |
| 219 | 4.9 | 9.8 | 4.4 | 235 | 4.9 | 1.7 | 5.3 | 259 | 4.9 | 6.5 | 3.2 | 229 | 4.9 | 1.8 | 5.3 | 228 | 4.9 | 5.9 | 2.8 |
| 226 | 4.9 | 9.4 | 4.6 | 242 | 4.9 | 6.5 | 3.2 | 266 | 4.9 | 6.6 | 3.2 | 236 | 4.9 | 6.6 | 3.2 | 235 | 4.9 | 8.9 | 4.3 |
| 233 | 4.9 | 1.6 | 5.2 | 246 | 4.9 | 6.4 | 3.9 | 273 | 4.9 | 6.6 | 3.2 | 243 | 4.9 | 9.6 | 4.7 | 242 | 4.9 | 9.8 | 4.8 |
| 240 | 1.5 | 5.3 | 0.8 | 253 | 4.9 | 8.8 | 3.9 | 280 | 4.9 | 14.4 | 7.8 | 250 | 4.9 | 9.2 | 4.5 | 249 | 4.9 | 8.8 | 4.3 |
| 247 | 4.9 | 7.6 | 3.4 | 260 | 4.9 | 1.1 | 4.9 | 287 | 4.9 | 9.0 | 4.4 | 257 | 4.9 | 11.1 | 5.4 | 256 | 4.9 | 18.8 | 9.1 |
| 254 | 4.9 | 8.3 | 4.4 | 267 | 4.9 | 11.4 | 5.5 | 294 | 4.9 | 9.2 | 4.5 | 264 | 4.9 | 9.3 | 4.5 | 263 | 4.9 | 15.4 | 7.5 |
| 261 | 4.9 | 1.3 | 5.1 | 274 | 4.9 | 12.1 | 5.9 | 301 | 4.9 | 9.0 | 4.4 | 271 | 3.3 | 13.4 | 4.4 | 270 | 4.9 | 9.5 | 4.6 |
| 268 | 4.9 | 9.5 | 4.6 | 281 | 4.9 | 9.3 | 4.5 | 308 | 4.9 | 14.8 | 7.2 | 278 | 4.9 | 13.2 | 6.4 | 284 | 4.9 | 12.8 | 6.2 |
| 275 | 4.9 | 15.2 | 7.4 | 288 | 4.9 | 1.5 | 5.2 | 315 | 4.9 | 17.9 | 8.7 | 285 | 4.9 | 12.2 | 5.9 | 298 | 4.9 | 17.7 | 8.6 |
| 282 | 4.9 | 11.8 | 5.7 | 295 | 4.9 | 9.7 | 4.7 | 322 | 4.9 | 9.1 | 4.4 | 292 | 4.9 | 11.3 | 5.5 | 305 | 4.9 | 15.9 | 7.7 |
| 289 | 4.9 | 13.5 | 6.6 | 337 | 4.9 | 12.1 | 5.9 | 336 | 4.9 | 19.4 | 9.4 | 299 | 4.9 | 11.1 | 5.4 | 319 | 4.9 | 13.1 | 6.4 |
| 296 | 4.9 | 1.2 | 5.0 | 344 | 4.9 | 9.5 | 4.6 | 343 | 4.9 | 17.9 | 8.7 | 306 | 4.9 | 9.3 | 4.5 | 333 | 4.9 | 18.4 | 9.0 |
| 303 | 4.9 | 11.0 | 5.4 | 351 | 4.9 | 14.6 | 7.2 | 350 | 4.9 | 16.0 | 7.8 | 313 | 4.9 | 9.4 | 4.6 | | | | |
| 310 | 4.9 | 13.3 | 6.5 | | | | | | | | | 335 | 4.9 | 19.1 | 9.3 | | | | |
| 317 | 4.9 | 16.3 | 7.9 | | | | | | | | | 341 | 4.9 | 12.8 | 6.2 | | | | |
| 324 | 4.9 | 14.5 | 7.6 | | | | | | | | | 348 | 4.9 | 11.5 | 5.6 | | | | |
| 331 | 4.9 | 17.3 | 8.4 | | | | | | | | | | | | | | | | |
| 338 | 4.9 | 14.6 | 7.2 | | | | | | | | | | | | | | | | |
| 345 | 4.9 | 13.3 | 6.5 | | | | | | | | | | | | | | | | |
| 352 | 4.9 | 7.8 | 3.8 | | | | | | | | | | | | | | | | |

[1]Obtained from weekly irrigation logs for grass field.
[2]Calculated using irrigation rate of 0.42 cm $h^{-1}$ and durations from turn-ON/OFF times for lateral 10-BR2 (see Figure 3-3).
[3]Obtained from PSU WWTP monthly reports.

