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The impact of irrigation on nutrient export from agricultural fields

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THE IMPACT OF IRRIGATION ON NUTRIENT EXPORT FROM AGRICULTURAL FIELDS

by

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ABSTRACT

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Title The Impact of irrigation of Nutrient Export from Agricultural Fields

The role that irrigation plays in runoff and nutrient export from agricultural areas in Alabama was examined using an industry standard crop model (DSSAT) together with a water and nitrogen export routine using the kinematic wave approximation. The goal was to estimate a percentage of the nitrate left by the DSSAT model at each time step that might be exported. The results show that irrigated crops do uptake significantly more nitrogen than do rain fed crops. The results of this study suggest that irrigation is an effective management practice to decrease the amount of nitrate in the surface layer, thus decreasing the amount of surface export. The study also concludes that irrigation decreases the residual (fall/post season) nitrate in the soil column. Irrigation provides the vertical movement and aerobic conditions for nitrogen to be consumed by the plant as compared to rain-fed fields.

Abstract Approval: Committee Chair James Cruise
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To my family and friends...

Cheers,

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LIST OF SYMBOLS

Symbol	Definition
N	Nitrogen
C	Carbon
NH_3	Ammonia
NH_4^+	Ammonium
N_2	Atmospheric nitrogen
N_2O	Nitrous oxide
NO_2^-	Nitrogen dioxide
NO	Nitric oxide
CO_2	Carbon dioxide
Q	Runoff (Flow)
P	Rainfall
Ia	The initial abstraction including surface storage, interception, and infiltration prior to runoff
S'	The potential maximum soil moisture retention after runoff
CN	Curve Number
SW	Soil moisture
SAT	Saturation point
LL	Lower limit
DUL	Drained upper limit
FLUX	Drainage
ET_{eq}	Equilibrium evaporation rate

R	Solar radiation
A’	Albedo
T_d	Approximate daytime temperature
T_{max}	Maximum temperature
T_{min}	Minimum temperature
s	Substrate concentration
m	Biomass
α	Oxidized N per unit weight per time
β	Enzyme per unit of biomass involved in waste metabolism
k_m	Saturated constant
N_{DN}	Denitrification rate
C_w	Soil soluble carbon
NO_3	Nitrate in the soil layer
D_B	Bulk density of the soil layer
W_F	Water factor
T_F	Temperature factor
D_l	Depth of the layer
θ_T	Total soil moisture
θ_m	Mobile moisture
A	Area
x	Distance
t	Time
q	Unit runoff (flow)
S_o	Normal slope

S_f	Friction slope
α	Conveyance factor for Manning's n
y	Depth
m	5/3 (Constant)
T_s	Equilibrium time
y_s	Equilibrium depth
L	Length of plane
S	Slope
n	Manning's n
r	Rainfall intensity
θ	Moisture content
z	Depth
$K(\theta)$	Unsaturated hydraulic conductivity
D	Diffusion coefficient
i	Lateral inflow
Ψ	Suction head
W	Soil wetness
θ_s	Saturated hydraulic conductivity
k	Relative hydraulic conductivity
$conc_{NO3,mobile}$	Concentration of nitrate transported
w_{mobile}	Mobile subsurface moisture
θ_e	Fraction of the porosity from which anions are excluded

CHAPTER I

INTRODUCTION

The southeastern United States receives a substantial amount of rainfall; however, contrary to popular belief, this rainfall is not a reliable source of water for agriculture. As much as 70% of the rainfall in the southeast can be attributed to frontal systems that occur between October and April, leaving the main growing season, existing usually between May and August, the hottest and driest of the year (Cruise and Arora, 1990). However, even with the growing season being the driest, irrigation is not the major source of water consumption. The number of acres under irrigation, though, has increased nationally over the past decade according to the National Agricultural Statistics Service (2007) with the majority of growth in the Southeastern region. It is expected to continue to rise. Studies have shown that even with small applications, irrigation can have a significant impact resulting in positive agricultural returns (Limaye et al., 2004; Paudel et al., 2005). Studies also suggest that the quantity of irrigated land will increase due to climate change (Mendolsohn et al., 1993; Adams et al., 1995; Darwin et al., 1995).

The sustainability of current agricultural systems has come under increased scrutiny as our understanding of the environment and ecosystems therein have increased.

As the Midwest continues to increase the stress on the Mississippi River ecosystems and as Western agricultural practices continue to pressure their ecosystems, the question of whether the Southeast can be a stress reducer under rain-fed, irrigated assisted agriculture needs to be addressed.

When looked at from a water availability perspective, including both economic and energy efficiency, southeastern irrigated crops appear sustainable. However whether this system is sustainable to its ecosystem is a major concern. The purpose of this investigation is to examine whether irrigation increases nitrogen runoff and leaching or, conversely, whether irrigation is an effective management strategy to reduce the loss of nutrients to ground water and surface water in the southeastern United States' humid environment.

1.1 Background

Efficient food and fiber production was the model of U.S. agriculture systems in the later twentieth century. According to the National Agricultural Statistics Service, 50% of the value of the U.S. agriculture is produced on only 20% of the agricultural land. This is due mainly to the agriculture of the dry plains and the arid west. In the Midwest farmers continue, through intensive rain-fed farming, to increase yields and production. This advance, however, comes with social and environmental cost (De Villers, 2000; Postel, 1992). Increasing evidence shows that as a result of the intensive grain farming in the Midwest, the nitrogen runoff is impairing the Mississippi River basin and the Gulf of

Mexico (Rabalais et al., 2001). A model of nitrate in the Gulf of Mexico and the Mississippi River Basin has been developed that accounts for 95% of annual variation in delivery (McIsaac et al., 2001). According to the authors, if nitrogen fertilizer was decreased by 12% the nitrogen flux would have decreased by 33%.

There is also concern that the Western agriculture system cannot sustain an irrigated agriculture system. As the urban demand for water continues to rise, the competition of agriculture and urban water needs could limit agricultural production. These concerns are exacerbated when coupled with climate change and the expected need for water (Reisner, 1986; Feng et al., 2010).

However, the first half of the twentieth century looked quite different. Not only was there more farm land (Dimitri et al., 2005), but a lot more, in contrast to present figures, was grown east of the Mississippi River. According to the United States Department of Agriculture, Maine was the nation's largest potato producer, while New York and Pennsylvania were right behind (Effland, 2000). Alabama, Georgia, and Mississippi were the most dominate states in cotton production and most states shared the production of corn for local consumption by livestock and poultry (Effland, 2000). The population centers of the East were served by regional vegetable markets.

This dispersed Eastern agricultural system, however, experienced the cost of seasonal drought losses. Western agriculture could combat this with exhaustive irrigation infrastructure and Midwest farmers in Iowa, Illinois, Missouri and Minnesota could rely

on their deep water holding soils. By the latter half of the twentieth century Western agriculture had replaced the dispersed Eastern agricultural systems. Not only did the West effectively implement irrigation, but the nation's massive improvement in transportation orchestrated the movement of an agricultural center in the West (Gardner, 2002). As a result, Arizona, California and Texas replaced the Deep South's cotton economy (Arax and Wartzman, 2003; Effland, 2000). Sequentially, Idaho and Washington became the nation's major producers of potatoes (Effland, 2000).

As one could assume, the competition brought on by Western and Midwestern agriculture insulated from drought, brought a precipitous decline of Eastern and Southeastern agriculture. In the South, rural economies that were dependent on agriculture diminished and forced communities into poverty. The Conservation Reserve Program (CRP), a program that provided payment for fallow idle land, was a last resort for most farmers that didn't replace their fields with timber. These options supplied the farmers with payment, however, could not resurrect the local economies. Though the farmer may not be losing money, a farms input into the local economy is unmatched when compared to that of the CRP program and timber production. A farmer turns large percentages of his earnings back into the local economy in fertilizer, seed, equipment, fuel and labor. Though several other factors could have contributed, including disease and insects, the inability of the Southeast to cope with drought has had a significant impact on the demise of its agricultural system.

1.2 Stressors from Changing Ecosystems

The agricultural systems that have evolved in the last century in both the West and Midwest are now subject to several stressors:

- Water Availability
- Climate Change
- Reactive Nitrogen

The agricultural system in the arid West is dependent on irrigation. The water needed for this is becoming scarce due to both supply and demand (Postel, 1992; Rosegrant et al., 2002; Gleick, 1995). The demand from tremendous population growth, and therefore the increasing landscape, the past couple of decades have also increased the stress on public water supply. According to the Department of Interior Colorado Pact, supply is being threatened from multiple fronts; cites are looking to supplies that traditionally were allocated for agricultural purposes because groundwater usually used to supply urban areas are being depleted and saline pollution of the groundwater has increased due to irrigation in arid areas where evaporation is rife (Weert et al., 2009).

While precipitation and regional climate change predictions are uncertain, the Intergovernmental Panel on Climate Change (2007) concludes with more consensuses that arid areas are more likely to become drier and humid areas more wet. This may add additional concerns about water availability in the west, however, may auspicate well for the precipitation of the Southeast. Another concern would be the likelihood of the West returning back to the drier climate characteristic of the last five hundred years. The latter

part of the twentieth century, when the current agricultural system began, was uncommonly wet for the Western US region. This can be seen in tree-ring reconstruction (Piechota et al., 2004). If this return to a drier region was to occur, the Western ecosystems and economies as a result would seriously undermine the current agriculture system.

The third stressor identified is the reactive nitrogen introduced in agricultural ecosystems. As a result from concentrated corn farming, the Midwest has increased the nitrogen runoff into the Mississippi River and has decreased its ability to sequester nitrogen (Rabalais et al., 2001). Thus, the nitrogen flux being discharged into the Gulf of Mexico is increasing in concentration. The Mississippi River basin contains 41% of the conterminous United States; most of the nitrogen fertilizer applied in the US is within the Mississippi basin (Goolsby and Battaglin, 2000). An excess of nitrogen in the environment is thought to have detrimental consequences, resulting in substantial pollution and creating a loss of other nutrients, acidification, and eutrophication, that is a decrease in dissolved oxygen (Vitousek et al., 1997).

1.3 A Southeastern Distributed Irrigated Agro-ecosystem

The stressors aforementioned create an overarching question to the United States as a whole; can the country sustain its agricultural output in the face of the potential declines in Western irrigated agriculture and the potential decline in the Midwest grain production? One option proposed to replace this potential lost production is to increase

the production in the Southeast under an irrigation assisted rain-fed agricultural system (McNider et al., 2005). With the exception of select regions like southern Georgia, only a relatively small portion of the Southeastern agriculture is irrigated. However the question is: Would an irrigated assisted agricultural system in the southeast be environmentally sustainable or would it be subject to the same water and nutrient stressors as the West and Midwest?

These questions are beginning to be understood and addressed. Irrigation in the Southeast appears to be sustainable with respect to the water resources required. The crops in the south only need supplemental irrigation of 6 to 12 inches per year. That amount can be attributed to the large amount of natural rainfall. Studies have shown, through sustainable winter harvesting, that approximately ten percent of basin land can be irrigated without a detectable change in stream flow statistics (Handyside et al., 2009).

The combination of shallow, poor water holding soils and sporadic precipitation throughout most of the growing season create inefficient rain-fed farming in most areas of the Southeast. Yields in this region are almost always less than the potential yields. If rains do not come at the right time, often the fuel, fertilizer, and human energy will be wasted (Hook, 2007). Irrigation could help reduce those losses and provide a better, more responsible use of energy.

1.4 The Impact of Irrigation on Nutrient Leaching and Runoff

With both water and efficiency addressed, lastly the subject of nutrient loading must be considered. The negative aspect to increased irrigated agricultural land in the Southeast could be that runoff from the agricultural land would increase as well. Nutrient content can be transported to surface waters during storm runoff by surface runoff and ground water intrusion (Williamson et al., 1998; Hill et al., 1999; Tesoriero et al., 2000). In the Southeast, subsurface flows leaching into surface streams are just as important since the majority of water quality problems that are associated with nutrient concentrations occur during summer low flow periods (Mulholland et al., 1997; Cruise et al., 1999; USGCRP, 2002).

The Southeast Regional Climate Assessment Panel (USGCRP, 2002) found that several Alabama watersheds, including the Warrior, Tombigbee, and Chattahoochee, already experience abnormally high levels of nitrate nitrogen. It is no surprise that these river basins are among the most agriculturally cultivated in the state. Thus before an irrigated Southeast agricultural system can be realized, the potential for harmful nutrient export from increasingly irrigated agricultural areas must be fully understood.

1.5 Research Objectives

It is assumed that irrigated crops are more efficient than rain-fed crops in up-taking nutrients from the soil since they sequester more biomass. After all, nutrients are

uptaken with water. Thus, one would expect that for irrigated crops, there would be less nitrogen left in the soil available for transport. In fact, droughts are known to substantially increase the nitrogen left in the soil. The difference in the residual nitrogen is the main focus of this investigation. On the other hand, when rainfall does occur, it is expected that the runoff generated would be greater for irrigated soils due to the fact that the moisture content would be higher than that of non-irrigated soils. The hypothesis considered is that with irrigated soils the amount of runoff would increase, however, the nutrient concentration would be reduced. This question of whether irrigation would lead to more or less nutrient export from the field will be studied in detail.

Objectives

1. Establish a calibrated model using the Decision Support System for Agro-technology Transfer (DSSAT) model on an agricultural research field, using the historic climate and the recorded yields and measured soil nitrogen concentrations.

2. Develop a kinematic based lateral soil flushing algorithm to compute export of residual nitrogen from the field for subsurface and surface analysis.

3. Apply DSSAT/kinematic wave model to a representative topographical area in Alabama.

4. Run various scenarios using variable inputs of applied nitrogen to the hypothetical farm.

5. Evaluate effects of irrigation on soil moisture and residual nitrogen and on export parameters from the fraction of export from the Soil and Water Assessment Tool (SWAT) transport equations.

6. Analyze data obtained and make conclusions and better management practice recommendations.

CHAPTER II

LITERATURE REVIEW

The nitrogen cycle in the in the soil-plant system has been studied exhaustively in an attempt to better understand, what some might consider, the single most important factor affecting plant yields. How nitrogen cycles throughout the soil column, its many transformations and plant availability, and its ecological effect in and outside agricultural systems have been researched. More than two decades of published scientific papers map the progress of this ongoing, pertinent research. This review does not include the entirety of the subject at hand, but simply selects a limited pertinent history of research to establish a foundation for this study.

2.1 Nutrient Dynamics

The soil environmental conditions of temperature and moisture are important factors in all phases of the nitrogen cycle (Heng and Nikolaidis, 1998). For example, studies from Frere et al. (1980) show that mineralization rates for ammonium nitrogen release (NH_4) increases exponentially with temperature up to 35° C and can increase linearly with moisture content up to field capacity. Similarly, the denitrification process

has been the subject of several studies finding comparable conclusions (Tesoriero et al., 2000; McMahon et al., 1999). Although these studies deal specifically with the chemistry of the saturated and unsaturated zones, the subsurface water balance and specific identification of flow paths is observed to be a principle component to the denitrification process (Tesoriero et al., 2000). Several researchers have found that the critical moisture content of 90% is needed to facilitate the development of the required anoxic conditions (Jones et al., 1984; Viney et al., 2000). Therefore, soil moisture and temperature play key roles in the plant nutrient uptake from the soil column and the biomass fixation. Nutrient uptake is associated with the photosynthetic processes and is absorbed with the available moisture by the root system. This key principle along with temperature conditions will strongly affect plant growth; thus, resulting in the final process: the leaching of the nutrients through the soil, beyond the root zone and thus is a direct function of the moisture in the soil column.

The nutrient transport and the cycle kinetics associated are closely related to the soil moisture dynamics. Hornberger et al. (1994) introduced the concept that nutrient transport is a function of the status of the soil moisture deficit, or known more commonly as “hydrologic flushing.” This study, along with others (Creed et al., 1996; Creed and Band, 1998), show that the soil moisture profile can have a regulating effect on the formation of nitrogen sinks, nitrogen sources and the flushing and export of nitrogen to nearby streams.

2.2 Nutrient Models

Many models have been developed to simulate nutrient dynamics both by the U.S. Agriculture Research Service (ARS) and others. The ARS models include

- Chemicals, Runoff and Erosion from Agricultural Management Systems model-CREAMS (Knisel et al., 1980)
- Simulator for Water Resources in Rural Basins- SWRRB (Williams et al., 1985)
- Agriculture Non-Point Source Pollution -AGNPS (Young et al., 1995)
- Soil Water Assessment Tool- SWAT (Neitsch et al., 2005)

These models all use the same basic algorithms for soil moisture. However, as nutrient kinetics evolved, models were developed for specific purposes and different spatial scales. These ARS models have been popular among the hydrologic communities and have been implemented into various studies (Kenner et al., 1998; Manguerra and Engle, 1998; Limeye et al., 2000).

Some have been criticized, however, of their empirical basic hydrological mechanics. The extent of these models stop at the empirical Curve Number technique for the surface partitioning of runoff and infiltration and the mass balance processes for subsurface leaching. This creates limitations for the simulation of nutrient cycle dynamics. Other models that have been introduced include PnET-BGC model for forest and aquatic ecosystems (Gbondo-Tugbawa et al., 2001), the Decision Support System for

Agro-technology Transfer (DSSAT) for agricultural studies (Jones et al., 1998), Century for mixed land uses (Parton et al., 1994), and the Large Scale Catchment Model (LASCAM) for both agricultural and forested environments (Viney et al., 2000). These hydrologic, ecosystem based, models are capable of continuous simulation of water, nutrient, and biomass over long periods of time and large spatial scale, but suffer from somewhat crude hydrologic transport representations.

2.3 Field Experiments

As mentioned before, being an integral part of the soil system, the nitrogen cycle has been studied in many agricultural experiments. The amount of nitrate that exists in the soil can reveal many factors affecting the growth and yield of crops. For example, The Southeastern Farm Press states that it takes about 1.5 pounds (.68 kg) of available nitrogen to produce a bushel of corn (Hollis, 2008). Thus, monitoring and predicting the amount of nitrogen in the soil would be helpful in mitigating the application and losses of nitrogen.

There have been several researchers throughout the early 1990's that studied the factors that affect the nitrate in agricultural systems. B.C. Lang et al. (1991) studied the influence of fertilizer, irrigation and non-growing season precipitation on nitrate under corn in southwestern Quebec. They found that under irrigation, large amounts of soil nitrate were lost in the top 40 centimeters under both normal and high fertilization applications. However there were no changes in the soil column below 40 cm. A later

study, also in Quebec, found that soil under corn for 6 years increased the Carbon: Nitrogen ratio for first three years then stabilized (Laing and Mackenzie, 1992). This study also noted that even though higher rates of nitrogen fertilizer increased the amount of nitrogen in the soil, it was of a different composition. The increased nitrogen in the soil from the high N applications was less hydrolyzable-N, thus unavailable to plants. Another study found that yield increases with high fertilization rates, up to 350 kg/ha, however, large amounts of N were still not recovered by the crop (Laing and Mackenzie, 1994). In comparison of unrecovered nitrogen in agricultural fields, the largest contributions of the lost nitrogen were found to be leached rather than a product of denitrification (Laing and Mackenzie, 1994).

Zhou et al. (1997) studied the effect of intercropping to conserve nitrate concentrations in the soil. This study concluded, among other things, that monocropping increased the downward movement of nitrate in both the growing season and following spring, with more available to leach in the high nitrogen applications. Pandey et al. (2000) experimented with corn on a clayey loam in Niger examining water deficit on plant growth and uptake of nitrogen. They reported that nitrogen uptake increased linearly as irrigation increases, though it was more dependent on the amount of nitrogen applied.

Another study in California focused on nitrate leaching as affected by irrigation on a carrot field (Allaire-Leung, 2000). In this study fertilization was applied with the irrigation water via sprinklers and was conducted on loamy sand. Allaire-Leung found

that nitrate leaching was correlated to soil nitrate concentration, but not to irrigation depth, irrigation uniformity, or deep percolation. The authors gave several reasons for the reported results. Among them was that the distribution uniformity of applied water needed to be below 80% before it would become a dominant factor, the study reported a distribution greater than 80%. Isidoro (2006) published research evaluating the impact of irrigation and fertilization on nitrate exports. This study was conducted on an irrigation district in Spain (ditch irrigation), which is part of a larger study basin. Isidoro found, like Pandy et al. (2000), that plant uptake increases with irrigation, especially under corn (D. Isidoro et al., 2006). Isidoro also concluded that large export events were associated with fertilization and irrigation applications. These studies along with many others mostly conclude on a common idea: better fertilizer and irrigation management would decrease the export of nitrate. Both nitrogen and irrigation seem to be overly used in modern farming, i.e. used beyond maximum efficiency.

2.4 Contribution of this Study

From the literature referenced above, it is understood that soil moisture, temperature and carbon content are dominating factors in the cyclical nitrogen processes. These factors will clearly interact differently under irrigated and rain-fed agricultural systems due to the controlling influence of soil moisture and biomass sequestration which increases plant uptake of nutrients. This project will evaluate these issues through a physically based distributed hydrologic model coupled with a sophisticated nutrient cycling and uptake model. These models will be verified at the field scale through soil

nutrient concentrations and observed corn yields. Once calibrated, this coupled model will be used to examine the factors that influence nutrient transport and fate under both irrigated and rain-fed conditions. Finally, with the flexibility of using simulated results, better fertilization and irrigated management strategies can be recommended.

CHAPTER III

THEORETICAL BACKGROUND

This chapter addresses theoretical principles used throughout this study. A detailed explanation of the soil nitrogen cycle relevant to agricultural systems is provided. This section also describes and discusses the agricultural model, DSSAT, used in this study. Finally, this chapter includes the hydrologic relationships applied to the lateral leaching scenario, followed by the nutrient flushing dynamics and formulas therein.

3.1 Nutrient Cycle

Nitrogen, next to carbon and oxygen, is the most abundant element by weight in organic matter and is present at 79% of the earth atmosphere in molecular form (Gaudy and Gaudy, 1988). Nitrogen is required for life, present in DNA, RNA and proteins and is essential for most ecological processes (Smil, 2000; Harrison, 2003). The nitrogen present in atmospheric form is mostly unavailable to plants due to a strong triple bond of the N atoms, unless utilized by fixation or chemical processing. This inert form of nitrogen gas commonly results in natural ecosystems lacking sufficient nitrogen, thus

limiting plant growth. According to the Mississippi State Agricultural Extension service, of the estimated 37,000 tons resting above each acre only about 5 pounds are deposited though precipitation illustrating the natural ecosystems lack of N for commercial crops (Oldham, 2010). Nitrogen can be found in all possible nitrogen–oxygen molecules including nitrous oxide, nitric oxide, and nitrogen dioxide. Ammonia is the most common form of reduced nitrogen, present during decomposition with its signature aroma. Nitrogen is also in abundance when present in solutions, at saturation or supersaturated (Sprent, 1987). It is also present in most living organisms to some degree.

The main processes involving nitrogen are fixation, assimilation and mineralization, nitrification, and denitrification. The nitrogen process described below in Figure 3.1 is a general schematic not indicating the energy contained or used or the total quantities of the components; the reactions presented below are subject to the biological, physical and geographic environment. However, the pictorial presented below gives the viewer, whether or not an expert, a more real idea of how the cycle processes though the environment. Nitrogen fixation is the process of reducing atmospheric nitrogen, N_2 to ammonia, NH_3.

There are three reductive processes that contribute to nitrogen fixation. These include: a small amount from high energy natural events such as lightning, radiation in the atmosphere and lava flows; biological fixation; and an ever increasing chemical manufacturing industry. The high energy from lightning and such events are capable

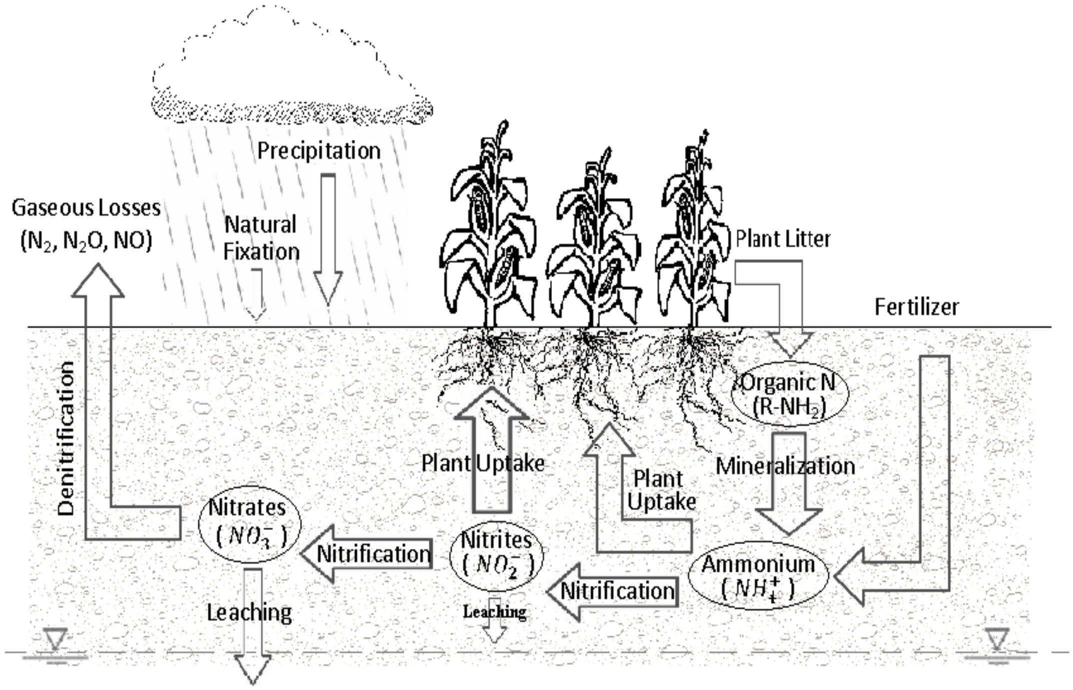


Figure 3.1: The Nitrogen Cycle.

of breaking the triple bond of N_2, leaving individual N atoms available for chemical transformation. Select bacteria, such as Rizobium, are capable of fixating atmospheric nitrogen. These certain bacteria are the only form of fixation through metabolic processes, forming a symbiotic relationship with host plants, such as legumes. This nitrogen may become part of the soil organic nitrogen available to other crops or can be harvested. Other biological fixation can occur in free-living bacteria such as blue green algae (Trautman, et al., 2008; Harrison, 2003).

The end product of fixation is ammonia. However, ammonia may only be present in low concentrations in most soils. This is because most of it is protonated into

ammonium, NH_4^+ due to the physiological pH and the high mobility of protons in water. Ammonium can then be biologically immobilized or assimilated into organic matter, i.e., via microbes or plant uptake respectively. The process of immobilization is largely dependent on the microbes, thus the carbon and other nutrient availability determines the rate. An article written by the Mississippi State University's extension program (Oldham, 2010) states that immobilization in agricultural fields may take precedence when high carbon-nitrogen ratios are being decomposed. However this usually in effect equals itself out because the microbial population will die out, decomposing and releasing nitrogen available to plants. And likewise, the organic matter can mineralize into ammonia eventually mostly becoming ammonium. This is accomplished due to energy obtained from the carbon used in the process; and therefore will take precedence with increased plant litter (Oldham, 2010). According to Gaudy (1988), these processes are neither oxidative nor reductive; however the nitrogen retains a valence of -3. This aspect of the nitrogen cycle should be largely occurring soon after fertilization as most commercially available fertilizers are ammonium derivatives, i.e., ammonium nitrate. However, depending on crop cycles and practices the lack of carbon used for energy could limit the plant uptake (Gaudy and Gaudy, 1988).

Nitrification is the process of converting ammonia, or usually in soils, ammonium to nitrites, NO_2^-, and nitrates, NO_3^-. This is done by aerobic autotrophic microorganisms. Due to its dependency on oxygen rich environments, this process usually takes place in semi-saturated soils with flowing or circulating water or at the soil's surface. Nitrites are easily oxidized into nitrates and ammonium usually resides only for a short period before converted to nitrite. This provides the largest problem in groundwater nitrogen leaching.

Both forms of nitrogen are available for plant uptake. However they react quite differently in soils. As a cation, NH_4^+ is attracted to the negative soil particles, this is especially the case for clayey soils, thus not only is it available for plant uptake it's positive charge protects it from leaching through the soil column too fast allowing the plant longer availability for uptake. This reaction also produces hydrogen, effectively lowering the pH of the soil (Oldham, 2010). Conversely, NO_3^- is negatively charged and is not held in the soil column. As an anion, the nitrate does not react with the soil particles and therefore is available to move through the soil more rapidly moving beyond the root zone, unavailable to the plants, eventually leaching into groundwater sources.

However, these nitrites and nitrates can be converted back to N_2 by microorganisms through denitrification. This process requires anaerobic conditions, and is greatly increased with high temperature (Smil, 2000). As oxygen becomes scarce, bacteria can utilize the nitrates and nitrites, however, this results in N_2 through NO and N_2O. In essence this nitrogen is lost from the ecosystem and is essentially irreversible, when the vast atmosphere is considered. The rate of denitrification is essentially a natural attempt to balance the amount of N fixated. This process completes the nitrogen cycle. It is important, however, to realize that not all of the nitrogen is recycled though N_2. Some microorganisms can also use the nitrites and nitrates as a source of nitrogen. Other losses can include volatilization of the ammonia, however if proper fertilization practices are used this can be avoided. When urea is used as a fertilizer, the process of conversion to NH_4^+ must first produce NH_3. This volatilization is

dependent on the temperature and the pH of the soil. Temperatures usually need to exceed 50 degrees Fahrenheit in an acidic soil.

There are many aspects of the natural environment that are crucial to the cycle nitrogen must go through to be available for plant uptake. The clayey southern region of the United States provides ample leaching to the groundwater systems. Irrigation will allow the watering in of the nutrients, however if the plant is unable to uptake the nitrogen before the nitrates pass the root zone, the loss is both environmental and economical. In addition irrigation may also provide heightened nitrification due to the amount of water and oxygen passing through the soil. However, "watering in" of the nutrients keep the nitrogen from the surface layers, a rich oxygen environment.

3.2 DSSAT Agricultural Model

Although every aspect of nutrient fate and transport and the linkage between hydrologic and bio-chemical components are not completely understood, the basic mechanisms are generally comprehended. It is clear that soil moisture, organic carbon and temperature are directly related, and are dominating factors in the nutrient cycling process. And, as stated by Band (1993), these factors also will vary both vertically and laterally within the unsaturated zone and the field, basin and watershed scale. These factors will be investigated in part using the agricultural model, DSSAT.

The main focus of this investigation is the transport of nitrogen, and thus the cycling dynamics involved. Organic nitrogen and applied nitrogen will be the significant sources considered. Since the nitrogen cycle balances of both organic and applied are kept in the soil, no attempt will be made to analytically differentiate between the two. The DSSAT model will simulate any nutrients derived from plant litter and combine with the organic nitrogen. The mineralization, denitrification and nitrification will also be simulated by the model. The DSSAT model will maintain the nutrient cycle in each vertical layer for each time step, as depicted in Figure 3.2.

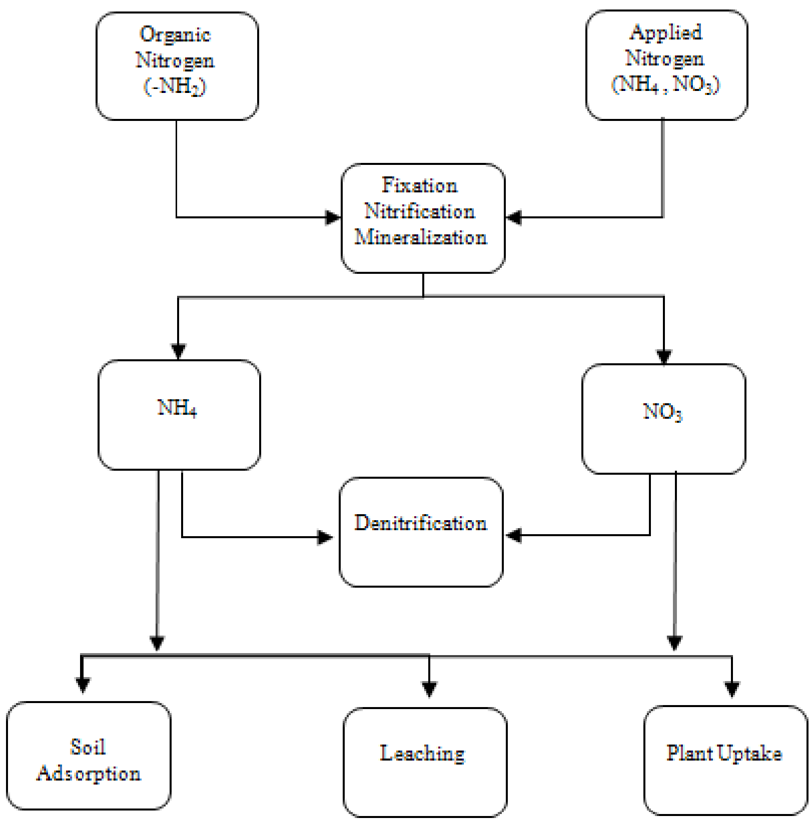


Figure 3.2: DSSAT Subsurface Nitrogen Cycle Dynamics.

As mentioned before, nutrient availability, soil moisture and soil temperature are controlling factors governing the plant uptake of nutrients. The nutrient and water needs are directly dependent on the phenological stage of the crop (Garcia and Hoogenboom, 2005). According to Limaye et al. (2004) the soil moisture stress during different periods of the growing season can affect the ultimate crop yield. Therefore, different irrigation schedules effectively applying the same amount of water could result in varying crop yields. To accurately simulate the nutrient dynamics and estimate the plant uptake by a crop, a modeling system is needed to differentiate the water and nutrient needs in relation to the crops growth stage. The Decision Support System for Agro-technology Transfer (DSSAT: Jones et al., 1998) provides this capability.

DSSAT allows the user to initialize the model with soil properties, climate data, specific cultivars and management practices. The final output of DSSAT is crop yield. To simulate this, several variables are controlled by the user. The soil can be simulated with inputs of moisture, temperature, carbon and nitrogen. Irrigation schedules can be automated, or with discrete scheduling on specific dates. The model requires climate data that includes minimum and maximum temperatures, precipitation and solar insolation. In addition the model takes into account crop management tools such a planting date, seed cultivar, soil type and fertilizer applications, both inorganic and organic. There have been several field studies validating DSSAT crop yield with actual crop yields (Zhang and Oweis, 1999; Guerena et al., 2001; Lopez-Cedron et al., 2008).

The soil water balance and water stress calculations are presented by J.T. Richie (1998). DSSAT evaluates the soil moisture and plant water stress of a crop based on a function of irrigation, evaporation, transpiration, runoff and drainage. Losses to the soil moisture can be attributed to evaporation, root absorption, or vertical flow. The soil inputs required for a functional water mass balance include: the lower limit of plant water availability (LL), the drained upper limit (DUL), and the field saturation (SAT) (Ritchie, 1998). The USDA-Natural Resources Conservation Service (NRCS), former Soil Conservation Service (SCS), curve number method is used to calculate infiltration and runoff. This method, an empirical calculation using the hydrologic soil group, land use, treatment and hydrologic condition, is used to estimate the partitioning of runoff and infiltration. The runoff can be calculated by

$$Q = \frac{(P-I_a)^2}{(P-I_a+S')} \quad , \qquad (3.1)$$

where:

Q = the runoff (mm)

P = the rainfall (mm)

I_a = the initial abstraction including surface storage, interception, and infiltration prior to runoff (mm)

S' = the potential maximum soil moisture retention after runoff begins (mm)

The Curve Number (CN) can then be related by:

$$S = \frac{1000}{CN} - 10 \quad . \qquad (3.2)$$

The curve numbers can range from around 25 to 100, with the lower numbers representing low runoff while higher numbers represent more impervious surfaces. For example, depending on the hydrologic soil group, cultivated land can range from the lower 60's to the upper 80's. This method, though empirical and quite crude, is used best with daily rainfall totals and storm events.

The soil water drainage is based off a simple water mass balance methodology. The drainage is calculated based on the holding capacity, the difference of the current soil moisture (SW) and the saturation point (SAT), of the layer of soil and the drained upper limit (DUL). The flux of water entering the soil layer from infiltration is added to the holding capacity. If this value is greater than the DUL, then drainage occurs. Figure 3.3 shows a simplified flowchart of the water mass balance for DSSAT.

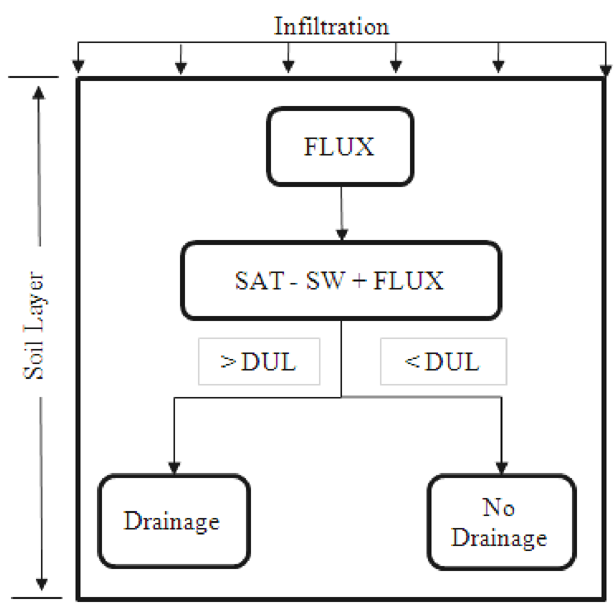


Figure 3.3: DSSAT Subsurface water mass balance

The evapotranspiration of the field is also calculated through DSSAT. Using the methodology prescribed in Priestley and Taylor (1972), the potential evaporation is calculated as a function of the equilibrium evaporation rate. Using the Priestly-Taylor for potential evaporation in place of the Penman equation eliminates the need for vapor pressure and wind inputs. DSSAT has modified the Priestly-Taylor equation for the equilibrium evaporation rate (ET_{eq}) into a simplified mathematical formula. However it has given similar results to the original equation in which long wave radiation is calculated separate (Ritchie, 1998).

$$ET_{eq} = R \cdot [4.88x10^{-3} - 4.37x10^{-3}(A')] \cdot [T_d] \quad , \tag{3.3}$$

where R is the solar radiation and A' is the albedo. This requires approximating daytime temperatures from the minimum and maximum temperatures inputted (Td).

$$T_d = (0.6 \cdot T_{max}) + (0.4 \cdot T_{min}) \quad . \tag{3.4}$$

The soil and plant solar reflection coefficients are calculated based on leaf area index and the percent of bare soil surface. For the potential evaporation, a constant of 1.1 is multiplied by the equilibrium evaporation rate. This constant is increased when the maximum temperature is greater than a high temperature threshold. The implementation of this into DSSAT can be found in J.T. Richie's description of the soil water balance and the plant water stress (Ritchie, 1998). Once evapotranspiration is conducted the moisture content of the top 4 cm is recalculated to allow for any upward movement of moisture through the soil column. The absorption of water by the roots of the crop in DSSAT is

governed by the soil resistance, the root resistance or the atmospheric demand. The flow of water from the soil to the roots is estimated using assumptions of the root s being distributed evenly throughout the soil layer. Taking into consideration the root size, the soil moisture properties and using approaches outlined by Ritchie (1981) the total amount of moisture uptake from each soil layer is calculated. From this a water uptake fraction is calculated as the ratio of plant potential evaporation and potential water uptake from the entire root zone. If this fraction is greater than 1.0, then the crop is considered to be in stress due to lack of water. This will affect the overall plant evapotranspiration and will be updated as well (Ritchie, 1998).

When simulating the nitrogen cycle, DSSAT by default uses the Crop-Environment Resource Synthesis (CERES) N model. CERES simulates the mineralization and immobilization associated with the turnover of organic matter as well as the decaying crop residues. Nitrification as well as denitrification is also simulated. In keeping with the overall goal and purpose of DSSAT, the nutrient model requires few inputs. The user can modify the soil inputs to account for past residues or green manure. DSSAT mineralization operations are comprised of three organic matter pools. One pool for each: carbohydrate, cellulose and lignin, each with differing decay rates: 0.2, 0.05, and 0.0095 respectively. A water factor is calculated for ammonification from the soil moisture taking into account for the lower limit of the soil and the drained upper limit. These processes can be seen in the documentation of Godwin and Singh (1998). The next factor calculated is the effect of the composition of the residue itself. This is reflected by the carbon/nitrogen ratio. The C:N ratio can be calculated from the C in the residue and

the nitrogen available for decay in the organic matter and the soil. Using these factors, the amount of decay can be estimated on a daily basis relative to the organic matter pool size. For the more stable fraction of organic matter the C:N ratio is replaced by a small rate constant. The immobilization processes are dependent on the organic matter and the N contained therein. The procedures that DSSAT follows for immobilization can be found as described by Seligman and van Kuelen (1981), where immobilization is controlled by a rate coefficient. Seligman and van Kuelen considers immobilization as the total immobilization of all mineral nitrogen, thus assuming that most microbes responsible for decomposition will mineralize first. The ammonium pool is drawn from first in the case of net mobilization then the nitrate pool to keep a balance of 1ppm in the ammonium pool (Godwin and Singh, 1998).

Nitrification processes in DSSAT are calculated using a potential nitrification rate. This rate is lessened by introducing a series of zero to unity indices that includes moisture content, temperature, ammonium concentrations and pH. The potential nitrification rate, a Michaelis-Menten kinetic function, is only dependent on the amount of ammonium present, thus, nitrification in DSSAT is not dependent on soil type (Godwin Singh, 1998). The Michaelis-Menten kinetic function as described by McLaren (1970) is as follows:

$$\frac{-d(s)}{dt} = \frac{adm}{dt} + \alpha m + \frac{k"\beta m(s)}{k_m + (s)} \quad , \tag{3.5}$$

where s is the substrate concentration, m is the biomass, a is a proportionality constant which is a reciprocal to growth yield, a is the nitrogen that is oxidized per unit weight per time, β is the amount of enzyme per unit of biomass involved in waste metabolism, k'' is a proportionality constant and km is a saturated constant. Included in this process is a lag term, "nitrification capacity", which uses the previous history of the soil, the
last two days, to consider favorable or unfavorable conditions for nitrification. The denitrification processes is governed by a modification of Rolston's (1980) procedure to estimate the amount of soluble carbon (Godwin and Singh, 1998). Factors are calculated to account for temperature and water. The water effectively acts as a surrogate for available oxygen. As the soil moisture approaches saturation, denitrification begins. If flood water is present, i.e., lowland crops, any nitrate present is lost except for 0.5ppm of residue. Denitrification is calculated as

$$N_{DN} = 6.0 \times (1.0 \times 10^{-5}) \times C_W \times NO_3 \times D_B \times W_F \times T_w \times D_l \quad , \qquad (3.6)$$

where

N_{DN} = the denitrification rate

C_W = the soil soluble carbon

NO_3 = the amount of nitrate in the soil layer

D_B= the bulk density of the soil layer

W_F and T_w are the water and temperature factors, respectively

D_l= the depth of the layer

For the movement of nitrogen, DSSAT assumes the same mechanics for nitrate and urea. Ammonium is not considered in the movement from one soil layer to the other. DSSAT's approach assumes that all nitrogen in a soil layer is uniformly, instantaneously, and entirely in solution of the soil water. Thus, a fraction of the total nitrate in a layer is moved with the flux of water moving and can be seen below.

$$NO_{3,m} = NO_{3,T}\left(\frac{\theta_m}{\theta_T+\theta_m}\right) \quad , \tag{3.7}$$

where $NO_{3,m}$ is the mobile nitrate moving downward to a different soil layer, $NO_{3,T}$ is the total amount of nitrate in the soil layer, and θ_T & θ_m are the soil moisture total in the soil layer and the amount mobile respectively.

