IMPROVING NITROGEN MANAGEMENT IN POTATOES THROUGH CROP ROTATION AND ENHANCED UPTAKE

By

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This work is dedicated to Luz Marina, José Fernando, and Isabela

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TABLE OF CONTENTS

page

ACKNOWLEDGMENTS iv

LIST OF TABLES ix

LIST OF FIGURES x

ABSTRACT xii

CHAPTER

1 INTRODUCTION 1

Nitrates as a Non-Point Source of Water Pollution 1
The Nitrate Problem in Northeast Florida 2
Organization of this Dissertation 4

2 NITRATE-N LOSSES FROM POTATOES GROWN UNDER DIFFERENT CROP ROTATIONS AND NITROGEN RATES 6

Introduction 6
Materials and Methods 9
Site Description 9
Soils 9
Statistical Design and Experimental Layout 10
Crop Production Practices 10
Plant materials 10
Pest management 12
Irrigation management 12
Nutrient management 12
Water and Soil Sampling Schedule 13
Soil sampling 13
Water sampling 14
Tissue Sampling Schedule 16
Potato tissue 16
Sorghum and cowpea tissue 17
Potato yield 17
Statistical Analysis 18
Concentrations of NO_3-N in the water table 18

Concentrations of NO_3-N and NH_4-N in the soil 18
Nitrogen uptake by the crops 19
Potato yield...20
Results and Discussion 20
Concentrations of NO_3-N in the Water Table under Potato 20
Concentrations of NO_3-N in the Soil Solution 30
Concentrations of NO_3-N in the Water Table under Cowpea and Sorghum.......33
Concentrations of NO_3-N and NH_4-N in the Soil...34
Nitrogen Uptake by the Crops 39
Sorghum 39
Cowpea...40
Potato...41
Potato Yield 42
Conclusions...47

3 POTATO ROOT DISTRIBUTION STUDY 49

Introduction...49
Materials and Methods 51
Site Description 51
Statistical Design 51
Root Sampling Methodology 51
Root Washing 53
Root Scanning and Image Analysis...53
Root Variables 53
Soil Strength, Bulk Density, and NO_3-N concentration by Depth 54
Statistical Analysis 55
Root sampler 55
Soil strength, bulk density, and NO_3-N concentrations by depth.................55
Roots...56
Results and Discussion 56
Root Sampler Device...56
Soil Strength and Bulk density 57
Rooting Depth, Root Length, and Root Surface Area..58
Root Length Density...60
Root Surface Area Density 61
Specific Root Length...63
Specific Root Surface Area 64
Conclusions...66

4 SUMMARY, OVERALL CONCLUSIONS AND FUTURE RESEARCH..............67

Summary..68
Crop Rotation and N rates 68
Concentrations of NO_3-N in the water table under potato 68
Concentrations of NO_3-N in the soil solution 69
Concentrations of NO_3-N in the water table under cowpea and sorghum ...69

Concentrations of NO_3-N and NH_4-N in the soil 69
Nitrogen recovery by the summer cover crops 70
Potato N uptake at full flowering 70
Potato yield 71
Potato Root Distribution Study 71
Root sampler 71
Soil strength, bulk density, and NO3-N by depth 72
Rooting depth, root length, and root surface area 72
Root length density and specific root length 72
Root surface area density and specific root surface area 73
Overall Conclusions 73
Future Research 76

APPENDIX

A REGRESSION PARAMETERS 77

B ANOVA TABLES FOR POTATO YIELD PARAMETERS 82

C GREEN BEAN YIELD 86

LIST OF REFERENCES 87

BIOGRAPHICAL SKETCH 93

LIST OF TABLES

Table page

2-1 Nitrogen rate treatments and nutrients applied to potato crop each year. 13

2-2 Precipitation during crops and intercrops periods during the study period.............29

2-3 Effect of crop rotation on soil NO_3-N concentration at potato planting 38

2-4 Nitrogen uptake of cowpea by year at incorporation time. 41

2-5 ANOVA of the annual potato N uptake over the 3 year period...............................41

2-6 Marketable and Total yield of potato under rotation by N rate...............................45

2-7 Tuber exported N, % TKN, and specific gravity of potato under year by N rate interaction...47

3-1 Soil strength, Bulk density, and Soil NO_3-N by depth...57

3-2 Root length and root surface area by diameter class and soil depth. 60

B-1 2001 ANOVA table for potato yield parameters 83

B-2 2002 ANOVA table for potato yield parameters 84

B-3 2003 ANOVA table for potato yield parameters 85

LIST OF FIGURES

Figure page

1-1 Localization map of the tri-county agricultural area (TCAA) in northeast Florida ...3

2-1 Field plot plan, crop rotations and N rates ...11

2-2 Crop cycles, sampling schedules, and precipitation pattern over the three-year period of study ...15

2-3a Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the first year ...21

2-3b Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the first year ...22

2-4a Predicted NO_3-N concentration in the water table under four crop rotations and five N rates during the second year ...24

2-4b Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the second year ...25

2-5a Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the third year ...27

2-5b Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the third year ...28

2-6a Predicted NO_3-N concentration in the soil solution under two crop rotations and five N rates during the second year ...31

2-6b Predicted NO_3-N concentration in the soil solution under two crop rotations and five N rates during the second year ...32

2-7 NO_3-N concentrations in the water table under sorghum and cowpea ...33

2-8 Predicted NO3-N concentration in the soil by effect of five N rates ...35

2-9 Predicted NH4-N concentration in the soil by effect of five N rates ...36

2-10 Nitrogen uptake of sorghum by residual effect of the fertilizer applied to potato ...40

2-11 Potato N uptake at full flowering during the study period 42

2-12 Predicted N rate for maximum marketable potato yield 43

3-1 Procedure to take the root samples..52

3-2 Distribution and sample size into the slice. 57

3-3 Detail of potato roots thickening 59

3-4 Root length density distribution 61

3-5 Root surface area density distribution..62

3-6 Specific root length distribution 64

3-7 Specific root surface area distribution..65

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IMPROVING NITROGEN MANAGEMENT IN POTATOES THROUGH CROP ROTATION AND ENHANCED UPTAKE