## Appendix L: Visual Basic code used to calculate daily reference evapotranspiration

```
'Prepared by Dr. Armen R. Kemanian (Assistant Professor of Production Systems and Modeling at Penn
State University, University Park, PA), March 2012.

'FAO Penman-Monteith Reference ET

'Reference: Allen et al., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements
– FAO Irrigation and drainage paper 56. ISBN 92-5-104219-5

Option Explicit

Const PI = 3.141593

Function ETref (lat As Double, altitude As Double, screeningHeight As Double, TMax As Double, _
     TMin As Double, sRad As Double, RHmax As Double, RHmin As Double, wind As Double, doy As
Integer) As Double
   'Daily estimate of Penman- Monteith Reference Evapotranspiration

   Const rs As Double = 0.00081     'Day/m
   Const CP As Double = 0.001013   'specific heat capacity of air, MJ/(kg °C)
   Const R As Double = 0.28704     'specific gas constant for dry air, kJ/(kg °C)

   Dim esTmax As Double     'saturation vapor pressure at Tmax, kPa
   Dim esTmin As Double     'saturation vapor pressure at Tmin, kPa
   Dim vp As Double         'actual vapor pressure (kPa)
   Dim Patm, vpd, potRad, netRad, ra, Tave, esTave, delta, gamma, lambda, Tkv, volHeatCap, aeroTerm,
radiTerm As Double

   Patm = 101.325 * Exp(altitude / 8200)
   Tave = 0.5 * (TMax + TMin)
   esTave = satVP(Tave)
   esTmax = satVP(TMax)
   esTmin = satVP(TMin)
   vp = 0.5 * (esTmin * RHmax + esTmax * RHmin) / 100
   vpd = 0.5 * (esTmax + esTmin) - vp
   potRad = PotentialRadiation(lat, doy)               'MJ/m2/Day
   netRad = NetRadiation(potRad, sRad, vp, TMax, TMin)     'MJ/m2/Day
   ra = AerodynamicResistance(wind, screeningHeight)       'Day/m
   delta = 4098 * esTave / (Tave + 237.3) ^ 2            'slope of saturated vapor pressure vs temperature
function, kPA/°C
   lambda = 2.501 - 0.002361 * Tave                'latent heat of vaporization, MJ/kg
   gamma = CP * Patm / (0.622 * lambda)               'psychrometric constant, kPa/°C
   Tkv = 1.01 * (Tave + 273)                    'approximates virtual temperature, K
   volHeatCap = CP * Patm / (R * Tkv)             'CP * AirDensity (J/kg * kg/m3)
   aeroTerm = (volHeatCap * vpd / ra) / (delta + gamma * (1 + rc / ra))   'MJ/m2
   radiTerm = delta * netRad / (delta + gamma * (1 + rc / ra))          'MJ/m2
   ETref = 0.1*((aeroTerm + radiTerm) / lambda)                    'kg water/m2 or-cm (water density =
1 Mg/m3)
If ETref < 0 Then ETref = 0.001 'preventing a negative value, usually small and indicative of condensation

End Function
Private Function satVP(ByVal T As Double) As Double
   satVP = 0.6108 * Exp(17.27 * T / (T + 237.3)) 'kPa
End Function
```