Newer studies, however, have introduced the Century (Parton) model to handle the soil organic module more accurately (Gijsman et al., 2002; Tojo Soler et al., 2011; Basso et al., 2010). These models effectively work the same for most of the nutrient dynamics. Each handles the fertilizer applications the same, and both Century (Parton) and Ceres (Godwin) handle the fresh organic matter from residue similarly. The difference lies in Century's ability to more accurately simulate N and CO_2 release from organic matter already in the soil when a cropping system is simulated. The CERES soil module does not adequately deal with the wide range of carbon qualities in the soil. The difficulty, however, with Century involves the initialization process. Thus, great care must be taken when initializing the carbon pools. According to Basso et al. (2010) if the soil carbon is mostly in the intermediate pool decomposition will occur over a period of

several years, releasing a lot of N during that time. This is the case for soils in good health. For degraded soils, the intermediate pool would be low and most of the soil carbon would be in a state with very slow decomposition rates (Basso et al., 2010). Though Century is geared more toward low input agricultural systems, the current investigation will take into account both growth and fallow scenarios. Thus, great care will be taken to initialize the century model to most effectively analyze the processes of nitrogen throughout both the growing season and is residual presence in the following follow season.

3.3 Kinematic Wave Model

The previous discussion described, in detail, the nutrient and moisture dynamics involved in the DSSAT agricultural simulation model and the routine modules therein. DSSAT, however, does not model the transport of moisture, and therefore nutrients, laterally in the surface or subsurface. DSSAT is a point model, and does not simulate spatial transport, and may actually underestimate the amount of nutrients leached from the soil column. Therefore, a simple kinematic wave routine will be used to simulate lateral movement between the grid cells for both surface and subsurface.

The kinematic wave model considers both local and convective acceleration and pressure gradients as well to be negligible, thus using simplified forms of Saint-Venant’s equations as follows (Henderson, 1966):

Continuity:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (3.8)$$

Momentum:

$$S_o - S_f = 0 \qquad (3.9)$$

Therefore, with the conditions of kinematic flow assuming no appreciable backwater effect, the runoff q can be described as a function of depth up to equilibrium as follows:

$$q = \alpha y^m \quad . \qquad (3.10)$$

Next, the equilibrium time and depth must be calculated i.e. the rising side of the hydrograph. Henderson (1966) derived the equation for the equilibrium time T_s where the depth of the water at the downstream end of the plane reaches equilibrium:

$$T_s = \frac{L}{\alpha y_s^{m-1}} \quad , \qquad (3.11)$$

where y_s is the steady state depth (maximum depth), L is the length of the plane, m is 5/3 when obtained from Manning's equation, and α is the conveyance factor from Manning's equation:

$$\alpha = \frac{k_m}{n} S^{1/2} \quad , \tag{3.12}$$

where *S* is the slope of the surface and *n* is the effective roughness coefficient (Manning's n). Due to the dimensionality of *n*, k_m retains the value of 1 for metric units and 1.49 for standard units. Henderson (1966) demonstrated that velocity (rainfall intensity *r*) is constant until steady state is reached and therefore shows the influence *r* has on T_s:

$$T_s = \left(\frac{L}{\alpha r^{m-1}}\right)^{1/m} \quad , \tag{3.13}$$

Combining both equations 3.11 and 3.12 results in

$$y_s = \left(\frac{rL}{\alpha}\right)^{1-m} \quad . \tag{3.14}$$

The kinematic wave model was developed for surface run-off; however, it has been used by hydrologist to model unsaturated subsurface flow for many years (Smith, 1983; Charbeneau, 1984; Germann and Beven, 1985; Yamada and Kobayashi, 1988; Charbeneau et al., 1989). Singh (1997) reduced the governing equations for lateral subsurface flow by first combining the continuity equation (3.15) with Darcy's equation (3.16) to form the general Richard's equation (3.17), and then extracted the diffusion coefficient (3.18) to produce equation 3.19.

$$\frac{\partial\theta}{\partial t} + \frac{\partial q}{\partial z} = 0 \tag{3.15}$$

$$q = -k(\theta)\frac{\partial}{\partial z}(\psi - z) \tag{3.16}$$

$$\frac{\partial q}{\partial t} - \frac{\partial}{\partial t}\left(k\frac{\partial\psi}{\partial z}\right) + \frac{\partial k(\theta)}{\partial t} = 0 \tag{3.17}$$

$$k(\theta)\frac{\partial\psi}{\partial\theta} = D(\theta) \tag{3.18}$$

$$\frac{\partial\theta}{\partial t} + \frac{dK(\theta)}{\partial\theta}\frac{\partial\theta}{\partial x_z} = \frac{\partial}{\partial x_z}\left[D(\theta)\frac{\partial\theta}{\partial x_z}\right] + i \quad , \tag{3.19}$$

where θ is the water content in a particular grid cell at depth z and time t, $K(\theta)$ is the unsaturated hydraulic conductivity, D is the diffusion coefficient, and i is the lateral inflow to the soil layer. In this case i would be the vertical flux from the layers above the index layer.

Kinematics refers to the study of motion without the influence of mass and force. Thus, the kinematic wave model governs without the inertial and pressure forces, therefore only being driven by gravity reflecting advection while considering diffusivity negligible i.e. capillary pressures are negligible (Charbeneau, 2000). Thus, the suction head Ψ is constant with respect to the depth z. This allows the left side of the equation above to be reduced to the following classic kinematic equation:

$$\frac{\partial\theta}{\partial t} + \frac{dK(\theta)}{\partial\theta}\frac{\partial\theta}{\partial x_z} = i \quad . \tag{3.20}$$

In the kinematic model, the value of the volume flux *q* at a specific depth *z* is only a function of the soil moisture θ and is equal to the unsaturated hydraulic conductivity $K(\theta)$. Equation 20 is simplified with a constant $K(\theta)$ for each time step as seen in equation 3.21:

$$q = ki\Delta x \quad , \tag{3.21}$$

The unsaturated hydraulic conductivity can be estimated from a procedure explained in detail by Clapp and Hornberger (1978), where first the wetness of the soil *W* is calculated from the volumetric moisture content θ and the saturated hydraulic conductivity θ_s or, as assumed in this study, the total porosity.

$$W = \frac{\theta}{\theta_s} \quad . \tag{3.22}$$

Given the difficulty in specifying the hydraulic relationships once ignoring capillary pressures, Campbell (1974) used a power curve to derive the relative hydraulic conductivity *k* by

$$k = W^{2b+3} \quad , \tag{3.23}$$

where b is an empirical exponent that must be estimated and k is equal to the ratio of the unsaturated hydraulic conductivity to the saturated (K/K_s). Clapp and Hornberger (1978) estimated values for b that ranged from 4.05 (St. Dev. = 1.78) for a sandy soil to 11.4 (St. Dev. = 3.70) for clay.

3.4 Nutrient Flushing

Once the amount of water flowing laterally from both the surface and subsurface is determined, the amount of transported nutrients can be calculated. The plant uptake of nitrogen as well as its cyclical dynamics will be determined from DSSAT. The net result of DSSAT will be the amount of nitrate N remaining in each soil layer. The fraction of nitrate that will be removed from each layer by the moving water can then be determined using the methodology of the Soil and Water Assessment Tool (SWAT) model as presented by Neitsch et al. (2005):

$$conc_{NO3,mobile} = \frac{NO3_{ly} \cdot \left(1 - e^{\frac{-w_{mobile}}{(1-\theta_e) \cdot SAT_{ly}}}\right)}{w_{mobile}} \quad , \tag{3.24}$$

Where $conc_{NO3,mobile}$ (kg N/mm H_2O) is the concentration of nitrate transported, $NO3_{ly}$ $NO3_{ly}$ (kg N/ha) is the amount of nitrate in the soil layer available for movement, w_{mobile} (mm H_2O) is the amount of mobile water in the layer,θ_e is the fraction of the

porosity from which anions are excluded, and SAT_{ly} (mm H_2O) is the saturated water content, or porosity in this study, of the soil layer. The amount of mobile water in each layer can be determined from the hydrologic equations above. For surface runoff, the amount of nitrate in the top 5cm of soil will be "flushed". Figure 3.4 summarizes the routing schemes throughout the soil profile.

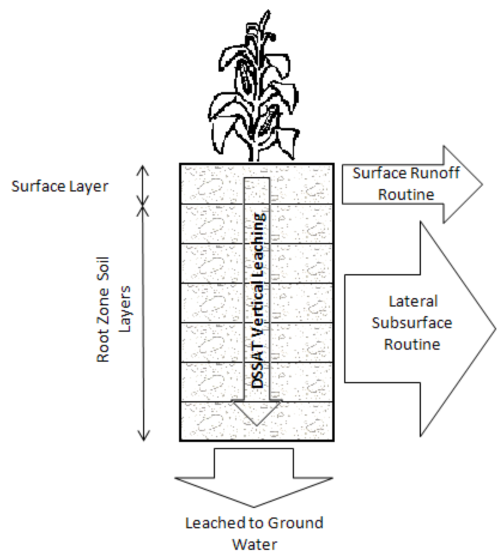


Figure 3.4: Soil column routing scheme

CHAPTER IV

METHODOLOGY

It is the aim of this chapter to present the basic outline of how the results of this investigation were accomplished through a generalized work flow of the procedures. It will include the nutrient and moisture transport routines and the overall coupled flowchart.

When first trying to understand how irrigation affects the nutrient fate and transport in agricultural areas, the main contributors and detractors must be known. In an agricultural field the obvious major contributor would be the application of fertilizer. The growth of the crop is crucial as well, as it is the purpose of the fertilizer application, and thus the major consumer of nutrients. Therefore, the first step in this study was the selection of a model to fully simulate the growth and nutrient cycles of agricultural crops. The DSSAT model was selected as an appropriate and universally used agricultural model.

Another initial step in this study was the selection of an agricultural field to monitor and use as a calibrator for the agricultural model. The Tennessee Valley

Research and Extension Station (TVS), also called Belle Mina, was chosen for several reasons. Belle Mina is an agricultural research station of Auburn University. Not only would this field provide the crops to simulate but also detailed information of all planting and growing procedures are known. In addition comprehensive climate data are recorded at the station.

Once the model and field were selected, the next step was to obtain all the data necessary to run and calibrate the model. An experiment lead by Dr. Brenda Ortiz (Assistant Professor and Extension Specialist, Department of Agronomy and Soils, Auburn University) was used and simulated. The experiment included several different fertilizer applications on corn. Planting dates, fertilizer application dates along with soil information as well and climate data and irrigation schedules were all compiled to run the DSSAT model. The experiment only included irrigated treatments, thus this was the only scenario used for calibration. The model was run for two seasons 2010 and 2011. The recorded yields for 2010 were used to calibrate an individual cultivar for the study. Next, soil samples were taken twice throughout the current growing season (2011) for each treatment in Dr. Ortiz's experiment. These data were used to further validate the model and provide values for the initialization of soil parameters. Then, each fertilizer application, as specified by Dr. Ortiz's treatments, was modeled in both an irrigated and rain-fed scenario.

As mentioned previously, DSSAT does not fully model the transport of the nitrogen, that is, it does not include lateral surface or subsurface transport. Thus, a main

objective of this study is to create a hydrologic routine to run outside of DSSAT and model those transport scenarios. To be able to accurately estimate both the surface and subsurface lateral transport, the kinematic wave approximation was used. Any nutrients that were available in the top 5cm of soil, as reported by DSSAT, were considered available to be transported with any surface runoff, that is, any excess water that is not infiltrated by the soil. Any water that was exported from the field would then take the calculated available nitrate with it.

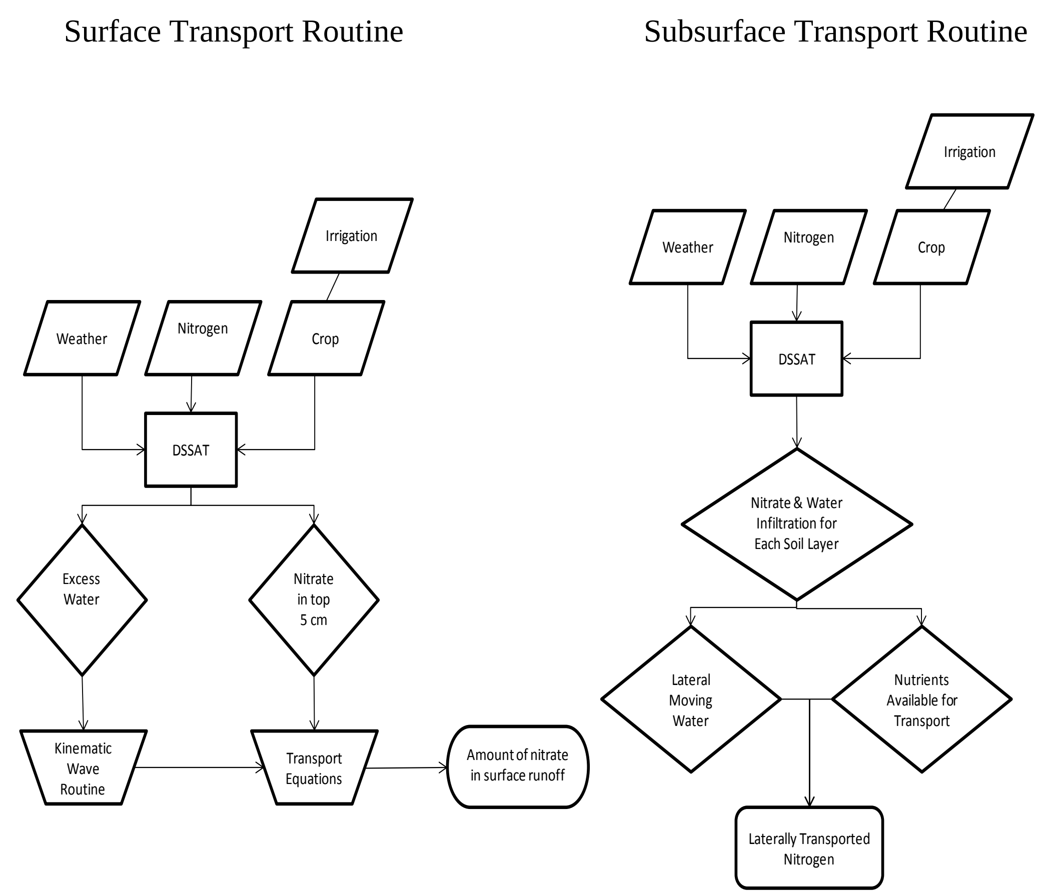


Figure 4.1: Surface and subsurface transport routines.

In the subsurface routine, the water content in each soil layer is reported by DSSAT as well as the amount of nitrate. The amount of water in the soil layer was used

to determine the amount of nitrate that was available to be transported. And thus, in similar fashion to the surface routine, the amount of water calculated to flow laterally would leach the available nitrate. A flow chart of the surface and subsurface transport routines can be seen in Figure 4.1.

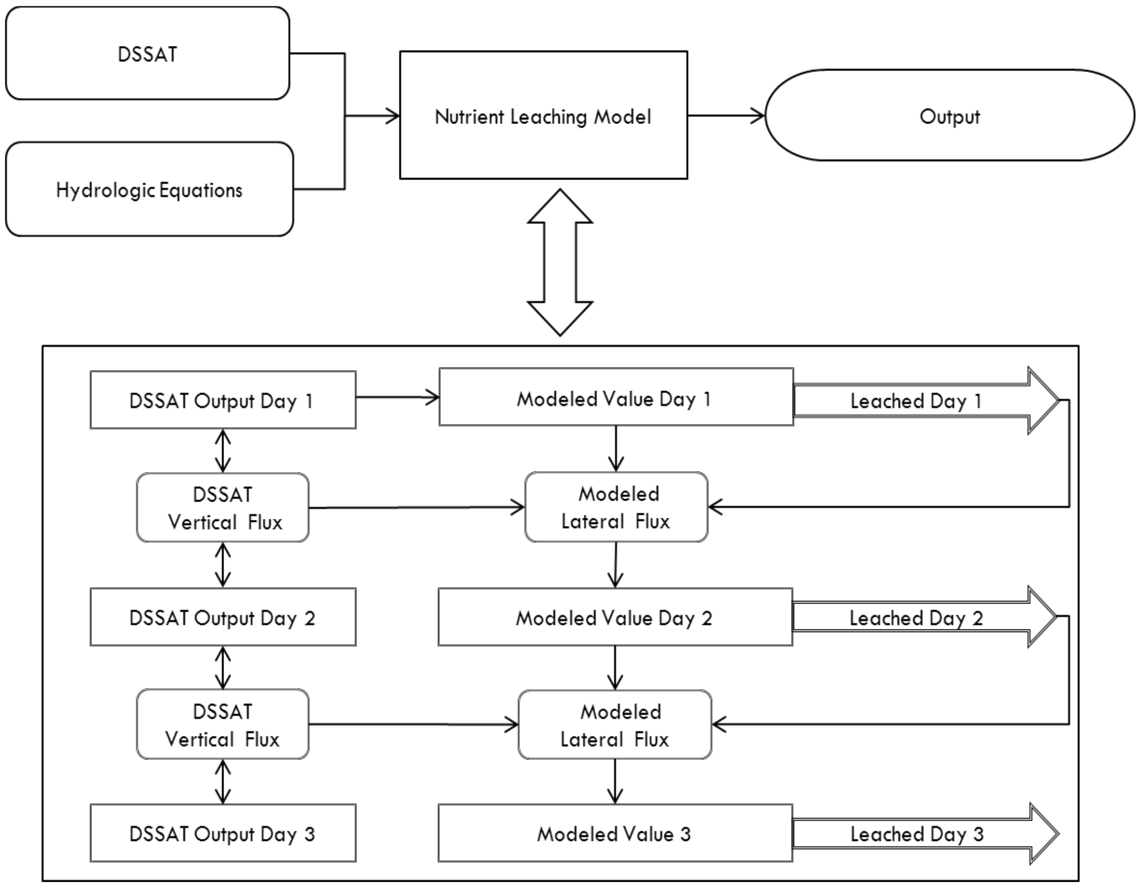


Figure 4.2: Detailed coupled process

It is important to note that the surface and subsurface nitrate transports are analyzed independently. Since the hydrologic routines occur outside the DSSAT model, any surface runoff events will not reflect that deficit in the subsurface. This error is accepted by the author as it does not compromise the overall study of the comparison of

rain-fed and irrigated scenarios. In addition, model error is recorded in the daily time step of export. Each day a value of moisture and nitrate are retrieved from DSSAT. Both the nitrogen and the moisture that carries it are routed laterally out of the soil column. The existing vertical transport by DSSAT is simply conducted on the remaining moisture and nitrate concentrations. This error is due to the fact that the hydraulic routing routines exist outside the DSSAT model. The error lies in the fact that the vertical leaching would change slightly with minor differences in the concentrations. This process can be seen in Figure 4.2. To measure this error an overall mass balance was tracked throughout each daily time step. This error exists in the top 5 cm of soil for the surface runoff and throughout the total soil column. The surface export experienced the greatest error with a value of 1.8% overall for the worst treatment, i.e. largest amount of applied fertilizer. The subsurface error was less with the greatest error less than 1%. This error is even less problematic when considering the contribution of the subsurface to the overall amount leached from the field. The error reported occurs for both the rain-fed and irrigated simulations and is not considered to effect the overall interpretation of the results.

To better represent the overall processes of this study, the flowchart featured in Figure 4.3 is presented to the reader. Output from DSSAT is dependent on the climate and soil data as well as the agricultural practices, i.e. planting date, fertilizer and irrigation applications etc. The hydrologic and nutrient transport routines are then performed on the DSSAT output.

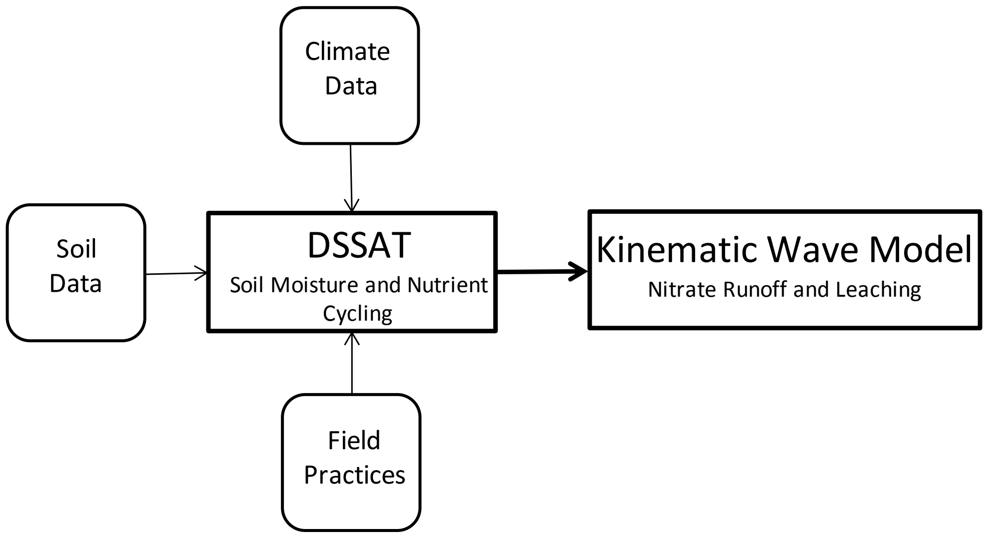


Figure 4.3: General transport routine

CHAPTER V

EXPERIMENTAL SET-UP

Several aspects of this study have yet to be discussed. It is the aim of this chapter to provide the reader with information about the setup of this investigation including a detailed analysis of the study area. The data acquisition and a description of the experiment conducted by Dr. Brenda Ortiz (Auburn University), from which calibrated data were received and measured, will be presented. In essence, this chapter will provide the reader with all aspects of the study needed to fully understand the results and discussion therein.

5.1 The Study Area

The selection of a field for these measurements and observations for model input and calibration is vital. The agricultural field that this study was based on was an agricultural research station of Auburn University. The TVS, also referred to as Belle Mina (the town in which it is located), was chosen based on location and accessibility. In addition, an Agricultural research station provides a more controlled environment along with detailed knowledge of the fields and their history. It resides in north Alabama in

western Limestone County, in between Huntsville and Decatur (Figure 5.1). The crop that was modeled was corn (*Zea mays L.)* due to its vast presence in cultivated North American fields. Corn, by its nature, needs a lot of nitrogen to produce profiting yields, and has become a major contributor to the agricultural runoff that presses our environment. In Alabama, corn is grown seasonally in the summer months leaving the winter and early spring as fallow, unless cover crops are planted. This provides the needed design to allow the movement of residual nitrogen to be observed and simulated, better representing actual practices of corn cultivation. The cultivar used in the experimental study was DeKalb 67-87, and was calibrated for the simulation models as well.

The most important aspect of this study, nitrate movement, is directly dependent on soil information. Due to the complex differential, both vertically and laterally, of soil properties, a single representative soil was used for this study. The soil used in this investigation is a silty clay loam, a common soil in the north Alabama region. The soil texture is brownish red, with moderate drainage. The soil classification for the representative soil was retrieved from the Natural Resources Conservation Service's (NRCS) soil survey (Table 5.1a). From this information soil properties seen in Table 5.1b were calculated. The curve number (CN) associated with this soil is 73, with an albedo of 0.13.

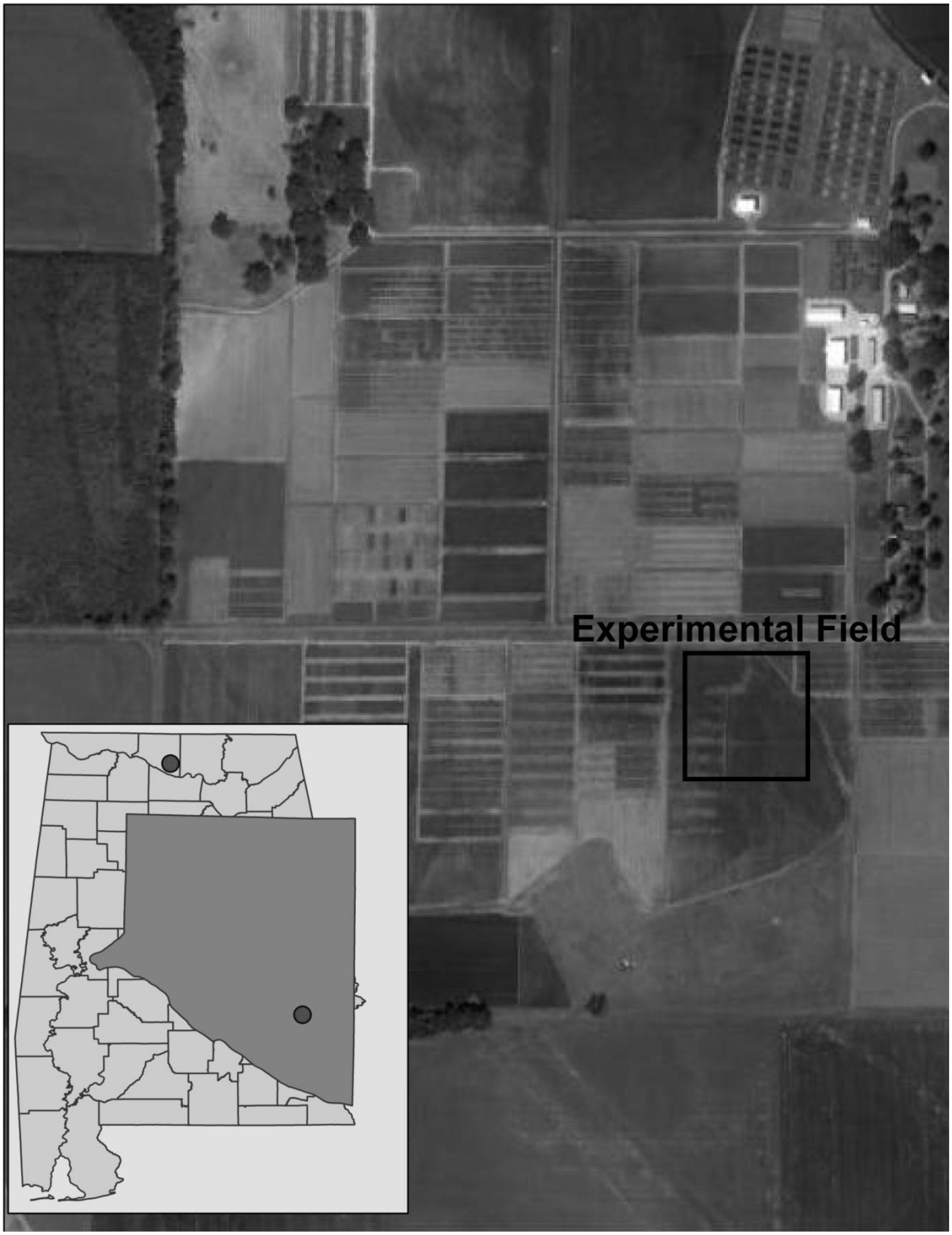


Figure 5.1: Tennessee Valley Station, Belle Mina, AL (Google Earth, 2011; Census, 2010)

Table 5.1: Soil a: classifications (NRCS) b: properties.

(a)

Depth (cm)	Master Horizon	Clay (%)	Silt (%)	Sand (%)	pH (In Water)	Cation Exchange Capacity (cmol/kg)	Total Nitrogen (%)
5	Ap	31.1	56.2	12.7	6.7	0.2	0.43
20	Bt 1	36.7	50.2	13.1	7.4	0.2	0.14
46	Bt 2	48.9	43.1	8	7.3	0.3	0.09
104	Bt 3	54.1	38.4	7.5	7.1	0.3	0.08
132	Bt 4	56.5	34.6	8.9	5.1	0.3	0.08
152	Bt 5	56.2	33.8	10	5.1	0.3	0.08

(b)

Depth (cm)	Master Horizon	Lower Limit	Drained Upper Limit	Saturation	Bulk Density (g/cm3)	Saturated Hydraulic Conductivity	Root Growth
5	Ap	0.172	0.346	0.485	1.29	0.15	1
20	Bt 1	0.204	0.373	0.492	1.27	0.15	1
46	Bt 2	0.284	0.444	0.514	1.21	0.09	0.54
104	Bt 3	0.319	0.472	0.517	1.2	0.06	0.001
132	Bt 4	0.334	0.483	0.521	1.19	0.06	0.001
152	Bt 5	0.332	0.48	0.517	1.2	0.06	0.001

Another factor directly affecting the results of this study is the weather data. With the selection of Belle Mina as the study area, local weather data was reasonably easy to obtain through the Alabama MesoNet. The Alabama MesoNet, is a collaboration of the National Aeronautics and Space Administration (NASA), United States Department of Agriculture (USDA), and Alabama A&M University that collects local weather and soil data throughout Alabama. TVS had a dedicated MesoNet Weather Station. This investigation utilized daily rainfall, minimum and maximum temperatures, and the solar radiation. The factors have direct influence on the models handling of the crop growth and soil water and nutrient balance. Weather data can vary drastically on a spatial scale; however, having data from the local site in question should provide an accurate representation of the actual weather. The weather data obtained for the model validation extends from January 2010 to August 2011, and generated weather data were used to

complet the 2011 simulation though March 2012. The weather data, both actual and generated can be seen in Appendix A.

5.2 Experimental Design

The experiment used in this study was designed and conducted by Dr. Brenda Ortiz of Auburn University. The objective of the experiment is to evaluate the impact of Nitrogen fertilizer rates and timing on the starch content, ethanol, and grain yield of two different corn hybrids. The experiment is a split plot design with the two hybrids assigned to the main plots. Nitrogen rates were assigned to the subplots and are applied in three different increments: pre-plant, split, and side-dress. The pre-plant application requires all the fertilizer to be placed before or at planting, split application requires the amount to be split over two applications, and the side-dressing requires roughly a 1/3 of the amount be applied up front as a pre-plant while the remaining 2/3 is to be applied with the second application. The experiment considers both the 2010 and 2011 seasons. Each experiment was conducted in different fields, and were therefore simulated separately and independantly. Including a control with no fertilizer applied, there were a total of 16 treatments with 4 replications in 2010 and 5 replications in 2011. The two application dates were to be determined by field conditions. The first application was applied on April 2, 2010 and April 7, 2011 with planting and the second application was applied on May 14, 2010 and May 11, 2011. Five different fertilizer amounts were used: 50, 100, 150, 200, 250 pounds per acre. The treatments and both plot layouts can be seen in Table 5.2, Figure 5.2 and 5.3, respectively. The 2010 experimental plots were 30 feet

long by 4 rows and the alleys between the replications were 30 feet (Figure 5.2). The 2011 experimental plots were 10 feet in width and 40 feet long (Figure 5.3). In Figure 5.2 and 4.3, the top number represents the replication number and the second number represents the treatment number.

Table 5.2: Treatment descriptions

Treatment Number	Nitrogen Application	Increment	Treatment Number	Nitrogen Application	Increment
1	100-0	pre-plant	9	60-140	side-dress
2	50-50	split	10	250-0	pre-plant
3	30-70	side-dress	11	125-125	split
4	150-0	pre-plant	12	80-170	side-dress
5	75-75	split	13	0-0	CONTROL
6	50-100	side-dress	14	50-0	pre-plant
7	200-0	pre-plant	15	25-25	split
8	100-100	split	16	0-50	side-dress

413 13	414 14	415 9	416 3	213 13	214 12	215 15	216 7
409 15	410 5	411 8	412 7	209 2	210 5	211 6	212 10
405 2	406 10	407 6	408 16	205 3	206 1	207 16	208 8
401 4	402 11	403 12	404 1	201 14	202 9	203 4	204 11
313 12	314 16	315 14	316 4	113 15	114 5	115 131	116 132
309 13	310 1	311 8	312 2	109 13	110 12	11 2	112 10
305 5	306 10	307 11	308 3	105 1	107 3	107 6	108 4
301 6	302 7	303 15	304 9	101 11	102 9	103 16	104 7

Figure 5.2: 2010 Experimental plot layout

501 12	502 13	503 7	504 14	505 10	506 6	507 3	508 4	509 5	510 2	511 1	512 11	513 16	514 15	515 8	516 9
401 9	402 11	403 16	404 8	405 12	406 10	407 5	408 3	409 7	410 15	411 4	412 2	413 1	414 14	415 6	416 13
301 13	302 4	303 11	304 2	305 12	306 7	307 1	308 5	309 8	310 15	311 10	312 3	313 16	314 14	315 9	316 6
201 5	202 1	203 6	204 4	205 11	206 7	207 14	208 3	209 2	210 13	211 10	212 9	213 16	214 8	215 12	216 15
101 6	102 14	103 7	104 10	105 16	106 2	107 5	108 8	109 15	110 11	111 13	112 3	113 12	114 9	115 1	116 4

Figure 5.3: 2011 Experimental plot layout

5.3 Model Calibration

With the experimental design in place along with all needed inputs, DSSAT could be calibrated. Both the crop development and the soil modules were calibrated. For the model to accurately predict the amount of residual nitrate N in the soil, the crop's developmental growth must be calibrated using measured data. The DSSAT model has both an ecotype and a cultivar coefficient that controls the growth and development of a crop. The ecotype coefficients define certain coefficients for groups of cultivars that show similar behavior and response to environmental conditions, while the cultivar coefficients affect a variety specific coefficient such as seed size, time to flowering and maturity etc. In addition each crop has species coefficients which are coefficients that are common to all cultivars. The calibration of the corn cultivar used in this study used the specific cultivar coefficients. The Crop-Environment Resource Synthesis (CERES) Maize cropping system model (CSM) has 6 controlling cultivar coefficients. There are three types of cultivar coefficients: life cycle, vegetative growth, and reproductive growth. Table 5.3 describes each cultivar coefficient (Jones et al., 1998).

Table 5.3: Cultivar coefficient descriptions (Jones et al., 1998)

	Variable	Definition
Life cycle	P1	Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not reponsive to photperiod
	P2	Delay in development (days) for each hour that daylenght is above 12.5 hours. Maximum development occur at less than 12.5
	P5	Thermal time from silking to physiological maturity
Vegitative Growth	PHINT	Phyllochron interval- the thermal time between successive leaf tip appearances
Reproductive Growth	G2	Maximum possible number of kernals per plant
	G3	Kernal growth rate during linear grain filling statge under optimum conditions

Based on the data available from Dr. Ortiz's experiment, the cultivar was calibrated on the crop yield. The coefficients that were adjusted were G2 and G3. The calibration moved G2 from 890.0 to 879.8 and G3 from 8.50 to 7.202. All other coefficients were unchanged.

The next state of calibration was the initialization of the carbon pool in the Century organic soil module. As previously stated in the theoretical chapter, the Century soil module was introduced to model the soil organic carbon more accurately. Century's ability lies in simulating N and CO_2 release from organic matter already in the soil when a cropping system is simulated. However, it is the initialization of the carbon pools that is essential. The three different pools were initialized based on the field history and current N concentrations. Soil samples were taken to monitor the DSSAT N simulations. The initialization values for the soil profile as well as the measured soil nitrate data and the 2010 measured yield can be found in Appendix E. Further detail of the calibration can be viewed in the results section.

CHAPTER VI

RESULTS AND DISCUSSION

The goal of this study is to evaluate the surface and subsurface transport of nutrients under irrigated agricultural fields as compared to rain-fed fields. This chapter will present the findings. Beginning with field data comparisons, attempting to show the validity of the model; this chapter will include a thorough discussion of the results. A representative selection of model runs was chosen to showcase different fertilizer amounts and applications including a control and will be described in detail to provide an overall synopsis of the results, however all data pertaining to the selected treatments and a comprehensive summary of all data simulated will be presented in Appendix B.

6.1 Model Validation

DSSAT is a widely used and a well calibrated and validated model used for many studies that include plant physiology and phenology (Zhang and Oweis, 1999; Guerena et al., 2001; Lopez-Cedron et al., 2008). These studies along with many others have used DSSAT for many different crops and scenarios refining its functions. Therefore, the only

parameters that were calibrated were for the individual corn cultivar and are mentioned in detail in the previous chapter.

Yield data for the 2010 growing season, from Dr. Ortiz's experiment, is known and can be compared with the simulated values. In addition to the yield, soil nitrate measurements were taken for all treatments in 2011. Figure 6.1 shows the comparison of the simulated versus the measured yield for the corn crop that was modeled. Since the experiment had 5 replications, the measured minimum and maximum were used. The simulated yield lies between the minimum and maximum recorded yield from most treatments, with the exception of the first three treatments, where it overestimated the yield. Treatment 13, the control treatment that received no fertilizer, was matched almost perfect.

For further examination a simulated vs. average measured plot is provided in Figure 6.2. Both Figure 6.1 and 6.2 show the lack of DSSAT to model the full variance in treatments, however, it provides a good estimate of the averages of each replication in most cases. Next Figure 6.3 and 6.4 showcase the simulated soil nitrate for two different treatments, 1 and 10, as compared to the measured values. Treatments 1 and 10 were chosen to represent a small and large nitrogen application. The two measurements were taken on March 23, 2011 and June 16, 2011. It is with regret that no soil samples was taken between to evaluate the most extreme dynamic simulation; conditions beyond the authors control would not permit. However, the measured points available do show the accuracy of the simulation. All measured calibration data can be found in Appendix E.

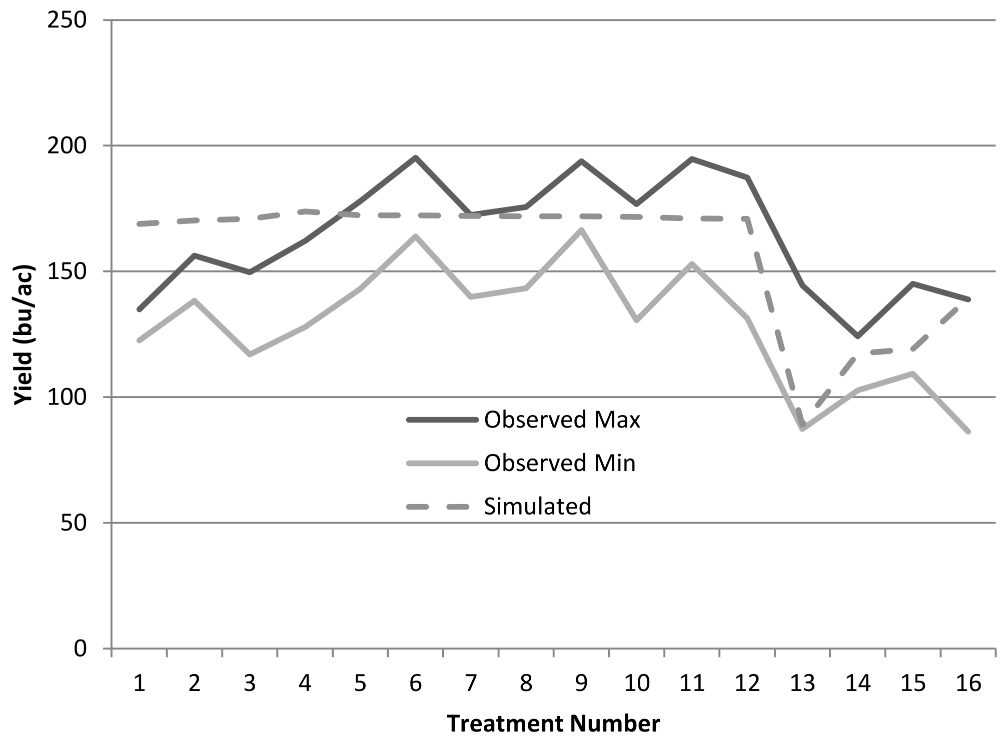


Figure 6.1: Comparison of measured and simulated yields

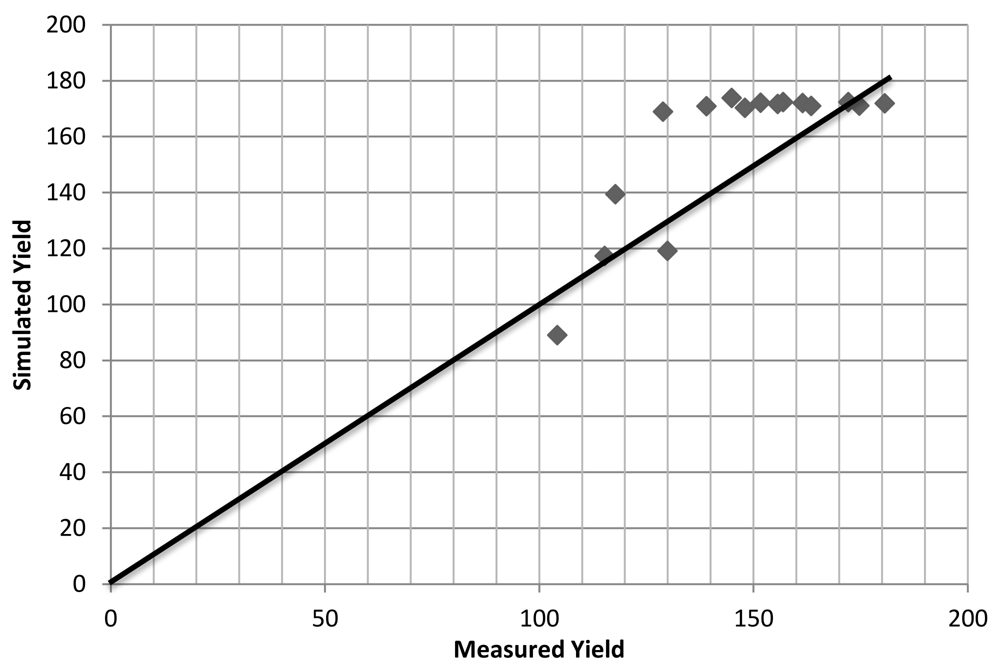


Figure 6.2: Simulated versus measured yield

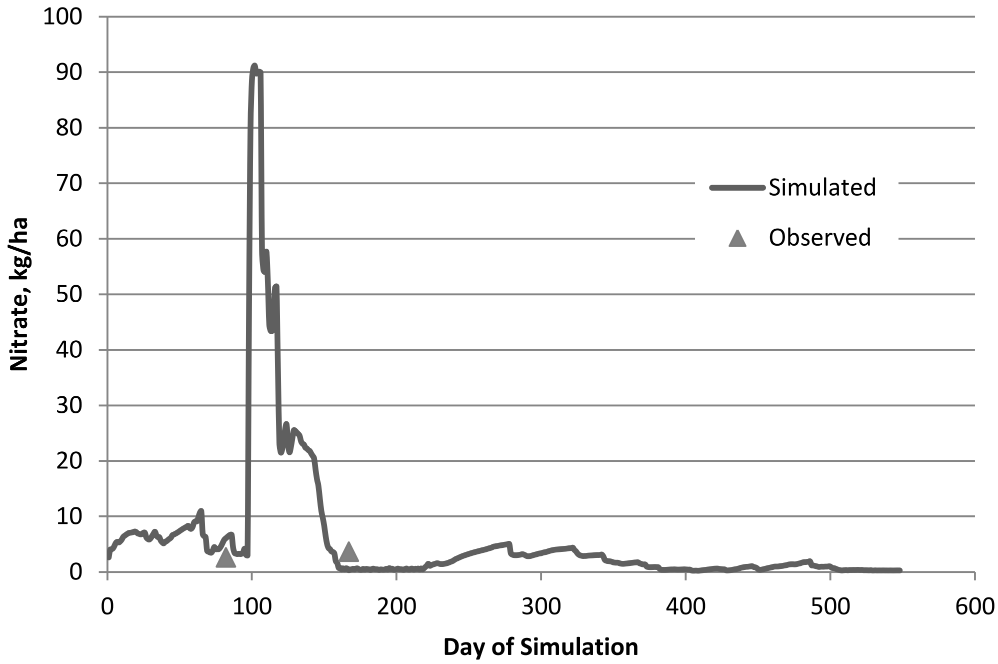


Figure 6.3: Comparison between simulated and observed subsurface nitrate for treatment 1 (112kg/ha)

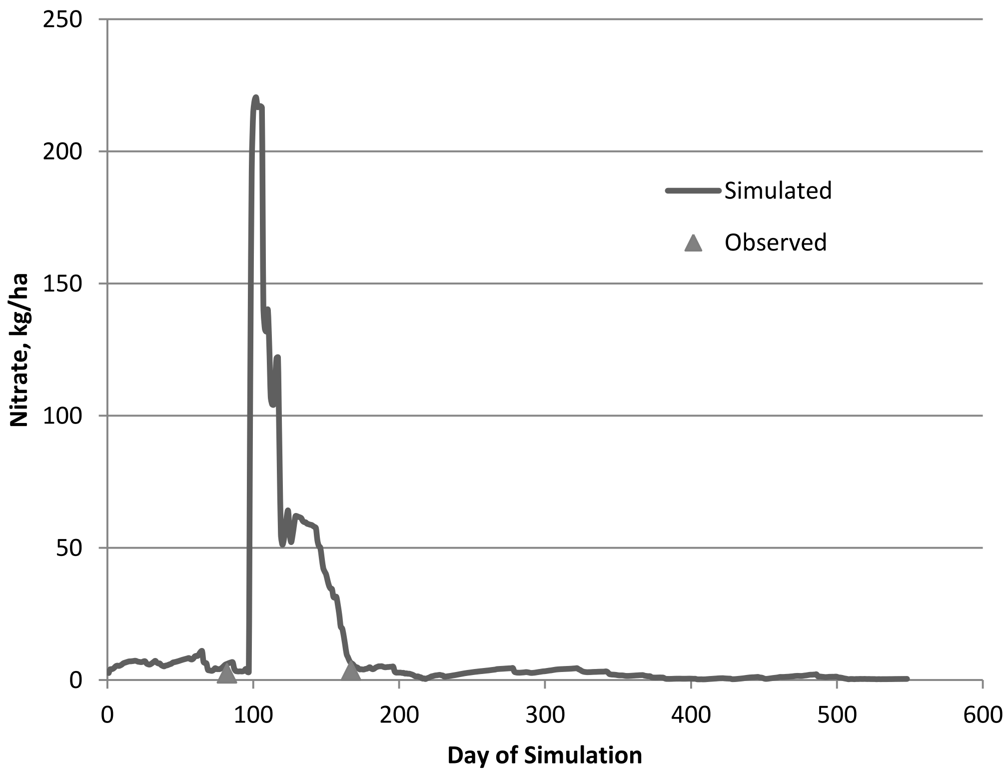


Figure 6.4: Comparison between simulated and observed subsurface nitrate for treatment 10 (280 kg/ha)

6.2 Surface Transport

It is clear that DSSAT is capable to simulate the soil nitrogen dynamics as well and the plant phenology and physiology, including the uptake of nitrogen by the plant. This section will provide the results and analysis of the surface transport of any nitrate that was not consumed by the plant or infiltrated beyond the top 5 cm of the soil column. Two different growing seasons were simulated, 2010 and 2011. Figures 6.5 and 6.6 show the daily rainfall for each simulation, 2010 and 2011, respectively. Each simulation ran from January of the beginning year to the following March to fully simulate the residual soil nitrate as well as while the crop was in the ground. Figures 6.5 and 6.6 also show the irrigation applications for each year. The 2010 simulated season received 180.8 centimeters (71.18 in) of precipitation, while the 2011 simulated season received 173.3 centimeters (68.23 in). However, the majority of the rainfall that occurred in the 2010 simulated season occurred after harvesting on September 19. Of the total precipitation that was recorded, only 69.9 centimeters (27.52 in) or about 40% was received during the crops growing season. This is the reason that more irrigation was applied to the 2010 season. The 2011 growing season received 52%, or 35.5 inches (90.1 cm). Tables 6.1 and 6.2 provide the irrigation application dates and amounts. The 2010 season received a total of 21.3 centimeters (8.4 in) of additional water (irrigation), while the 2011 received 17.9 centimeters (7 in).