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Impact on water quality due to nutrient loading of our finite water resources is a growing concern. Nitrate and phosphates originating from agricultural operations have been identified as the primary contributors to such non-source point pollution of water. The Tri-County Agricultural Area (TCAA) in north-east Florida is predominantly dedicated to intensive potato production system with producers often resorting to over-fertilization, particularly with N sources. Best management practices (BMPs) including crop rotation and enhanced N uptake have been proposed as options to minimize the risk of nitrate contamination of the surface and groundwater in the St. Johns River watershed. To evaluate the effect of NO3-N concentration on shallow water table and to determine optimum N requirement for an economically successful potato crop (var. Atlantic), a 3-year field study with four potato-cover crop rotations and five N rates was conducted in the TCAA. Increased NO3-N concentrations in the shallow water table were recorded immediately after N application at planting but not after the side dressing. At the end of potato season an increase in soil NO3-N resulting from residual effect of N side-dress was found. While nitrate concentrations produced linear and quadratic increase of sorghum N uptake across N rates, cowpea did not exhibit any response. Rotation with green bean in the fall increased soil NO3-N concentration at potato planting in the next season, and a high rainfall between during the intervening period increased the potential for nitrate leaching and run-off. Potato in rotation with sorghum produced higher yields than in rotation with cowpea. Sorghum was found to be a more efficient catch crop for residual NO3-N.

A study of potato root distribution under the effect of three N rates was done in the third year. There was no effect of N rate on root length density, specific root length, root surface area density, and specific root surface. Observations suggested that potato root system was constrained due to soil compaction, and increased soil bulk density recorded at the study site. A soil region where the potato root system showed highest activity was identified which could guide precise fertilizer placement.

CHAPTER 1
INTRODUCTION

Nitrates as a Non-Point Source of Water Pollution

Worldwide, agriculture has been identified as a major contributor of nitrate-N to surface water (Randall and Mulla, 2001). A recent study showed that the mean annual input of N to the Gulf of Mexico from the Mississippi-Atchafalaya River Basin, the third largest river basin in the world, was estimated to be 1,568,000 t yr^{-1} in the period 1980-1996; the mean annual flux of N was about 61% nitrate-N, 37% organic-N, and 2% ammonium-N (Goolsby *et al*. 2001). The high N load, mainly as nitrate, has been related to increased eutrophication and hypoxia in the Mississippi River Delta (Rabalais *et al.* 2002). A US nationwide study reported nine times greater total N concentration downstream from agricultural lands than downstream from forested areas (Omernik, 1977). Along with several major horticultural crops, potato (Solanum tuberosum L.) cropping regions have been suspected of adding excess nitrate to surface and underground waters in Germany (Honisch *et al*. 2002) and Canada (Milburn *et al*. 1990). The nitrate concentration in rural well water in New Brunswick (Richards et al. 1990) and the nitrate concentration in streams flowing through the cropped fields in Ontario (Hill and McCague, 1974) have been associated with the proportion of the land cropped to potatoes. Therefore, emphasis on how intensive management practices impact the environment has been the primary focus of current day research (Ruser et al. 1998; Honish *et a*l. 2002).

Application of higher rates of N than are required for optimum potato production coupled with the susceptibility of NO_3^- leaching by rainfall and irrigation have been the primary focus of current day research (Milburn *et al.* 1990). Furthermore, studies characterizing N uptake by potato roots have shown that N fertilizers are generally applied in excess of the optimal rate for maximum yield (Tyler *et al*. 1983; Joern and Vitosh, 1995a; Prunty and Greenland, 1997). Over-fertilization increases the risk of environmental pollution because N not taken up by the plant can move out of the root zone. Synchronization between N availability in the soil and N uptake by the potato root has been proposed as a core strategy to maximize yield and minimize N loss (Ruser *et al*. 1998; Waddel *et al*. 2000; Mortvedt *et al*. 2001). Furthermore, the efficiency of N uptake can be improved by placing fertilizer in bands and/or applying fertilizer in multiple, relatively small applications (Ruser *et al*. 1998; Waddel *et al*. 1999).

Measures such as suppression of tile-drainage systems, construction of wetland restoration areas before discharge into ditches and rivers, application of correct rate of N at the optimum time, development of improved soil N testing methods to predict availability of mineralized N and carryover from previous crops, improved management of green and animal manures (Randall and Mulla, 2001), and increasing N uptake, and use efficiencies (Errebhi *et al*. 1998, 1999) are accepted strategies to reduce nitrate losses to surface and groundwater.

The Nitrate Problem in Northeast Florida

The TCAA (Tri-County Agricultural Area), located in Flagler, Putnam and St. Johns counties in northeast Florida (Fig. 1-1), contains approximately 15,000 ha of irrigated cropland, predominantly potato and cabbage farms. For more than a century, agricultural production and services have contributed significantly to the economic viability of the basin. Non-point source pollution resulting from storm water runoff from agricultural systems is considered to be one of the major sources of pollution in the low

Figure 1-1. Localization map of the tri-county agricultural area (TCAA) in northeast Florida. * Approximate location of the study site.

St. Johns River Basin (LSJRB). It has been estimated that nonpoint pollutant sources induced by human activities may account for as much as 36% of the amount of pollutants entering the basin today (SJRWMD, 2004). Past work has identified the TCAA as a possible source of non-point pollution from enriched nutrient runoff. Enhanced algal growth in the St. Johns River coinciding with peak runoff associated with the TCAA potato season have been reported (SJRWMD, 1996). Best management practices (BMPs) to control water runoff and to improve fertilizer management by reduced rates and improved timing lowered the phosphorus runoff into the St. Johns River watershed 22.5 % the first year and about 55 % in 15 years (SJRWMD, 2004). A study comparing the traditional water furrow irrigation-drainage system with a system using subsurface irrigation and drainage showed that surface runoff nitrate concentrations were often higher than concentrations in the subsurface drains (Campbell *et al*. 1985). Best management practices to minimize potential runoff and leaching of nitrates from potato-cropped lands including nutrient management, irrigation and sediment management, and crop rotation with low N requiring crops have been implemented in the TCAA (Hutchinson *et al*. 2002).

This three year study was initiated to document the impact the impact of legume rotation crops on NO_3-N concentrations in the water table under potato beds, N uptake by cover crops, potato tuber production, and possible reduction of the N rate of soluble fertilizers currently used in the TCAA for potato production. Along with this study, a study of the potato root system addressed to describe its spatial distribution under a sufficient N fertilization regime. The knowledge of the spatial distribution of potato would allow in the future optimize fertilizer placement in order to increase potato N uptake.