## Appendix L: Visual Basic code used to calculate daily reference evapotranspiration (Continued)

```
Private Function PotentialRadiation(ByVal lat As Double, ByVal doy As Integer) As Double
    Const Solar_Constant As Double = 118.02
    Dim DR, SolDec, SunsetHourAngle, x1 As Double

    lat = lat * PI / 180                              'latitude in radians
    DR = 1 + 0.033 * Cos(2 * PI * doy / 365)
    SolDec = 0.409 * Sin(2 * PI * doy / 365 - 1.39)
    SunsetHourAngle = Application.Acos((-Tan(lat) * Tan(SolDec)))   'acos = arcsin function using a
worksheet function
    x1 = SunsetHourAngle * Sin(lat) * Sin(SolDec) + Cos(lat) * Cos(SolDec) * Sin(SunsetHourAngle)
    PotentialRadiation = Solar_Constant * DR * x1 / PI
End Function


Private Function NetRadiation(ByVal Pot_Rad As Double, ByVal Solar_Rad As Double, ByVal
Actual_VP As Double, ByVal TMax As Double, ByVal TMin As Double) As Double

    Dim Rns, F_Cloud, F_Hum, LWR, Rnl As Double
    Const Albedo As Double = 0.23

    Rns = (1 - Albedo) * Solar_Rad                                    'shortwave net radiation
    F_Cloud = 1.35 * (Solar_Rad / (Pot_Rad * 0.75)) - 0.35           'cloud factor
    F_Hum = (0.34 - 0.14 * (Actual_VP) ^ 0.5)                        'humidity factor
    LWR = 86400 * 0.0000000567 * 0.5 * ((TMax + 273.15) ^ 4 + (TMin + 273.15) ^ 4) / 1000000
'isothermal LW net radiation
    Rnl = LWR * F_Cloud * F_Hum
    NetRadiation = Rns - Rnl
End Function


Private Function AerodynamicResistance(ByVal uz As Double, ByVal z As Double) As Double

    Dim u2, d, zom, zoh, zm, zh As Double
    Const VK As Double = 0.41   'von Karman's constant

    If uz = 0 Then uz = 0.00001
    If z = 2 Then u2 = uz Else u2 = uz * (4.87 / (Log(67.8 * z - 5.42)))
    u2 = u2 * 86400     'convert to m/Day
    d = 0.08          'zero plane displacement, m
    zom = 0.01476      'roughness lenght for momentum transfer, m
    zoh = 0.001476      'roughness lenght for heat and vapor transfer, m
    zm = 2            'wind speeding measurement height, m
    zh = 2            'water vapor measurement height, m
AerodynamicResistance = Log((zm - d) / zom) * Log((zh - d) / zoh) / (VK * VK * u2)
End Function
```