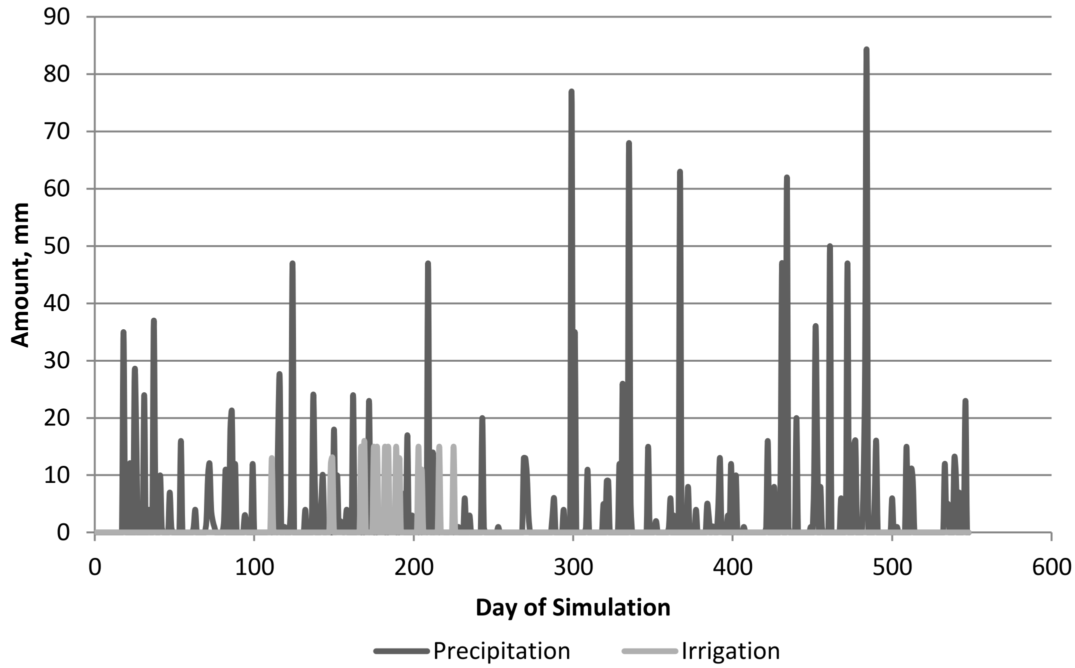


Figure 6.5: 2010 Precipitation and irrigation events

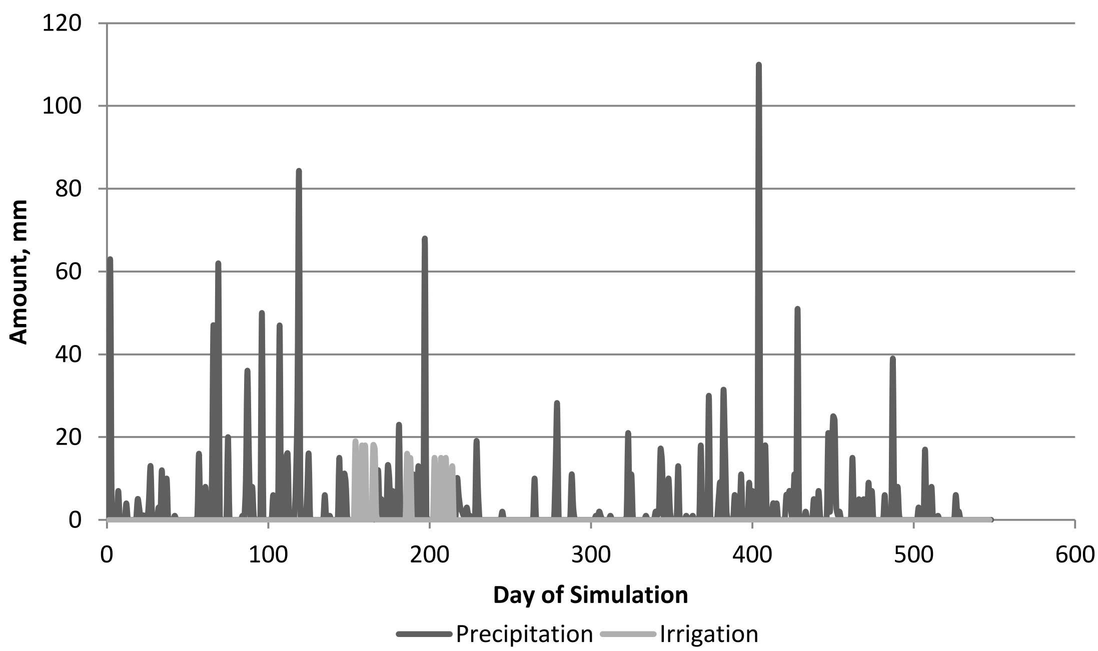


Figure 6.6: 2011 Precipitation and irrigation events

Table 6.1: 2010 Irrigation schedule

Date	Amount (mm)	Date	Amount (mm)
4/20/2010	12.7	7/2/2010	15.24
5/27/2010	12.7	7/7/2010	15.24
5/28/2010	12.7	7/9/2010	12.7
6/15/2010	15.24	7/21/2010	15.24
6/17/2010	15.24	7/23/2010	10.16
6/23/2010	15.24	8/3/2010	15.24
6/25/2010	15.24	8/12/2010	15.24
6/30/2010	15.24		

Table 6.2: 2011 Irrigation schedule

	Amount (mm)	Date	Amount (mm)
6/3/2011	19.05	7/7/2011	15.24
6/7/2011	17.78	7/22/2011	15.24
6/9/2011	15.24	7/26/2011	15.24
6/14/2011	15.24	7/29/2011	15.24
6/15/2011	15.24	8/2/2011	12.7
7/5/2011	15.24		

As mentioned, the method DSSAT uses to partition the runoff form the infiltrated water is the SCS curve-number method. Any surface water that is not infiltrated by DSSAT is routed off the surface using the kinematic wave approximation. It was expected that once irrigation commences in each season, the runoff values should begin to differ from the rain-fed field. Figures 6.7 and 6.8 present the daily runoff values for both the 2010 and 2011 season and compares the irrigated fields to the rain-fed fields. The rain-fed field's daily values were offset by 5 days to be able to show both simultaneously. It can be seen, from both Figures 6.7 and 6.8 that once irrigation begins the runoff values for the irrigated fields begin to accumulate more than the rain-fed. The 2010 season begins irrigation on April 20, but actually starts irrigating regularly on May 27. This corresponds to the simulation days 97 and 147, respectively. Any runoff values between the start of irrigation and the end of the season results in the irrigated field transporting more water off the field. This can be seen as well in the 2011 season; irrigation begins on June 3, 2011 (day 153).

As mentioned previously, any nitrate that is present in the top 5 cm of the soil column that is available for transport will be carried with any water that runs off the surface of the field. Figures 6.9 through 6.16 showcase the surface nitrate runoff for 4 different treatments, for both rain-fed and irrigated simulations while Table 6.3 presents the summary totals. In these graphs, the irrigated runs were offset by 5 days for visual interpretability. For treatment 1 (Figure 6.9), where 112 kg/ha was applied in a single pre-plant application, the total nitrate that was exported was 33.8 kg/ha for the irrigated while the rain-fed field transported 33.5 kg/ha.

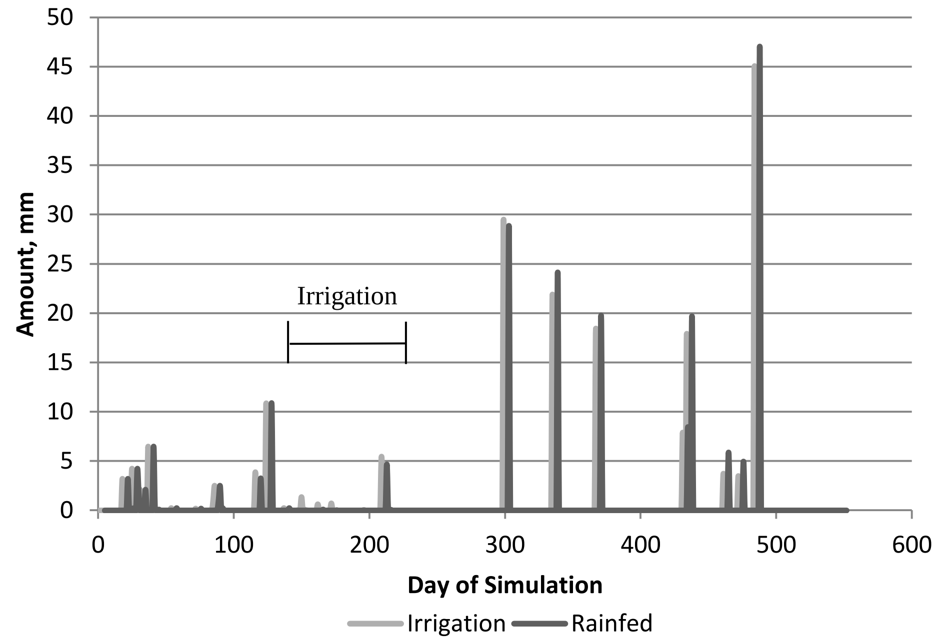


Figure 6.7: 2010 Surface runoff events

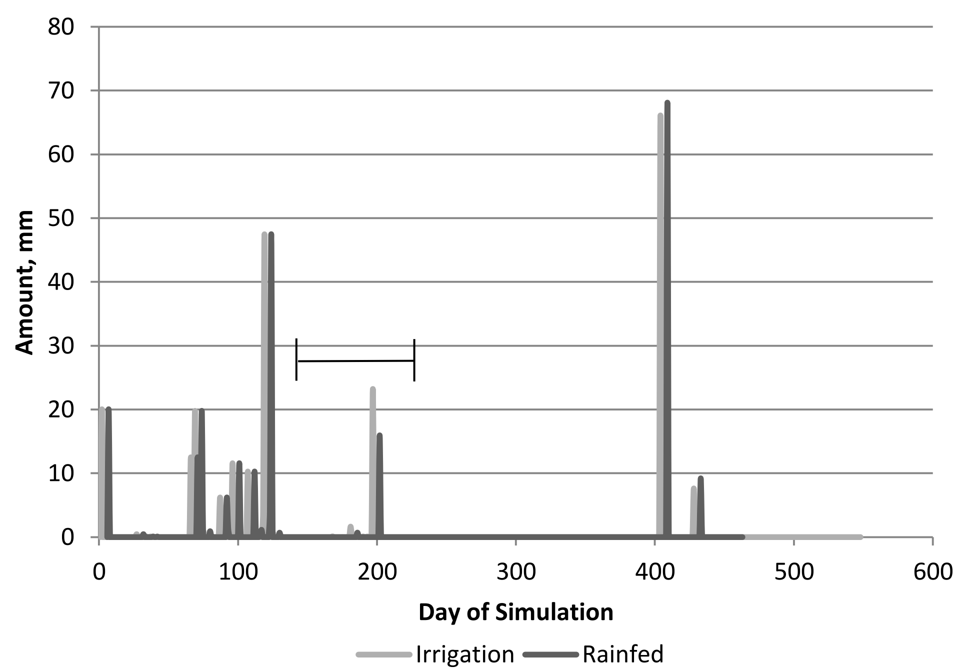


Figure 6.8: 2011 Surface runoff events

The individual runoff events are associated, as expected, to the individual precipitation runoff events. Most runoff events in Figure 6.9 appear to be equal however the major runoff event on April 26, 2010 (day 116) shows that the rain-fed field exported more nitrate than the irrigated, despite the fact that the amount of precipitation runoff was more on the irrigated field, 3.88 mm compared to 3.26 mm. This suggests that the irrigation applied on April 20 (day 111) moved the surface nitrate into the soil column more effectively. 2011 shows similar results. However, when the totals amounts exported, there does not appear to be a major difference in rain-fed and irrigated fields for treatment 1 (Figure 6.10).

Table 6.3: Export totals, kg/ha

	2010		2011	
	Nitrate Runoff		Nitrate Runoff	
Treatment	Irrigated	Rain-fed	Irrigated	Rain-fed
1	33.8	33.5	42	41.7
6	26.6	40.8	23.6	25.7
11	47.5	63.6	50.9	54.9
13	8.1	6.9	6.7	6.5

Figures 6.11 and 6.12 provide the results for the surface export of treatment 6. Treatment 6 consists of 168 kg/ha applied nitrogen, with roughly a third applied at pre-planting and the rest side dressed. In both seasons, the irrigated fields exported less nitrate than the rain-fed field. This can be seen especially in the 2010 season. If the previous treatment suggested that the nitrate moves into the soil column more effectively

with irrigation, Figure 6.11 proves it. The amount of runoff for the irrigated and rain-fed fields on October 25, 2010 (day 299) was 29.5 mm and 28.86 mm, respectively, however, no significant amount of nitrate was exported from the irrigated field. The 2011 season (Figure 6.12) resulted in less nitrate exported than the rain-fed simulation, however, not as significant of a difference. This is expected because, as mentioned before, 2010 experienced more of a drought than 2011 did.

The last two treatments that are presented are treatment 11 and 13. Treatment 11 considers 280 kg/ha of fertilizer evenly split between pre-pant and a side dress, while treatment 13 is the control and considers no applied nitrogen fertilizer. In both treatment simulations, the similar pattern that was recognized earlier exists: The differences in exported nitrate on the irrigated field compared to rain-fed are more drastic in the 2010 season than the 2011. Treatment 11 simulations suggest that the benefit of irrigation increases as the amount of nitrogen fertilizer increases. The irrigated field exported 24.5% less nitrate than the rain-fed (Figure 6.13 and 6.14, Table 6.3). The amount of exported nitrate in the control treatment is much less in both the irrigated and rain-fed than other treatments since no fertilizer was applied (Figure 6.15 and 6.16, Table 6.3). The rain-fed field's total exports were less than the irrigated in both seasons. The comparative increase in irrigated nitrate transport can be simply attributed to the fact that more precipitation ran off the field than the rain-fed. This includes days were minimal runoff occurred on the irrigated fields when no runoff occurred on the rain-fed field. The total surface nitrate exports from all treatments can be seen in Table 6.3.

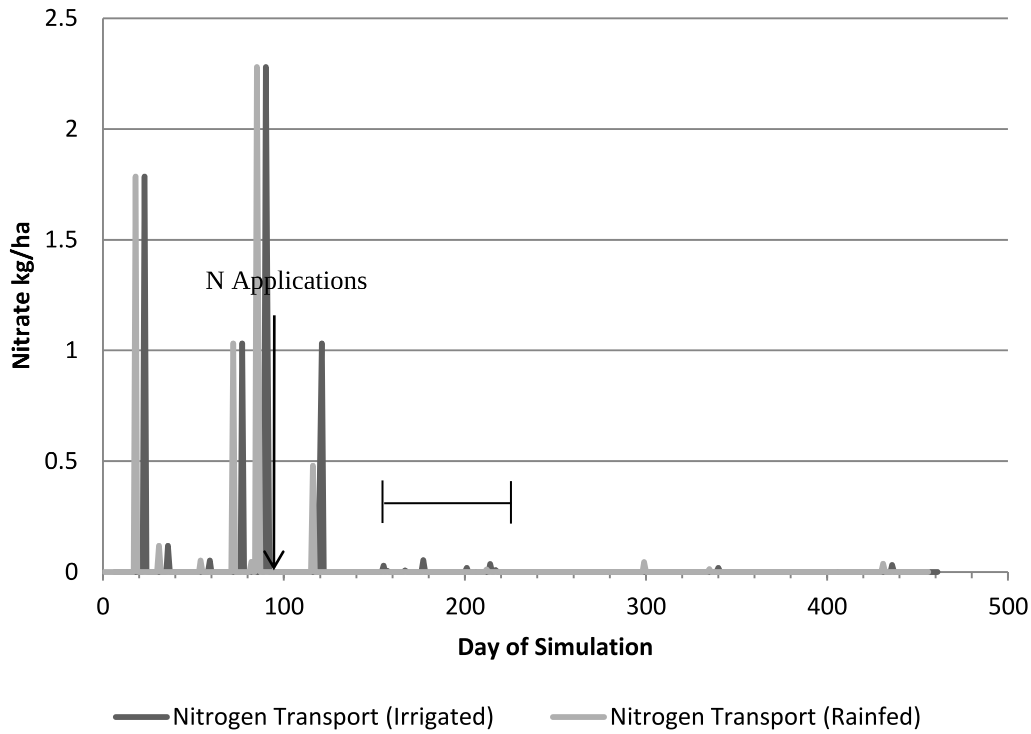


Figure 6.9: Comparative surface nitrate runoff for treatment 1 (Jan. 2010- March 2011)

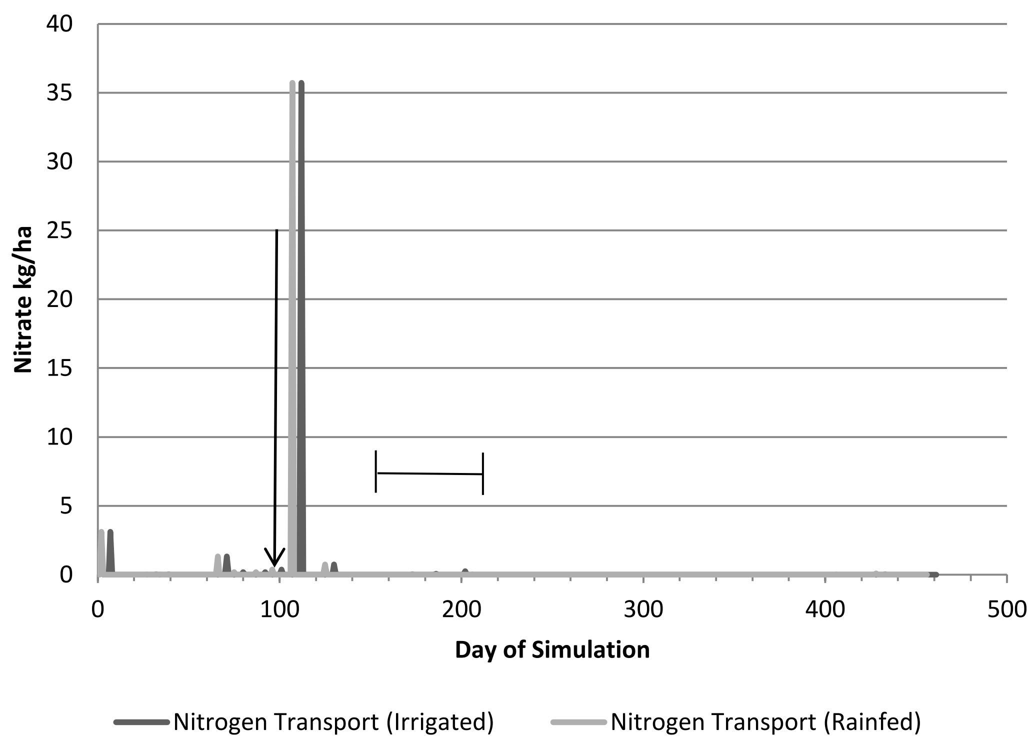


Figure 6.10: Comparative surface nitrate runoff for treatment 1 (Jan. 2011- March 2012)

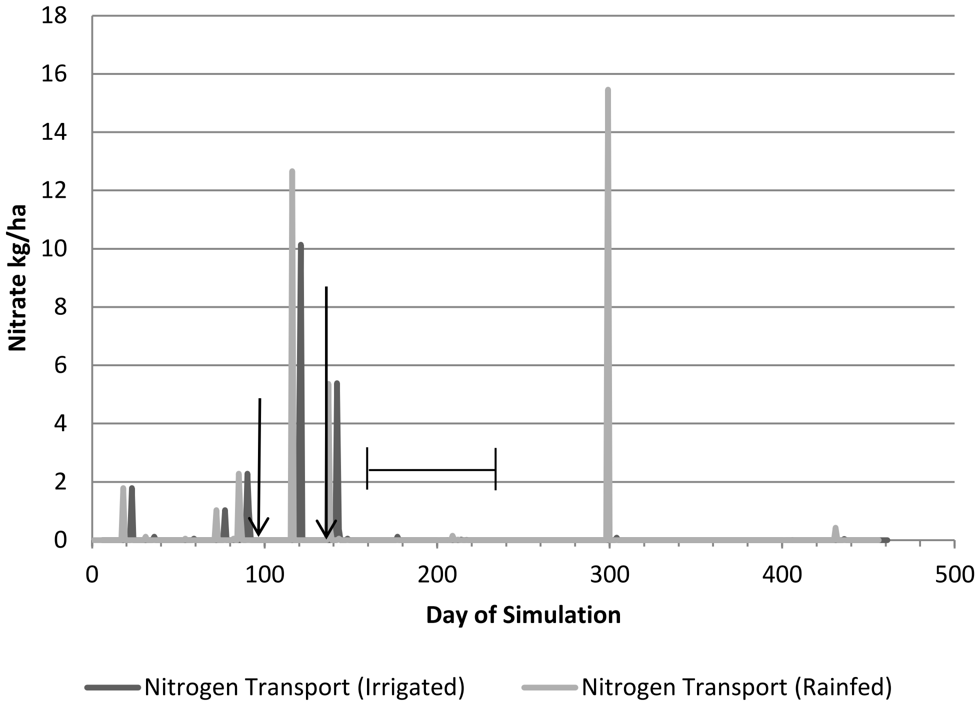


Figure 6.11: Comparative surface nitrate runoff for treatment 6 (Jan. 2010- March 2011)

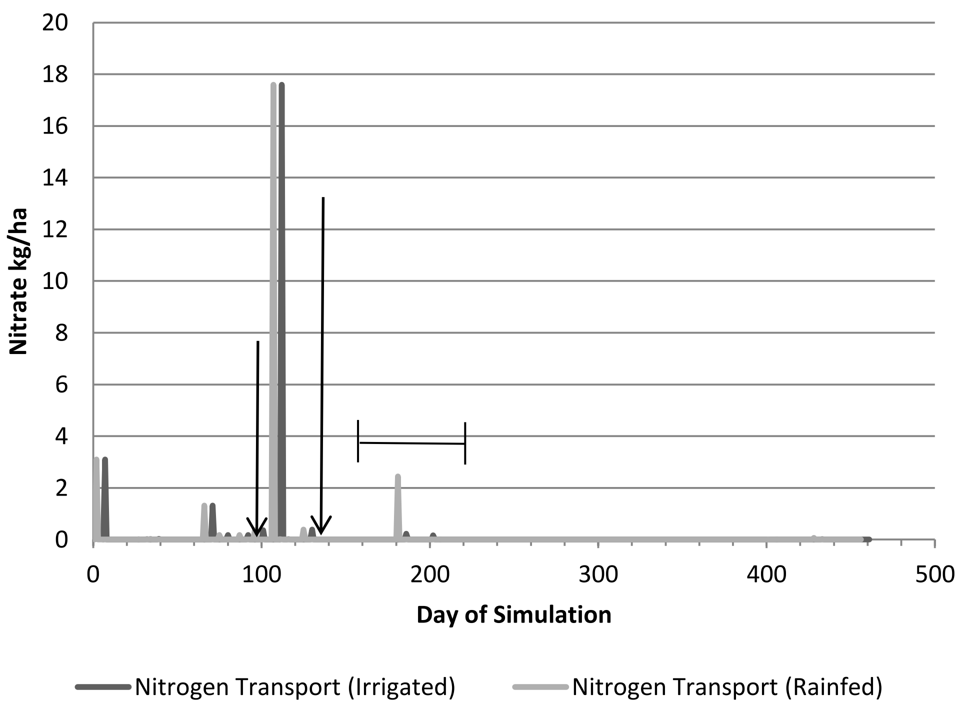


Figure 6.12: Comparative surface nitrate runoff for treatment 6 (Jan. 2011- March 2012)

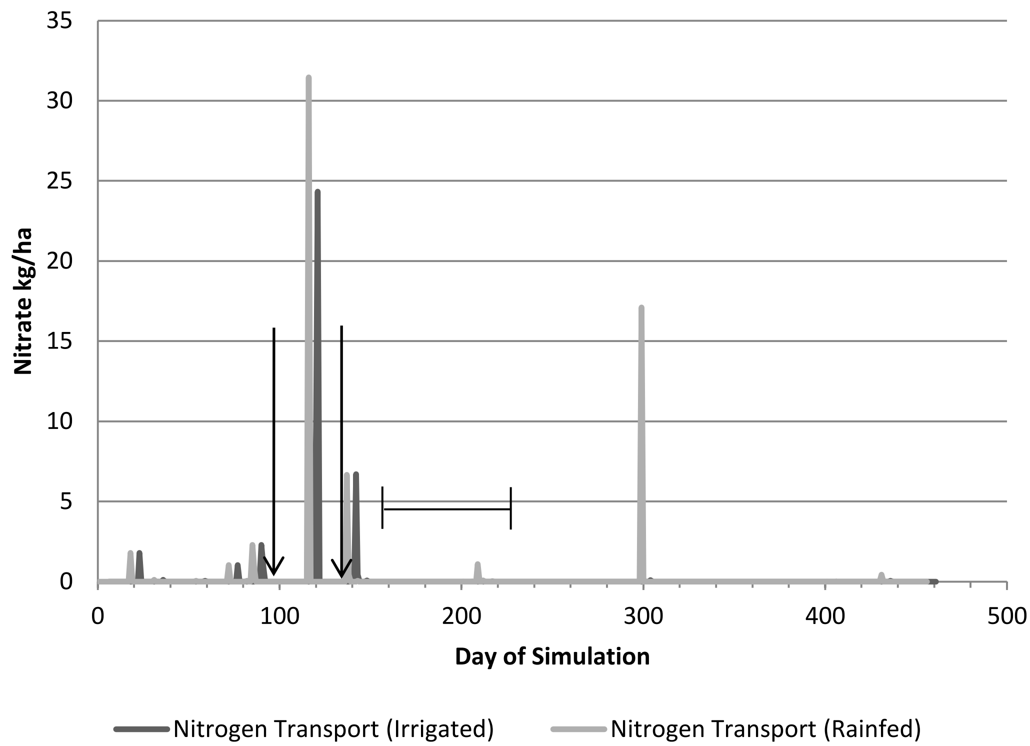


Figure 6.13: Comparative surface nitrate runoff for treatment 11 (Jan. 2010- March 2011)

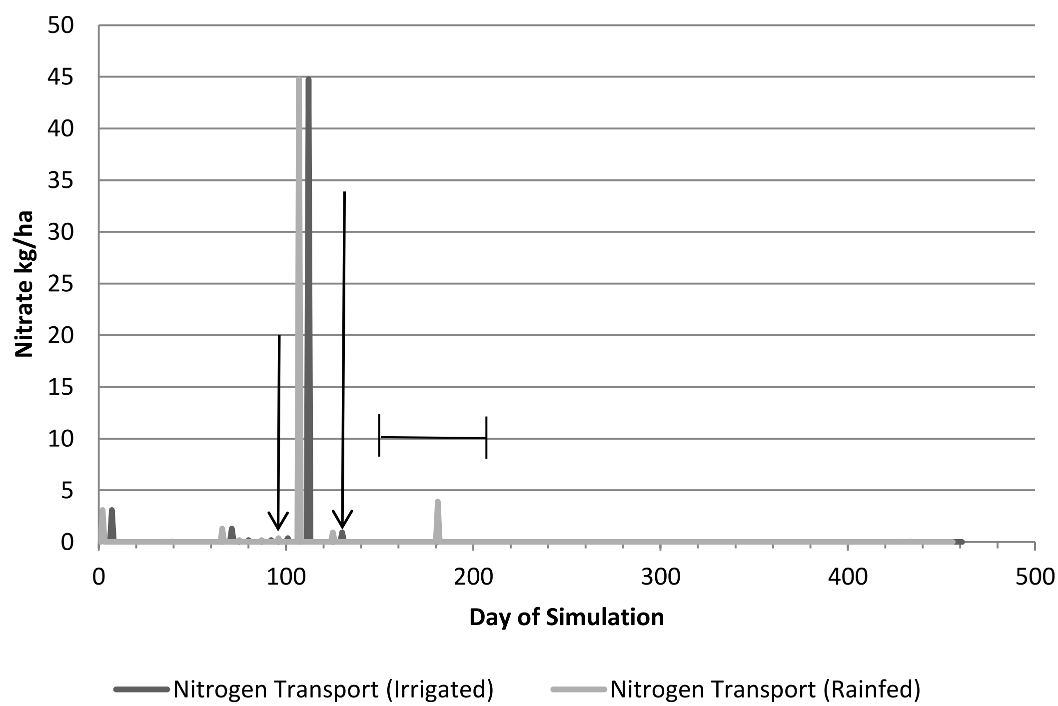


Figure 6.14: Comparative surface nitrate runoff for treatment 11 (Jan. 2011- March 2012)

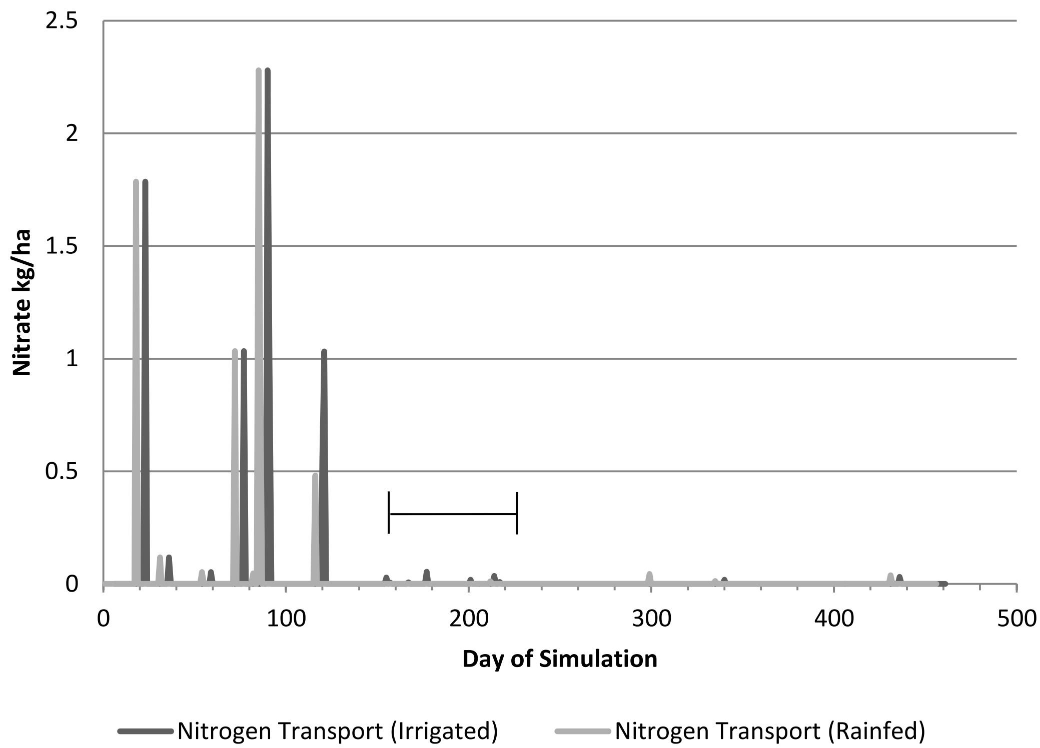


Figure 6.15: Comparative surface nitrate runoff for treatment 13 (Jan. 2010- March 2011)

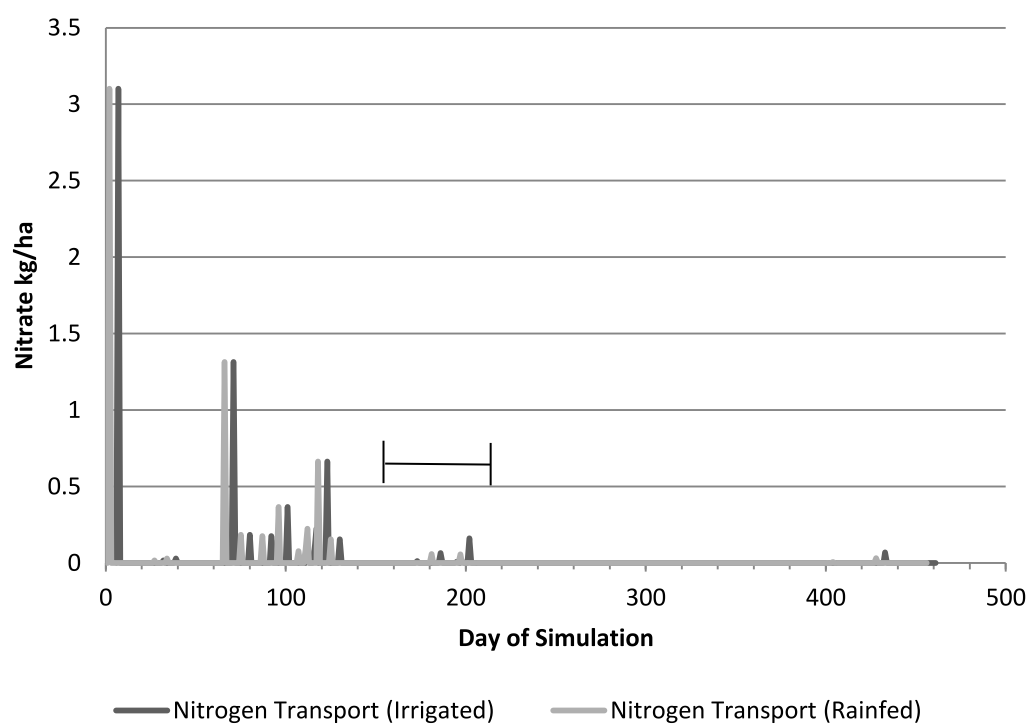


Figure 6.16: Comparative surface nitrate runoff for treatment 13 (Jan. 2011- March 2012)

6.3 Subsurface Export

The next aspect of this study focused on the lateral subsurface transport of nitrate throughout the soil column. The subsurface transport was considered independent of the surface transport. Therefore, any lateral nitrate leaching that occurs in the soil column would not be decreased due to the amount exported from the surface. When comparing irrigated fields to rain-fed fields, one must assume since the nitrogen cycle is dependent on a changing variable, moisture, the fate and transport of nitrogen would be different. To best analyze this phenomenon, the nitrogen concentrations in the soil column for each scenario will be discussed.

For each treatment discussed previously: 1, 6, 11 and 13, a plot of the soil nitrate concentrations are presented in Figures 6.17 and 6.18 as well as Figures 6.21 through 6.26. Each figure showcases three different soil layers of the nine total that was simulated. Soil layer 2, 5-15 cm (2-6 in) below the soil surface, is the first layer beyond the top 5 cm considered for surface export. This soil layer will provide insight of the initial "watering in" of the nitrate from the surface layer. The next soil layer displayed is soil layer 5, 33-46 cm (13-18 in) below the surface. This layer is representative of the root zone, where the plant's roots are concentrated and uptake most of the nutrients and moisture. The last soil layer presented is the bottom soil layer 9, 132-152 cm (52-60 in) below the surface. This soil layer represents the bottom of the soil column. Any nitrate in this soil layer has potential to leach vertically into the water table. All other soil layer concentrations of the selected simulations are presented in Appendix B.

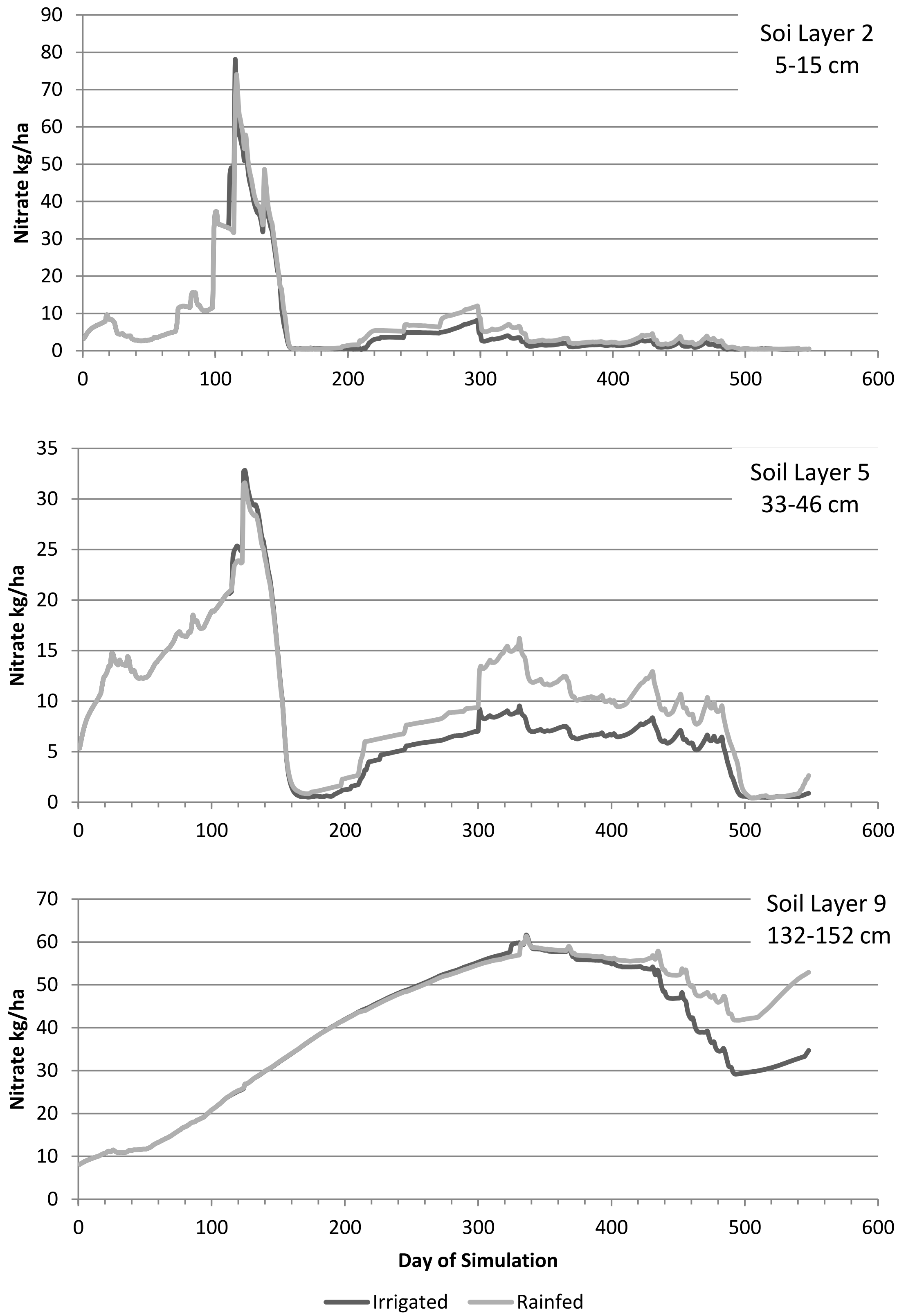


Figure 6.17: 2010 Soil nitrate concentrations for treatment 1

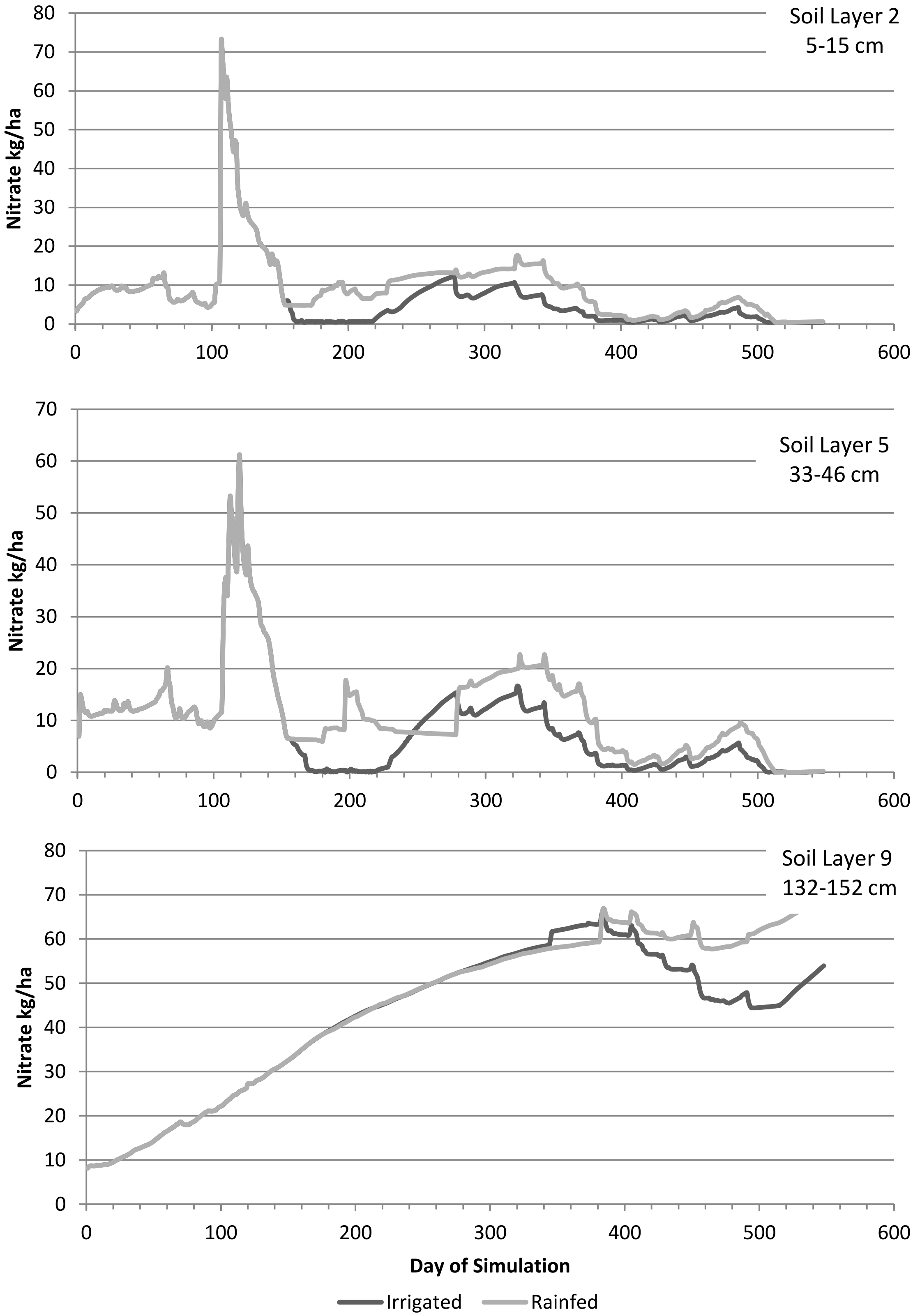


Figure 6.18: 2011 Soil nitrate concentrations for treatment 1

Two different time series will be analyzed. The first will be the beginning of simulation until harvest, fully containing the growing season. This, as can be seen in the figures is the most dynamic due to the addition of fertilizer. The next time series follows the residual nitrate in the soil and begins after the crop harvest until the following spring. The latter will be a result of the amount of nitrate used or exported during the growing season.