Organization of this Dissertation

This work is organized in four chapters. First chapter is a general introduction addressing the leaching/runoff problem from potato fields with emphasis in northeast

Florida potato production. The second chapter reports results of an 3-year experiment with four crop rotations including legume crops as supplemental N source to five N rates applied to potato. Effect of rotation and N rate on NO_3-N concentration, N uptake by the crops and potato yield are discussed. The third chapter describe and report results of a study of the potato root distribution under effect of three sufficient N rates. The fourth chapter is addressed to summarize, state general conclusions, and suggest future research topics.

CHAPTER 2
NITRATE-N LOSSES FROM POTATOES GROWN UNDER DIFFERENT CROP ROTATIONS AND NITROGEN RATES

Introduction

Potato has been reported as a crop with high potential to generate groundwater contamination due to its high N demand to produce optimum yields. Farmers usually apply N fertilizer in excess of the recommended rate as an insurance against N losses due to N deficiency. In northeast Florida, potato is grown as a late winter or early spring crop using seepage irrigation. Seepage irrigation is a subsurface irrigation system where the depth to or the level of water in the perched water table is controlled taking advantage of the naturally existing hardpan averaging at a depth of 1.5 meters. Seepage irrigation is very unique to this region of the country in contrast with the overhead irrigation used in the rest of the potato producing states in the US. The sandy nature of Florida soils, excess nitrate in the potato beds, and seasons with high rainfall can create conditions resulting in N leaching and/or runoff with the subsequent eutrophication of water bodies. In northeast Florida, most of 9000 ha under potato production are located in the Tri-County Agricultural Area (TCAA) a major agricultural region under the St. Johns River Water Management District (SJRWMD) boundaries. The SJRWMD being responsible for both the water quality and quantity is particularly concerned about the potential nutrient losses from the TCAA to the St. Johns River (Livingston-Way, 2000).

The agricultural practice of alternating crops on a particular during a defined period of time (crop rotation) has several benefits, including interrupting plant disease and insect cycles, increasing mineral or organic content, and improving soil structure. This practice can be used to store N in a catch crop during fallow periods, decreasing potential nitrate leaching (Nielsen and Jensen, 1985; Schroder et al. 1996). Cover crops fit the definition of a rotational crop and are used extensively in production systems that utilize organic fertilizers. Cover crops also provide soil coverage during the periods when no commercial crops are grown, serve as a N sink after the commercial crop is harvested, and act as a green manure for subsequently planted cash crops (Goulding, 2000). Using a cover crop as a green manure lessens the impact of nitrate leaching by maintaining the N in a slow-release form (Thorup-Kristensen and Nielsen, 1998). However, the mineralization of green manures under specific environmental conditions must be known to insure that mineralization of residues is synchronized with crop need (Griffin and Hesterman, 1991; Porter et al. 1999; Schmidt et al. 1999).

In the US, crop rotation with cover crops is used in areas such as the Great Plains, Florida, the northeast and along the west coast where well drained soils and intensive farming of row crops like potato cause high nitrate concentrations in groundwater (Mueller and Dennis, 1996). It has been further reported that plant residues of arable crops such as potato increased N leaching over at least two winters in free drained soils (Mitchell et al. 2001). The great challenge in establishment of a successful crop rotation with catch crops is synchronizing the availability of nutrients from mineralized residues with nutrient demand of the target crop in the rotation. Generally, most commercial crops are fertilized with close to optimum rates and the primary objective of catch crops would be to replace only part of the soluble fertilizer N (Thorup-Kristensen, 1994).

Factors and processes such as content of nitrate in the soil, N mineralization and biomass production of the catch crop (Jensen, 1992), rooting depth of the catch crop, climate, soil type, and rooting depth of the succeeding crop (Thorup-Kristensen and Nielsen, 1998) must be taken in account to select the most appropriate catch crop species under specific environmental conditions. Nitrogen residues from fertilizers in the soil after potato harvest are generally high and depending of the irrigation applied, could be deep in the soil profile (Webb et al, 2000). Therefore, the catch crop used in rotation with potatoes would require an efficient root system in order to recover the N not taken up by the potato (Thorup-Kristensen and Nielsen, 1998; Singh and Sekhon, 1977). C/N ratio and incorporation time of catch crop must also be considered and adapted to the specific environmental condition (Thorup-Kristensen and Nielsen, 1998).

Legume cover-crops such as lupin (Sanderson and MacLeod, 1994), green bean (Hutchinson et al. 2002) and red clover (Porter and Sisson, 1991), and cereal crops wheat and maize (Singh and Sekhon, 1976a, 1976b, 1977), sorghum (Hutchinson et al. 2002), winter rye, wheat, and barley (Shepherd and Lord, 1996; Vos and van der Putten, 2000) have been used as green manures and/or additional cash crops in rotation with potato. Modification of potato production practices including rotation with cash crops and green manure crops adapted to specific environmental situations could help producers increase net revenues by reduction of purchased inputs and increase tuber quality and/or yield (Westra et al. 1995). This research studied the effect of replacing sorghum sudangrass, the traditional summer cover crop used in the TCAA, with cowpea and/or the introduction of green bean as a fall cash crop.

The objectives of this study were i) to identify and to quantify elevations in nitrate concentrations in the perched water table under potato beds due to leaching and ii) to study the effect of legume crops as possible rotation with potato on nitrate leaching and potato yield.

Materials and Methods

Site Description

The study included three potato seasons in the spring of the years 2001, 2002, and 2003 at the UF/IFAS Plant Science and Education Unit, Yelvington Farm in Hastings, FL. The mission of the research farm is to conduct applied and adaptive production research in vegetables, agronomic, and other crops produced in north Florida and to disseminate new information to the academic and agricultural communities. The facility contains 20 ha of land for university research in plant and soil science. Weather data is continuously recorded at the research site through the Florida Automated Weather Network (FAWN)

Soils

The soil at the experimental site was classified as sandy, siliceous, hyperthermic Arenic Ochraqualf belonging to the Ellzey series (USDA, 1981). This soil has a sandy loam layer about 1 m deep with a clayey restricting layer below. As a result the profile is very poorly drained profile even though the saturated hydraulic conductivity in the top 1 m is about 10 $cm{\cdot}h^{-1}$. This soil is about 94% sand, 2.5% silt, and 3.5% clay (Campbell *et al.* 1978). In its natural state, the water table is within 25 cm of the surface for 1 to 6 months in most years and slopes are less than 2% (USDA, 1981).