**Appendix M: Calculated daily reference evapotranspiration (ETo) (cm)**

| Day of month | April 2011 | April 2012 | May 2011 | May 2012 | June 2011 | June 2012 | July 2011 | July 2012 | August 2011 | August 2012 | September 2011 | September 2012 | October 2011 | October 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.11 | 0.21 | 0.19 | 0.44 | 0.56 | 0.24 | 0.53 | 0.57 | 0.53 | 0.42 | 0.33 | 0.42 | 0.04 | 0.24 |
| 2 | 0.2 | 0.26 | 0.27 | 0.29 | 0.45 | 0.33 | 0.5 | 0.58 | 0.57 | 0.49 | 0.27 | 0.21 | 0.1 | 0.19 |
| 3 | 0.24 | 0.33 | 0.36 | 0.48 | 0.5 | 0.32 | 0.53 | 0.52 | 0.2 | 0.39 | 0.38 | 0.21 | 0.12 | 0.22 |
| 4 | 0.29 | 0.42 | 0.17 | 0.45 | 0.32 | 0.27 | 0.39 | 0.59 | 0.32 | 0.46 | 0.34 | 0.25 | 0.19 | 0.19 |
| 5 | 0.22 | 0.27 | 0.38 | 0.32 | 0.5 | 0.27 | 0.51 | 0.57 | 0.32 | 0.39 | 0.13 | 0.32 | 0.29 | 0.28 |
| 6 | 0.12 | 0.32 | 0.36 | 0.24 | 0.5 | 0.33 | 0.55 | 0.6 | 0.19 | 0.51 | 0.09 | 0.36 | 0.19 | 0.14 |
| 7 | 0.22 | 0.37 | 0.34 | 0.14 | 0.36 | 0.42 | 0.43 | 0.63 | 0.36 | 0.44 | 0.13 | 0.4 | 0.21 | 0.08 |
| 8 | 0.07 | 0.39 | 0.37 | 0.15 | 0.6 | 0.47 | 0.19 | 0.47 | 0.42 | 0.47 | 0.19 | 0.16 | 0.24 | 0.1 |
| 9 | 0.11 | 0.27 | 0.43 | 0.24 | 0.6 | 0.55 | 0.5 | 0.46 | 0.36 | 0.3 | 0.22 | 0.31 | 0.23 | 0.16 |
| 10 | 0.24 | 0.17 | 0.42 | 0.25 | 0.49 | 0.56 | 0.56 | 0.49 | 0.42 | 0.26 | 0.3 | 0.29 | 0.18 | 0.18 |
| 11 | 0.4 | 0.15 | 0.46 | 0.42 | 0.46 | 0.46 | 0.54 | 0.46 | 0.42 | 0.41 | 0.23 | 0.29 | 0.17 | 0.17 |
| 12 | 0.19 | 0.22 | 0.45 | 0.47 | 0.41 | 0.23 | 0.59 | 0.53 | 0.43 | 0.3 | 0.29 | 0.35 | 0.09 | 0.16 |
| 13 | 0.12 | 0.31 | 0.28 | 0.28 | 0.37 | 0.5 | 0.41 | 0.29 | 0.32 | 0.39 | 0.37 | 0.37 | 0.11 | 0.18 |
| 14 | 0.36 | 0.31 | 0.15 | 0.14 | 0.34 | 0.43 | 0.55 | 0.31 | 0.32 | 0.35 | 0.32 | 0.34 | 0.08 | 0.38 |
| 15 | 0.34 | 0.44 | 0.23 | 0.33 | 0.49 | 0.46 | 0.51 | 0.37 | 0.22 | 0.28 | 0.12 | 0.31 | 0.18 | 0.14 |
| 16 | 0.16 | 0.57 | 0.25 | 0.47 | 0.33 | 0.45 | 0.56 | 0.51 | 0.45 | 0.43 | 0.24 | 0.29 | 0.21 | 0.11 |
| 17 | 0.26 | 0.4 | 0.16 | 0.43 | 0.42 | 0.49 | 0.54 | 0.62 | 0.43 | 0.25 | 0.21 | 0.33 | 0.22 | 0.18 |
| 18 | 0.27 | 0.21 | 0.21 | 0.45 | 0.46 | 0.16 | 0.55 | 0.38 | 0.43 | 0.4 | 0.26 | 0.29 | 0.21 | 0.29 |
| 19 | 0.13 | 0.37 | 0.22 | 0.46 | 0.42 | 0.49 | 0.47 | 0.36 | 0.26 | 0.2 | 0.21 | 0.25 | 0.18 | 0.11 |
| 20 | 0.39 | 0.45 | 0.3 | 0.52 | 0.38 | 0.6 | 0.55 | 0.13 | 0.42 | 0.25 | 0.25 | 0.29 | 0.1 | 0.11 |
| 21 | 0.27 | 0.3 | 0.43 | 0.22 | 0.48 | 0.58 | 0.66 | 0.24 | 0.32 | 0.38 | 0.21 | 0.33 | 0.08 | 0.15 |
| 22 | 0.1 | 0.09 | 0.29 | 0.32 | 0.48 | 0.48 | 0.65 | 0.46 | 0.39 | 0.36 | 0.22 | 0.28 | 0.07 | 0.2 |
| 23 | 0.37 | 0.09 | 0.34 | 0.38 | 0.34 | 0.49 | 0.51 | 0.43 | 0.39 | 0.38 | 0.13 | 0.2 | 0.14 | 0.18 |
| 24 | 0.34 | 0.19 | 0.33 | 0.42 | 0.3 | 0.43 | 0.39 | 0.56 | 0.46 | 0.38 | 0.25 | 0.21 | 0.17 | 0.19 |
| 25 | 0.47 | 0.33 | 0.44 | 0.49 | 0.19 | 0.42 | 0.25 | 0.52 | 0.37 | 0.38 | 0.27 | 0.24 | 0.18 | 0.17 |
| 26 | 0.47 | 0.35 | 0.55 | 0.41 | 0.28 | 0.48 | 0.53 | 0.63 | 0.34 | 0.32 | 0.26 | 0.24 | 0.18 | 0.13 |
| 27 | 0.41 | 0.25 | 0.36 | 0.39 | 0.33 | 0.53 | 0.53 | 0.42 | 0.32 | 0.41 | 0.11 | 0.15 | 0.1 | 0.06 |
| 28 | 0.36 | 0.15 | 0.4 | 0.53 | 0.46 | 0.58 | 0.21 | 0.36 | 0.25 | 0.4 | 0.16 | 0.17 | 0.09 | 0.07 |
| 29 | 0.17 | 0.38 | 0.55 | 0.42 | 0.47 | 0.64 | 0.53 | 0.47 | 0.35 | 0.38 | 0.13 | 0.16 | 0.06 | 0.06 |
| 30 | 0.38 | 0.41 | 0.57 | 0.47 | 0.51 | 0.32 | 0.57 | 0.46 | 0.37 | 0.38 | 0.12 | 0.16 | 0.1 | 0.07 |
| 31 |  |  | 0.54 | 0.43 |  |  | 0.52 | 0.44 | 0.35 | 0.51 |  |  | 0.1 | 0.05 |

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**PUBLICATIONS/PRESENTATIONS/AWARDS**
**Publications**
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Wastewater-Irrigated Systems." ASA/CSA/SSSA International Meeting. November 2-5, 2014.
Long Beach CA, USA.

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irrigated with municipal secondary-treated effluent." North East Agricultural and Biological
Engineering Conference (NABEC). June 16-19, 2013. Altoona PA, USA.

**AWARDS**
2nd place, poster presentation award, NABEC. June, 2013
Alpha Epsilon Society, High Academic Achievements in Agric. and Bio Eng. Nov., 2010