First in looking at the 2010 season (Figure 6.17), the initial fertilizer application occurs on April 4 (day 93). The response in soil layer 2 can be seen as the nitrate concentration jumps from 11.6 kg/ha on April 7 (day 98) to 37.1 kg/ha on April 8 (day 99) (Figure 6.17). This response is the same for both the irrigated and the rain-fed fields because no irrigation has taken place and thus the fields are exactly the same. The second application of fertilizer is applied on May 14, 2010. At this point the responses of the irrigated and rain-fed fields begin to differ. Regular irrigation begins on May 27 (day 148). The initial response to the second fertilizer occurs on April 20, 2010 for the irrigated. This can be attributed to the fact that the 12.7 mm of irrigation received moved the nitrate into the soil column more quickly than the rain-fed field, which didn’t experience an increase in nitrate until April 24 (day 115) when it rained 18 mm. As a result, the nitrate concentration in soil layer 2 experienced a slightly higher maximum concentration for the irrigated case and a day before the rain-fed. At this point in the simulation both the rain-fed and irrigated nitrate concentrations responded practically the same, the only exception being when the irrigated responds slightly sooner due to more moisture movement.

The nitrate concentrations begin to increase in the rain-fed scenario on July 13 (day 195). In fact the concentration increases 40%. When the nutrient dynamics are analyzed no drastic difference occurs between the two scenarios. The only difference in the two simulations is the irrigation. The concentrations begin to match again and mimic each other after the final irrigation date on August 12 (day225). From this point forward in the simulation, the amount of nitrate in soil layer 2 is always less in the irrigated than in the rain-fed.

More information of the 2010 season can be gained from soil layer 5 (Figure 6.17). Again, similar conclusions as to the previous soil layer can be drawn from soil layer 5 in the first 150 days of simulation. Irrigation increases the amount of nitrate during the fertilizer applications by flushing it through the soil column. The timing is increased due to the depth of the soil layer. And, as discussed previously, the irrigated scenario results in a lower nitrate concentration for the rest of the simulated period. Since this soil layer represents the root zone, a comparison of the nitrogen uptake as reported by DSSAT can be presented and analyzed. There are two apparent diversions from the rain-fed scenario that the irrigated nitrate concentration takes. These both lie between the start of June (day 152) and August 12 (day 225) which happens to be the last irrigation application. Figure 6.19 shows this section of the simulation, and the apparent diversion in the irrigated and rain-fed scenarios and Figure 6.20 shows the amount of total nitrogen uptake by the plant during the same time period. It can be seen that the amount of nitrogen uptake begins when the major differences in the soil nitrate begin.

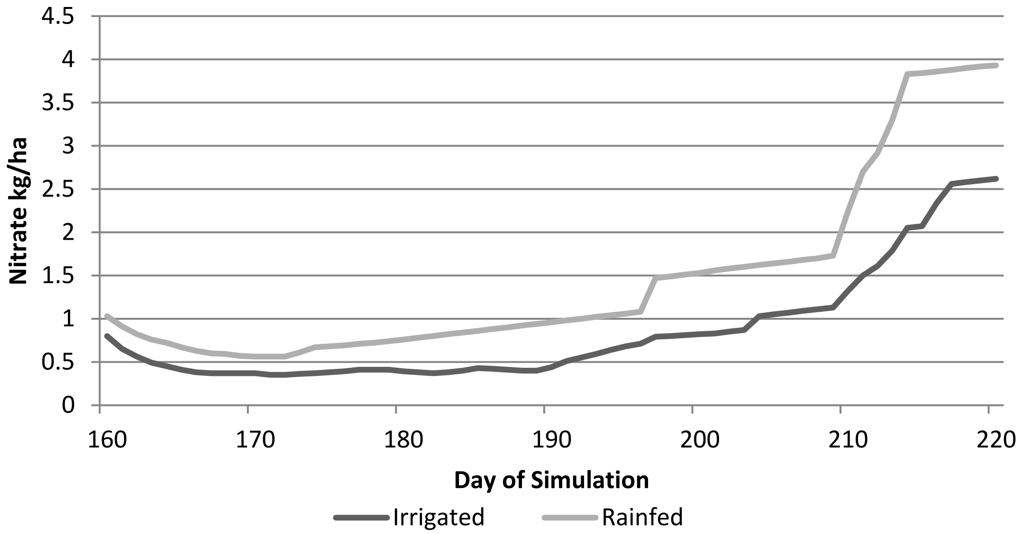


Figure 6.19: 2010 Soil nitrate concentration for treatment 1 (Day 160-220)

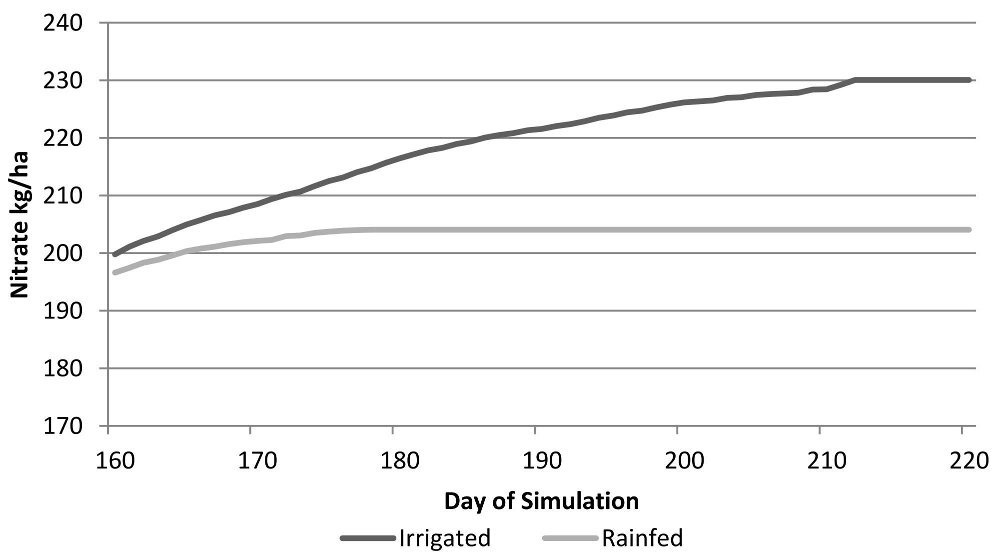


Figure 6.20: 2010 Total plant uptake of nitrogen (Day 160-220)

It has been seen that the increase in soil moisture due to irrigation has not only allowed the nitrate to move into the soil column more quickly, but the aerobic conditions needed for nitrification and thus plant uptake are achieved more consistently. However, if the nitrate is moving more freely through the soil, will the plant uptake offset the higher capability of nitrate to leach vertically though the soil column? To analyze this, the bottom of the soil column is presented in Figure 6.17. Neither the irrigated nor the rain-fed scenarios show any response to the fertilizer application until well into the simulation. The timing of the nitrate reaching the layer is increased, again signifying the depth traveled. When all soil layers are analyzed, this "wave" can be seen traveling down the soil column reaching each layer later than the next. Once the rain-fed concentrations reach that of the irrigated, they both follow similar trends. And, as in every layer thus far for the 2010 treatment 1, the amount of nitrate in the soil layer of the irrigated scenario is less than the rain-fed for the rest of the simulation. In fact the difference increases in the bottom layer. This suggests that any nitrate leaching to the ground water will leach at higher concentrations in the rain-fed field.

Next, the 2011 season can be analyzed (Figure 6.18). As in the 2010 season, similar trends exist suggesting that the amount of nitrate in the soil layers is less for the irrigated scenarios. The increase in precipitation for 2011 can explain any differences. However, the same conclusions can be assessed. It is also apparent that during a year with less precipitation irrigation mitigates not only more substantial yield than the rain-fed, but also mitigates the amount of nitrogen in the soil layer more effectively. These similar trends exist in all four of the treatments analyzed.

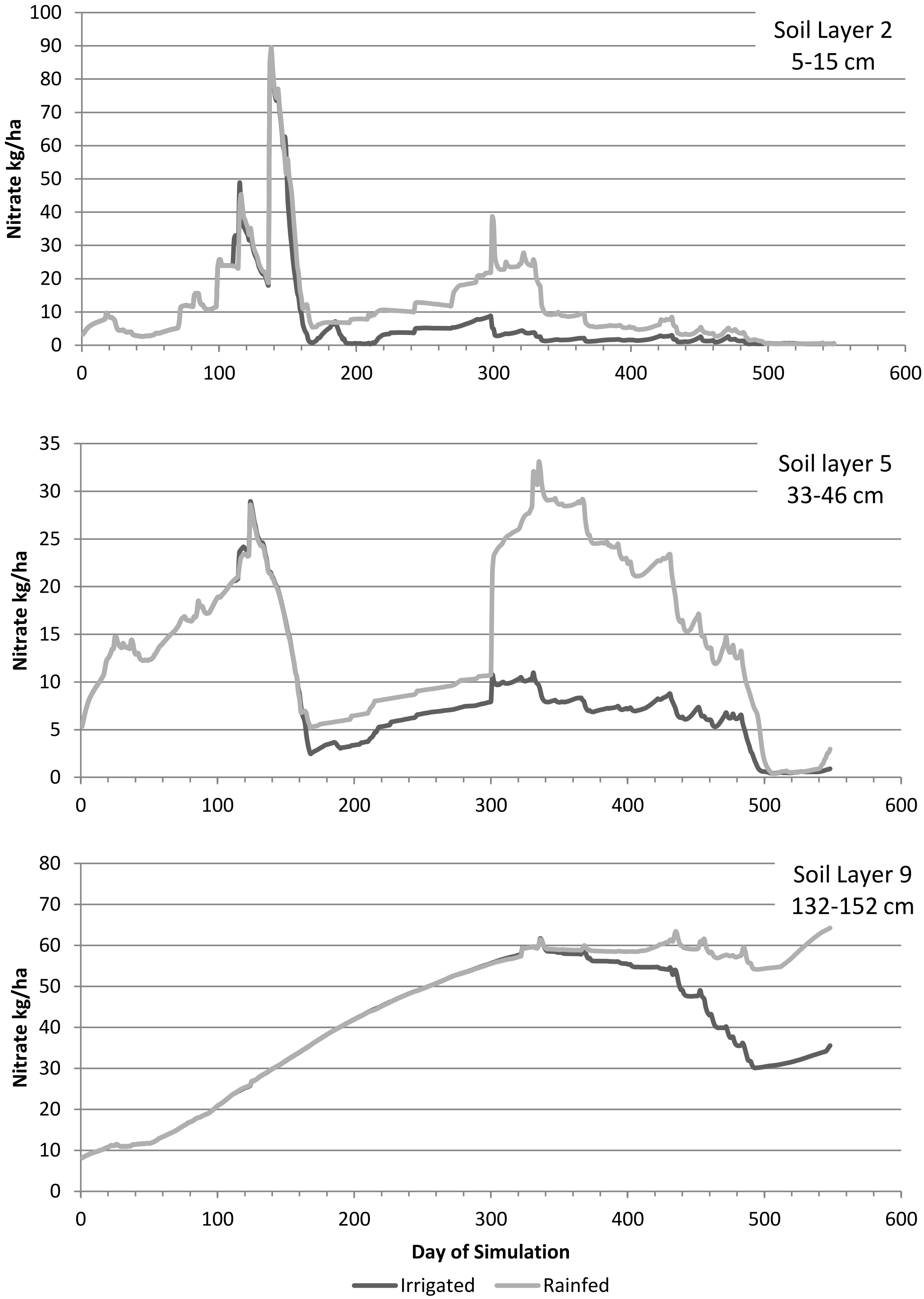


Figure 6.21: 2010 Soil nitrate concentrations for treatment 6

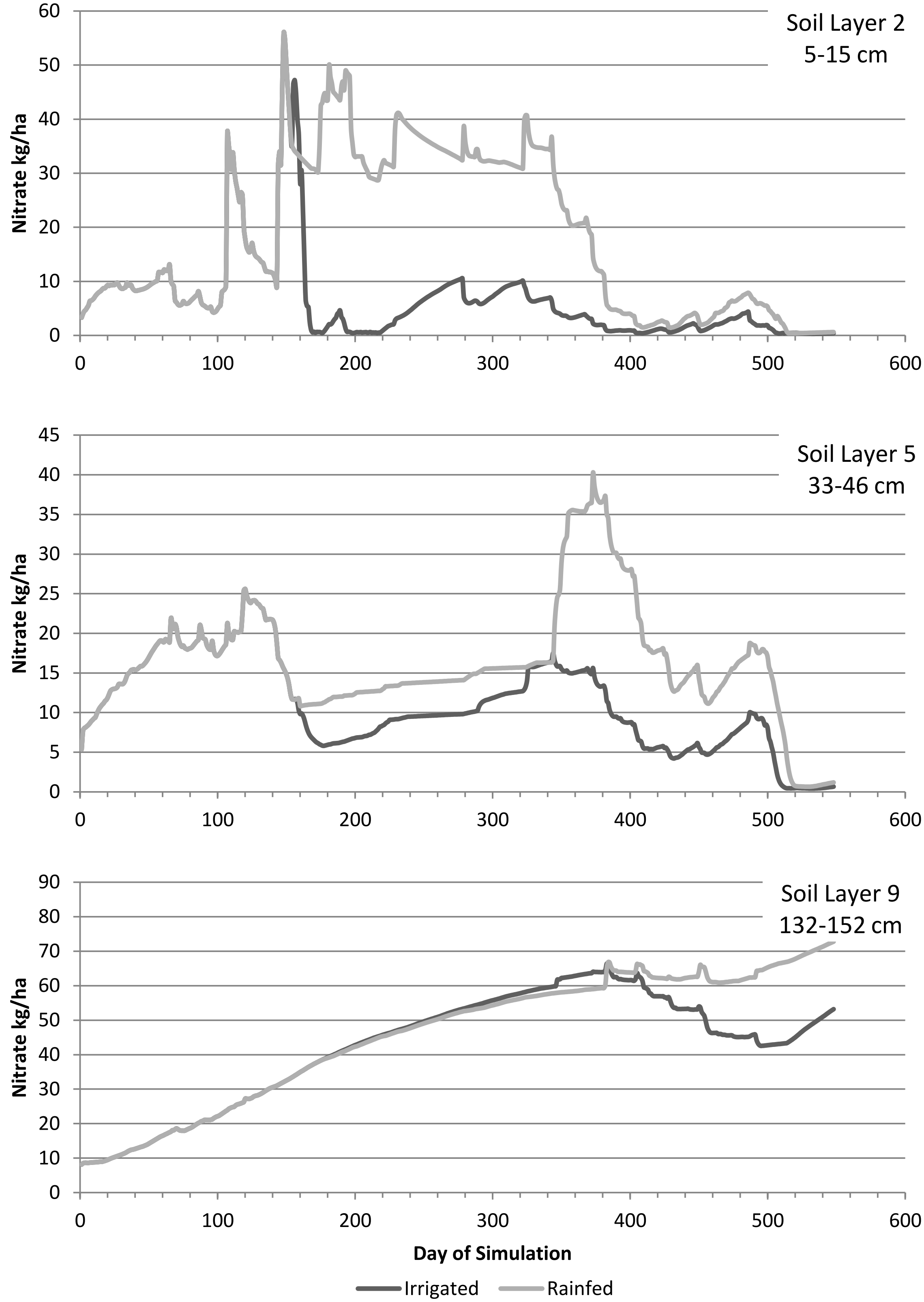


Figure 6.22: 2011 Soil nitrate concentrations for treatment 6

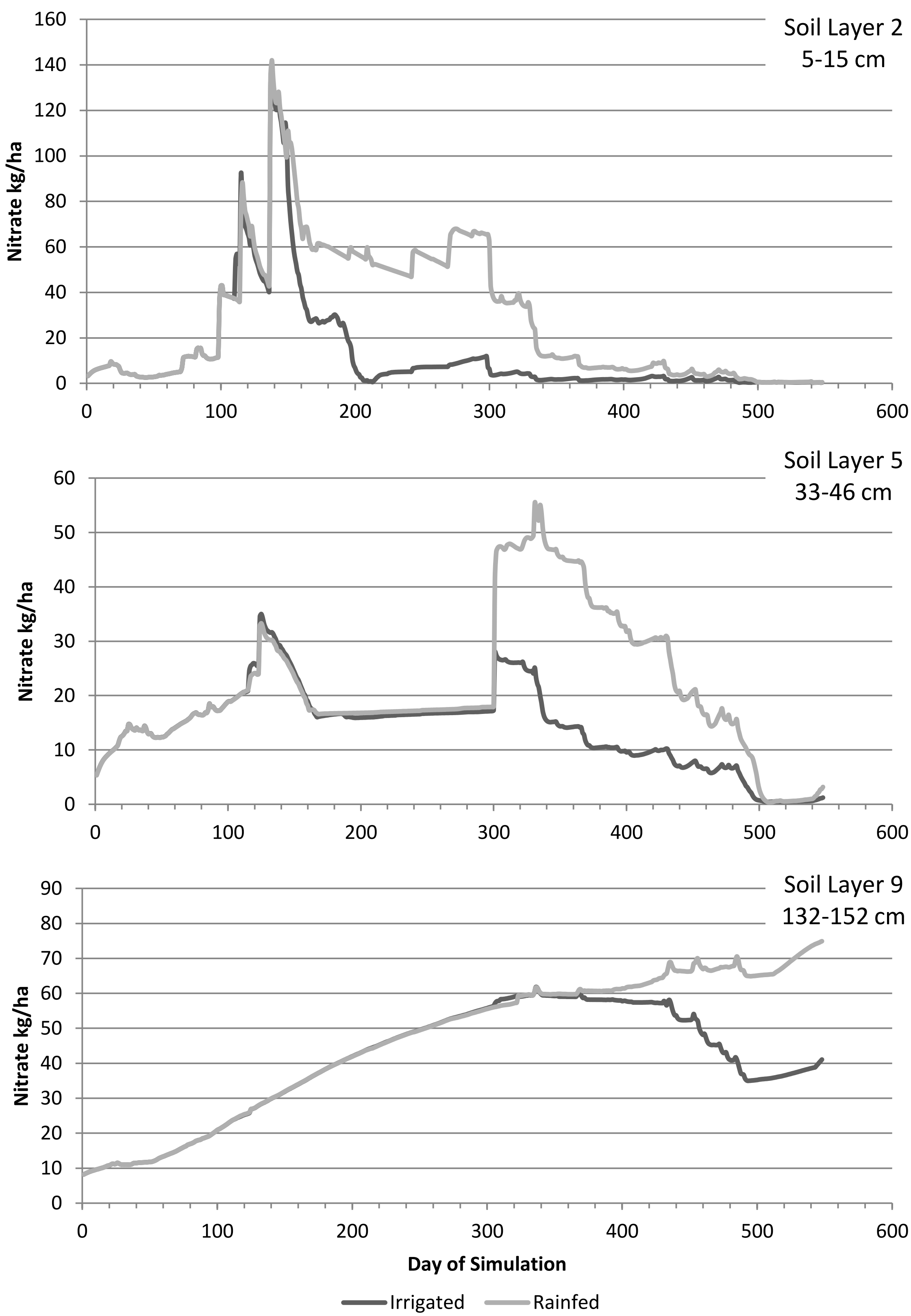


Figure 6.23: 2010 Soil nitrate concentrations for treatment 11

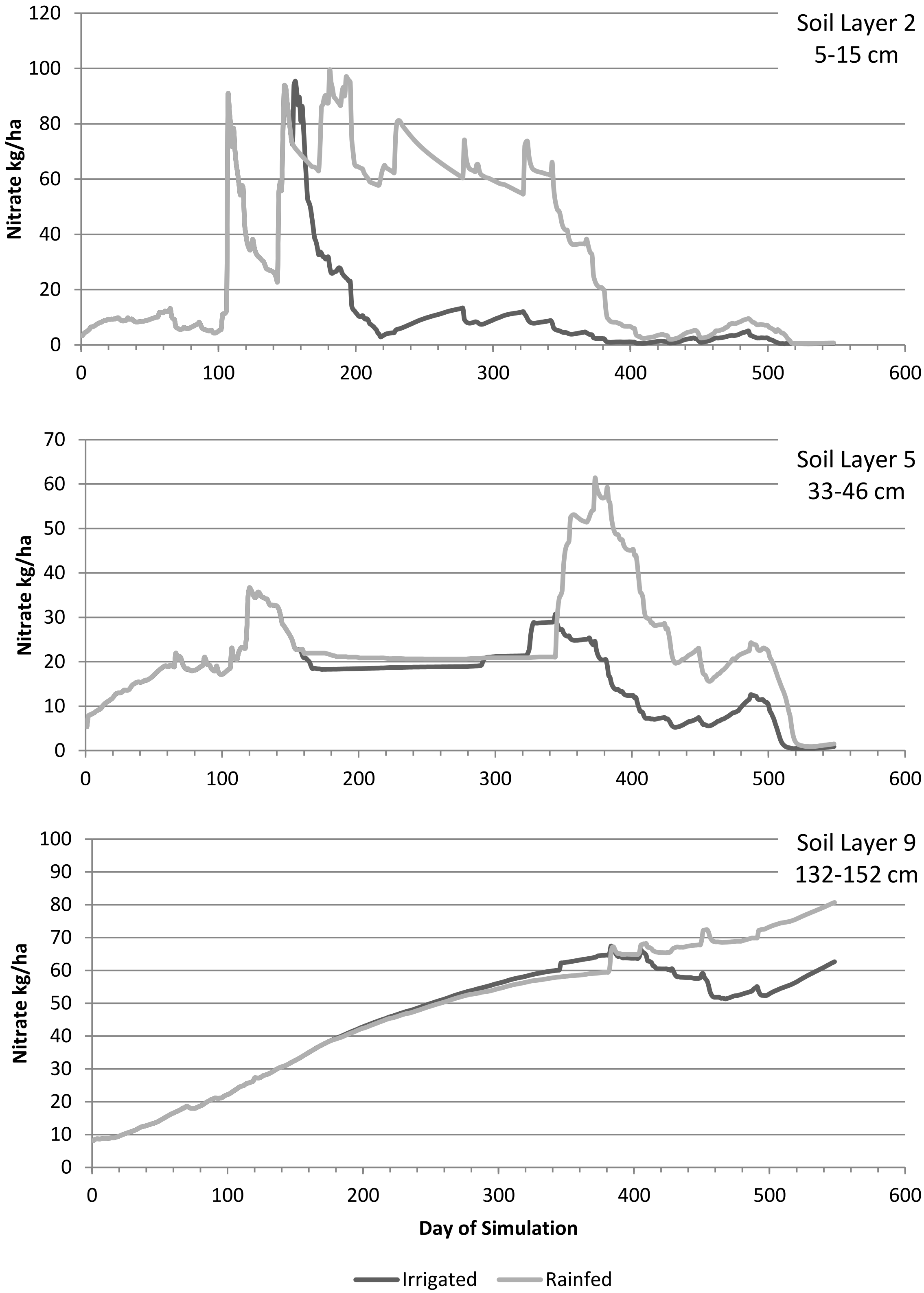


Figure 6.24: 2011 Soil nitrate concentrations for treatment 11

Figures 6.21 through 6.24 show the soil nitrate concentrations for treatments 6 and 13. Several trends still need to be explained that each treatment experiences and will be further discussed in an effort to fully represent all treatments simulated.

First, the rain-fed soil nitrate does not decrease with the irrigated nitrate for treatments 6 and 11 for the 2011 season in second soil layer, effectively creating an even larger difference in the soil nitrate. The irrigated scenarios spike on June 3 (day 155) similar to the other treatments then drops back to appreciable levels. However, the rain-fed scenarios do not experience this expected spike and decreases for about 20 days (treatment 6) until it spikes on June 24 (day 176) and a concentration above 30 kg/ha for most of the time until it starts to recede back to just above the irrigated on December 8 (day 343). Figure 6.25 compares the precipitation for this period in the 2011 season, day 154 through day 210, with the applied irrigation. Figure 6.26 presents the soil nitrate concentrations for the same period. It is not coincidence that irrigation began on June 3 (day 155). The drop in the irrigated nitrate suggests, and is proven in Figure 6.27, that the irrigation flushed the nitrate out of the top layers of soil to be uptaken by the plant. The rain-fed field was unable to flush the nitrate and it held a large amount in the top layers until precipitation events occurred. The irrigated field received 15.1 centimeters (6 in) more water than the rain-fed field did in this time period. Figure 6.27 shows that it was at this point in the simulation that the irrigated field began to uptake significantly more nitrogen then the rain-fed field. In addition Figure 6.28 displays the soil moisture content for the soil layer in question. Once again, this graph illustrates the importance that irrigation plays in transporting the nitrate through the soil column.

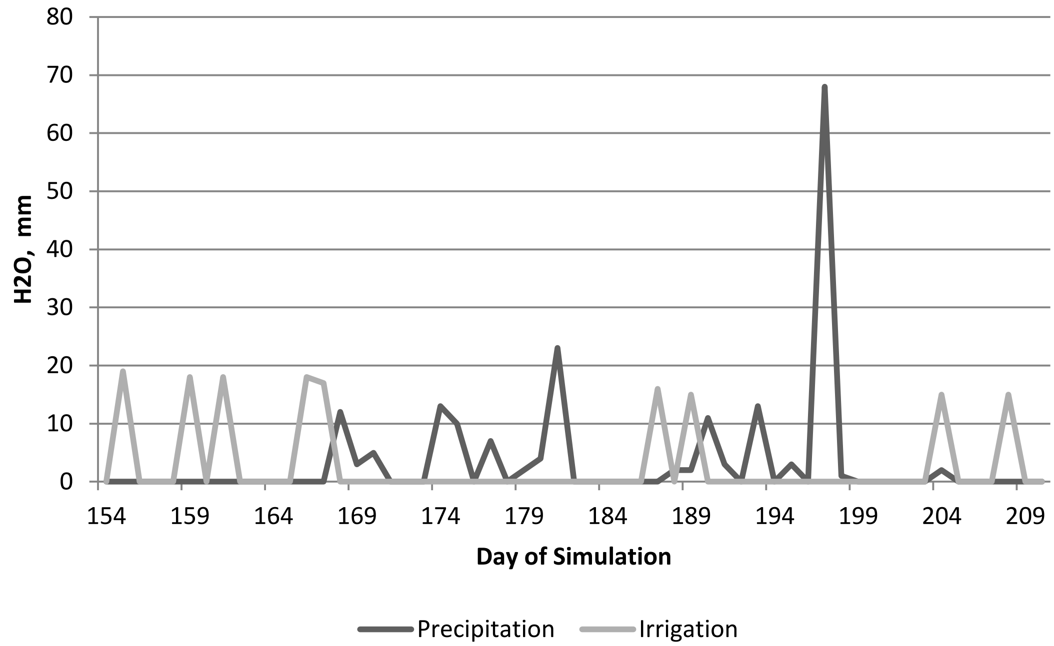


Figure 6.25: 2011 Precipitation events and irrigation applications (Day 154-210)

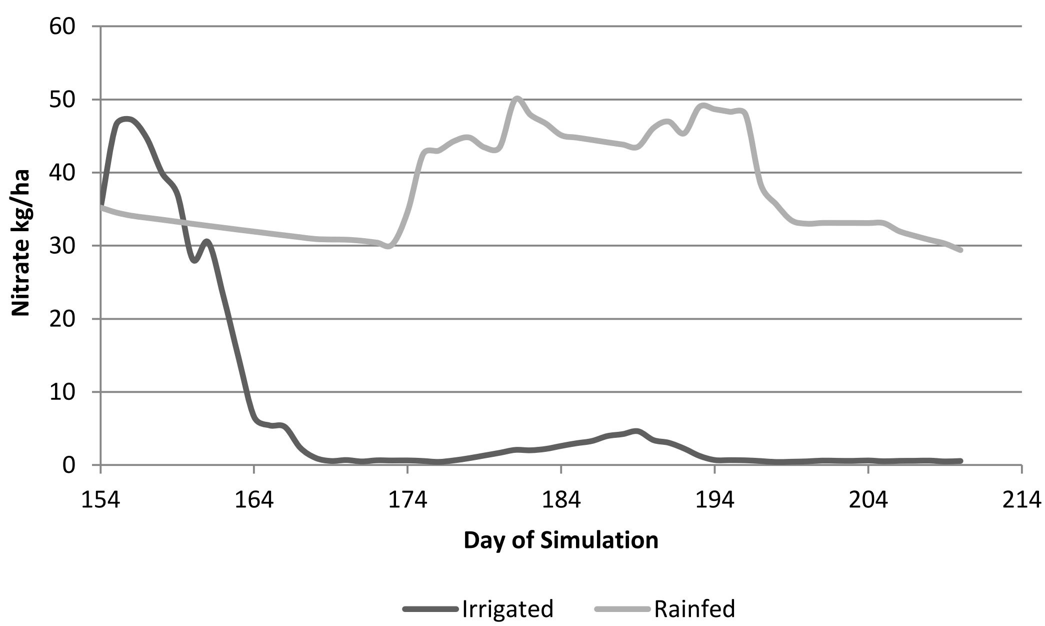


Figure 6.26: 2011 Soil nitrate concentrations for treatment 6 (Day 154-210)

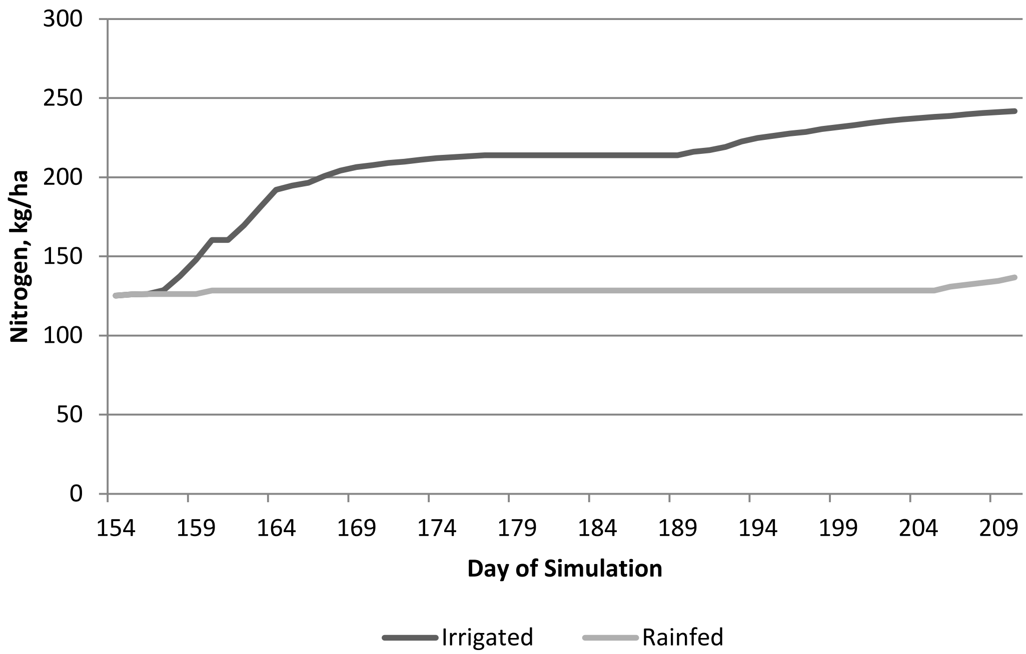


Figure 6.27: 2011 Nitrogen uptake for treatment 6 (Day 154-210)

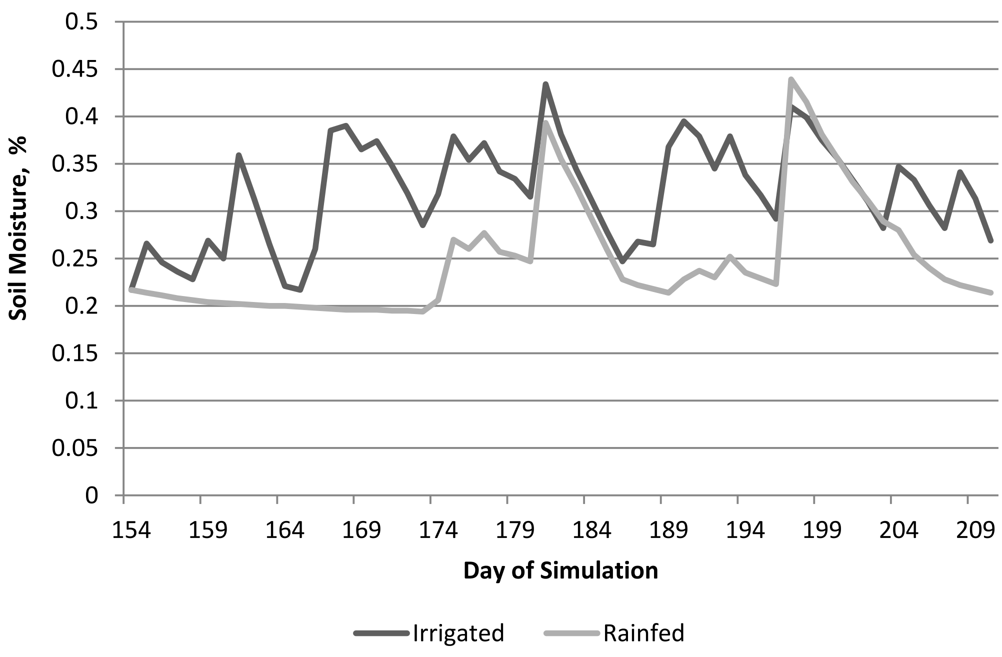


Figure 6.28: Soil moisture for soil layer 2 for treatment 6 (Day 154-210)

A similar phenomenon occurs in the second soil layer for treatment 11 in the 2010 season (Figure 6.23). The trend, however, is similar to that of the other treatments in the 2010 season. The reason that it seems to follow the 2010 trends just discussed is because of the amount of nitrogen fertilizer applied. Treatment 11 has 280 kg/ha applied in equal intervals, more than 80% more nitrogen than was applied in treatment 6.

In each treatment and season discussed thus far, with the exception of the 2011 treatment 1, a large spike in nitrate exists in the fifth soil layer. This occurs around day 300 of the simulation in each of the cases. This is the large difference that emerges after the second fertilizer application in treatments 6 and 11. Treatment 1 did not have a second application and therefore the 2010 simulation results in a very small spike comparatively, while the 2011 doesn’t even give the response. This large spike in the nitrate concentration represents a vital conclusion. By the time the nitrate made it into the lower soil layers, the plant uptake has already started to cease. Therefore any nitrate in the soil layer at this time will simply leach throughout the soil, either vertically or laterally. The harvest of both seasons occurs before or during September, while large amounts of nitrate do not appear in the root zone layers until well into October.

The last treatment presented is treatment 13 Figures 6.29 and 6.30. This is the control treatment and received no fertilizer. Both the rain-fed and irrigated scenarios for both season 2010 and 2011 are closely related. The added irrigation does not appear to influence the soil nitrate concentration much. However, the total uptake of nitrogen was 50% more in the 2011 irrigated simulation and 20% more in the 2010 season.

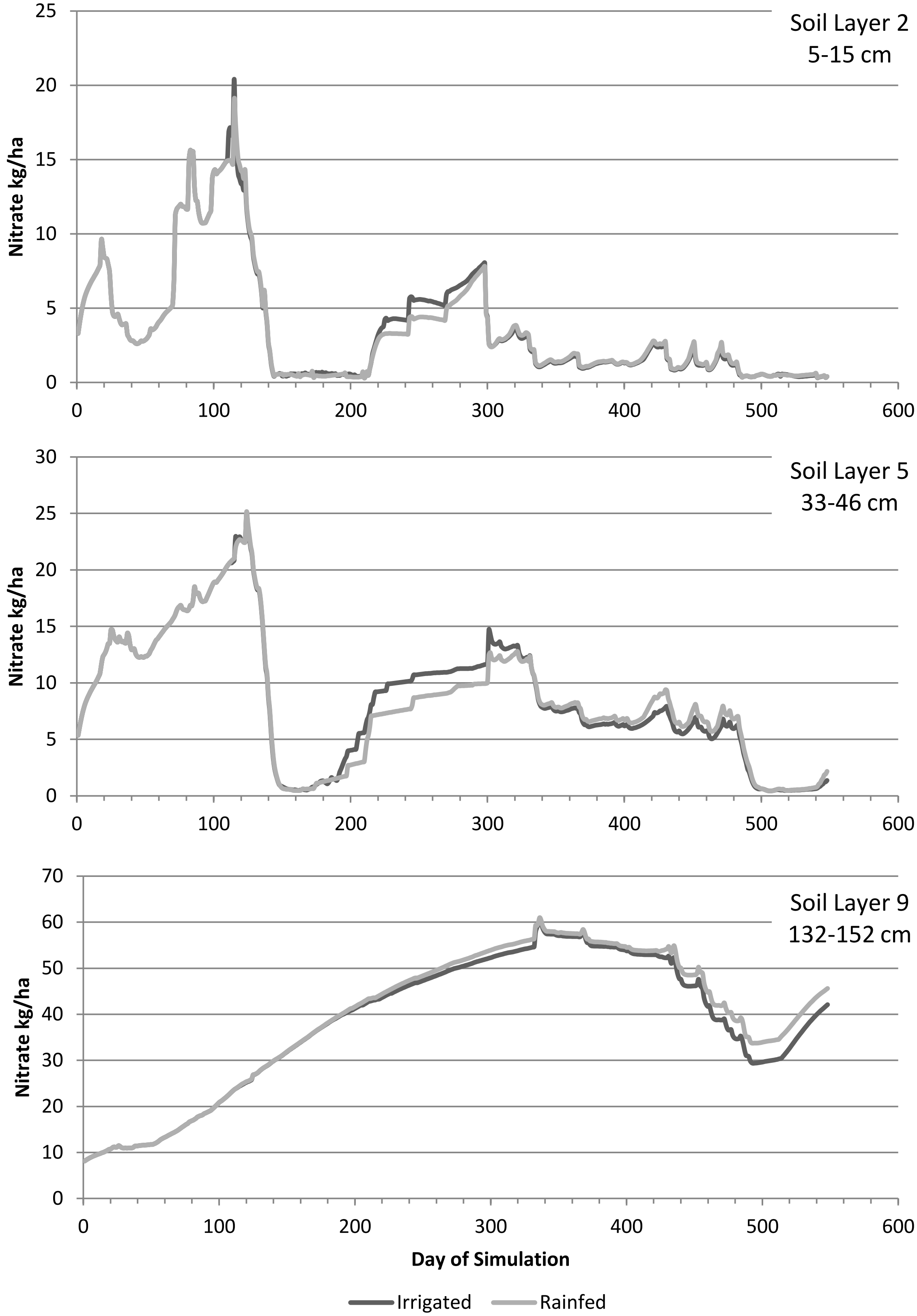


Figure 6.29: 2010 Soil nitrate concentrations for treatment 13

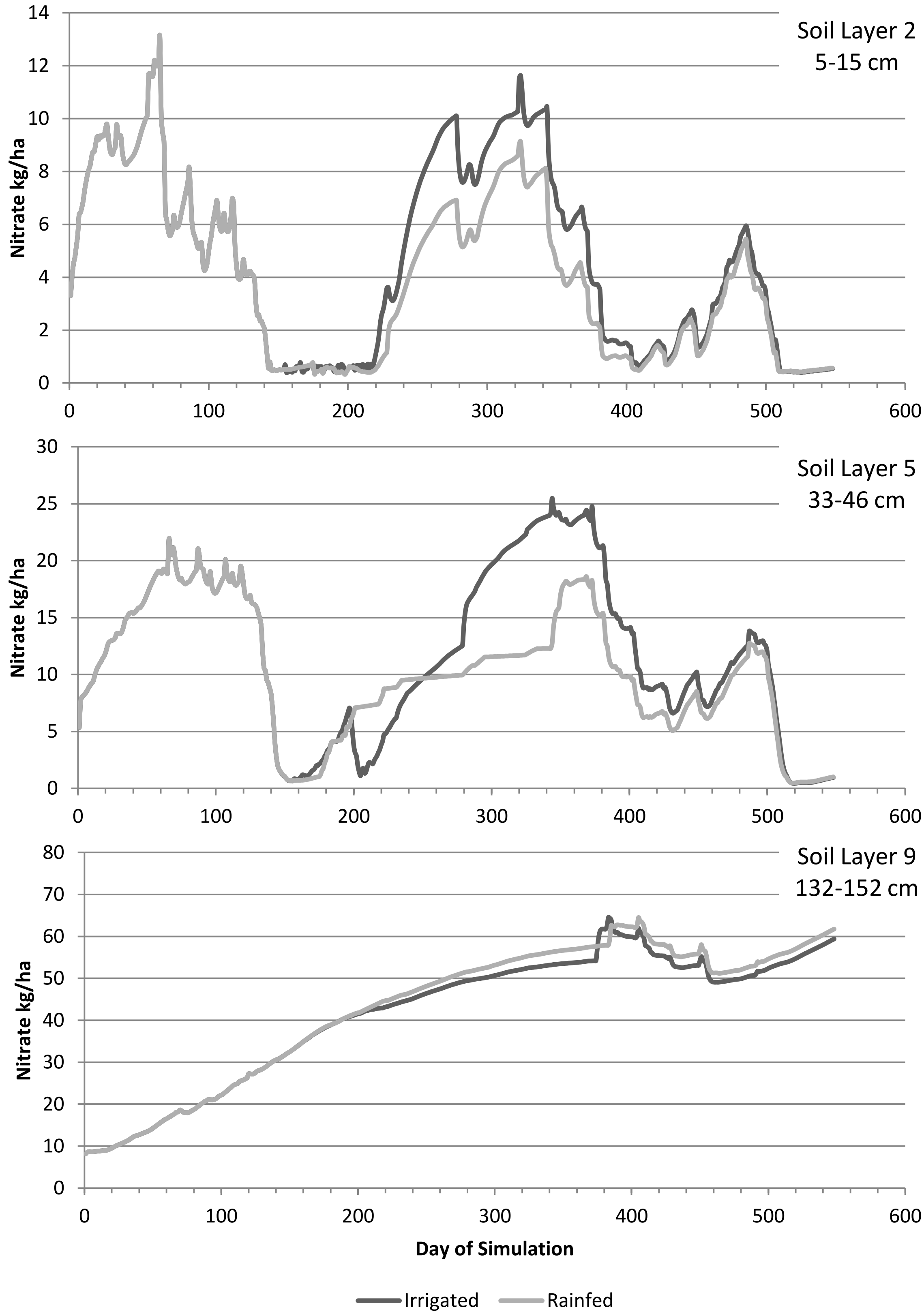


Figure 6.30: 2011 Soil nitrate concentrations for treatment 13

The kinematic wave approximation was the method used to transport the nitrate laterally from the soil layer. The amount of nitrate that was available to transport was based on the amount of soil moisture present. The available nitrate was then exported with the water that was moved laterally with the kinematic wave approximation. Tables 6.5 through 6.8 display the total amount of nitrate that was exported in each layer. The overall total amount of nitrate exported laterally from each simulation from all soil layers is presented in Figures 6.31 and 6.32. The total amount of laterally leached nitrate from the subsurface was tallied for two different time periods. First, Figure 6.27 displays the total amount of laterally leached nitrate from the start of the simulation through the growing season. The 2010 and the 2011 seasons harvested the crop on different dates, however, September 30 extends beyond both and was used as the beginning of the fallow/residual analysis. Next, Figure 6.28 shows the total leaching over the entire simulation. Among the totals for the growing season and the overall transport, 4 simulations resulted in more nitrate being leached from the irrigated scenarios and 4 simulations where the rain-fed scenarios leached more nitrate. Tables 6.4 through 6.7 present the overall total subsurface export. The amounts leached were minimal compared to those exported from the surface runoff. The maximum amount leached was 4.97 kg/ha during the 2010 rain-fed simulation. The differences range from 4% to 7.5% with two exceptions. The two highest differences in nitrogen exported were both where the rain-fed fields exported more nitrate: both treatment 6 and 11 in the 2010 season. The rain-fed simulation for the 2010 treatment 6 exported 16.6% more nitrate then the irrigated and the 2010 treatment 11 exported 17.5% more. These two treatments are from the highest N application selected and both in the driest season.