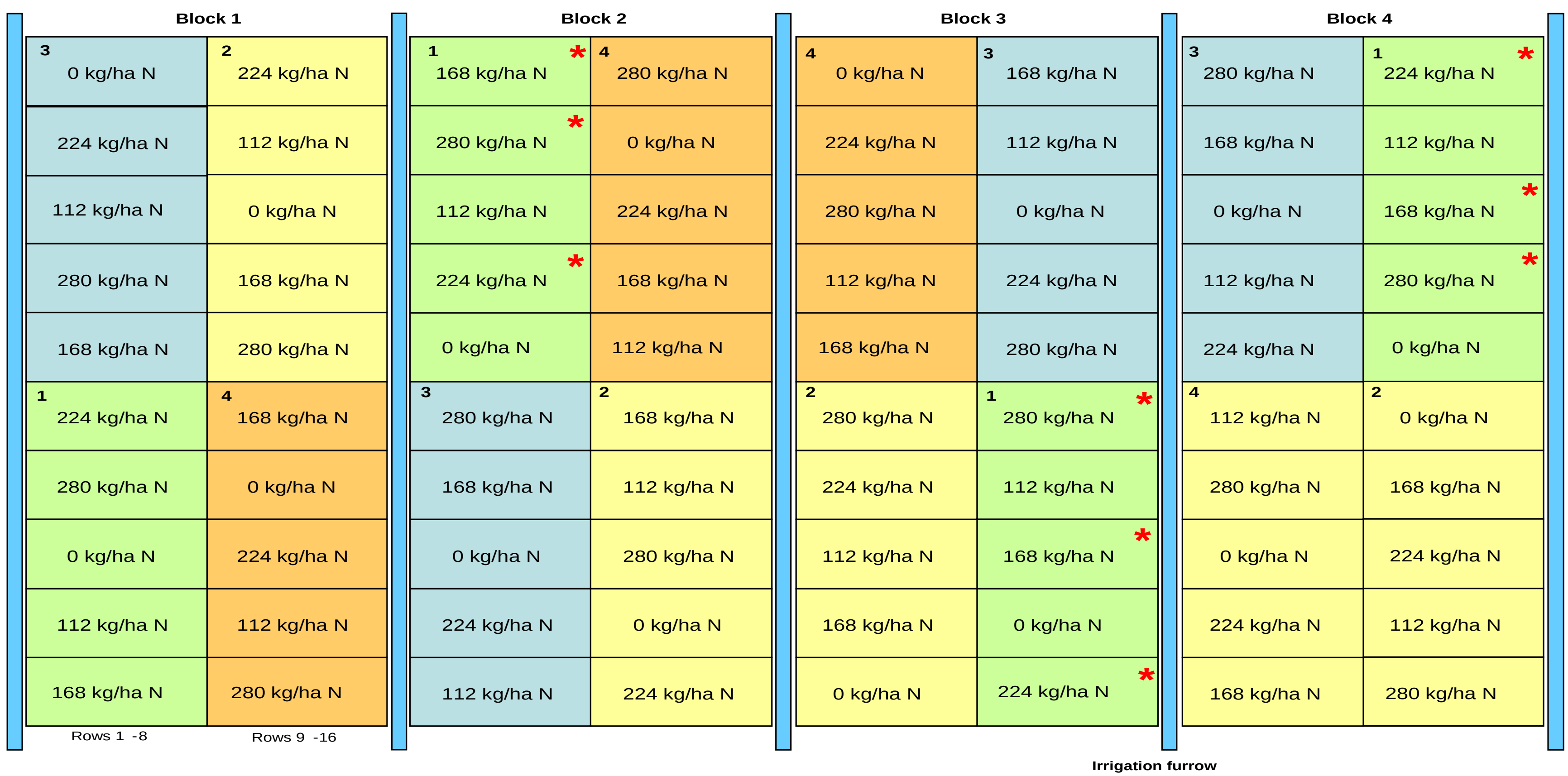
Statistical Design and Experimental Layout

The study was conducted at the same location all the three years of the study. The experiment was replicated four times, and arranged in a split-plot design where the main plot factor was crop rotation and the sub-plot factor was N fertilizer rate applied to potato (Table 2-1). Each block consisted of one bed 16.32 m wide (16 rows) by 160 m long (Fig. 2-1). The block was divided into two strips of 8.16 m (8 rows) by 160 m. Each of the strips (8.16 m x 160 m) was divided again in two parts resulting 4 areas (main plots) of 8.16 m wide (8 rows) by 80 m long in each block (Fig. 2-1). To each of these main plots a crop rotation was randomly assigned for summer and fall. In summer 2000 main plots planted with sorghum and cowpea as summer cover crops (SCC) were randomly assigned. Green bean and fallow main plots were randomly assigned in Fall 2000. In spring 2001, before potato planting each of the main plots was divided into five subplots (8 rows x 16m) and the five nitrogen rates (Table 2-1) were randomly assigned to each of the subplots. Randomization of both the main plot subplot treatments was maintained during the 3-year study period. A code consisting on three letters to identify the four rotations is detailed in Fig. 2-1.

Crop Production Practices

Plant materials

Potatoes (*Solanum tuberosum*, var. 'Atlantic') were planted in early February each year. Seed pieces were cut to a target size of 57 g and planted at an in-row spacing of 20.3 cm with a 101.6 cm between-row spacing resulting in a crop density of 48,216 plants·ha^{-1}. The sorghum/sudan grass hybrid (*Sorghum vulgare* x *Sorghum vulgare, var*. *Sudanese*, var. SX17) and cowpea (*Vigna unguiculata*, var. Iron Clay) were seeded in a single row on a 101.6 cm between-row spacing and a within-row seed spacing of 2.5 cm



Main Plot	Spring	Summer cover crop	Fall crop	Code
1	Potato	Sorghum sudan	Fallow	PSF
2	Potato	Sorghum sudan	Green beans	PSG
3	Potato	Cowpea	Fallow	PCF
4	Potato	Cowpea	Green beans	PCG

*Plots used for the root study

Figure 2-1. Field plot plan, crop rotations and N rates resulting in a density of 392,000 plants·ha^{-1}. Cowpea and sorghum were planted in June after potato harvest in each production year as summer cover-crops (SCC). Bush green bean (Phaseolus vulgare, var. Espada) was planted in September in a single drill per row. with in-row spacing of 2.5 cm thus resulting in a density of 392,000 plants·ha^{-1}. Cowpea and bush green bean were inoculated with specific R*hizobium* strains. Plots not planted with bush green bean in fall were maintained as a weed-free fallow

Pest management

All ground was fumigated with 1, 3-dichloropropene (56 L·ha^{-1}) 4 weeks before planting potatoes for nematode control.