Table 6.4: Total subsurface lateral nitrate export (kg/ha) for treatment 1 (112 kg/ha)

		Growing Season (Jan-Sept)				Total (Jan -Mar)			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.0135	0.0131	0.0257	0.0256	0.0159	0.0171	0.0296	0.0314
3	5	0.0045	0.0041	0.0077	0.0078	0.0053	0.0057	0.0094	0.0099
4	13	0.3750	0.3329	0.4745	0.4738	0.4489	0.4544	0.6227	0.5957
5	13	0.0374	0.0365	0.0476	0.0476	0.0585	0.0690	0.0892	0.0849
6	29	0.3034	0.2942	0.3793	0.4119	0.6264	0.6315	0.7670	0.7444
7	29	0.3887	0.3779	0.3972	0.3991	0.8461	0.8352	0.8747	0.8053
8	28	0.3809	0.3772	0.4184	0.4244	0.9467	0.9203	0.9859	0.9103
9	20	0.2541	0.2535	0.2557	0.2598	0.6109	0.5920	0.6090	0.5526
Total Exported		**1.76**	**1.69**	**2.01**	**2.05**	**3.56**	**3.53**	**3.99**	**3.73**

Table 6.5: Total subsurface lateral nitrate export (kg/ha) for treatment 6 (168 kg/ha)

		Growing Season (Jan-Sept)				Total (Jan -Mar)			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.0130	0.0115	0.0161	0.0180	0.0155	0.0246	0.0199	0.0302
3	5	0.0043	0.0034	0.0053	0.0061	0.0052	0.0081	0.0068	0.0100
4	13	0.3069	0.2783	0.3633	0.3636	0.3882	0.6526	0.4908	0.5971
5	13	0.0364	0.0358	0.0449	0.0449	0.0597	0.1031	0.0725	0.1001
6	29	0.3491	0.4174	0.3820	0.3950	0.6981	0.9626	0.7033	0.7817
7	29	0.3958	0.3926	0.4242	0.3947	0.8874	0.9798	0.8965	0.8275
8	28	0.3891	0.3914	0.4518	0.4234	0.9723	1.0178	1.0342	0.9216
9	20	0.2592	0.2618	0.2760	0.2597	0.6231	0.6254	0.6431	0.5558
Total Exported		**1.75**	**1.79**	**1.96**	**1.91**	**3.65**	**4.37**	**3.87**	**3.82**

Table 6.6: Total subsurface lateral nitrate export (kg/ha) for treatment 11 (280 kg/ha)

		Growing Season (Jan-Sept)				Total (Jan -Mar)			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.0198	0.0177	0.0319	0.0340	0.0228	0.0368	0.0363	0.0555
3	5	0.0063	0.0045	0.0090	0.0102	0.0074	0.0117	0.0109	0.0171
4	13	0.4140	0.3613	0.5321	0.5305	0.5092	0.8815	0.6871	0.9234
5	13	0.0378	0.0369	0.0490	0.0490	0.0776	0.1399	0.0903	0.1344
6	29	0.4090	0.4237	0.4801	0.4245	0.8578	1.1221	0.9284	0.9305
7	29	0.3976	0.3934	0.4449	0.4054	0.9542	1.0700	0.9690	0.9071
8	28	0.3899	0.3914	0.4646	0.4281	1.0288	1.0675	1.0826	0.9657
9	20	0.2597	0.2618	0.2834	0.2622	0.6475	0.6408	0.6661	0.5709
Total Exported		**1.93**	**1.89**	**2.29**	**2.14**	**4.11**	**4.97**	**4.47**	**4.50**

Table 6.7: Total subsurface lateral nitrate export (kg/ha) for treatment 13 (0 kg/ha)

		Growing Season (Jan-Sept)				Total (Jan -Mar)			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.0075	0.0074	0.0080	0.0074	0.0097	0.0096	0.0122	0.0102
3	5	0.0028	0.0028	0.0033	0.0031	0.0037	0.0037	0.0052	0.0043
4	13	0.2377	0.2287	0.2822	0.2538	0.3027	0.2981	0.4605	0.3206
5	13	0.0352	0.0347	0.0420	0.0419	0.0582	0.0585	0.0913	0.0656
6	29	0.2746	0.2601	0.2837	0.2814	0.5516	0.5383	0.5868	0.4937
7	29	0.3104	0.3555	0.3180	0.3630	0.7052	0.7682	0.6555	0.6842
8	28	0.3088	0.3582	0.3361	0.3916	0.8128	0.8780	0.7319	0.7927
9	20	0.2077	0.2413	0.2046	0.2407	0.5231	0.5696	0.4547	0.4978
Total Exported		**1.38**	**1.49**	**1.48**	**1.58**	**2.97**	**3.12**	**3.00**	**2.87**

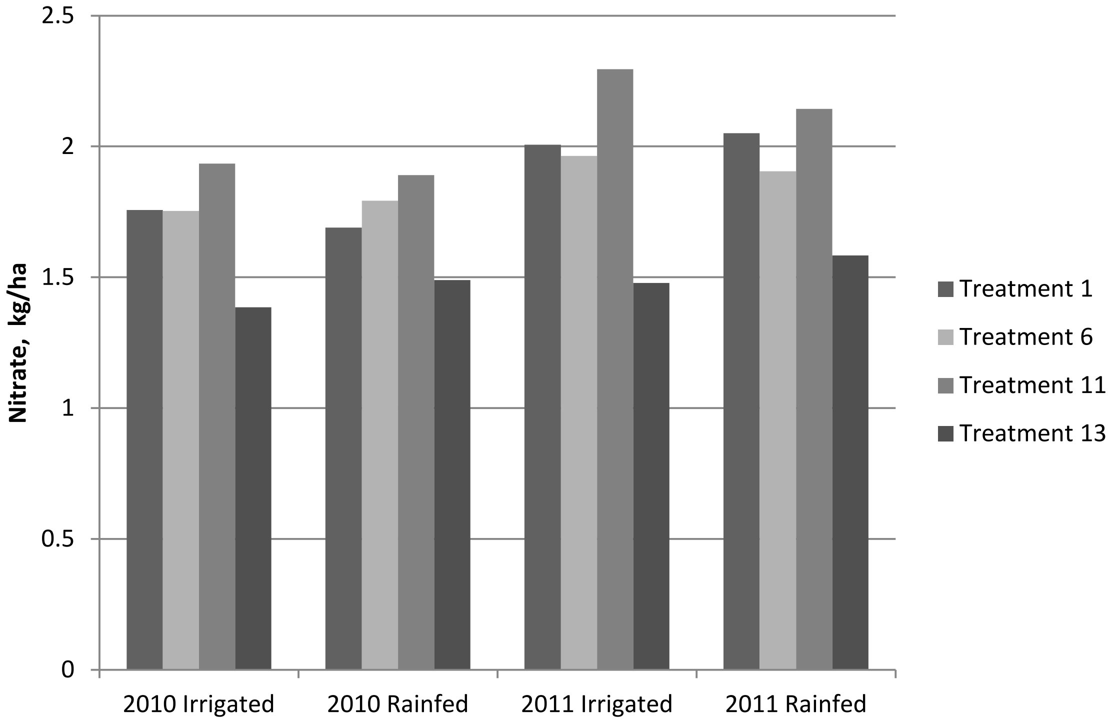


Figure 6.31: Total nitrate leached through the growing season (Jan-Sept)

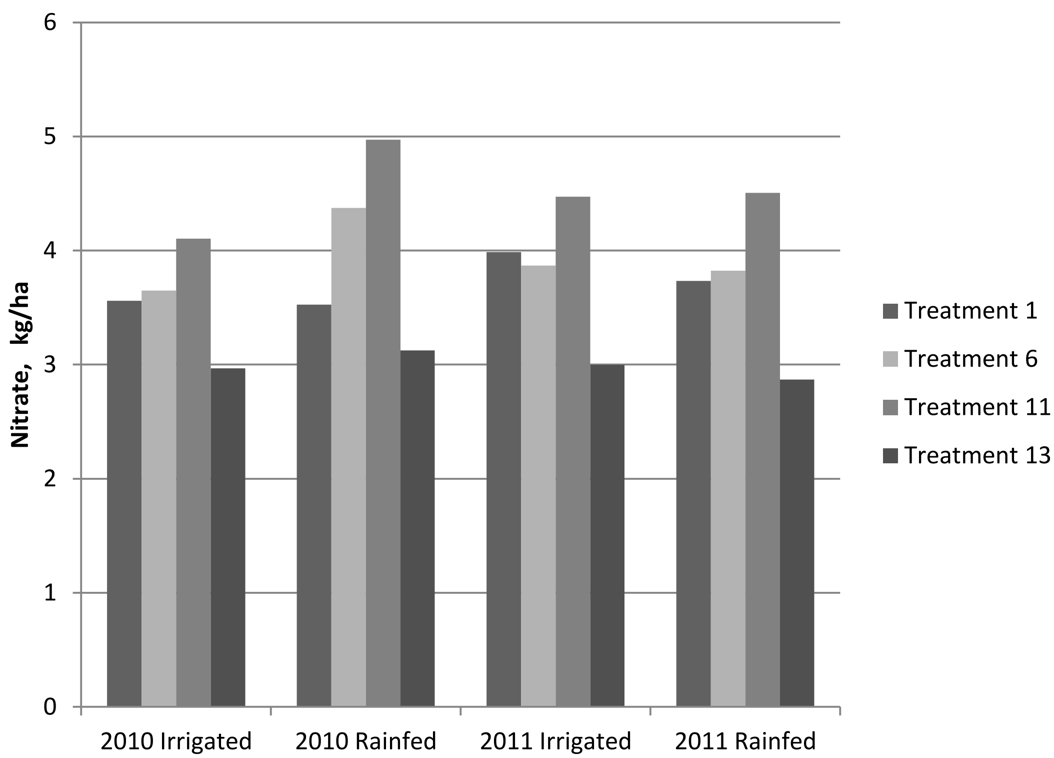


Figure 6.32: Total nitrate leached through the simulation period (Jan-Mar)

6.4 Alternate Gradient

Lastly, an alternate gradient was applied to analyze the differences in irrigated fields compared to rain-fed field. As mentioned previously, a 3% gradient was applied to all simulations. For additional analysis, the slope was increased to 10%. The previous simulation that resulted in the overall maximum amount of nitrate runoff and leaching was treatment 11, so this simulation was used in the alternate slope analysis for both season 2010 and 2011.

Figure 6.33 showcases the differences in surface transport of nitrate of the irrigated simulations as compared to the rain-fed for both the previous 3% slope and the increased 10% slope. For both simulations in 2010, the amount of nitrate that was transported from surface runoff increased under a 10% slope. However, neither was increased in the 2011 season where more precipitation fell. More importantly the difference in the irrigated and rain-fed simulations did not change significantly. The rain-fed simulation in 2010 resulted in 2.3% more nitrate transported for a 3% slope, while that increase rose to 2.5% for the 10% slope. In fact the amount more that the rain-fed exported compared to the irrigated increased slightly under a 10% slope for 2010.

Considering the subsurface leaching, the comparative results for the 3 and 10 percent slopes can be found in Figures 6.34 and 6.35 and Tables 6.8 and 6.9. The results are again separated into growing season subsurface export and total subsurface export. For both seasons and both scenarios the amount of nitrate exported in the subsurface increased, as expected. However, Figures 6.36 and 6.37 present the change in

percent increase of exported nitrate from rain-fed fields as compared to the irrigated fields. For the 2010 growing season, the amount of nitrate leached from the irrigated field increased from 1.93 kg/ha to 4.67 kg/ha and from 1.89 to 4.54 in the rain-fed scenario (Table 6.8). Therefore, the amount more that the irrigated exported compared to the rain-fed increased from 2.29% to 2.97% (Figure 6.35). The opposite occurred in the wetter 2011 season. The amount more that the irrigated exported compared to the rain-fed decreased from 7.05% to 5.51% (Figure 6.35). When the total subsurface export is considered, both the 2010 and 2011 seasons resulted in the irrigated scenario exporting a lesser amount compared to the rain-fed even though the total amount exported increased for both scenarios (Figure 6.36). In 2010 under a 3% slope the rain-fed exported 17.41% more nitrate than the irrigated, while under a 10% slope the rain-fed scenario exported 18.16% more nitrate. In 2011 rain-fed fields exported less than one percent more than the irrigated field under a 3% slope, but on a 10% slope that increased to 4.03%. Therefore, a 10% increase in slope increase the amount of nitrate leached in both rain-fed and irrigated scenarios. This is expected, as since the routing methods are kinematic, i.e. driven by gravity, an increased slope would positively influence the amount of export. However, under a 10% slope, though more nitrate is exported, the irrigated scenarios exported even less nitrate than the rain-fed when compared to a 3% slope. Therefore, in general, whether on a 3% or 10% slope, irrigated fields export fewer nitrates than rain-fed fields.

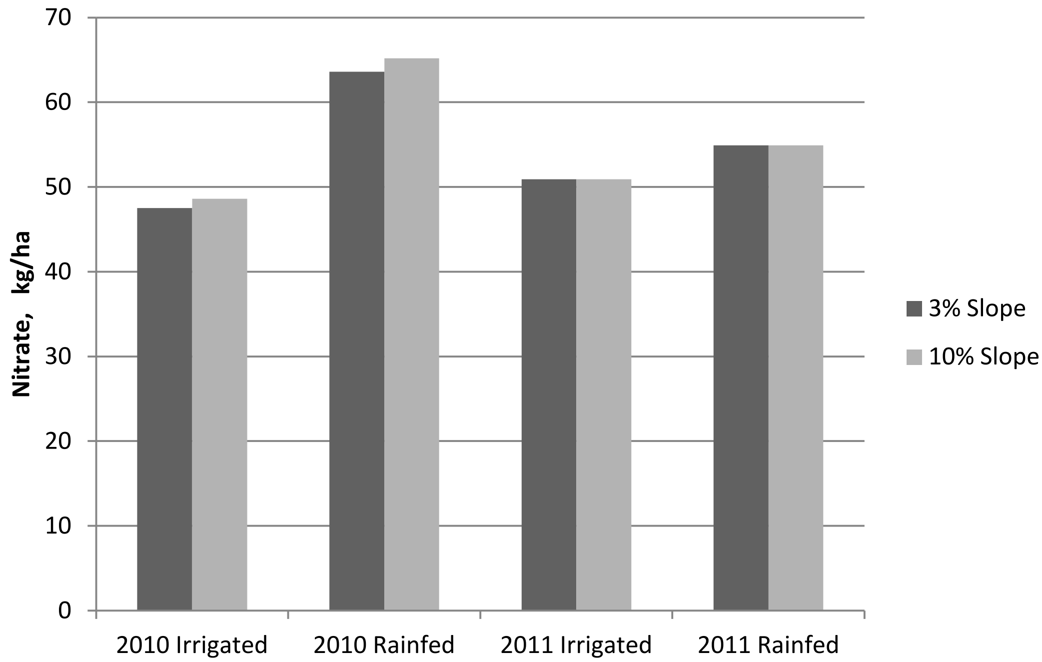


Figure 6.33: Comparison of total surface export for a 3% and 10% slope

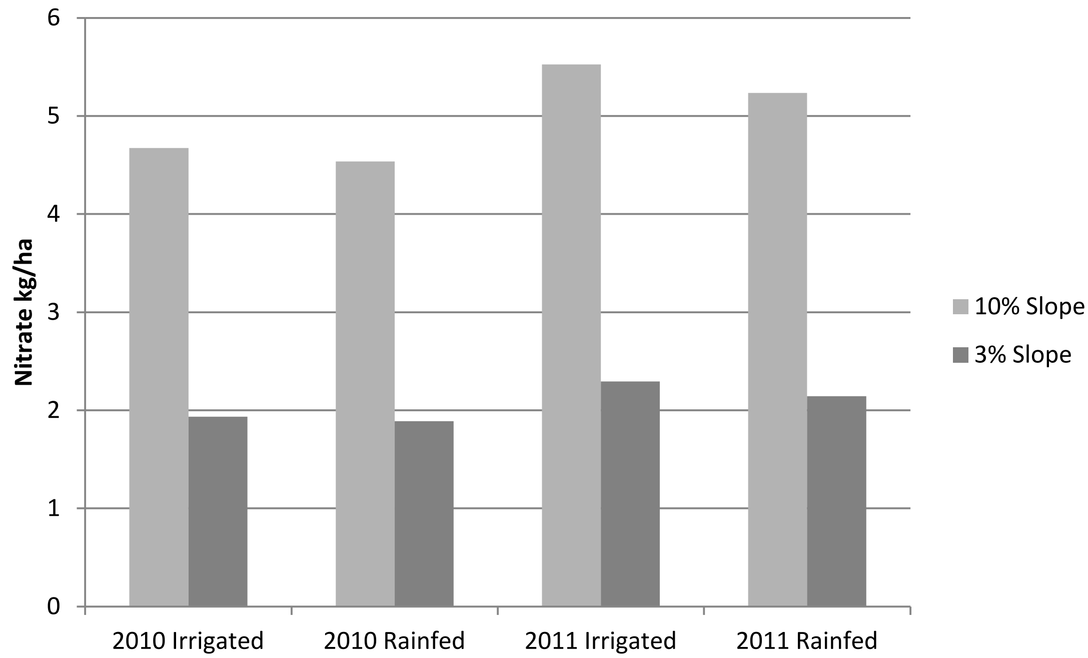


Figure 6.34: Comparison of subsurface export for a 3% and 10% slope during the growing season

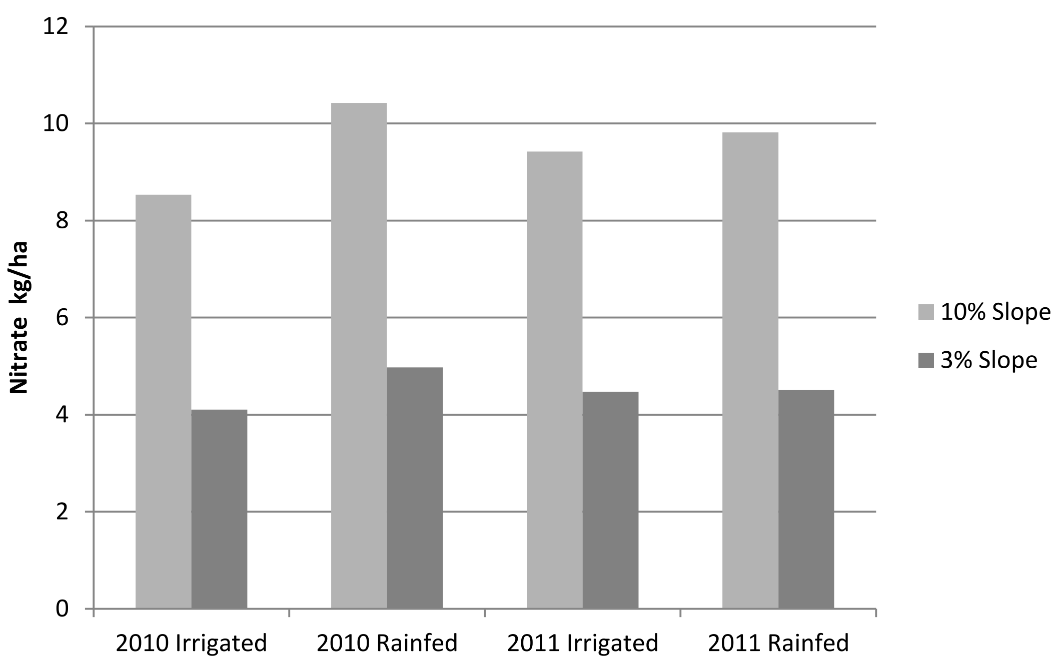


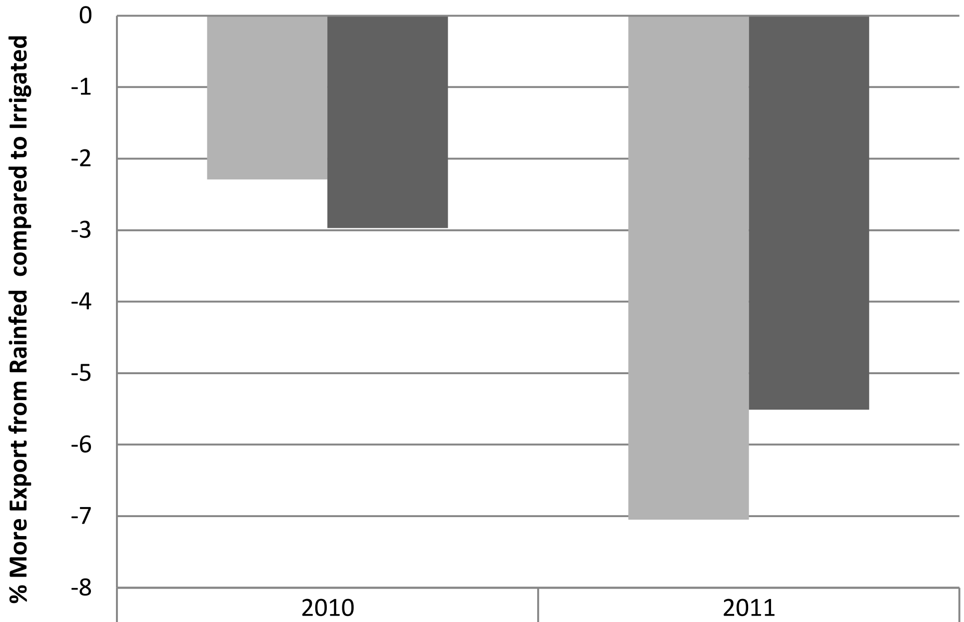
Figure 3.35: Comparison of total subsurface export for a 3% and 10% slope

Table 6.8: Total lateral nitrate export (kg/ha) for treatment 11 at a 3% slope

		Growing Season (Jan-Sept)				Total (Jan -Mar)			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.0198	0.0177	0.0319	0.0340	0.0228	0.0368	0.0363	0.0555
3	5	0.0063	0.0045	0.0090	0.0102	0.0074	0.0117	0.0109	0.0171
4	13	0.4140	0.3613	0.5321	0.5305	0.5092	0.8815	0.6871	0.9234
5	13	0.0378	0.0369	0.0490	0.0490	0.0776	0.1399	0.0903	0.1344
6	29	0.4090	0.4237	0.4801	0.4245	0.8578	1.1221	0.9284	0.9305
7	29	0.3976	0.3934	0.4449	0.4054	0.9542	1.0700	0.9690	0.9071
8	28	0.3899	0.3914	0.4646	0.4281	1.0288	1.0675	1.0826	0.9657
9	20	0.2597	0.2618	0.2834	0.2622	0.6475	0.6408	0.6661	0.5709
Total Exported		**1.93**	**1.89**	**2.29**	**2.14**	**4.11**	**4.97**	**4.47**	**4.50**

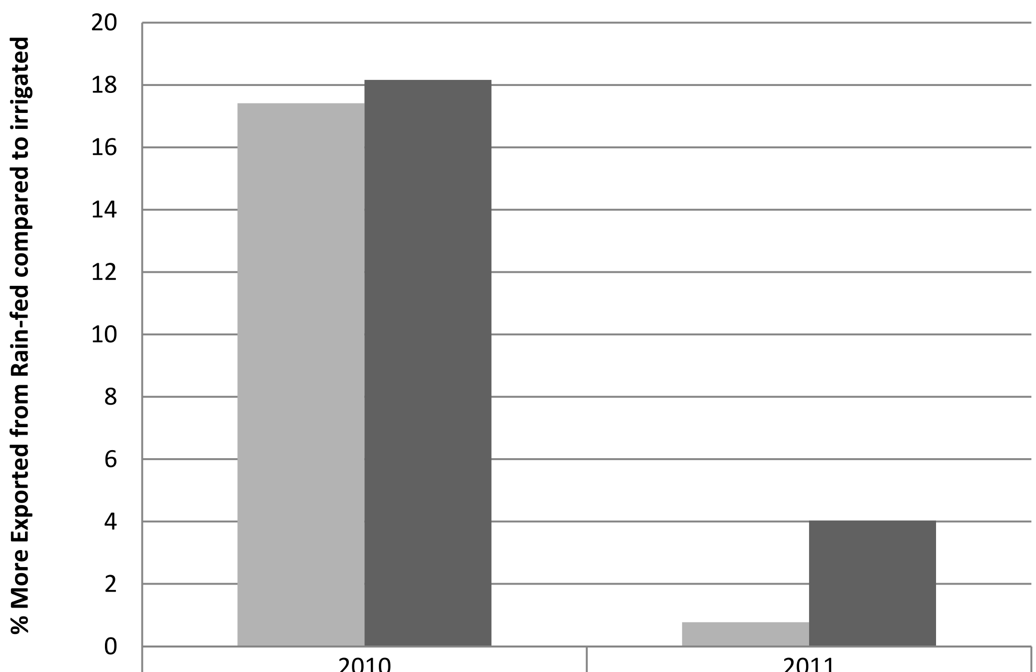
Table 6.9: Total lateral nitrate export (kg/ha) for treatment 11 at a 10% slope

		Growing Season (Jan-Sept)				Total (Jan -Mar)			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.0613	0.0549	0.0990	0.1052	0.0701	0.1120	0.1116	0.1685
3	5	0.0200	0.0144	0.0285	0.0325	0.0235	0.0367	0.0344	0.0533
4	13	1.1948	1.0480	1.5192	1.5151	1.3874	2.3517	1.8637	2.4659
5	13	0.1128	0.1101	0.1445	0.1445	0.2169	0.3802	0.2521	0.3687
6	29	0.9428	0.9710	1.0907	0.9818	1.7562	2.2172	1.8955	1.9214
7	29	0.9052	0.8972	1.0076	0.9306	1.8900	2.0902	1.9337	1.8428
8	28	0.8403	0.8426	0.9878	0.9213	1.8941	1.9545	2.0006	1.8258
9	20	0.5951	0.5992	0.6466	0.6045	1.2920	1.2806	1.3304	1.1712
Total Exported		**4.67**	**4.54**	**5.52**	**5.24**	**8.53**	**10.42**	**9.42**	**9.82**



	2010	2011
3% Slope	-2.29	-7.05
10% Slope	-2.97	-5.51

Figure 6.36: Change in percent increase from rain-fed to irrigated for growing season export (Jan-Sept)



	2010	2011
3% Slope	17.41	0.77
10% Slope	18.16	4.03

Figure 6.37: Change in percent increase from rain-fed to irrigated for total export (Jan-Mar)

CHAPTER VII

CONCLUSIONS

The overall objective of this study was to model the fate and transport of nitrate on the surface and in the subsurface for both rain-fed and irrigated assisted agricultural fields. As irrigation practices increase nationally and especially in the Southeast, whether or not this practice impacts the environment negatively is crucial to an expanded Southeastern agricultural system. This objective was achieved by examining whether irrigation increases nitrogen runoff and leaching or, conversely, whether irrigation is an effective management strategy to reduce the loss of nutrients to ground water and surface water in the southeastern United Sates' humid environment. This chapter will provide concise, yet thorough conclusions of the results reported. In addition, recommendations based of the aforementioned conclusions will be presented.

The study yielded positive, expected, results. Early season frontal systems have a major impact on the surface nitrate runoff, however irrigation benefits by allowing the nitrate to move beyond the surface layer. The most important mitigation factor to decrease surface nitrate runoff on both irrigated and rain-fed agricultural fields is allowing flexible fertilizer applications. The closer a rain event is to an application, the

more likely nitrate export will occur. The results of this study do suggest, however, that irrigation is an effective management practice to decrease the amount of nitrate in the surface layer, thus decreasing the amount of surface export. From the 8 simulations reported in the results, a total of 4 resulted in the irrigated field exporting more nitrate while 4 resulted in the opposite. However, of those cases where the irrigated exported more nitrate it was at an average of 5% more than the rain-fed fields. Contrarily, when the rain-fed filed exported more nitrates it was at an average of 26% more than that of the irrigated. In fact, during the dryer year of 2010 that average was 44%.

Irrigation has a minimal effect of the amount of lateral leaching of nitrate during the growing season. There was no considerable difference overall of the rain-fed leaching compared to the irrigated. However, the study does suggest that irrigation decreases the residual (fall/post season) nitrate in the soil column, thus decreasing the amount of lateral export in the subsurface. Irrigation provides the vertical movement and aerobic conditions for nitrogen to be consumed by the plant as compared to rain-fed fields. If precipitation does not occur at the right times, the applied nitrogen on a rain-fed field will not move vertically into the soil column to be taken up by the plant. The overall results of this study suggest that irrigation allows the applied nitrogen to be more available for plant uptake and decreases the amount of nitrate available to be exported form the fields.

There have many other studies concerning the nitrogen transport and how it is affected by agricultural practices (Hollis, 2008; Lang et al., 1991; Lang and Mackenzie, 1994; Zhou et al., 1997; Pandy et al., 2000; Allaire-Leung, 2000; Isidoro et al., 2006

etc.). The investigation at hand, along with many others including those cited, mostly conclude on a common idea: better fertilizer and irrigation management would decrease the export of nitrate. Both nitrogen and irrigation seem to be overly used in modern farming, i.e. used beyond maximum efficiency.

Therefore, from the conclusions of this study, it is recommended that firstly, and most obviously, that better management of fertilizer applications be implemented. This can have the largest amount of impact on the reduction of surface nitrate transport. Nitrogen applications that occur within days of large precipitation events will export more. However, the implementation of irrigation mitigates this even further. Thus irrigation is recommended because it decreases the amount of surface runoff available for transport during runoff events. Similar recommendations are suitable for the subsurface as well, as the same principle applies. When dry periods occur during the growing season, the nitrate cannot be transported vertically to the root zone and is unavailable to the plants for uptake. However, if irrigation is not applied efficiently and based on crop demand, the likelyhood of excessive nitrate leaching and runoff is possible.

These conclusions are based on the results of this simulation in north Alabama. Different regions with different soil properties and chemical makeups will have an effect on the results and was not considered. Also, the quality of the applied water was not evaluated or included in this analysis.

APPENDICIES

APPENDIX A

Weather Data

Table A.1: 2010 Recorded weather data (AWIS)

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
1/1/2010	49	35	724	0
1/2/2010	38	22	3312	0
1/3/2010	29	18	3801	0
1/4/2010	31	17	3584	0
1/5/2010	29	13	2416	0
1/6/2010	31	12	4051	0
1/7/2010	35	12	4004	0
1/8/2010	32	11	457	0.01
1/9/2010	22	13	1785	0
1/10/2010	28	12	2911	0
1/11/2010	30	10	4143	0
1/12/2010	46	12	3503	0
1/13/2010	36	15	4103	0
1/14/2010	47	15	4166	0
1/15/2010	52	18	3192	0
1/16/2010	60	23	4106	0
1/17/2010	52	39	469	1.35
1/18/2010	51	35	624	0.22
1/19/2010	58	34	2944	0
1/20/2010	58	34	1328	0.01
1/21/2010	62	51	1829	0.47
1/22/2010	68	47	1828	0.22
1/23/2010	53	37	1037	0
1/24/2010	53	46	2002	1.11
1/25/2010	55	38	489	0.7
1/26/2010	49	32	3370	0
1/27/2010	43	24	2787	0
1/28/2010	49	25	3879	0
1/29/2010	55	33	2274	0
1/30/2010	39	31	324	0.96
1/31/2010	35	21	509	0
2/1/2010	42	21	4698	0
2/2/2010	48	24	3367	0.15
2/3/2010	52	37	1801	0
2/4/2010	48	36	4690	0
2/5/2010	43	37	540	1.46
2/6/2010	47	36	609	0.25
2/7/2010	37	31	468	0
2/8/2010	34	30	801	0

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m	Rainfall (in)
2/9/2010	44	31	968	0.4
2/10/2010	44	24	880	0.05
2/11/2010	36	24	2732	0
2/12/2010	38	24	3633	0
2/13/2010	36	25	1215	0
2/14/2010	44	29	3709	0
2/15/2010	45	23	1090	0.27
2/16/2010	29	20	2625	0.02
2/17/2010	30	24	2231	0
2/18/2010	42	22	4792	0
2/19/2010	50	24	5579	0
2/20/2010	55	25	5355	0
2/21/2010	64	28	5681	0
2/22/2010	68	36	5338	0.63
2/23/2010	53	38	1573	0
2/24/2010	40	31	1033	0
2/25/2010	42	21	3720	0
2/26/2010	42	23	5957	0
2/27/2010	48	23	5475	0
2/28/2010	51	25	6260	0
3/1/2010	53	29	6252	0
3/2/2010	47	31	2801	0.06
3/3/2010	39	32	1374	0.17
3/4/2010	39	25	1359	0
3/5/2010	51	25	4614	0
3/6/2010	52	25	6600	0
3/7/2010	57	27	6782	0
3/8/2010	62	29	4658	0
3/9/2010	72	35	6348	0
3/10/2010	61	48	1979	0.08
3/11/2010	61	53	1599	0.39
3/12/2010	74	49	2667	0.48
3/13/2010	63	45	5173	0.13
3/14/2010	52	42	2850	0.1
3/15/2010	51	42	1554	0.01
3/16/2010	51	44	2598	0.01
3/17/2010	49	45	1249	0
3/18/2010	51	44	1328	0
3/19/2010	65	35	4014	0

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
3/20/2010	71	39	7041	0
3/21/2010	72	45	4208	0.1
3/22/2010	55	35	939	0.43
3/23/2010	44	35	1359	0.14
3/24/2010	66	40	5524	0
3/25/2010	73	47	7177	0.72
3/26/2010	60	43	1029	0.84
3/27/2010	55	35	5168	0
3/28/2010	68	45	7399	0.45
3/29/2010	63	44	4326	0.02
3/30/2010	63	38	6921	0
3/31/2010	67	40	7551	0
4/1/2010	77	46	7188	0
4/2/2010	81	51	7733	0
4/3/2010	82	59	7033	0.12
4/4/2010	75	48	4543	0.06
4/5/2010	81	56	7558	0
4/6/2010	86	57	7345	0
4/7/2010	85	64	7951	0
4/8/2010	78	56	6201	0.46
4/9/2010	68	39	5198	0
4/10/2010	69	39	8428	0
4/11/2010	74	43	8101	0
4/12/2010	78	45	8417	0
4/13/2010	82	49	8271	0
4/14/2010	82	50	8172	0
4/15/2010	84	54	7933	0
4/16/2010	83	52	7983	0
4/17/2010	85	54	7917	0
4/18/2010	70	45	6913	0
4/19/2010	68	46	8909	0
4/20/2010	69	50	5600	0
4/21/2010	73	42	5625	0
4/22/2010	76	47	7943	0
4/23/2010	80	54	7149	0
4/24/2010	82	63	7715	0.72
4/25/2010	71	59	1758	1.06
4/26/2010	78	55	8291	0
4/27/2010	64	53	3298	0.01

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
4/28/2010	61	40	4637	0.03
4/29/2010	69	47	5560	0
4/30/2010	76	56	8477	0
5/1/2010	80	65	7360	0
5/2/2010	78	68	1673	0.26
5/3/2010	77	63	1411	1.84
5/4/2010	82	54	9024	0
5/5/2010	86	56	9194	0
5/6/2010	85	59	9011	0
5/7/2010	88	62	8962	0
5/8/2010	87	61	8687	0
5/9/2010	71	47	9054	0
5/10/2010	66	49	7097	0
5/11/2010	60	52	2109	0.14
5/12/2010	79	60	4458	0
5/13/2010	85	65	6451	0
5/14/2010	87	66	7718	0
5/15/2010	88	65	7762	0
5/16/2010	87	66	7110	0.95
5/17/2010	76	65	2816	0.35
5/18/2010	79	60	7435	0
5/19/2010	73	52	6901	0
5/20/2010	77	57	8733	0
5/21/2010	82	63	5904	0.2
5/22/2010	75	62	4465	0.39
5/23/2010	85	63	6826	0
5/24/2010	91	65	7033	0
5/25/2010	89	67	6771	0
5/26/2010	82	62	8311	0
5/27/2010	87	64	8256	0.12
5/28/2010	86	65	7478	0
5/29/2010	88	66	7052	0.73
5/30/2010	79	66	5828	0.01
5/31/2010	81	65	4296	0.43
6/1/2010	86	68	6186	0.02
6/2/2010	84	66	6025	0.09
6/3/2010	87	66	5970	0.03
6/4/2010	86	70	6673	0
6/5/2010	85	68	4544	0.03

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
6/6/2010	88	69	7573	0.16
6/7/2010	88	59	5000	0.01
6/8/2010	85	67	8786	0
6/9/2010	86	68	6811	0
6/10/2010	89	69	4806	0.93
6/11/2010	90	72	4751	0
6/12/2010	89	73	8085	0
6/13/2010	95	72	8326	0
6/14/2010	95	73	8949	0
6/15/2010	96	72	8098	0
6/16/2010	90	71	4258	0.07
6/17/2010	91	69	5373	0
6/18/2010	90	68	6979	0
6/19/2010	93	72	8243	0
6/20/2010	88	70	4727	0.9
6/21/2010	92	68	8527	0
6/22/2010	95	72	8682	0
6/23/2010	92	71	7644	0
6/24/2010	91	71	8120	0
6/25/2010	94	72	8741	0
6/26/2010	93	69	5952	0
6/27/2010	90	69	4281	0
6/28/2010	92	74	6106	0
6/29/2010	95	70	7861	0
6/30/2010	89	72	7169	0
7/1/2010	89	68	5633	0
7/2/2010	88	63	8704	0
7/3/2010	91	71	8659	0
7/4/2010	88	65	7077	0
7/5/2010	88	62	7785	0
7/6/2010	91	69	9367	0
7/7/2010	92	69	8856	0
7/8/2010	96	72	6084	0
7/9/2010	98	72	8801	0
7/10/2010	96	72	6064	0.29
7/11/2010	90	70	6826	0
7/12/2010	93	73	6040	0.2
7/13/2010	91	71	4861	0
7/14/2010	87	70	4201	0.67

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
7/15/2010	94	71	8869	0
7/16/2010	97	74	8032	0
7/17/2010	94	72	5352	0.11
7/18/2010	87	73	4255	0
7/19/2010	91	74	6996	0.01
7/20/2010	91	73	5814	0
7/21/2010	93	72	8861	0
7/22/2010	98	73	8950	0
7/23/2010	98	73	8545	0
7/24/2010	99	72	8106	0
7/25/2010	100	74	7996	0
7/26/2010	100	74	6476	0
7/27/2010	97	71	5756	1.86
7/28/2010	92	73	8435	0.04
7/29/2010	92	72	7601	0
7/30/2010	92	71	3982	0.52
7/31/2010	92	73	6891	0
8/1/2010	97	75	8962	0
8/2/2010	96	73	7387	0
8/3/2010	97	76	9209	0
8/4/2010	98	75	7497	0
8/5/2010	102	76	8632	0
8/6/2010	96	73	6754	0.01
8/7/2010	93	71	7857	0
8/8/2010	95	70	8506	0
8/9/2010	98	77	7757	0
8/10/2010	97	75	5884	0
8/11/2010	99	74	7127	0
8/12/2010	100	75	7945	0
8/13/2010	100	74	7828	0
8/14/2010	99	74	7571	0
8/15/2010	96	75	5971	0.06
8/16/2010	97	73	6620	0
8/17/2010	97	74	7333	0
8/18/2010	96	75	3930	0
8/19/2010	91	76	4304	0.23
8/20/2010	92	72	5846	0
8/21/2010	96	71	6424	0
8/22/2010	98	72	6813	0.12

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
8/23/2010	92	70	7934	0
8/24/2010	92	64	8310	0
8/25/2010	89	64	8326	0
8/26/2010	85	64	7569	0
8/27/2010	90	66	8228	0
8/28/2010	92	69	6173	0
8/29/2010	92	74	6277	0
8/30/2010	79	69	1725	0.79
8/31/2010	79	68	3262	0.01
9/1/2010	88	63	6518	0
9/2/2010	90	62	7797	0
9/3/2010	94	65	7743	0
9/4/2010	92	53	6454	0
9/5/2010	81	48	8071	0
9/6/2010	84	50	8027	0
9/7/2010	90	62	7962	0
9/8/2010	94	69	7199	0
9/9/2010	84	69	3362	0.06
9/10/2010	88	65	3674	0
9/11/2010	92	68	5420	0
9/12/2010	97	64	5983	0
9/13/2010	86	52	7568	0
9/14/2010	90	55	7351	0
9/15/2010	91	64	7097	0
9/16/2010	93	71	6955	0
9/17/2010	94	66	4221	0
9/18/2010	92	60	6300	0
9/19/2010	94	63	7365	0
9/20/2010	97	63	6396	0
9/21/2010	97	64	6714	0
9/22/2010	98	64	5926	0
9/23/2010	95	68	6514	0
9/24/2010	95	61	6100	0
9/25/2010	94	70	4880	0.52
9/26/2010	74	65	1613	0.5
9/27/2010	76	56	2680	0.4
9/28/2010	63	49	2983	0.1
9/29/2010	72	47	6089	0
9/30/2010	77	54	6768	0

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
10/1/2010	81	59	6602	0
10/2/2010	77	48	6793	0
10/3/2010	78	50	6701	0
10/4/2010	64	39	6147	0
10/5/2010	64	37	7052	0
10/6/2010	70	35	6649	0
10/7/2010	75	41	6542	0
10/8/2010	83	47	6236	0
10/9/2010	85	49	6225	0
10/10/2010	87	49	6200	0
10/11/2010	88	49	6166	0
10/12/2010	88	56	4980	0
10/13/2010	79	53	2652	0.14
10/14/2010	78	53	4482	0.22
10/15/2010	71	40	6137	0
10/16/2010	76	38	5963	0
10/17/2010	75	38	6108	0
10/18/2010	80	44	6152	0
10/19/2010	77	46	2992	0
10/20/2010	82	52	4505	0.18
10/21/2010	74	42	5504	0
10/22/2010	79	41	5556	0
10/23/2010	78	42	5477	0
10/24/2010	80	53	4931	0
10/25/2010	82	60	3793	3.03
10/26/2010	79	61	3192	0.04
10/27/2010	82	55	1697	1.35
10/28/2010	74	53	3417	0
10/29/2010	72	40	5326	0
10/30/2010	63	33	5402	0
10/31/2010	71	37	5397	0
11/1/2010	76	42	5214	0
11/2/2010	75	47	4662	0
11/3/2010	69	50	2815	0.04
11/4/2010	53	50	677	0.43
11/5/2010	59	39	4956	0
11/6/2010	50	29	1702	0
11/7/2010	50	28	4879	0
11/8/2010	60	31	4846	0

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
11/9/2010	69	34	4710	0
11/10/2010	74	36	4689	0
11/11/2010	75	37	4510	0
11/12/2010	78	37	4599	0
11/13/2010	75	39	4446	0
11/14/2010	72	48	4208	0.23
11/15/2010	57	37	1536	0
11/16/2010	56	41	576	0.35
11/17/2010	63	34	1707	0.33
11/18/2010	60	35	4222	0
11/19/2010	61	38	2592	0
11/20/2010	64	39	4094	0
11/21/2010	71	46	3510	0
11/22/2010	73	50	3344	0
11/23/2010	76	55	3924	0
11/24/2010	67	46	2225	0.49
11/25/2010	67	48	1937	0
11/26/2010	74	36	2332	1.03
11/27/2010	44	26	1589	0
11/28/2010	55	26	4087	0
11/29/2010	57	29	3080	0
11/30/2010	62	48	1095	2.68
12/1/2010	56	31	680	0.23
12/2/2010	44	25	4002	0
12/3/2010	51	25	3584	0
12/4/2010	57	31	3699	0
12/5/2010	59	32	499	0
12/6/2010	39	26	1349	0
12/7/2010	37	23	3970	0
12/8/2010	38	23	3667	0
12/9/2010	34	15	2290	0
12/10/2010	45	16	3725	0
12/11/2010	49	27	1690	0
12/12/2010	53	28	955	0.58
12/13/2010	28	18	1421	0
12/14/2010	27	10	3704	0
12/15/2010	30	10	3842	0
12/16/2010	53	29	543	0.04
12/17/2010	60	32	670	0.09

Table A.1Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
12/18/2010	38	31	2008	0
12/19/2010	42	23	3210	0
12/20/2010	46	22	3655	0
12/21/2010	51	23	3039	0
12/22/2010	58	47	708	0.01
12/23/2010	52	30	2579	0
12/24/2010	42	27	3519	0
12/25/2010	49	28	3668	0.01
12/26/2010	33	27	653	0.24
12/27/2010	30	27	2327	0
12/28/2010	36	15	3038	0.11
12/29/2010	44	15	3822	0
12/30/2010	51	37	1747	0
12/31/2010	55	46	1111	0.01

Table A.2: 2011 Recorded weather data (AWIS)

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
1/1/2011	69	53	1532	2.48
1/2/2011	59	29	742	0.02
1/3/2011	41	20	4008	0
1/4/2011	47	20	4055	0
1/5/2011	56	30	2986	0
1/6/2011	42	34	489	0.3
1/7/2011	47	34	2947	0
1/8/2011	57	33	2487	0
1/9/2011	41	16	4162	0
1/10/2011	33	17	1631	0
1/11/2011	32	27	1464	0.16
1/12/2011	33	17	1643	0
1/13/2011	27	14	4237	0
1/14/2011	30	6	4351	0
1/15/2011	37	7	4129	0
1/16/2011	42	17	2219	0
1/17/2011	48	22	3896	0
1/18/2011	51	34	1779	0.19
1/19/2011	47	38	359	0.13
1/20/2011	38	34	618	0
1/21/2011	40	20	658	0.04
1/22/2011	31	20	4229	0.01
1/23/2011	40	22	4399	0
1/24/2011	41	27	2372	0
1/25/2011	56	36	2724	0.2
1/26/2011	45	33	667	0.54
1/27/2011	41	24	2284	0.01
1/28/2011	53	24	4186	0
1/29/2011	55	29	4360	0
1/30/2011	70	33	4510	0
1/31/2011	68	35	3184	0.12
2/1/2011	58	48	886	0
2/2/2011	58	27	514	0.47
2/3/2011	35	22	4510	0
2/4/2011	34	22	1977	0.05
2/5/2011	40	32	617	0.38
2/6/2011	35	26	892	0
2/7/2011	53	27	4728	0
2/8/2011	52	30	1093	0

Table A.2 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
2/9/2011	40	21	4025	0
2/10/2011	41	19	2519	0.04
2/11/2011	36	15	4464	0
2/12/2011	41	16	5541	0
2/13/2011	53	23	5384	0
2/14/2011	65	28	5232	0
2/15/2011	67	33	5415	0
2/16/2011	65	34	4693	0
2/17/2011	68	40	3305	0
2/18/2011	67	47	2185	0
2/19/2011	68	51	2407	0
2/20/2011	64	44	2381	0
2/21/2011	73	50	3914	0
2/22/2011	71	49	2172	0
2/23/2011	61	31	4896	0
2/24/2011	67	35	3213	0.05
2/25/2011	73	51	2751	0.65
2/26/2011	51	29	3426	0
2/27/2011	69	32	5910	0
2/28/2011	76	61	3214	0
3/1/2011	75	38	2275	0.31
3/2/2011	63	32	6292	0
3/3/2011	67	35	5262	0
3/4/2011	72	48	6025	0
3/5/2011	69	52	3673	0.37
3/6/2011	59	38	605	1.86
3/7/2011	39	37	841	0
3/8/2011	52	38	3589	0
3/9/2011	56	46	1605	2.43
3/10/2011	63	41	1416	0.05
3/11/2011	44	32	1354	0
3/12/2011	56	34	6739	0
3/13/2011	72	40	6431	0
3/14/2011	71	49	4175	0
3/15/2011	71	45	3235	0.79
3/16/2011	50	43	1135	0
3/17/2011	62	41	3462	0
3/18/2011	77	47	3831	0
3/19/2011	81	54	4002	0

Table A.2 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
3/20/2011	74	51	3498	0
3/21/2011	82	56	4281	0
3/22/2011	79	53	4021	0
3/23/2011	79	62	4006	0
3/24/2011	70	45	910	0.04
3/25/2011	57	33	4535	0
3/26/2011	60	38	5348	0.35
3/27/2011	61	40	1190	1.42
3/28/2011	44	40	1497	0.63
3/29/2011	52	40	3568	0
3/30/2011	59	44	3395	0.31
3/31/2011	57	40	1137	0.03
4/1/2011	48	41	1801	0
4/2/2011	60	37	4270	0
4/3/2011	70	41	7488	0
4/4/2011	81	52	7428	0
4/5/2011	77	40	1715	1.99
4/6/2011	59	37	7952	0
4/7/2011	72	47	7413	0
4/8/2011	74	57	7152	0
4/9/2011	85	63	4098	0
4/10/2011	89	60	6393	0
4/11/2011	84	67	5510	0
4/12/2011	82	52	4966	0.23
4/13/2011	71	42	8153	0
4/14/2011	75	47	8389	0
4/15/2011	78	53	7288	0.13
4/16/2011	63	49	743	1.86
4/17/2011	60	37	3694	0
4/18/2011	71	44	7896	0
4/19/2011	77	56	6270	0
4/20/2011	83	62	7080	0.57
4/21/2011	77	56	3044	0.65
4/22/2011	67	55	2975	0
4/23/2011	80	65	7703	0
4/24/2011	82	68	7779	0
4/25/2011	82	64	5589	0
4/26/2011	82	58	5366	0.34
4/27/2011	81	61	3787	1.13

Table A.2 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
4/28/2011	72	54	2091	3.31
4/29/2011	69	50	7510	0.01
4/30/2011	77	52	7687	0
5/1/2011	80	61	7100	0
5/2/2011	78	63	6029	0
5/3/2011	83	51	5776	0.23
5/4/2011	54	40	1555	0.65
5/5/2011	64	41	8845	0
5/6/2011	67	46	8129	0
5/7/2011	72	48	6885	0
5/8/2011	77	56	6750	0
5/9/2011	84	62	7680	0
5/10/2011	86	63	7850	0
5/11/2011	88	63	7055	0
5/12/2011	89	65	7515	0
5/13/2011	88	65	8363	0
5/14/2011	74	60	3000	0.21
5/15/2011	70	54	5469	0
5/16/2011	61	52	2198	0
5/17/2011	59	46	3528	0.03
5/18/2011	65	45	4040	0
5/19/2011	67	51	7059	0
5/20/2011	79	55	8056	0
5/21/2011	87	61	8426	0
5/22/2011	89	64	7685	0
5/23/2011	89	65	6261	0.61
5/24/2011	87	68	6017	0
5/25/2011	86	69	6874	0
5/26/2011	87	63	6805	0.44
5/27/2011	82	58	6231	0.36
5/28/2011	77	58	8718	0
5/29/2011	88	68	9390	0
5/30/2011	90	67	8918	0
5/31/2011	93	69	8589	0
6/1/2011	94	69	9151	0
6/2/2011	93	70	8896	0
6/3/2011	95	69	8827	0
6/4/2011	96	69	8273	0
6/5/2011	93	70	6332	0

Table A.2 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
6/6/2011	95	68	7608	0
6/7/2011	93	70	8734	0
6/8/2011	94	67	7538	0
6/9/2011	95	68	8657	0
6/10/2011	94	68	8565	0
6/11/2011	96	69	8629	0
6/12/2011	96	69	8136	0
6/13/2011	93	67	7700	0
6/14/2011	91	66	7299	0
6/15/2011	91	69	7340	0
6/16/2011	97	64	7174	0.45
6/17/2011	93	68	7179	0.11
6/18/2011	79	67	3602	0.23
6/19/2011	92	69	6174	0
6/20/2011	94	72	7692	0
6/21/2011	92	76	8014	0
6/22/2011	89	68	4051	0.5
6/23/2011	82	69	2818	0.38
6/24/2011	87	74	5580	0
6/25/2011	88	64	2979	0.28
6/26/2011	91	70	7584	0
6/27/2011	89	66	4706	0.09
6/28/2011	93	68	7824	0.14
6/29/2011	78	66	2209	0.93
6/30/2011	87	61	7392	0
7/1/2011	89	65	8559	0
7/2/2011	93	66	8198	0
7/3/2011	94	67	8091	0
7/4/2011	95	70	6048	0
7/5/2011	94	70	6385	0
7/6/2011	86	68	4543	0.05
7/7/2011	88	71	6913	0.1
7/8/2011	90	69	5155	0.44
7/9/2011	90	70	4934	0.12
7/10/2011	92	73	7735	0
7/11/2011	95	74	6519	0.51
7/12/2011	97	77	8339	0
7/13/2011	97	74	6911	0.12
7/14/2011	91	74	6145	0

Table A.2 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (in)
7/15/2011	95	72	8109	2.65
7/16/2011	84	69	4196	0.06
7/17/2011	82	71	5707	0
7/18/2011	87	69	7585	0
7/19/2011	91	71	9192	0
7/20/2011	93	72	7435	0
7/21/2011	95	74	8076	0
7/22/2011	82	72	2727	0.06
7/23/2011	93	71	7990	0
7/24/2011	92	74	6458	0
7/25/2011	88	75	5165	0
7/26/2011	91	72	5087	0
7/27/2011	95	70	8430	0
7/28/2011	96	74	8667	0
7/29/2011	92	73	7083	0
7/30/2011	90	74	5924	0
7/31/2011	91	73	5677	0.17
8/1/2011	94	75	8318	0
8/2/2011	95	69	8769	0
8/3/2011	99	69	7550	0
8/4/2011	101	70	8062	0.39
8/5/2011	82	72	2020	0.23
8/6/2011	90	74	3931	0.15
8/7/2011	87	72	3096	0.08
8/8/2011	95	71	6521	0.04
8/9/2011	93	71	4817	0.04
8/10/2011	88	68	3903	0.1
8/11/2011	92	70	7957	0.07
8/12/2011	87	69	4969	0.01
8/13/2011	92	69	7223	0.02
8/14/2011	92	68	6902	0
8/15/2011	88	62	6385	0.01

Table A.3: 2011 Simulated weather data

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
8/16/2011	85	70	4806	0.72
8/17/2011	82	67	4694	0.28
8/18/2011	79	65	4583	0.01
8/19/2011	87	62	6222	0
8/20/2011	85	62	5861	0
8/21/2011	90	69	5528	0
8/22/2011	88	69	5278	0
8/23/2011	91	67	5917	0
8/24/2011	92	69	5722	0
8/25/2011	91	70	5389	0
8/26/2011	92	73	5139	0
8/27/2011	98	72	6000	0
8/28/2011	95	70	5806	0
8/29/2011	94	67	6083	0
8/30/2011	92	63	6222	0
8/31/2011	90	62	6083	0
9/1/2011	89	66	5528	0.07
9/2/2011	88	62	5750	0
9/3/2011	87	58	6111	0
9/4/2011	91	64	5944	0
9/5/2011	92	62	6278	0
9/6/2011	89	60	6028	0
9/7/2011	79	58	5111	0
9/8/2011	80	50	6139	0
9/9/2011	92	58	6444	0
9/10/2011	93	65	5722	0
9/11/2011	81	61	4889	0
9/12/2011	82	59	5194	0
9/13/2011	77	56	4889	0
9/14/2011	92	53	6667	0
9/15/2011	97	58	6583	0
9/16/2011	94	72	4972	0
9/17/2011	92	66	5389	0
9/18/2011	95	66	5611	0
9/19/2011	92	58	6028	0
9/20/2011	92	61	5750	0
9/21/2011	83	67	4139	0.4
9/22/2011	84	56	5361	0
9/23/2011	81	54	5194	0

Table A.3 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
9/24/2011	86	48	6111	0
9/25/2011	80	54	5111	0
9/26/2011	82	55	5167	0
9/27/2011	84	54	5333	0
9/28/2011	80	56	4722	0
9/29/2011	82	57	4778	0
9/30/2011	81	60	4333	0
10/1/2011	64	54	2917	0
10/2/2011	74	42	5278	0
10/3/2011	79	49	5139	0
10/4/2011	73	55	3889	0.53
10/5/2011	83	58	4611	1.08
10/6/2011	82	58	4472	0
10/7/2011	89	63	4583	0
10/8/2011	82	59	4250	0
10/9/2011	75	44	4944	0
10/10/2011	70	50	3972	0
10/11/2011	70	52	3750	0
10/12/2011	77	39	5333	0
10/13/2011	78	43	5056	0
10/14/2011	79	53	4306	0.44
10/15/2011	89	71	3556	0.13
10/16/2011	75	45	4611	0
10/17/2011	76	47	4528	0
10/18/2011	87	65	3806	0
10/19/2011	88	65	3917	0
10/20/2011	84	54	4389	0
10/21/2011	72	60	2833	0
10/22/2011	66	51	3000	0
10/23/2011	82	57	3889	0
10/24/2011	72	43	4194	0
10/25/2011	68	48	3444	0
10/26/2011	76	49	3972	0
10/27/2011	74	62	2611	0
10/28/2011	76	54	3556	0
10/29/2011	83	60	3583	0.03
10/30/2011	96	72	3639	0
10/31/2011	76	72	1472	0.08
11/1/2011	68	63	1667	0.03

Table A.3 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
11/2/2011	56	53	1250	0
11/3/2011	71	54	2944	0
11/4/2011	71	49	3361	0
11/5/2011	64	41	3361	0
11/6/2011	56	39	2833	0.01
11/7/2011	60	50	2167	0.03
11/8/2011	59	32	3528	0
11/9/2011	63	35	3639	0
11/10/2011	66	41	3361	0
11/11/2011	61	40	3056	0
11/12/2011	75	48	3472	0
11/13/2011	78	43	3889	0
11/14/2011	67	44	3111	0
11/15/2011	74	60	2444	0
11/16/2011	74	56	2806	0
11/17/2011	73	49	3139	0.04
11/18/2011	55	47	1889	0.83
11/19/2011	61	47	2278	0.04
11/20/2011	72	35	3806	0.44
11/21/2011	66	38	3306	0
11/22/2011	70	39	3389	0
11/23/2011	63	45	2611	0
11/24/2011	72	47	3028	0
11/25/2011	60	37	2917	0
11/26/2011	55	32	2917	0
11/27/2011	58	27	3333	0
11/28/2011	53	37	2417	0
11/29/2011	47	34	2194	0.04
11/30/2011	54	31	2806	0
12/1/2011	55	17	3611	0
12/2/2011	52	20	3306	0
12/3/2011	47	30	2361	0
12/4/2011	37	31	1444	0
12/5/2011	60	45	2250	0.07
12/6/2011	65	49	2333	0.04
12/7/2011	61	48	2056	0.11
12/8/2011	65	51	2139	0.64
12/9/2011	65	36	3083	0.58
12/10/2011	60	25	3361	0

Table A.3 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
12/11/2011	64	25	3528	0
12/12/2011	43	27	2250	0
12/13/2011	48	34	2111	0.37
12/14/2011	57	33	2778	0.11
12/15/2011	52	32	2472	0
12/16/2011	53	33	2556	0
12/17/2011	51	32	2389	0
12/18/2011	51	28	2639	0
12/19/2011	55	42	2000	0.5
12/20/2011	62	33	3000	0
12/21/2011	58	36	2583	0
12/22/2011	65	35	3083	0
12/23/2011	54	29	2778	0
12/24/2011	65	46	2417	0.03
12/25/2011	56	39	2306	0
12/26/2011	61	34	2944	0
12/27/2011	54	31	2694	0
12/28/2011	57	32	2806	0.05
12/29/2011	54	24	3083	0
12/30/2011	39	30	1722	0
12/31/2011	51	31	2500	0

Table A.4: 2012 Simulated weather data

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
1/1/2012	35	30	1250	0
1/2/2012	44	33	1917	0.7
1/3/2012	57	33	2778	0.06
1/4/2012	53	23	3111	0
1/5/2012	47	33	2083	0
1/6/2012	62	44	2444	0
1/7/2012	57	52	1278	1.17
1/8/2012	48	47	556	0
1/9/2012	35	31	1194	0
1/10/2012	39	26	2167	0
1/11/2012	34	12	2750	0
1/12/2012	37	7	3278	0
1/13/2012	54	24	3250	0.18
1/14/2012	47	27	2722	0.35
1/15/2012	44	26	2611	0.06
1/16/2012	40	27	2194	1.23
1/17/2012	48	31	2472	0.72
1/18/2012	48	33	2389	0.1
1/19/2012	45	31	2333	0
1/20/2012	44	24	2722	0
1/21/2012	39	15	3083	0
1/22/2012	38	24	2333	0
1/23/2012	53	40	2361	0.23
1/24/2012	54	41	2306	0.09
1/25/2012	31	23	1944	0
1/26/2012	24	15	1972	0
1/27/2012	34	17	2750	0.42
1/28/2012	37	7	3639	0
1/29/2012	49	11	4139	0
1/30/2012	36	3	3861	0
1/31/2012	26	-1	3528	0
2/1/2012	31	14	2750	0.35
2/2/2012	31	15	2778	0
2/3/2012	37	18	3028	0.26
2/4/2012	45	19	3556	0
2/5/2012	48	25	3389	0
2/6/2012	52	33	3083	0.02
2/7/2012	51	32	3139	4.34
2/8/2012	58	37	3389	0.29

Table A.4 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
2/9/2012	56	37	3167	0
2/10/2012	56	44	2611	0.19
2/11/2012	50	35	2861	0.68
2/12/2012	64	29	4500	0
2/13/2012	58	33	3806	0
2/14/2012	55	36	3306	0.02
2/15/2012	50	25	3833	0.06
2/16/2012	63	40	3778	0.18
2/17/2012	58	33	3889	0
2/18/2012	51	47	1528	0.13
2/19/2012	52	34	3417	0
2/20/2012	58	35	3917	0
2/21/2012	52	28	3972	0
2/22/2012	38	12	4194	0
2/23/2012	15	-4	3639	0
2/24/2012	32	11	3861	0.23
2/25/2012	33	14	3667	0.16
2/26/2012	39	24	3278	0.3
2/27/2012	55	28	4389	0.09
2/28/2012	48	22	4472	0
2/29/2012	64	45	3778	0.43
3/1/2012	63	32	4861	0
3/2/2012	64	39	4472	2
3/3/2012	62	44	3778	0
3/4/2012	44	39	2083	0
3/5/2012	56	42	3417	0
3/6/2012	59	33	4722	0
3/7/2012	61	42	4083	0.06
3/8/2012	63	45	3944	0
3/9/2012	89	57	5333	0
3/10/2012	64	50	3639	0
3/11/2012	72	39	5472	0
3/12/2012	73	53	4361	0.19
3/13/2012	72	62	3028	0.1
3/14/2012	67	48	4250	0.01
3/15/2012	63	46	4000	0.26
3/16/2012	54	52	1472	0.02
3/17/2012	65	41	4889	0
3/18/2012	56	37	4361	0

Table A.4 Continued

Date	Max Temp (F)	Min Temp (F)	Solar Radiation (W-hr/m^2)	Rainfall (mm)
3/19/2012	50	35	3972	0
3/20/2012	47	37	3222	0
3/21/2012	52	49	1583	0.84
3/22/2012	78	55	4944	0.08
3/23/2012	73	55	4389	0.55
3/24/2012	77	59	4444	0.99
3/25/2012	71	53	4583	0.95
3/26/2012	63	56	2722	0.09
3/27/2012	74	51	5139	0.05
3/28/2012	62	42	4722	0.1
3/29/2012	63	45	4694	0
3/30/2012	58	41	4528	0
3/31/2012	68	36	6194	0

Appendix B

Soil Nitrate Concentrations for Treatments 1, 6, 11, and 13

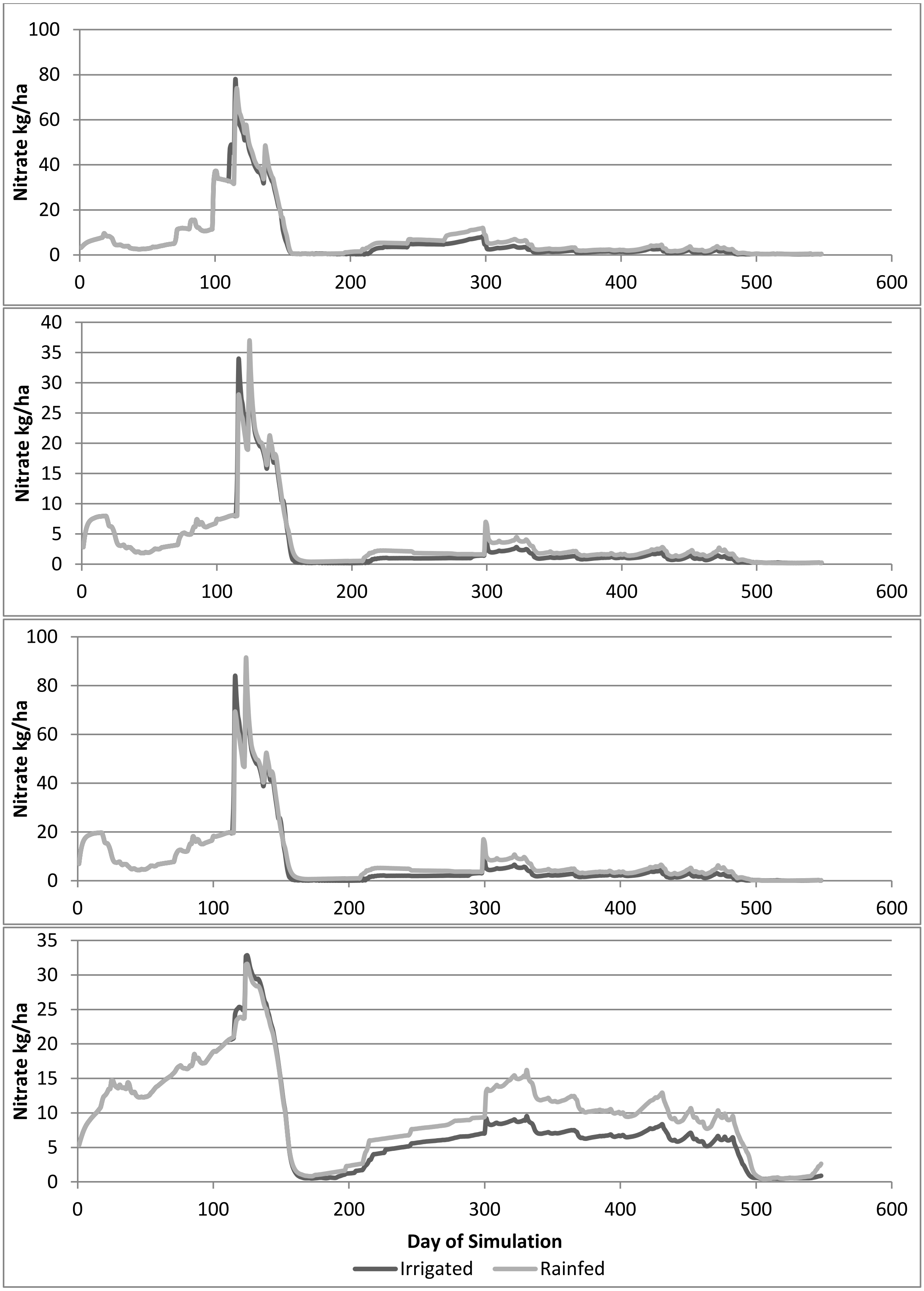


Figure B.1: 2010 Soil nitrate concentrations for treatment 1 **a:** (5-46 cm)

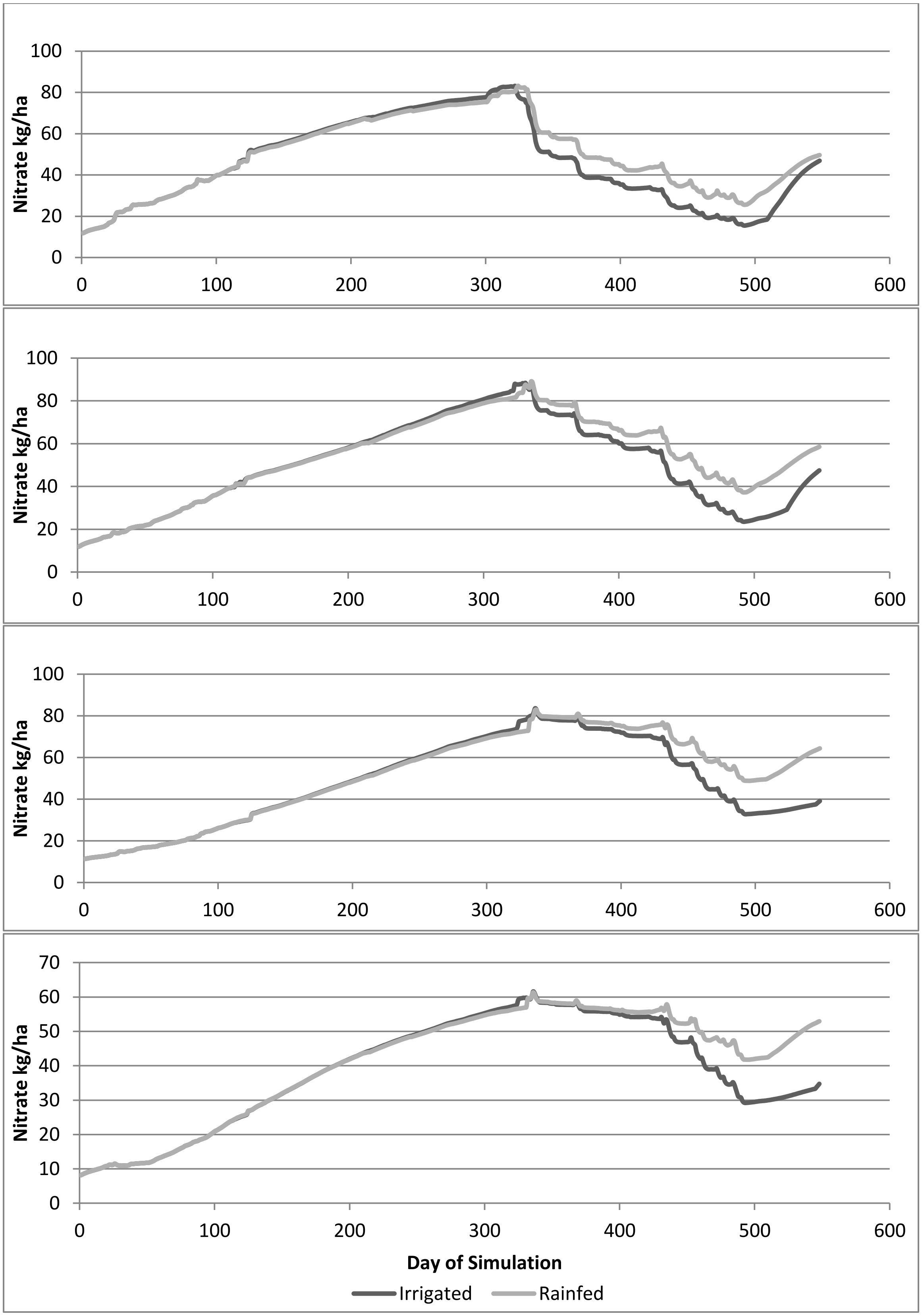


Figure B.1: Continued **b:** (46-152 cm)

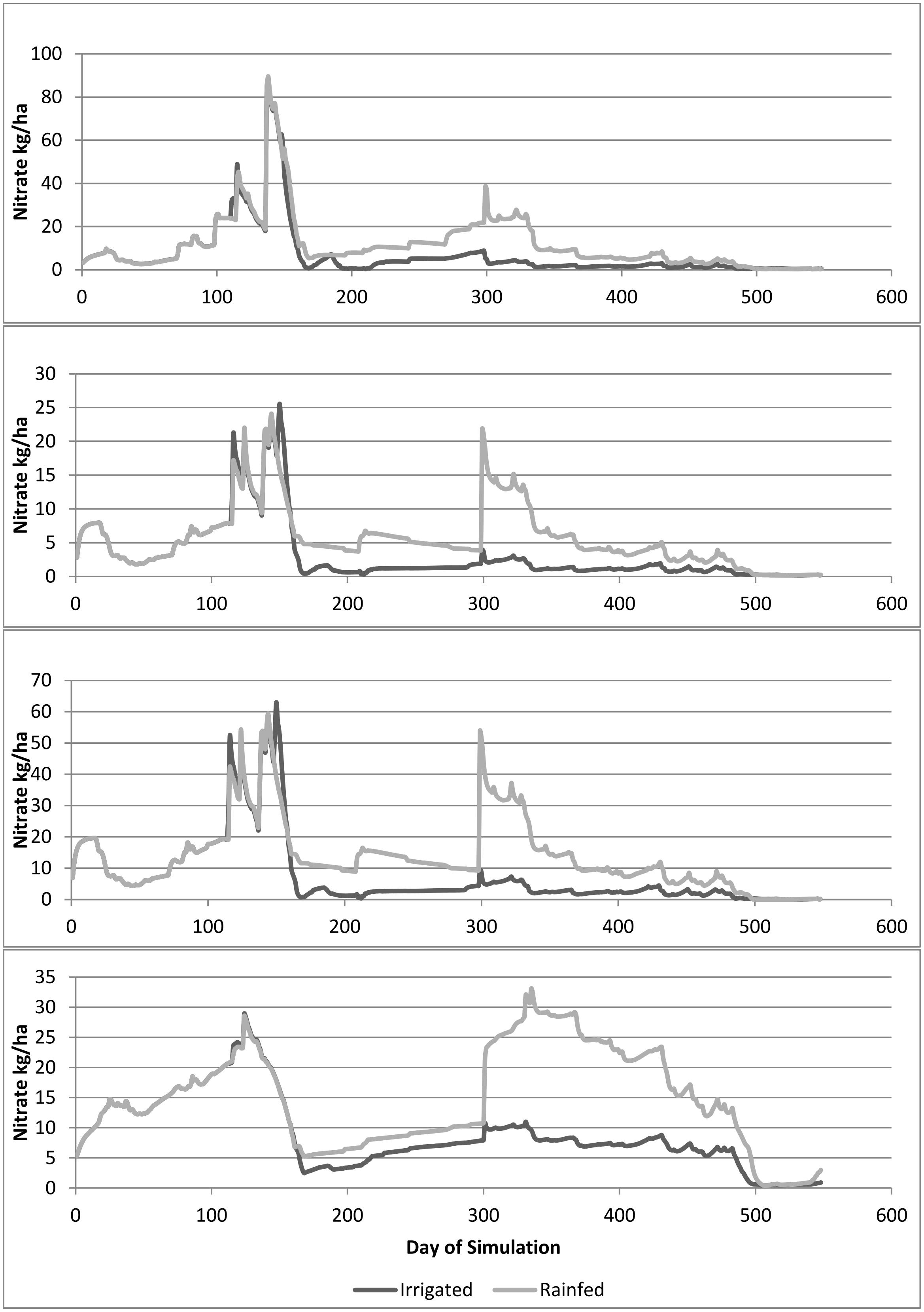


Figure B.2: 2010 Soil nitrate concentrations for treatment 6 **a:** (5-46 cm)

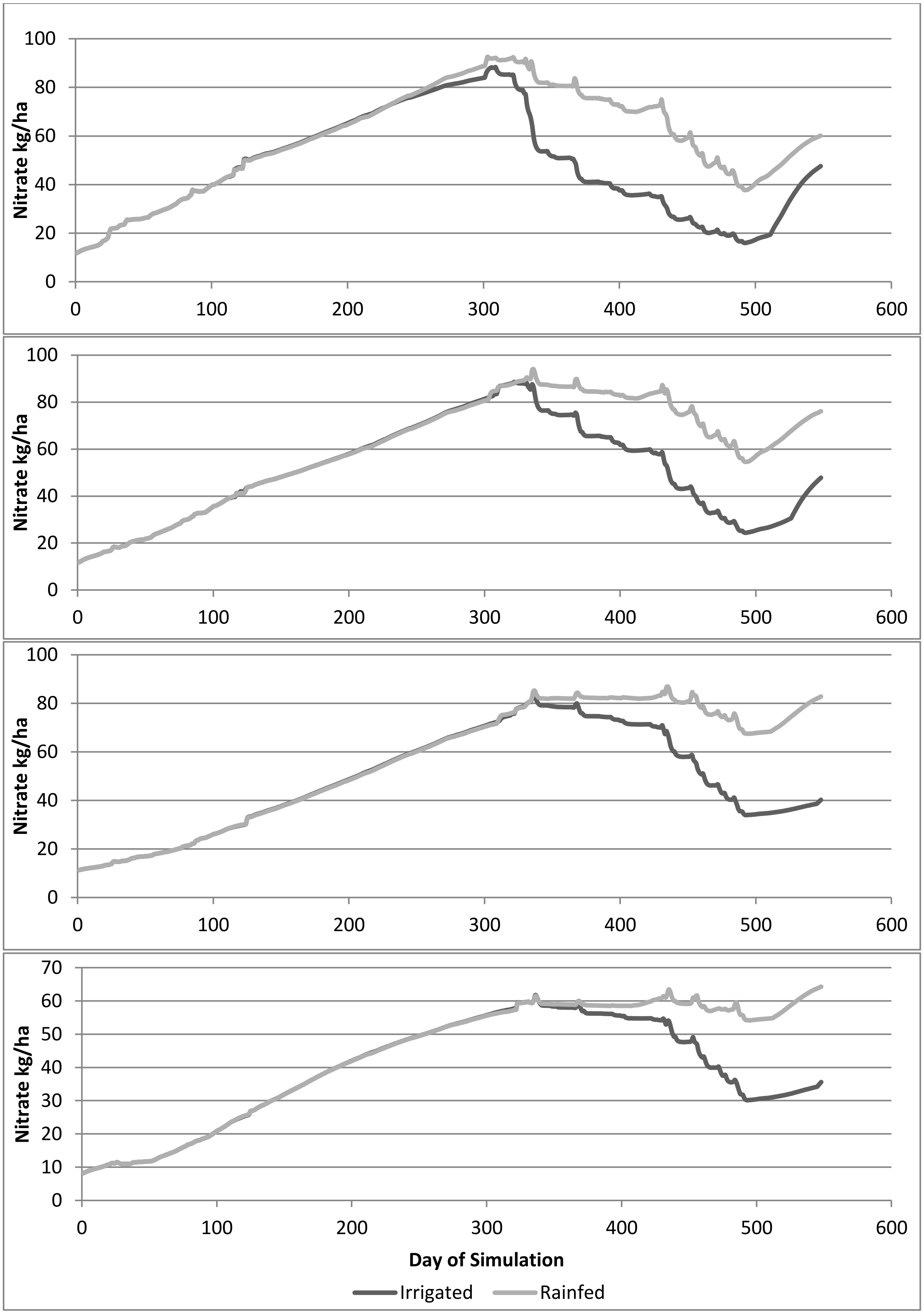


Figure B.2: Continued **b:** (46-152 cm)

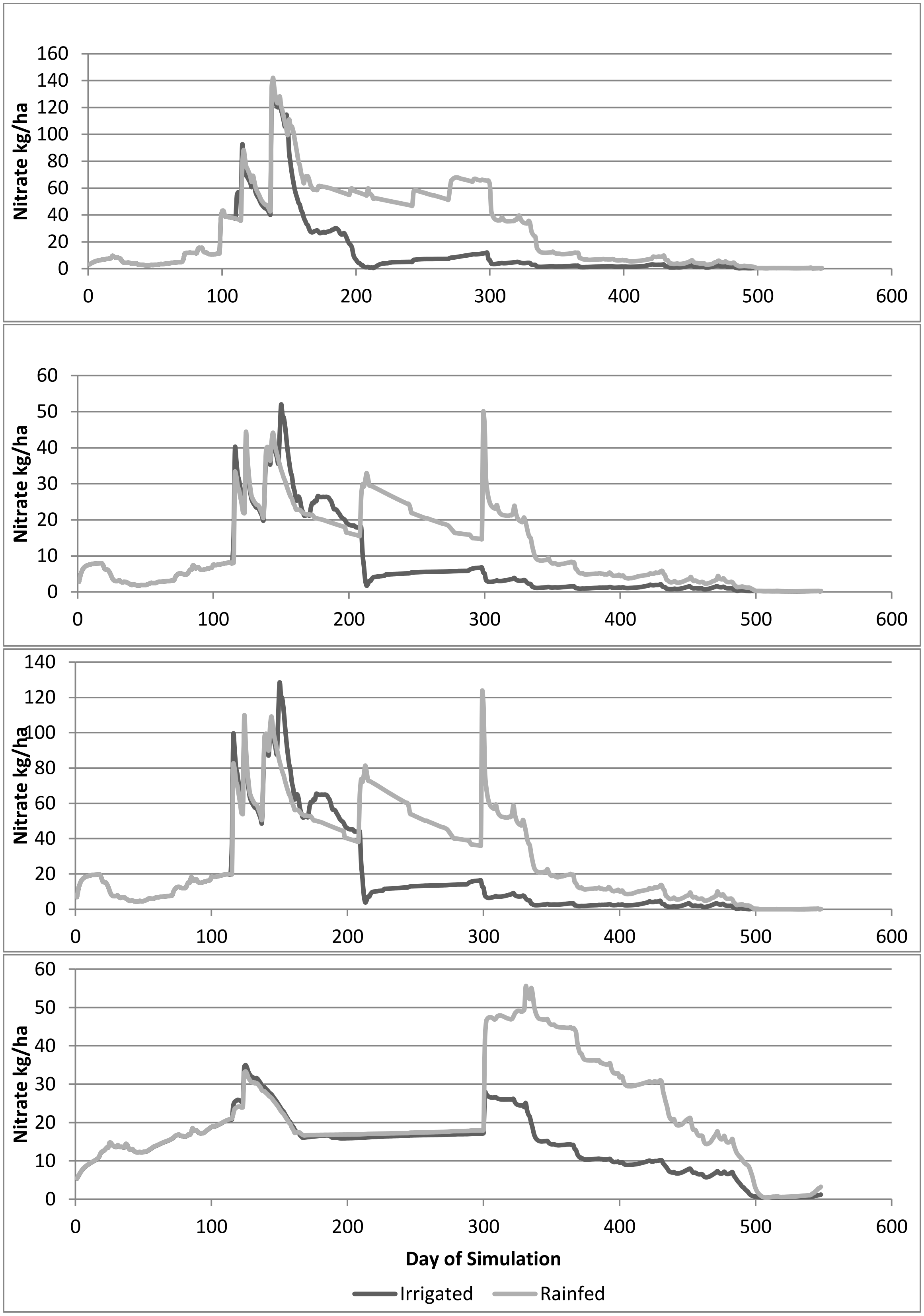


Figure B.3: 2010 Soil nitrate concentrations for treatment 11 **a:** (5-46 cm)

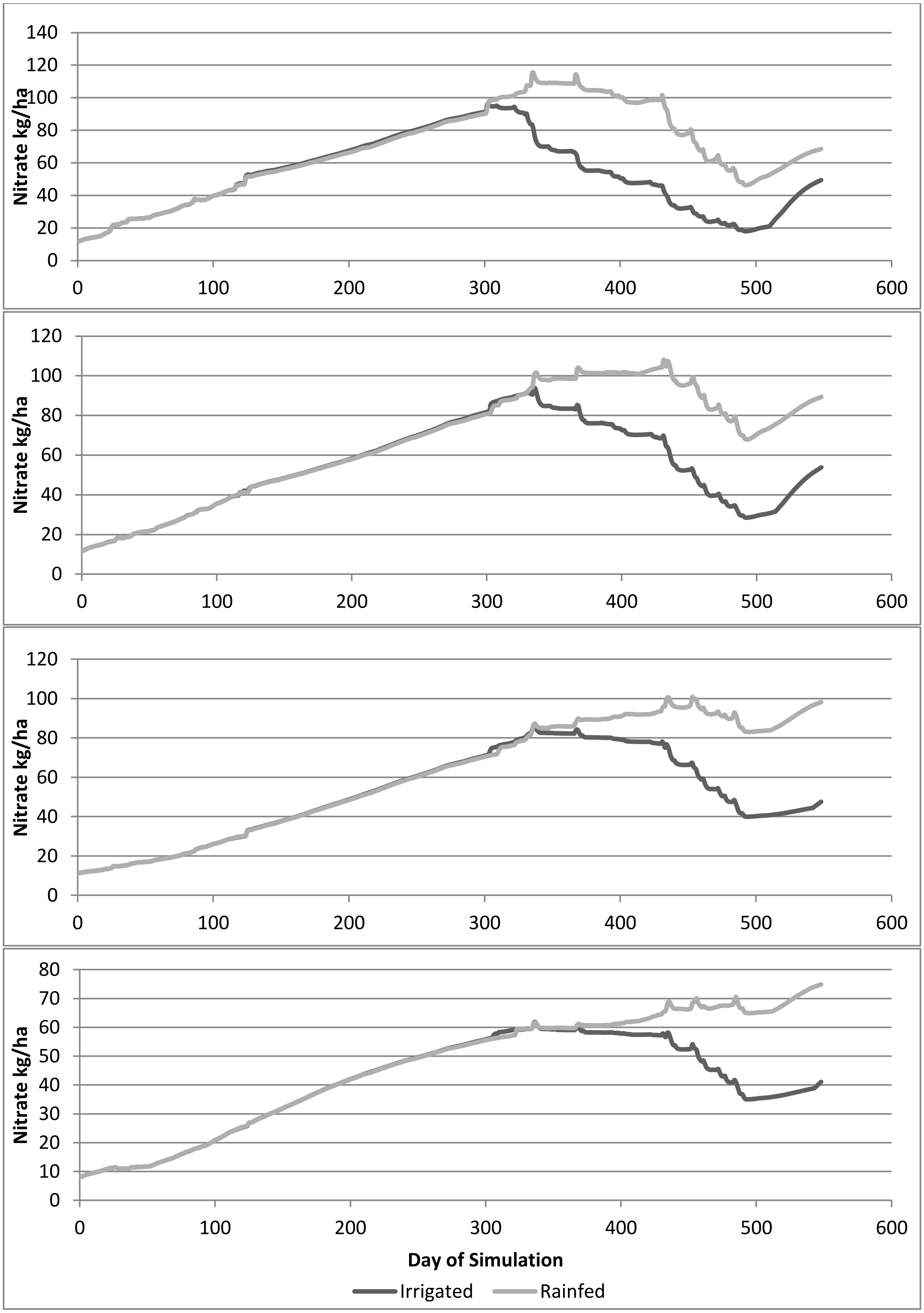


Figure B.3: Continued **b:** (46-152 cm)