Irrigation management

The seepage irrigation system uses high row beds to plant potatoes and shallow water furrows to supply irrigation water and to remove drainage water. The natural high water table combined with the sandy and flat nature of the soils and landscape in this area make the irrigation and drainage by the subsurface seepage method possible. The rows were raised to 40 cm in height with a between-row spacing of 102 cm. Each bed consisted of 16 rows separated by irrigation-drainage furrows. The water furrow was about 20 cm deeper than the alley between rows in the bed. During dry periods water was added continuously to the head of the water furrow to maintain the water table 60 cm beneath the top of the bed.

Nutrient management

Each year at potato planting, 112 kg·ha^{-1} N as ammonium nitrate (NH_4NO_3), was banded and incorporated in the plots receiving N. However, the control plot was not fertilized with any source of N. Two weeks after emergence of potato plants, the remaining N rates of 56, 112, and 168 kg·ha^{-1} were side-dressed using the same NH_4NO_3

at hilling to complete the final treatmental dosages of 0, 112, 168, 224, and 280 kg·ha^{-1} of N respectively (Table 2-1). Recommended N rate for potatoes in the region is 224 kg.ha^{-1} (Hochmuth and Hanlon, 2000). Based on pre-plant soil tests 34 and 168 kg·ha^{-1} of P and K, respectively, were incorporated I all the plots prior to potato planting in each production year (Table 2-1). No fertilizers or nutrients were applied at any time to either cowpea or sorghum crops. In each production year, around mid August both sorghum and cowpea (before the cowpea set seed) were chopped and incorporated into the soil as green manure. Bush green beans were fertilized pre-plant and a month after planting with 400 kg·ha^{-1} of 14-3-10 and 600 kg·ha^{-1} of 14-0-10 fertilizer blends respectively. Total N applied to bush green bean through the split application amounted to 140 kg·ha^{-1}.

Table 2-1. Nitrogen rate treatments and nutrients applied to potato crop each year.

N (kg.ha^{-1})			**P** (kg.ha^{-1})	**K** (kg.ha^{-1})
At planting	Side-dress	Total	At planting	
0	0	0	56	168
112	0	112		
112	56	168		
112	112	224		
112	168	280		

Water and Soil Sampling Schedule

Soil sampling

Soil samples were taken with an open side tubular auger (diam. 1.9 cm) to a depth of 20 cm. A composite soil sample from eight randomly selected points located in the two central rows of the plots was taken at each soil sampling time. A margin of at least 1 m was left at both ends of each sampled row in order to avoid border effects such as a rare sample contamination with soil or fertilizer movement between adjoining plots. Samples were collected in labeled plastic bags, air-dried, and sieved in preparation for subsequent laboratory analyses. Soil samples were tested for NO_3-N, NH_4-N, P, K, Ca, and Mg at the UF/IFAS Analytical Research Laboratory (ARL) in Gainesville per the procedures manual (Mylavarapu and Kennelley, 2002). Both NO_3-N and NH_4-N in solution were analyzed in an air-segmented continuous autoflow analyzer. Mehlich-1 extraction procedure also referred to as the "dilute double acid" extractant (0.05M HCl + 0.0125M H2SO4) was used to extract soil samples and determine P, K, Ca, and Mg by the ICP method EPA 200.7. Results from analyses of only soil NO_3-N and NH_4-N concentrations analyses were interpreted and reported in this chapter as other nutrients will be outside the scope of this manuscript. The soil sampling schedule throughout the 3-year period is described in Fig. 2-2.

Water sampling

A 10 cm diameter PVC pipe was buried in each potato plot to a depth of 70 cm from the top of each ridge. The pipe acted as a well casing providing easy access to sample the water table below each plot. Additionally, a lysimeter was buried at 30 cm depth on one of the central ridges to sample water from the soil solution at the root zone during the potato season. During the first year (2001) water was sampled from wells and lysimeters on weekly basis, and on a bi-weekly basis during the second (2002) and third (2003) year (Fig. 2-2). In summer 2003, sampling wells were installed to sample the water table under cowpea and sorghum in the plots where potato was fertilized with 0, 168, and 280 $kg.ha^{-1}$ of N. Three bi-weekly samplings were taken following the same procedure for water sampling during the potato season. At each sampling time water samples from wells and lysimeters were collected in plastic vials and frozen immediately to measure NO_3-N and NH_4-N concentrations.