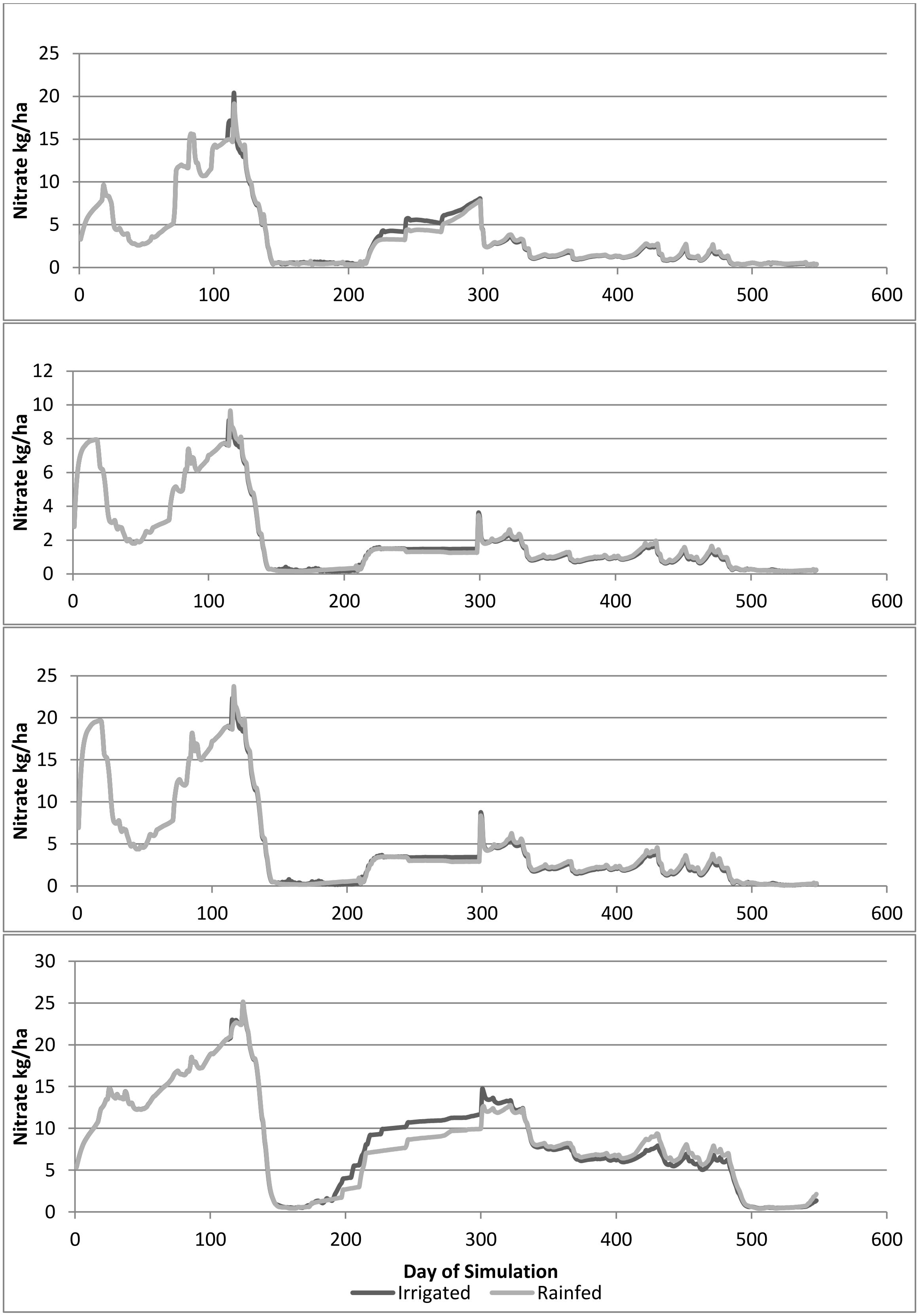


Figure B.4: 2010 Soil nitrate concentrations for treatment 13 **a:** (5-46 cm)

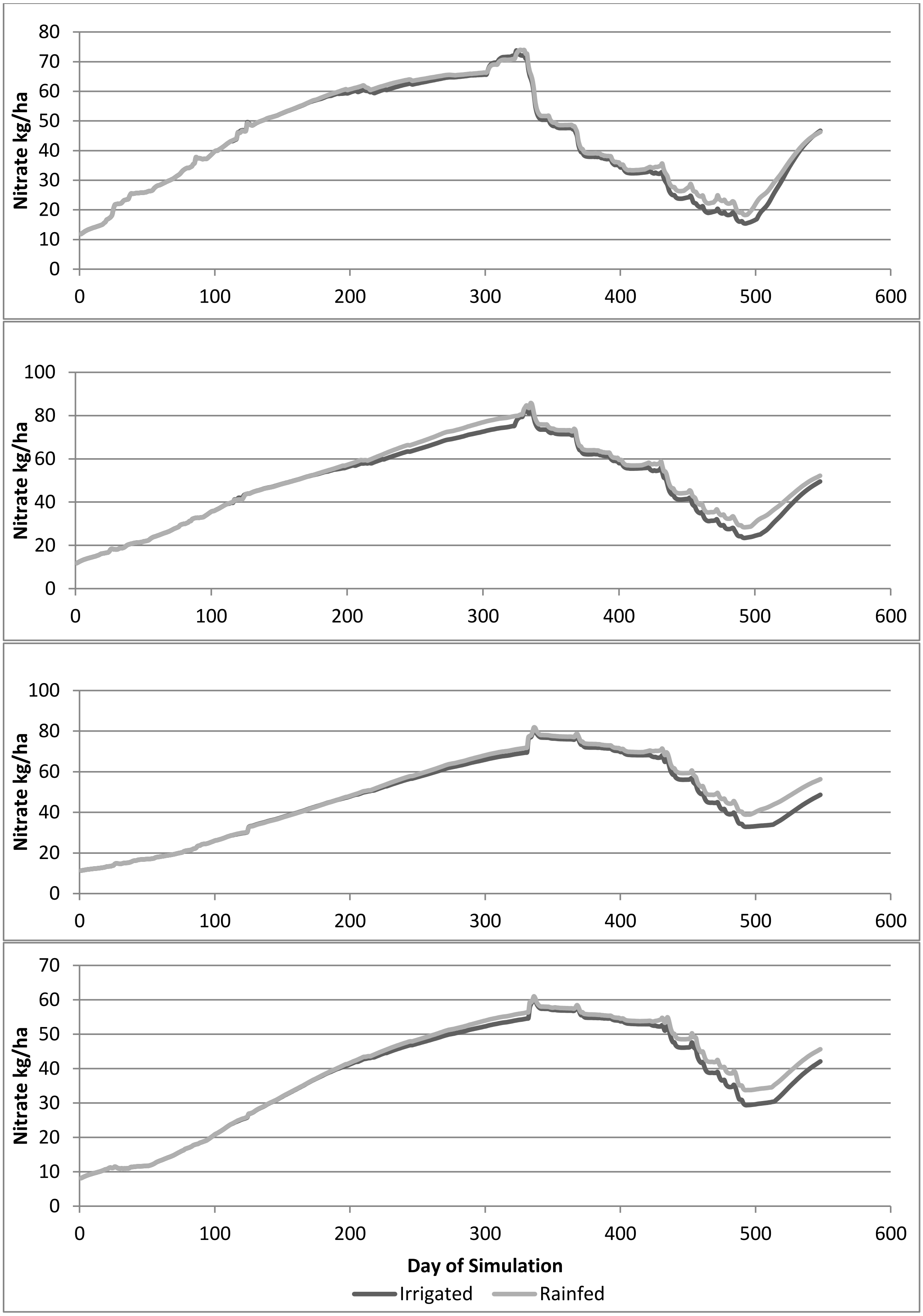


Figure B.4: Continued **b:** (46-152 cm)

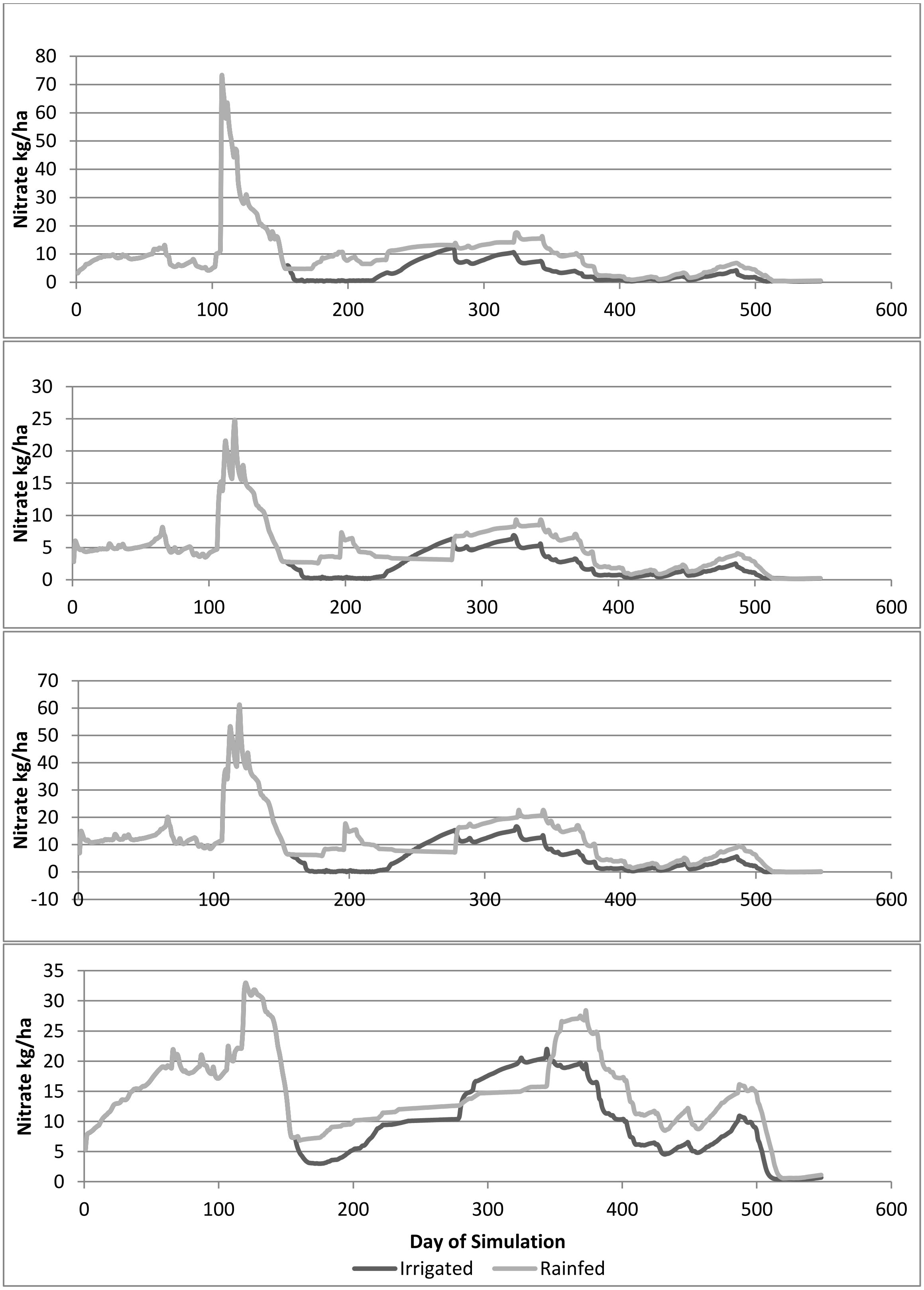


Figure B.5: 2011Soil nitrate concentrations for treatment 1 **a:** (5-46 cm)

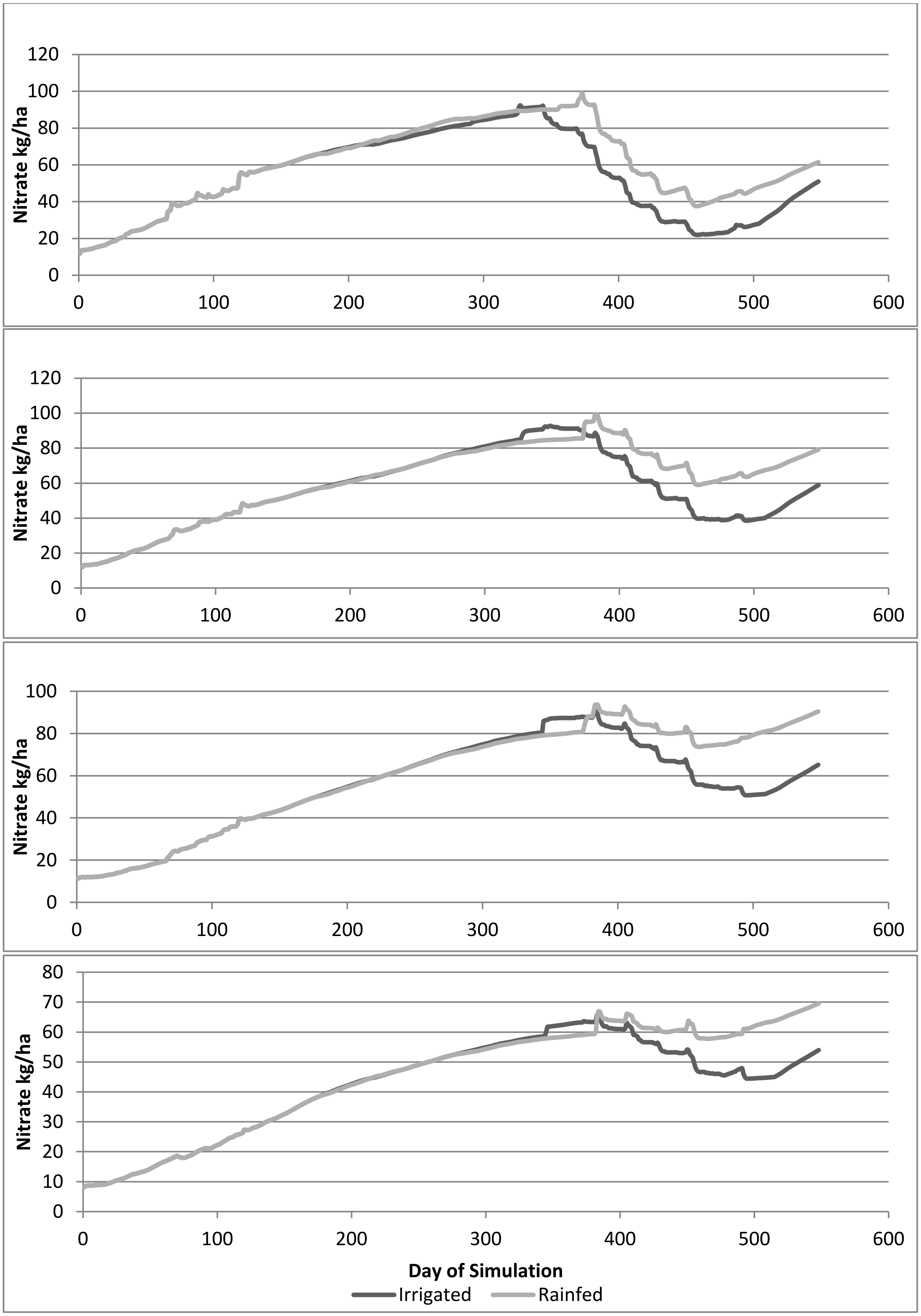


Figure B.5: Continued **b:** (46-152 cm)

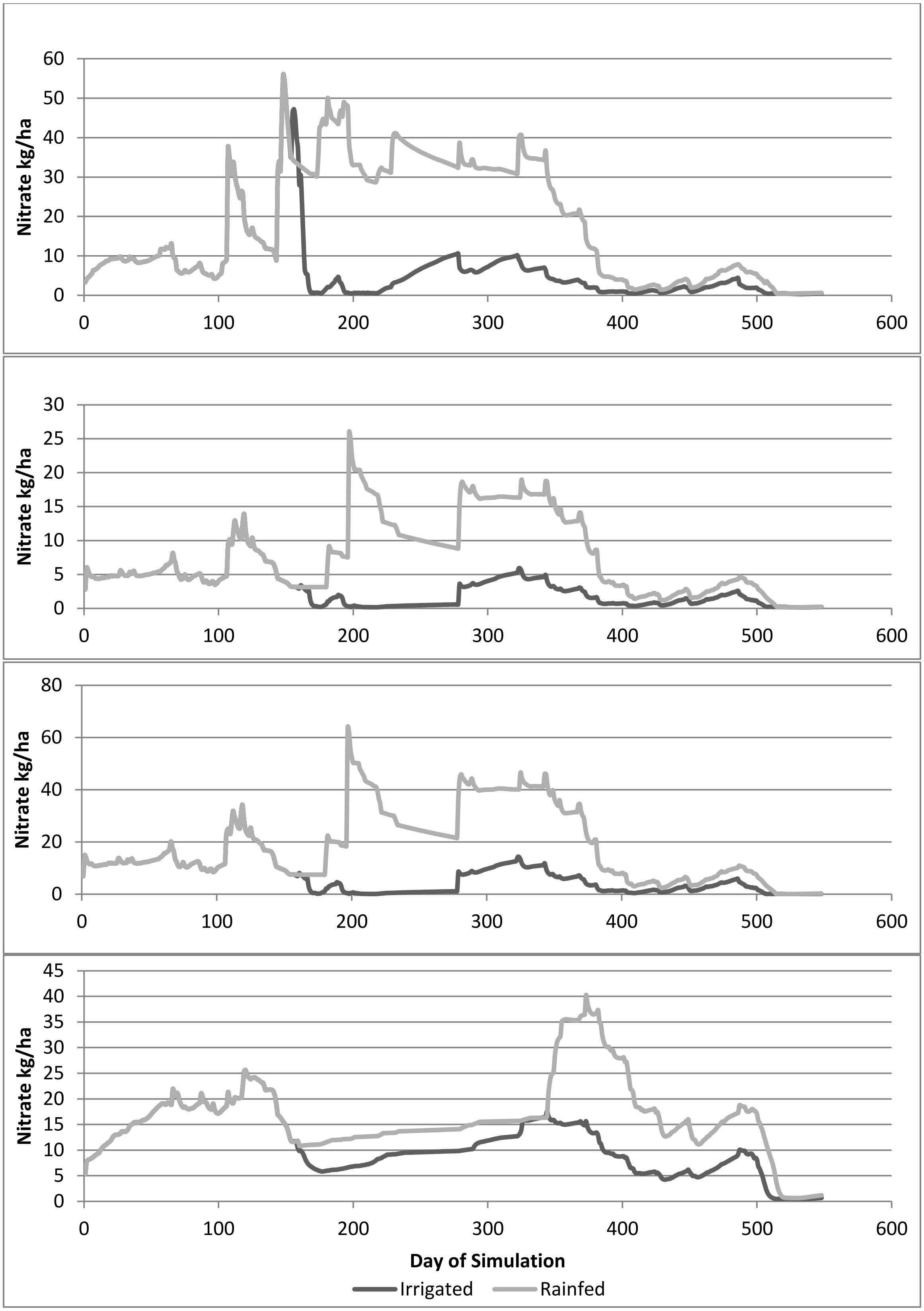


Figure B.6: 2011Soil nitrate concentrations for treatment 6 **a:** (5-46 cm)

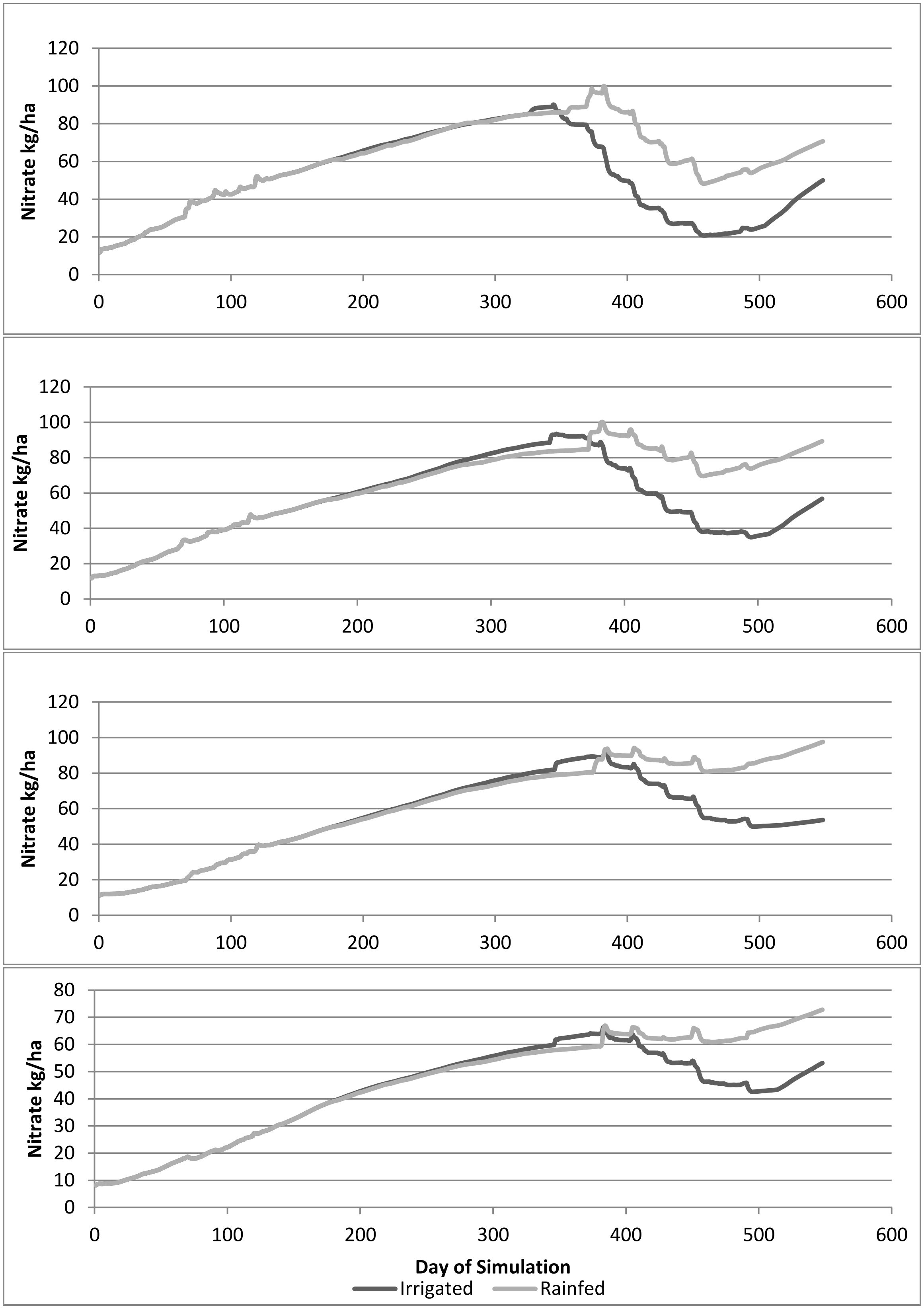


Figure B.6: Continued **b:** (46-152 cm)

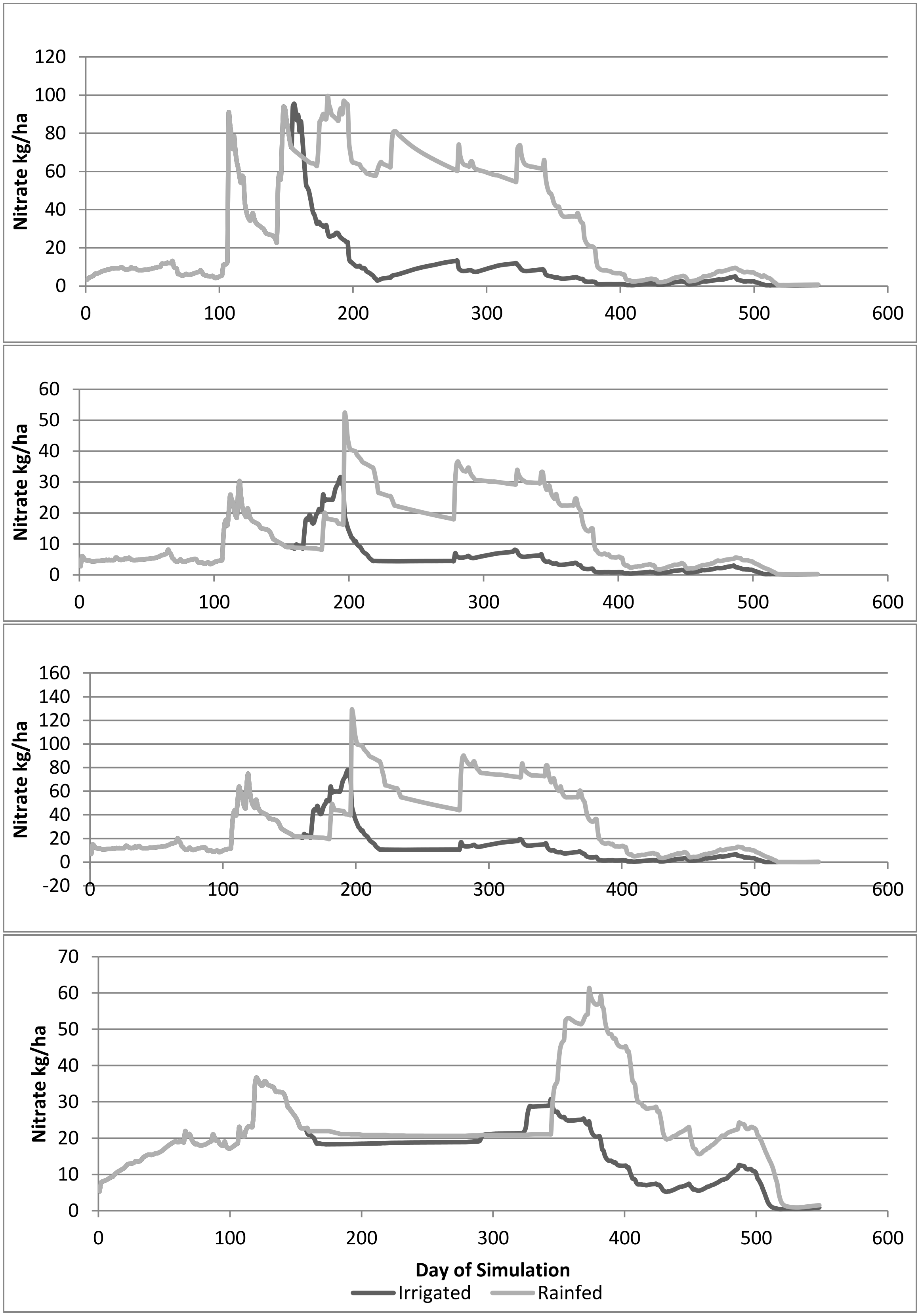


Figure B.7: 2011Soil nitrate concentrations for treatment 11 **a:** (5-46 cm)

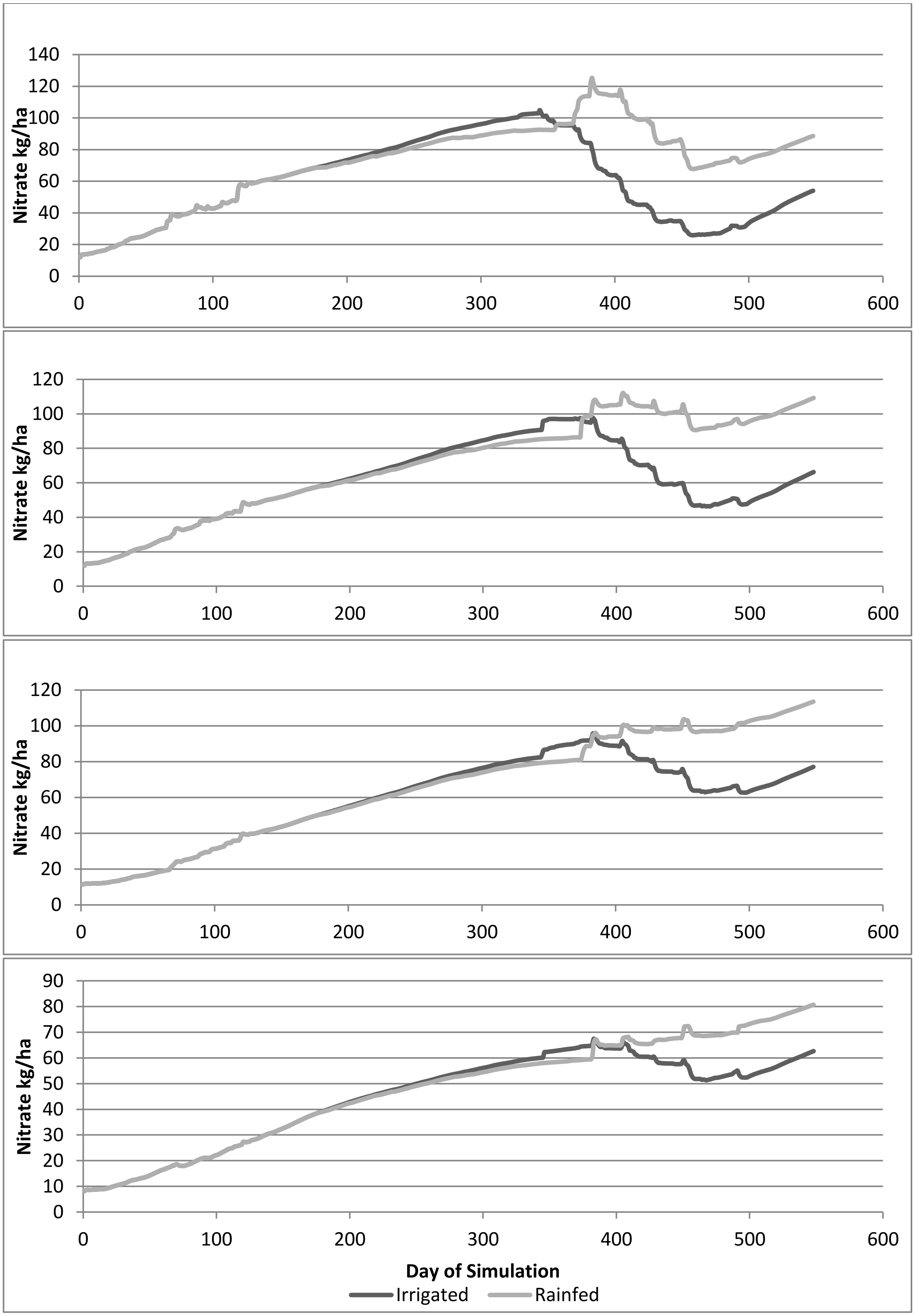


Figure B.7: Continued **b:** (46-152 cm)

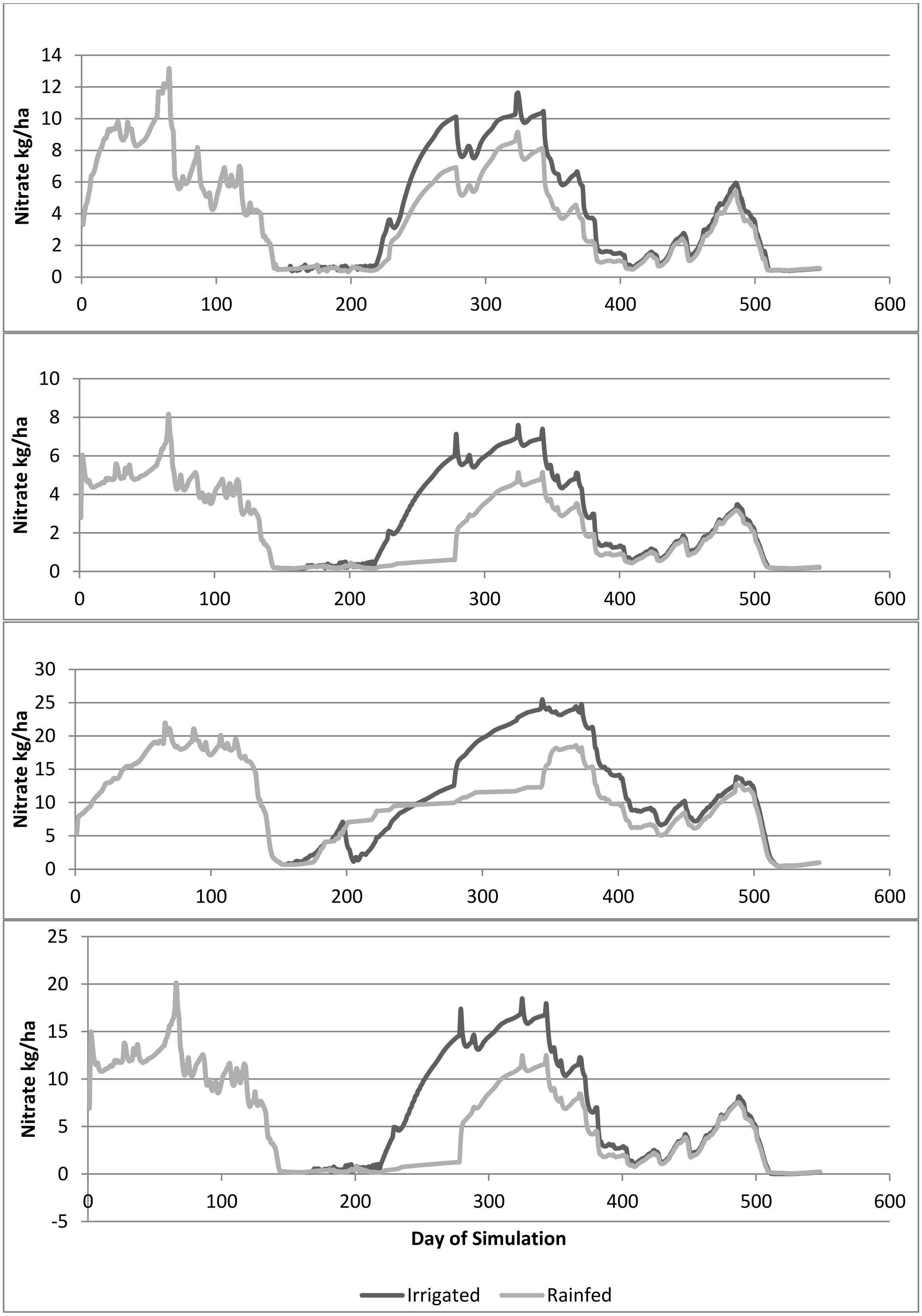


Figure B.8: 2011Soil nitrate concentrations for treatment 13 **a:** (5-46 cm)

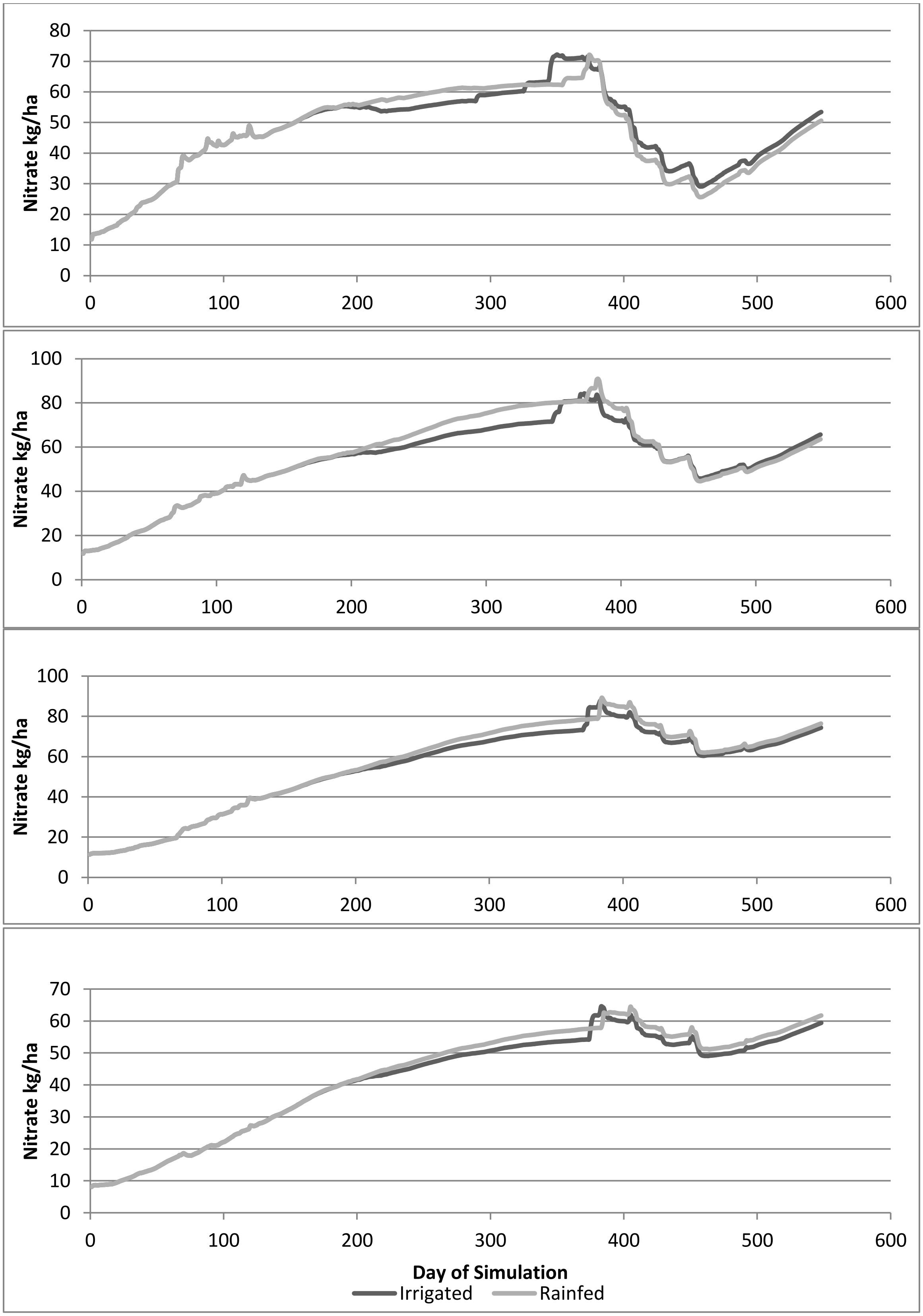


Figure B.8: Continued **b:** (46-152 cm)

APPENDIX C

Total Surface and Subsurface Nitrate Export (All Treatments)

Table C.1: Total surface export of nitrate (kg/ha)

Treatement Number	2010 Irrigated	2010 Rain-fed	2011 Irrigated	2011 Rain-fed
1	33.8	33.45	42.01	41.73
2	23.32	23.93	23.55	23.26
3	19.61	20.69	16.44	16.79
4	47.02	59.83	60.51	60.21
5	31.51	45.37	32.79	33.36
6	26.61	40.79	23.61	25.69
7	60.08	73.57	79.04	78.65
8	39.51	54.36	41.68	44.02
9	31.62	47.085	26.83	31.81
10	73.12	87.4	97.07	97.06
11	47.58	63.58	50.92	54.85
12	38.84	55.55	34.42	41.28
13	8.1	6.88	6.72	6.55
14	17.72	16.2	23.53	23.78
15	12.59	11.34	14.48	14.31
16	11.11	9.93	6.74	6.46
Total Exported	**522.14**	**649.955**	**580.34**	**599.81**

Table C.2: Total lateral export of nitrate for treatment 1 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.013518	0.013112	0.025705	0.025637	0.015864	0.017136	0.029604	0.031379
3	5	0.004452	0.004117	0.007686	0.007776	0.005343	0.005711	0.009355	0.00988
4	13	0.374961	0.332912	0.474454	0.47375	0.448934	0.454364	0.622665	0.595685
5	13	0.037383	0.03653	0.047587	0.047587	0.058513	0.06902	0.089166	0.084882
6	29	0.303403	0.29423	0.379291	0.411906	0.626364	0.631492	0.767003	0.744414
7	29	0.388667	0.377855	0.39721	0.399123	0.84611	0.835232	0.87469	0.80528
8	28	0.380862	0.377216	0.418353	0.424437	0.946719	0.920262	0.985892	0.91025
9	20	0.254085	0.253516	0.255698	0.259831	0.610875	0.591991	0.609045	0.552603
Total Exported		**1.76**	**1.69**	**2.01**	**2.05**	**3.56**	**3.53**	**3.99**	**3.73**

Table C.3: Total lateral export of nitrate for treatment 2 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.011383	0.010736	0.016413	0.016677	0.013694	0.014935	0.020237	0.023355
3	5	0.003797	0.003425	0.00542	0.005615	0.004678	0.00508	0.007054	0.007966
4	13	0.305609	0.278003	0.363612	0.363279	0.380327	0.405529	0.509815	0.50184
5	13	0.036411	0.035804	0.044919	0.04492	0.057297	0.068843	0.084146	0.083755
6	29	0.300461	0.292511	0.364621	0.39495	0.619029	0.629939	0.734962	0.72419
7	29	0.388846	0.377431	0.402955	0.394656	0.843249	0.834088	0.884401	0.796624
8	28	0.381258	0.377245	0.428477	0.423393	0.944499	0.919473	0.997282	0.906007
9	20	0.254559	0.253655	0.263018	0.259734	0.611371	0.592096	0.618737	0.551355
Total Exported		**1.68**	**1.63**	**1.89**	**1.90**	**3.47**	**3.47**	**3.86**	**3.60**

Table C.4: Total lateral export of nitrate for treatment 3 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.010635	0.009879	0.012822	0.013264	0.012937	0.0142	0.016649	0.020427
3	5	0.003556	0.003192	0.00454	0.004789	0.004434	0.00489	0.006163	0.007261
4	13	0.278712	0.258598	0.321058	0.320796	0.353841	0.38979	0.467643	0.467379
5	13	0.03601	0.035449	0.043851	0.043851	0.056813	0.068811	0.082277	0.083396
6	29	0.299415	0.292076	0.358036	0.388326	0.616364	0.630165	0.720485	0.716606
7	29	0.388706	0.377229	0.405164	0.392922	0.842289	0.833823	0.889588	0.793339
8	28	0.381607	0.377292	0.432673	0.422875	0.944545	0.919354	0.998445	0.904347
9	20	0.254748	0.253657	0.264838	0.259693	0.61152	0.591991	0.621353	0.55086
Total Exported		**1.65**	**1.61**	**1.84**	**1.85**	**3.44**	**3.45**	**3.80**	**3.54**

Table C.5: Total lateral export of nitrate for treatment 4 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.017076	0.016186	0.034661	0.035654	0.019612	0.029066	0.038432	0.045009
3	5	0.005561	0.004822	0.009855	0.01036	0.006517	0.009339	0.011354	0.013686
4	13	0.445592	0.388139	0.585378	0.585612	0.525334	0.753862	0.711664	0.773517
5	13	0.038276	0.037197	0.050233	0.050234	0.061264	0.102822	0.079041	0.102596
6	29	0.340011	0.425613	0.402951	0.433118	0.691045	0.96909	0.741122	0.828257
7	29	0.396018	0.393517	0.435235	0.407612	0.889478	0.980245	0.927256	0.851782
8	28	0.386271	0.391452	0.455689	0.428605	0.966884	1.018085	1.049836	0.937883
9	20	0.257469	0.261823	0.277179	0.262299	0.6228	0.625612	0.646758	0.562995
Total Exported		**1.89**	**1.92**	**2.25**	**2.21**	**3.78**	**4.49**	**4.21**	**4.12**

Table C.6: Total lateral export of nitrate for treatment 5 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.014015	0.01266	0.020668	0.022331	0.016528	0.025737	0.024428	0.033853
3	5	0.004602	0.003782	0.00644	0.007132	0.005548	0.008397	0.007931	0.010941
4	13	0.341508	0.305671	0.418337	0.418649	0.422625	0.678432	0.543718	0.640834
5	13	0.036923	0.036188	0.046292	0.046292	0.060114	0.103088	0.074139	0.100863
6	29	0.351218	0.419504	0.387982	0.403409	0.701961	0.964332	0.715405	0.792442
7	29	0.396009	0.392946	0.4265	0.39691	0.88876	0.979938	0.904351	0.83226
8	28	0.388895	0.39139	0.452348	0.423914	0.973365	1.017859	1.039179	0.924057
9	20	0.259191	0.261823	0.275973	0.259777	0.623364	0.625469	0.64452	0.556558
Total Exported		**1.79**	**1.82**	**2.03**	**1.98**	**3.69**	**4.40**	**3.95**	**3.89**

Table C.7: Total lateral export of nitrate for treatment 6 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.013034	0.011517	0.016097	0.017974	0.015528	0.024635	0.019855	0.030237
3	5	0.004286	0.003436	0.005311	0.006071	0.005224	0.008088	0.006798	0.010046
4	13	0.306867	0.278291	0.363264	0.363601	0.388228	0.652626	0.490775	0.597141
5	13	0.036418	0.035811	0.044942	0.044942	0.059668	0.103123	0.072507	0.100113
6	29	0.349131	0.417407	0.382001	0.39495	0.698061	0.962648	0.703322	0.781746
7	29	0.395777	0.392595	0.424156	0.394656	0.887377	0.979754	0.896485	0.827466
8	28	0.389061	0.391364	0.451787	0.423393	0.972274	1.01782	1.034169	0.921624
9	20	0.259242	0.261823	0.275962	0.259734	0.623077	0.625444	0.64308	0.555836
Total Exported		**1.75**	**1.79**	**1.96**	**1.91**	**3.65**	**4.37**	**3.87**	**3.82**