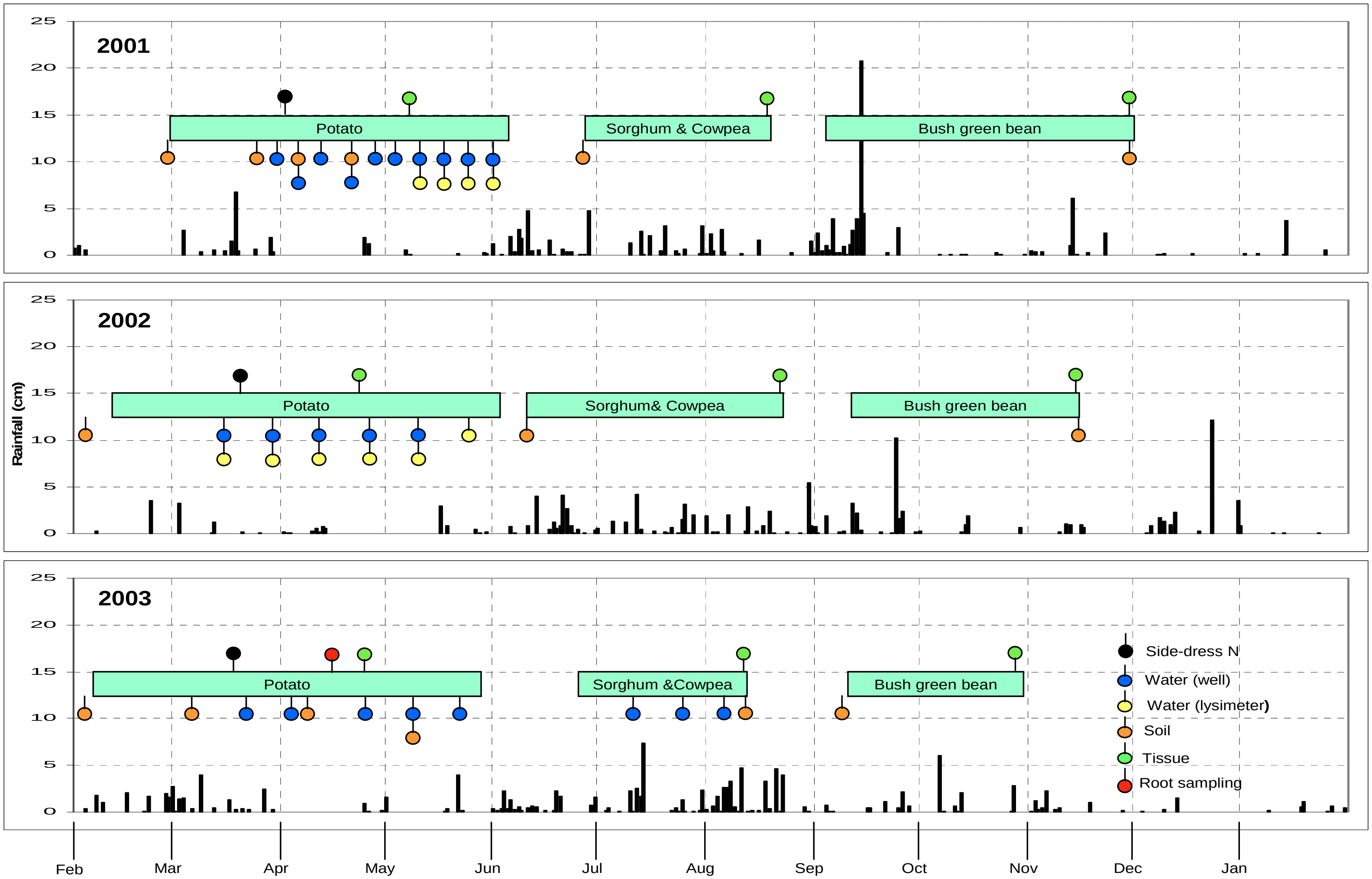


Figure 2-2. Crop cycles, sampling schedules, and precipitation pattern over the three-year period of study

In the first year and second years wells were installed 3 and 8 days before N side-dressing respectively, and 2 days after side-dressing in the third year. Lysimeters were installed at the end of the potato season (early May), and 1 week before N side-dressing in the second and third years. Due to the late installation of the lysimeters in the first year (early May) and problems with recovery of the water samples from lysimeters during the third year, only samples from the second year were analyzed and included in this dissertation. The wells and lysimeters sampling schedule is illustrated in Fig. 2-2. Water samples from wells and lysimeters were tested at the UF/IFAS ARL in Gainesville. Water samples were tested in an air-segmented continuous autoflow analyzer for NO3-N and NH4-N (Mylavarapu and Kennelley, 2002). Only NO3-N concentrations are analyzed, reported and discussed in this dissertation.

Tissue Sampling Schedule

Tissue samples from the crops were tested for Total Kjeldahl Nitrogen (TKN), P, and K at the UF/IFAS ARL in Gainesville. Digestates from the Kjeldahl digestion process were tested using semi-automated colorimetric analysis (EPA Method 351.2) to determine nitrogen. The instrument (Alpkem autoanalyzer) was set up and calibrated. Calibration standards and quality control samples were digested in the same manner as the samples as per the procedures described in manual (Mylavarapu and Kennelley, 2002).

Potato tissue

Potato tissue was sampled at full flowering 60 to 65 days after planting (DAP) in each of the three-years (Fig. 2-2). Shoots of two plants from the two central rows in each plot were cut at ground level and divided in leaves and stems, oven-dried, weighed, ground, and individually labeled. At harvest time a sample of marketable potato tubers from each plot was taken. Tubers were diced, fresh weighed, oven-dried, dry weighed, ground, and individually labeled. Leaves, stems, and tuber samples were sent to the UF/IFAS ARL in Gainesville for analysis. Pooled TKN concentrations of leaves and stems were analyzed and reported as shoots TKN.

Sorghum and cowpea tissue

Sorghum and cowpea plants were chopped and incorporated into the soil in August (Fig. 2-2). Before incorporating sorghum and cowpea, a tissue sample of each to estimate biomass and N added to the soil was taken following the same procedure described for potato plant sampling. Ground tissue samples were sent to the UF/IFAS ARL in Gainesville.

Potato yield

In all potato plots, two-row segments 6.1 m long from the central rows were harvested with a mechanical harvester 100 DAP. A margin of at least 1 m was left at both ends of each sampled row in order to avoid the border effect of adjoining plots. Potato tubers were graded by size (tuber diameter) into five classes (B= <4.8, A1= 4.8-6.4, A2 = 6.4-8.3, A3 = 8.3-10.2, A4 = >10.2 cm). Marketable yield was comprised of classes A1 to A3 only. Total yield was calculated by the summation of all of the classes. Tubers were rated for general appearance, disease, and nematode damage. In this dissertation, total and marketable yield, specific gravity, and % TKN in the tubers were analyzed and reported. Agronomic or physiological interpretation of the yield results was not attempted.

Statistical Analysis

Concentrations of NO_3-N in the water table

The assumptions of homogeneity of variance and normality of the population were checked for the water data sets (wells and lysimeters). Normality was checked by residual analysis using the Shapiro-Wilk test as implemented in the CAPABILITY procedure of SAS (SAS Institute, 2004). Concentration of NO_3-N in water was log transformed and checked again for normality. An exploratory analysis consisting of a time series plot to see the general pattern of NO_3-N concentration in water, and a general linear model analysis on the log transformed data set were performed. Using orthogonal polynomial contrasts the N rate factor on the subplot was partitioned into linear, quadratic, cubic, and quartic components to determine which regression best described NO_3-N concentrations in water with-time. Subsequently, the RSREG procedure of SAS (SAS institute, 2004) was used to estimate the regression parameters and predicted values. The number of days after or before N side-dressing were used as the independent variables.

A general linear model by individual sampling times was performed to check the effect of residual fertilization on the NO_3-N concentration in the water table under sorghum and cowpea planted in summer 2003. The analysis was implemented as a split plot design where crops (cowpea and sorghum) were the main plot factor and residual effect from the five nitrogen rates applied to potato were the sub-plot factor. Means were separated by the Tukey test as implemented in the GLM procedure of SAS (SAS Institute, 2004) and confidence limits of 95% were calculated for each mean.

Concentrations of NO_3-N and NH_4-N in the soil

The soil sampling schedule was not the same for each year (Fig. 2-2) therefore a general linear model by individual soil sampling times was performed and therefore was not combined over years. The Tukey multiple comparison procedure was used to separate rotation and N treatment means when overall significant effects were observed. The N treatment effect was decomposed into linear, quadratic, cubic and quartic components using orthogonal polynomials in order to identify the response of soil NO_3-N to the five N rates applied to potato. Soil NO_3-N content at the time of the previous soil sampling was used as a covariate to check the effect of past NO_3-N concentration on selected sampling times. Since N treatment had either linear or quadratic effect on soil NO_3-N and NH_4-N concentrations, regression analysis was used to test hypothesis and estimate regression parameters. A general linear model combining soil samplings at potato harvest was used to compare residual NO_3-N before SCC planting.

Nitrogen uptake by the crops

Statistical analysis of N as TKN in the biomass of the summer cover crops at the time of incorporation into the soil was done to estimate N uptake and N provided by the soil incorporation of each of the crops. The assumptions of homogeneity of variance and normality of the population were checked. Normality was checked by residual analysis using the Shapiro-Wilk test as implemented in the CAPABILITY procedure of SAS (SAS Institute, 2004). A general linear model by individual years was used to determine the effect of crop rotation and N rate on N uptake by the SCC. Using orthogonal polynomial contrasts the N rate factor on the subplot was partitioned in linear, quadratic, cubic, and quartic components to determine the regression that best described total N uptake of the cover crops over-time. Cowpea did not respond to residual N from the potato fertilization therefore no regression was adjusted.

Similarly, homogeneity of variance and normality of residues were checked prior to performing the statistical analysis for N uptake values for potatoes. A general linear model by individual years on potato N uptake at full flowering was performed. N rate factor was partitioned in its linear, quadratic, cubic, and quartic components by using orthogonal polynomial contrasts in order to determine the best regression to describe the effect of N rate on potato N uptake. Finally, the REG procedure as implemented in SAS (SAS Institute, 2004) was used to estimate regression parameters (Appendix A).

Potato yield

The assumptions of homogeneity of variance and normality of the population were individually checked for potato size classes. A correlation analysis including all of the variables was performed. Normality was checked by residual analysis using the Shapiro-Wilk test as implemented in the CAPABILITY procedure of SAS (SAS Institute, 2004). A general linear model by individual years was used to study yield response to crop rotation and N rate. The LSMEANS with Tukey adjustment as implemented in SAS (SAS institute, 2004) was used to separate individual factor means and/or interaction means when they resulted significant. Subsequently, a general linear model decomposing N rate in its linear, quadratic, cubic, and quartic components was used to determine the best regression explaining the response of marketable potato yield to N rate. The quadratic model explained the response of yield to fertilizer rates. The first derivative of the quadratic regression equation was solved for N rate to determine the N rate required to reach maximum marketable yield.

Results and Discussion

Concentrations of NO_3-N in the Water Table under Potato

The time of application of side-dressed ammonium nitrate, approximately 40 DAP (days after planting) was used as the reference point to describe the effect of the five rates of applied fertilizer on the NO_3-N concentration in the water table (Figs. 2-3a to 2-5b).

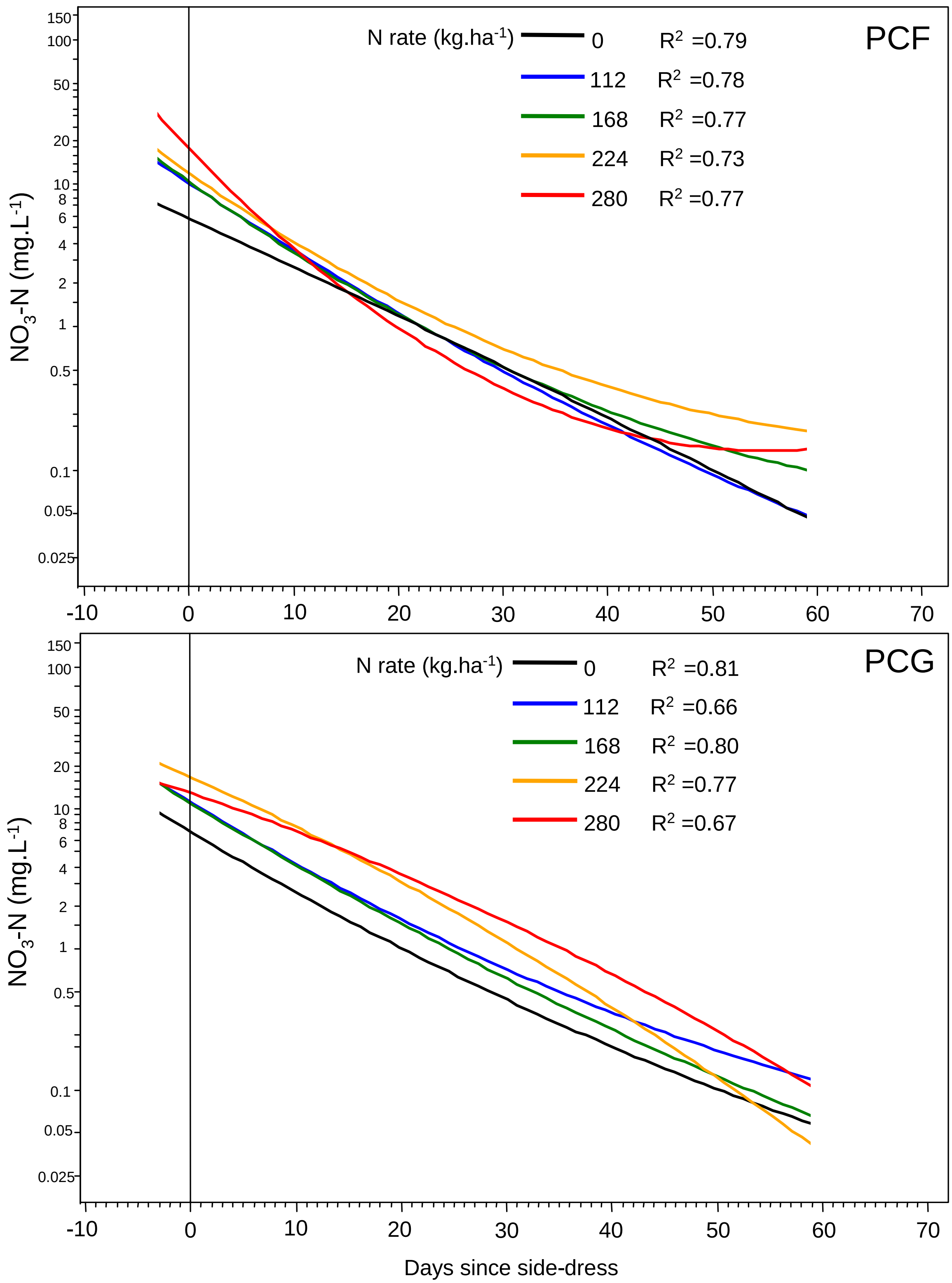


Figure 2-3a. Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the first year. PCF=Potato-Cowpea-Fallow, PCG=Potato-Cowpea-Green bean