Table C.8: Total lateral export of nitrate for treatment 7 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.020841	0.019631	0.044203	0.045763	0.023524	0.034365	0.048047	0.058898
3	5	0.006731	0.005531	0.012166	0.012973	0.007747	0.011074	0.013708	0.017538
4	13	0.516545	0.443508	0.697389	0.697654	0.59972	0.857057	0.825594	0.953391
5	13	0.039167	0.037842	0.052847	0.052847	0.070223	0.121387	0.084924	0.119429
6	29	0.36624	0.42968	0.446567	0.450327	0.767451	1.052213	0.825926	0.903533
7	29	0.398416	0.394102	0.444381	0.412099	0.924186	1.028018	0.959889	0.889921
8	28	0.389841	0.3915	0.458412	0.429638	0.996825	1.045134	1.069281	0.957041
9	20	0.259596	0.261827	0.278336	0.262397	0.630331	0.634298	0.657004	0.568552
Total Exported		**2.00**	**1.98**	**2.43**	**2.36**	**4.02**	**4.78**	**4.48**	**4.47**

Table C.9: Total lateral export of nitrate for treatment 8 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.01684	0.015094	0.025977	0.028087	0.019519	0.030601	0.029811	0.044233
3	5	0.005439	0.004143	0.00765	0.008667	0.00645	0.009957	0.009181	0.013863
4	13	0.377636	0.333525	0.474641	0.47445	0.463788	0.765768	0.599193	0.776051
5	13	0.0374	0.036543	0.047633	0.047632	0.068526	0.121409	0.078881	0.116444
6	29	0.359303	0.421676	0.422446	0.41187	0.753727	1.043759	0.790363	0.854808
7	29	0.397085	0.393189	0.438622	0.399123	0.918157	1.025975	0.938905	0.864466
8	28	0.389758	0.391416	0.46135	0.424437	0.994976	1.043853	1.064782	0.940256
9	20	0.259597	0.261825	0.281606	0.259831	0.62901	0.633816	0.659431	0.56122
Total Exported		**1.84**	**1.86**	**2.16**	**2.05**	**3.85**	**4.68**	**4.17**	**4.17**

Table C.10: Total lateral export of nitrate for treatment 9 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.015326	0.013321	0.018986	0.021132	0.017988	0.029196	0.022855	0.03869
3	5	0.004938	0.003585	0.005889	0.006984	0.005944	0.009529	0.007434	0.012491
4	13	0.322012	0.289314	0.386138	0.385537	0.409013	0.730359	0.513841	0.708106
5	13	0.036638	0.035973	0.045479	0.045478	0.067639	0.121316	0.076223	0.115469
6	29	0.357513	0.418352	0.421262	0.398283	0.748578	1.039843	0.795854	0.838442
7	29	0.396455	0.392809	0.434562	0.395665	0.91536	1.024833	0.92484	0.857265
8	28	0.389708	0.391378	0.460436	0.423603	0.994791	1.04313	1.057185	0.936555
9	20	0.259601	0.261825	0.281434	0.259747	0.628294	0.63354	0.656569	0.560115
Total Exported		**1.78**	**1.81**	**2.05**	**1.94**	**3.79**	**4.63**	**4.05**	**4.07**

Table C.11: Total lateral export of nitrate for treatment 10 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.024733	0.02329	0.054045	0.055899	0.027659	0.040948	0.057989	0.072755
3	5	0.007933	0.006252	0.014546	0.015596	0.009047	0.012919	0.016173	0.021347
4	13	0.588479	0.499755	0.809915	0.809531	0.67858	0.986067	0.932949	1.132733
5	13	0.040065	0.038478	0.055472	0.055471	0.081469	0.139361	0.094111	0.136445
6	29	0.380693	0.433724	0.519034	0.462646	0.840332	1.13125	0.996026	0.974039
7	29	0.399145	0.394556	0.453786	0.412359	0.963002	1.072066	0.997145	0.922414
8	28	0.390014	0.391538	0.464843	0.427537	1.026101	1.069007	1.096597	0.969389
9	20	0.259619	0.261828	0.281911	0.260133	0.639848	0.641477	0.670645	0.569781
Total Exported		**2.09**	**2.05**	**2.65**	**2.50**	**4.27**	**5.09**	**4.86**	**4.80**

Table C.12: Total lateral export of nitrate for treatment 11 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.019778	0.017664	0.031909	0.033953	0.022783	0.036758	0.036298	0.05553
3	5	0.006296	0.004504	0.008962	0.010241	0.00743	0.011681	0.010895	0.017062
4	13	0.413959	0.361341	0.532095	0.530503	0.509175	0.88153	0.687144	0.923416
5	13	0.03784	0.036887	0.048958	0.048956	0.077568	0.139885	0.090346	0.134383
6	29	0.40902	0.423659	0.480122	0.4245	0.857792	1.122094	0.92843	0.930515
7	29	0.397577	0.393426	0.444886	0.405371	0.954164	1.069993	0.968986	0.907086
8	28	0.38991	0.391437	0.464595	0.428083	1.028767	1.067468	1.082646	0.965722
9	20	0.259661	0.261826	0.283425	0.262243	0.647457	0.640847	0.666075	0.570919
Total Exported		**1.93**	**1.89**	**2.29**	**2.14**	**4.11**	**4.97**	**4.47**	**4.50**

Table C.13: Total lateral export of nitrate for treatment 12 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.018135	0.015729	0.024214	0.026187	0.021361	0.035463	0.028933	0.049768
3	5	0.00574	0.003884	0.007	0.00836	0.006947	0.011293	0.00912	0.015574
4	13	0.35204	0.312173	0.433273	0.431107	0.45442	0.847193	0.60705	0.853383
5	13	0.037036	0.036272	0.046602	0.0466	0.07738	0.140351	0.088864	0.133838
6	29	0.424287	0.420056	0.456677	0.405213	0.87848	1.120106	0.892279	0.909518
7	29	0.396941	0.393014	0.436619	0.397394	0.952715	1.069952	0.952423	0.894144
8	28	0.389855	0.391392	0.460916	0.424028	1.029577	1.067254	1.070882	0.95513
9	20	0.259664	0.261825	0.281548	0.259789	0.649482	0.640704	0.660304	0.565431
Total Exported		**1.88**	**1.83**	**2.15**	**2.00**	**4.07**	**4.93**	**4.31**	**4.38**

Table C.14: Total lateral export of nitrate for treatment 13 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.007525	0.007387	0.007956	0.007421	0.009694	0.009577	0.012157	0.010237
3	5	0.002822	0.002816	0.003345	0.00313	0.003665	0.003711	0.005192	0.004252
4	13	0.237732	0.228676	0.282198	0.253787	0.302695	0.29813	0.46055	0.320615
5	13	0.035194	0.03473	0.042042	0.04192	0.058152	0.058525	0.091318	0.065577
6	29	0.274649	0.260073	0.283673	0.281408	0.551619	0.538329	0.586776	0.493743
7	29	0.310432	0.355504	0.31798	0.362987	0.705167	0.768248	0.655518	0.684232
8	28	0.308809	0.358214	0.336108	0.391584	0.812757	0.878041	0.731923	0.792729
9	20	0.207663	0.241313	0.204592	0.240741	0.52314	0.569623	0.454652	0.497797
Total Exported		**1.38**	**1.49**	**1.48**	**1.58**	**2.97**	**3.12**	**3.00**	**2.87**

Table C.15: Total lateral export of nitrate for treatment 14 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.008158	0.00804	0.016496	0.015924	0.01036	0.010394	0.020164	0.018819
3	5	0.003014	0.002918	0.005513	0.005314	0.003855	0.00387	0.007188	0.006492
4	13	0.265915	0.242239	0.379511	0.362925	0.333606	0.31613	0.530724	0.430422
5	13	0.035212	0.034676	0.044876	0.044874	0.056864	0.059483	0.085272	0.069631
6	29	0.284539	0.273407	0.323747	0.320382	0.570296	0.564182	0.662597	0.550433
7	29	0.342206	0.367571	0.356256	0.39622	0.76111	0.794891	0.762457	0.770964
8	28	0.340513	0.368514	0.377661	0.423711	0.863993	0.89644	0.889181	0.889744
9	20	0.227941	0.247528	0.231507	0.259777	0.55946	0.580992	0.548217	0.550755
Total Exported		**1.51**	**1.54**	**1.74**	**1.83**	**3.16**	**3.23**	**3.51**	**3.29**

Table C.16: Total lateral export of nitrate for treatment 15 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.007053	0.006921	0.011939	0.011364	0.009233	0.009262	0.015626	0.014238
3	5	0.002666	0.002614	0.004386	0.004203	0.0035	0.003562	0.00605	0.005376
4	13	0.231922	0.217255	0.320871	0.308924	0.300187	0.291358	0.472908	0.377108
5	13	0.034631	0.034186	0.043492	0.043491	0.056092	0.058784	0.083011	0.068204
6	29	0.283118	0.272243	0.32045	0.321677	0.56737	0.561397	0.664892	0.552248
7	29	0.344292	0.367764	0.357868	0.394203	0.763014	0.795099	0.762251	0.767257
8	28	0.34206	0.369086	0.382109	0.423547	0.86664	0.897345	0.893826	0.889717
9	20	0.229653	0.247587	0.234133	0.260044	0.561641	0.581919	0.555251	0.552471
Total Exported		**1.48**	**1.52**	**1.68**	**1.77**	**3.13**	**3.20**	**3.45**	**3.23**

Table C.17: Total lateral export of nitrate for treatment 16 (kg/ha)

		Growing Season				Total			
		2010		2011		2010		2011	
Soil Layer	Depth (cm)	Irr.	RF	Irr	RF	Irr	RF	Irr	RF
2	10	0.008124	0.00793	0.008011	0.007569	0.010315	0.010299	0.011712	0.010751
3	5	0.002846	0.002827	0.003288	0.003186	0.003684	0.003788	0.004929	0.00446
4	13	0.237963	0.228891	0.260742	0.253974	0.307738	0.303943	0.412465	0.330551
5	13	0.03521	0.034747	0.042001	0.042	0.056279	0.059611	0.080886	0.068157
6	29	0.288498	0.278918	0.319116	0.358642	0.583011	0.573181	0.660565	0.618717
7	29	0.362728	0.372329	0.36224	0.389398	0.796454	0.806712	0.768631	0.76076
8	28	0.359667	0.373091	0.388506	0.421134	0.901049	0.905453	0.906331	0.888007
9	20	0.240786	0.250461	0.238473	0.258948	0.57942	0.586325	0.562532	0.5494
Total Exported		**1.54**	**1.55**	**1.62**	**1.73**	**3.24**	**3.25**	**3.41**	**3.23**

APPENDIX D

Soil Moisture Data

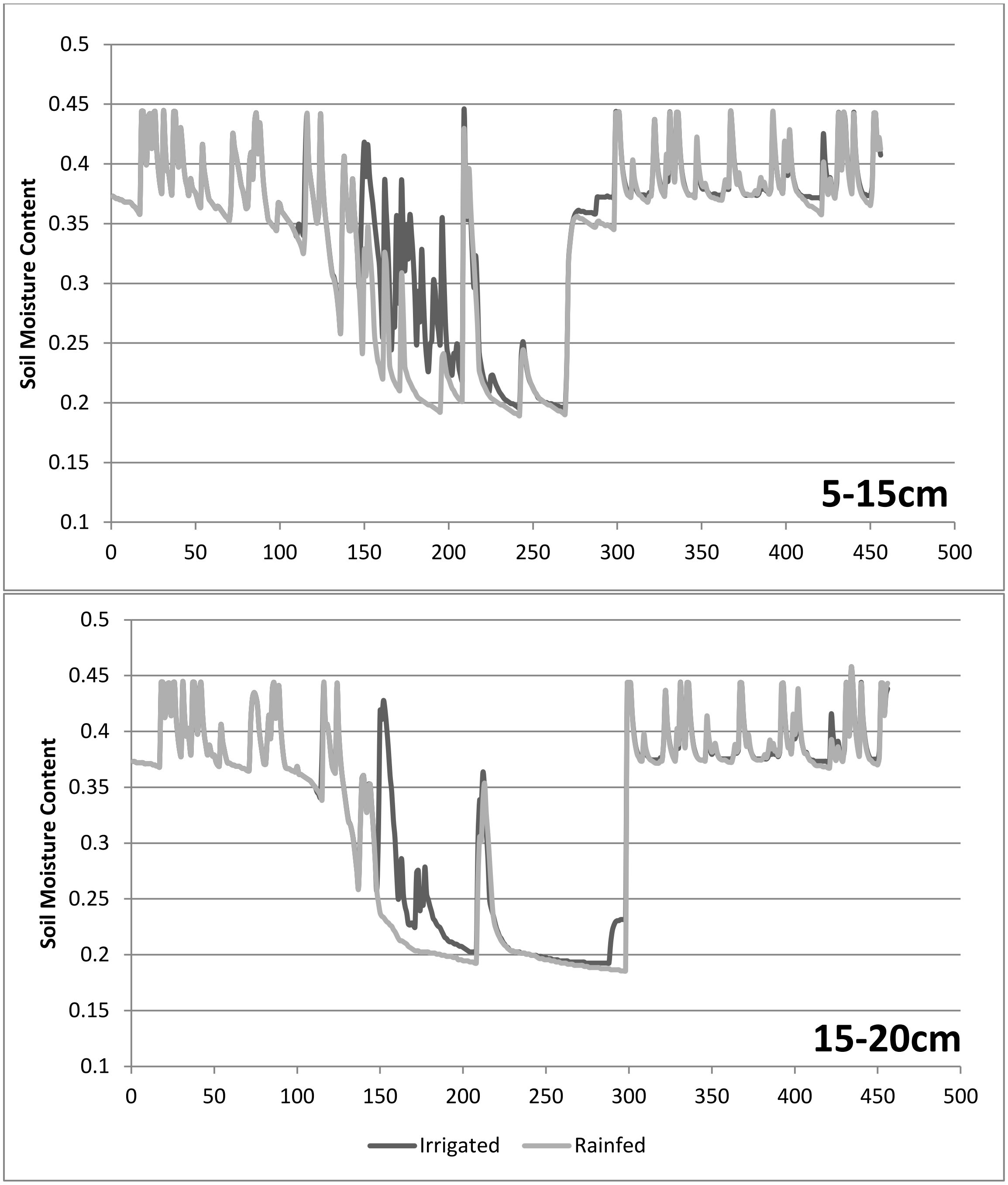


Figure D.1: 2010 Soil Moisture **a:** (5-20 cm)

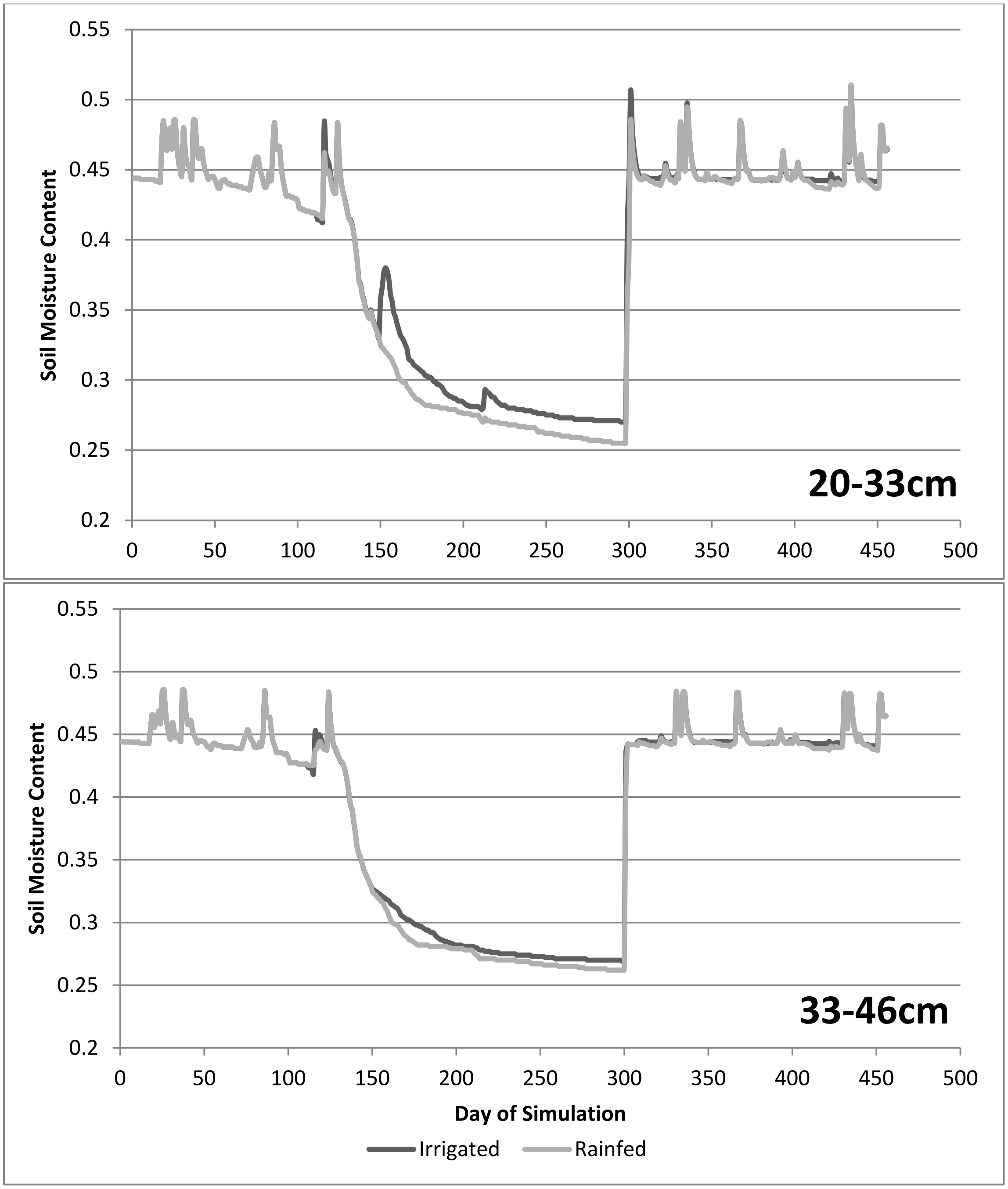


Figure D.1: Continued **b:** (20-46 cm)

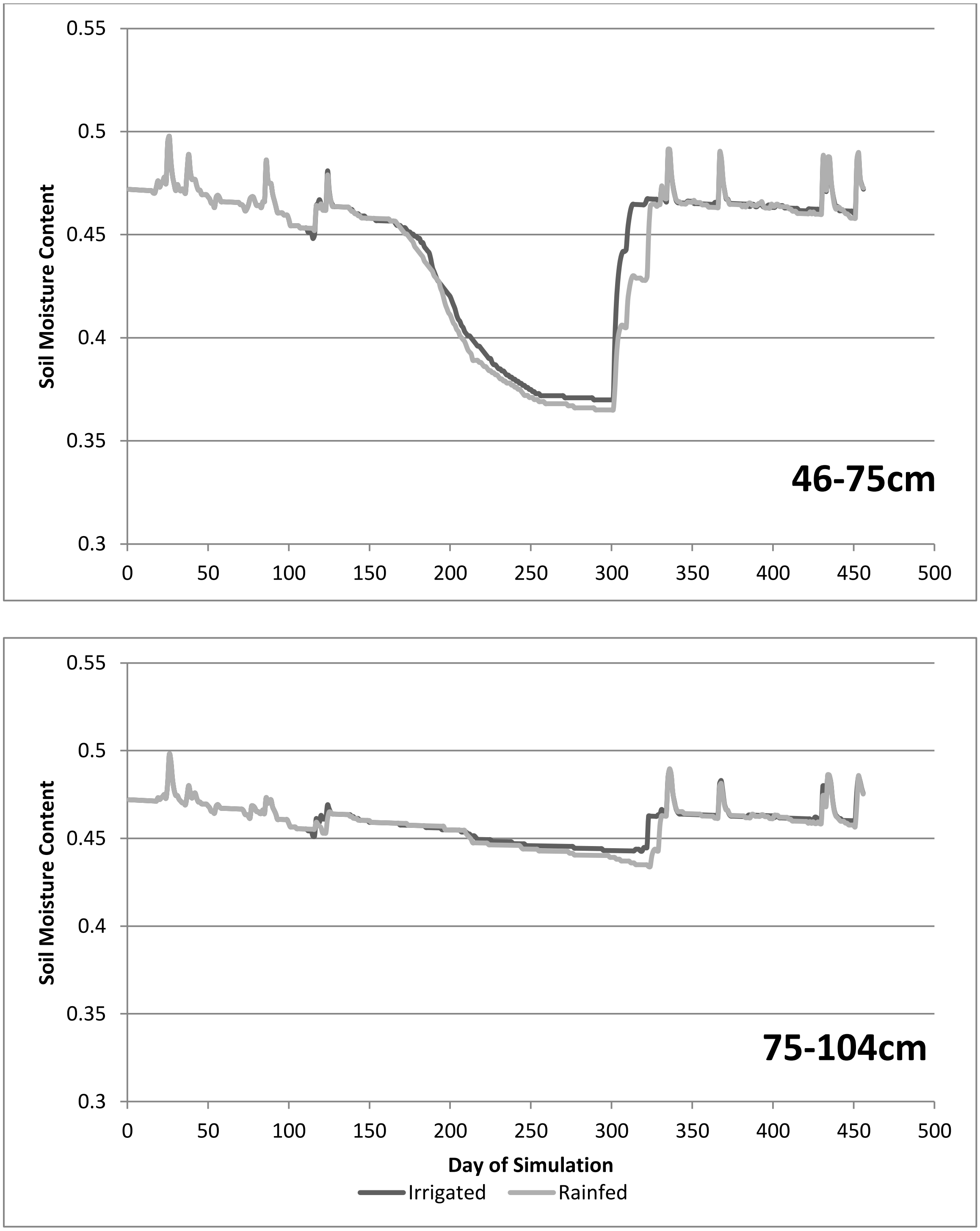


Figure D.1: Continued **c:** (46-104 cm)

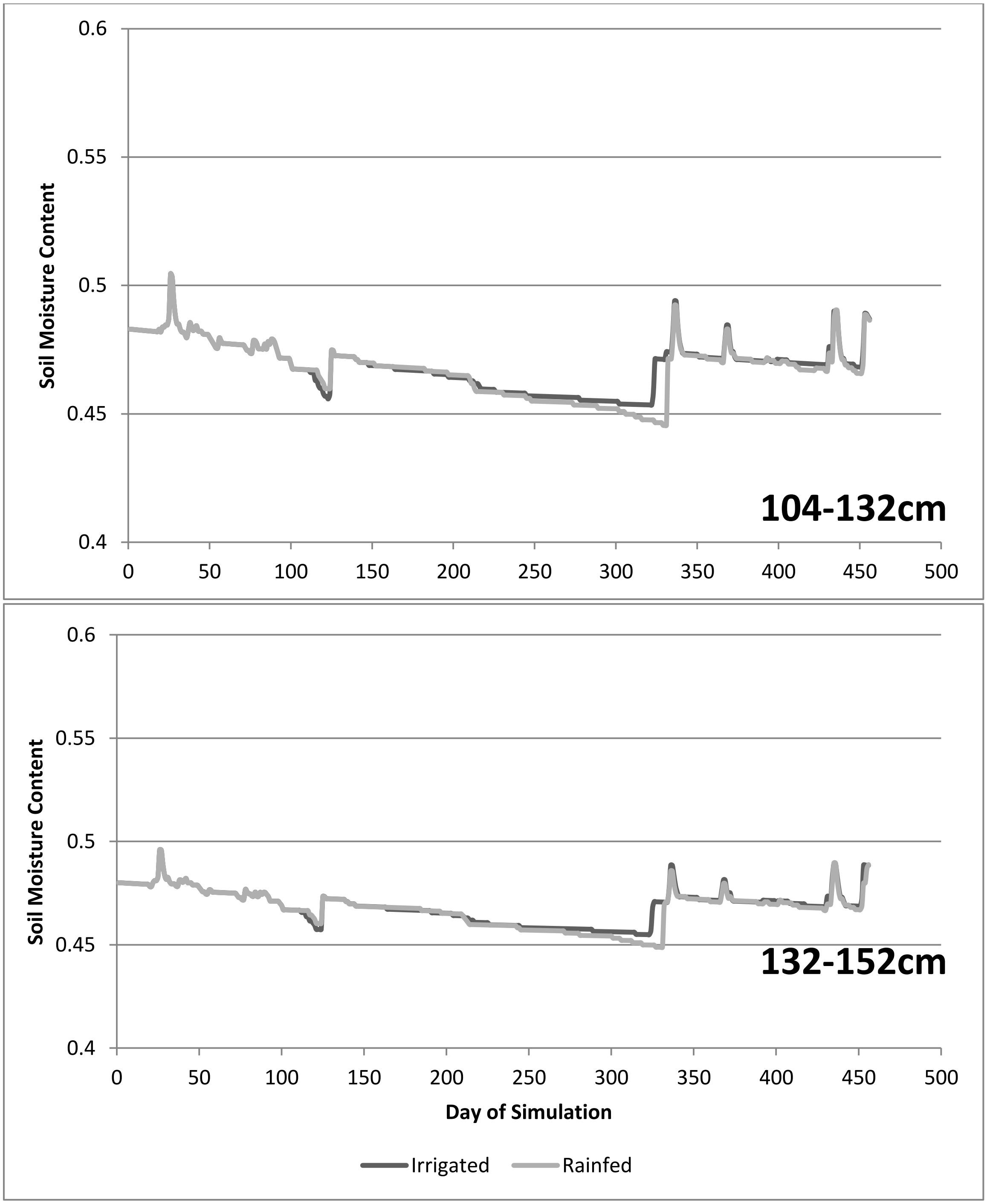


Figure D.1: Continued **d:** (104-152 cm)

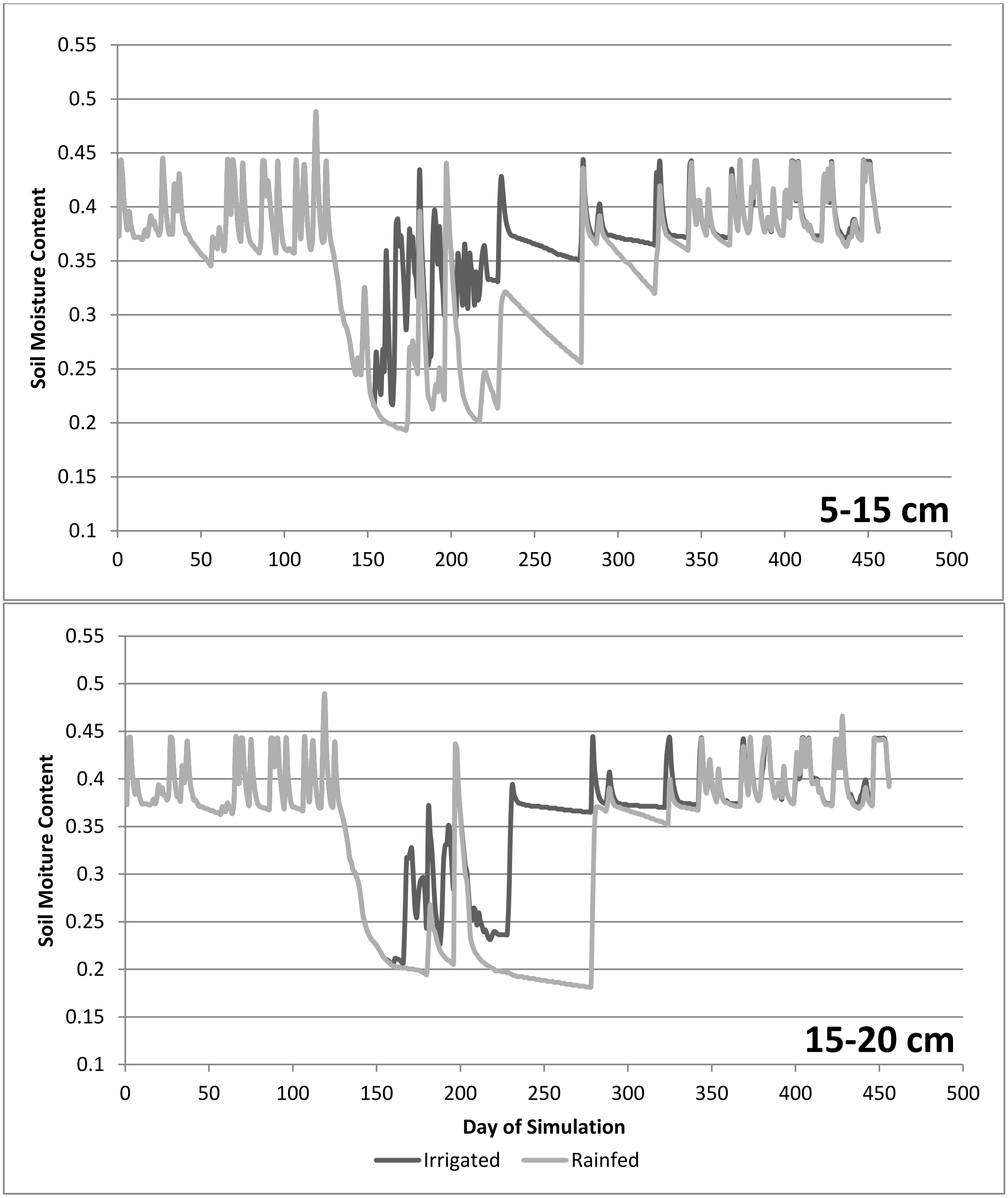


Figure D.2: 2011 Soil Moisture **a:** (5-20 cm)

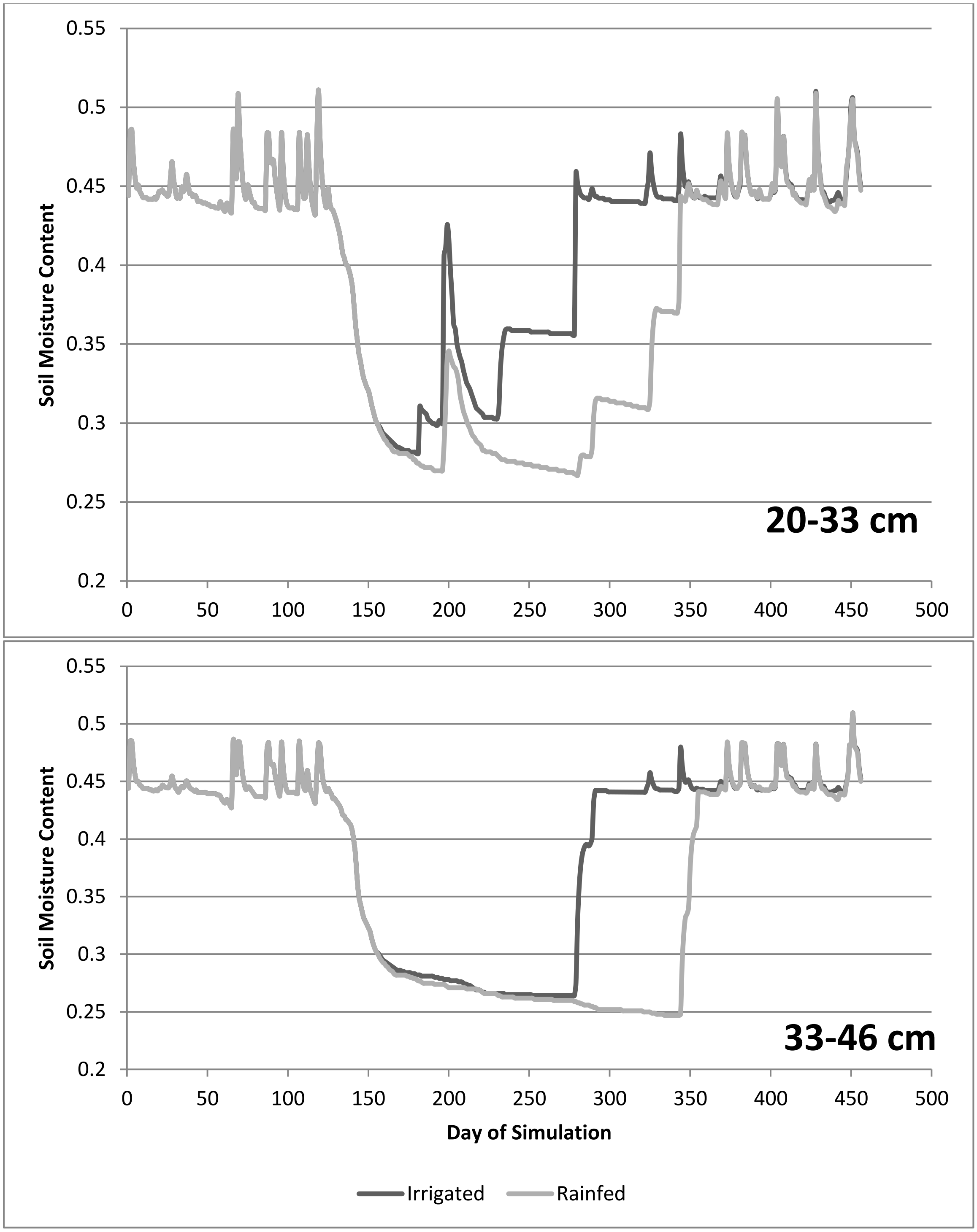


Figure D.2: Continued **b:** (20-46 cm)

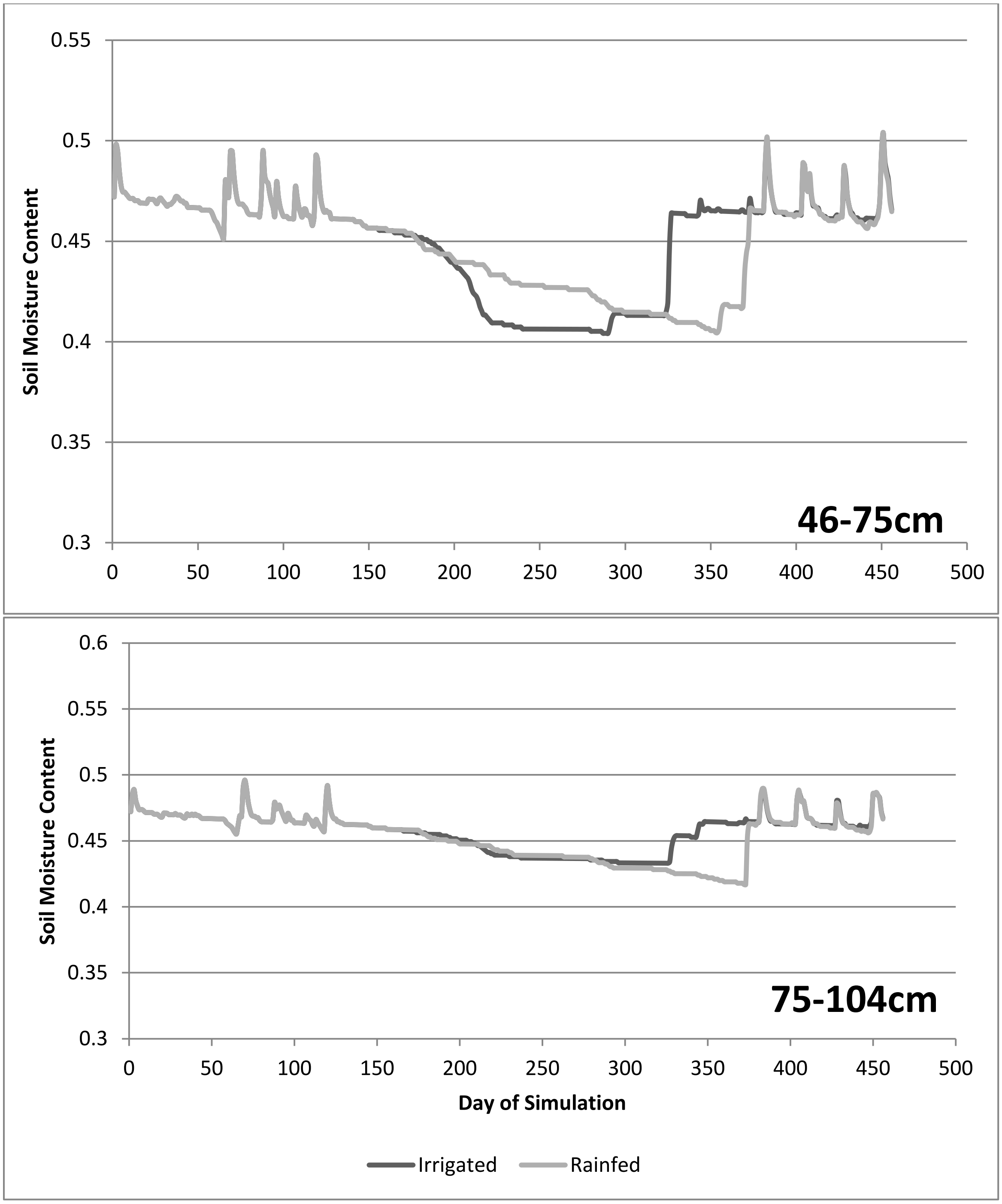


Figure D.2: Continued **c:** Moisture (46-104cm)

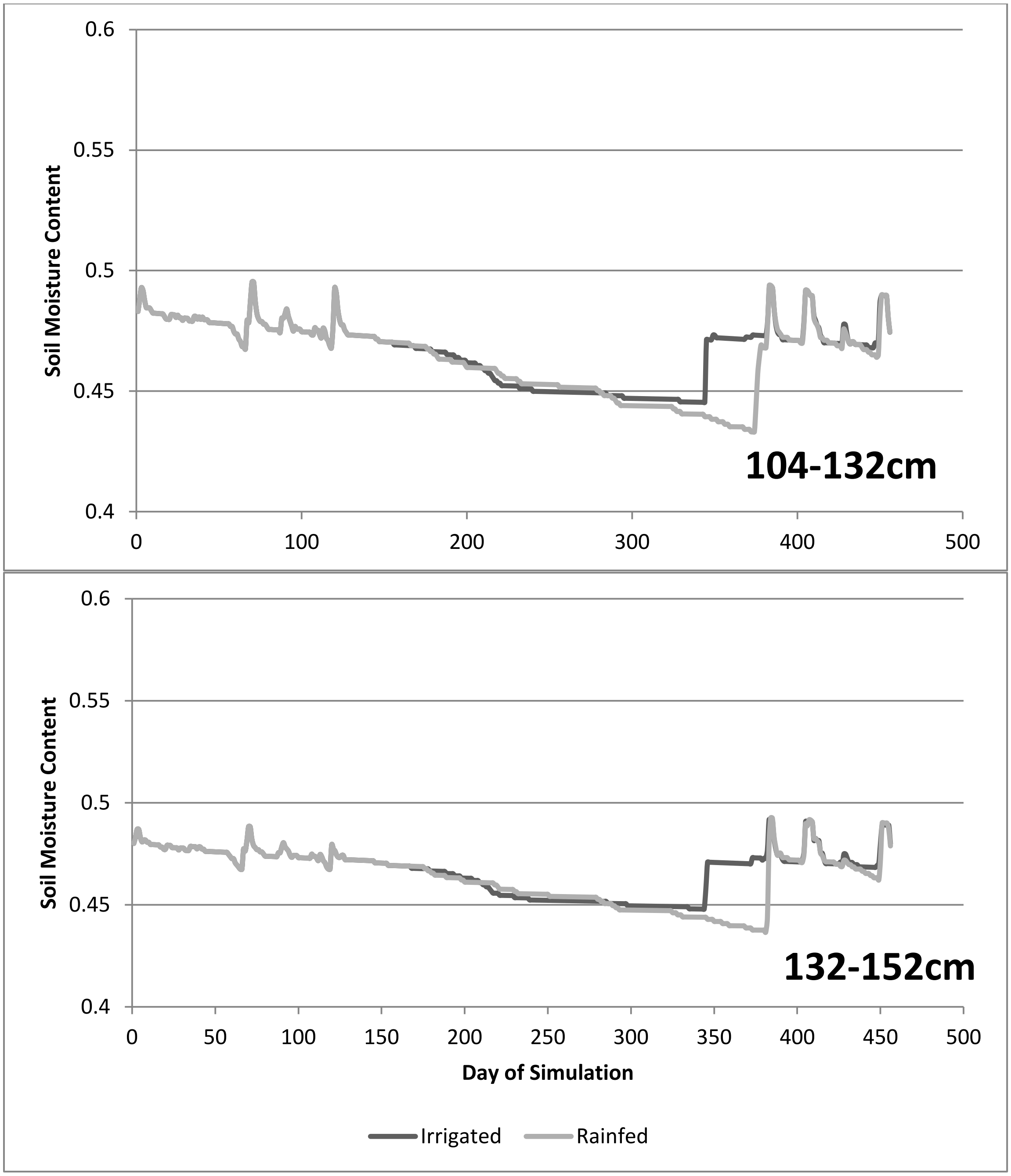


Figure D.2: Continued **d:** (104-152 cm)

APPENDIX E
Calibration and Validation Data

Table E.1: Measured 2010 Yields

Plot ID	Treatment	Yield (lb/ac)	Plot ID	Treatment	Yield (lb/ac)
117	11	167.91	301	6	163.90
118	9	183.16	302	7	172.48
119	16	86.32	303	15	129.95
120	7	141.67	304	9	179.09
121	1	134.88	305	5	177.92
122	3	117.01	306	10	176.78
123	6	164.97	307	11	194.77
124	4	144.67	308	3	149.65
125	13	87.36	309	13	93.25
126	12	131.29	310	1	122.54
127	2	146.33	311	8	163.24
128	10	146.15	312	2	138.35
129	15	145.09	313	12	187.32
130	5	153.34	314	16	138.80
131	8	163.59	315	14	124.16
132	14	102.74	316	4	162.10
201	4	127.95	418	11	183.17
202	9	166.45	419	12	183.59
203	14	116.74	420	1	133.88
204	11	152.99	421	2	156.29
205	3	146.75	422	10	169.08
206	1	124.23	423	6	195.24
207	16	122.89	424	16	123.08
208	8	143.36	425	15	135.33
209	2	151.04	426	5	153.42
210	5	142.99	427	8	175.65
211	6	164.44	428	7	139.88
212	10	130.56	429	13	91.77
213	13	144.47	430	14	117.41
214	12	151.66	431	9	193.84
215	15	109.34	432	3	142.70
216	7	152.63			

Table E.2: Soil analysis (4/22/2011)

Sample I.D.	Replication	Depth	% Nitrogen	% Carbon	% Organic Matter	NH4-N, ppm	NO3-N, ppm
11.S1611	1	6"	0.12	0.91	1.6	5.23	1.95
11.S1612	1	12"	0.09	0.58	1	4.75	3.03
11.S1613	1	18"	0.11	0.6	1	8.1	4.07
11.S1614	2	6"	0.12	0.74	1.3	5.26	2.83
11.S1615	2	12"	0.11	0.73	1.3	5.79	2.3
11.S1616	2	18"	0.12	0.79	1.4	6.38	2.26
11.S1617	3	6"	0.11	0.91	1.6	6.82	2.55
11.S1618	3	12"	0.1	0.54	0.9	15.86	9.39
11.S1619	3	18"	0.09	0.4	0.7	8.85	2.21
11.S1620	4	6"	0.12	0.86	1.5	7.48	2.38
11.S1621	4	12"	0.08	0.43	0.7	7.45	3.18
11.S1622	4	18"	0.08	0.39	0.7	7.72	2.61
11.S1623	5	6"	0.11	0.8	1.4	7.8	3.38
11.S1624	5	12"	0.1	0.49	0.8	8.4	4.16
11.S1625	5	18"	0.08	0.39	0.7	7.57	6.02

Table E.3: Soil analysis (6/23/2011)

		Averages	
Number of Samples	Treatment #	NH-4, ppm	NO-3, ppm
2	1	8.20	3.65
3	2	8.20	4.27
3	3	8.93	4.07
2	4	8.25	3.00
3	5	7.60	4.00
-	6	-	-
1	7	9.10	2.60
3	8	6.60	2.87
2	9	6.80	4.05
1	10	6.20	1.70
2	11	7.85	6.85
-	12	-	-
1	13	6.70	2.20
5	14	7.60	12.40
2	15	8.35	4.85
-	16	-	-

Table E.4: Soil initialization profile

Depth, cm	Organic Carbon, %	Total Nitrogen, %	Stable Organic Carbon, %
5	1.1	0.12	0.4
15	1.1	0.12	0.4
20	1.1	0.1	0.4
33	1.1	0.1	0.4
46	1.1	0.09	0.4
75	1.1	0.09	0.4
104	1.1	0.08	0.4
132	1.1	0.08	0.4
152	1.1	0.07	0.4

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