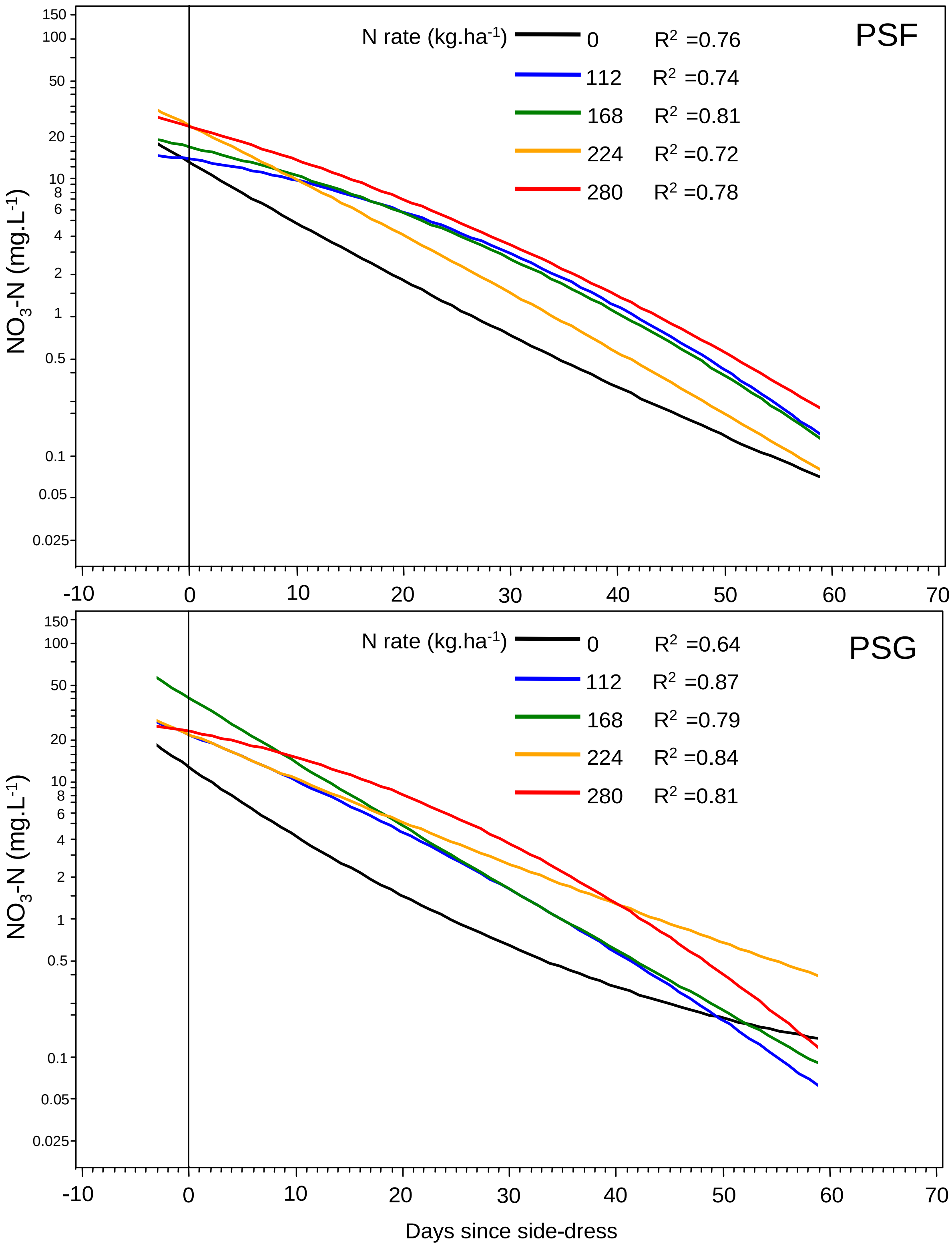


Figure 2-3b. Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the first year. PSF=Potato-Sorghum-Fallow, PSG=Potato-Sorhum-Green bean

The concentration of NO_3-N in the water table was explained by linear and quadratic regressions (Appendix A). During the 3 year study period, NO_3-N concentration in the water table under the four rotations exhibited decreasing trend from high values before N side-dressing to values close to zero two months after N side-dressing(Fig. 2-3 to 2-5).

In the first year, at the time of the first water sampling (3 days before side-dressing) the predicted values for fertilized plots were in the range of 13.5 to 54.5 $mg \cdot L^{-1}$ of NO_3-N. The predicted values for the unfertilized plots were between 8.2 and 18.2 $mg \cdot L^{-1}$ of NO_3-N. In the PSF rotation the predicted value for the control plot was higher than the value for the 112 $kg \cdot ha^{-1}$ N rate suggesting a possible cross-contamination of the control plot from the adjoining plots. The declining trend was explained by a significant linear regression model with coefficients of determination ranging between 0.64 and 0.87 (Fig. 3-2). NO_3-N in the water table under plots with the rotations PCF and PSG with 280 $kg \cdot ha^{-1}$ of N, and plots with the rotation PSF and 112 $kg \cdot ha^{-1}$ of N were described by a quadratic model. In spite of these exceptions, an overall similar pattern was observed for each one of the 4 rotations studied. No differences between N treatments including the control were observed (Fig. 2-3a, b).

In the second year, coefficients of determination ranged from 0.57 to 0.32 (Fig 2-4a, b). The predicted values at the first sampling (8 days before N side-dressing) were in a range of 0.3 to 5.0 $mg \cdot L^{-1}$ of NO_3-N in the water table. No differences between fertilized and unfertilized plots were observed. The relative low concentrations of NO_3-N in the water table in this year produced tendency for lower values of R^2 and low adjustment of the models suggesting high variability when NO_3-N concentration values

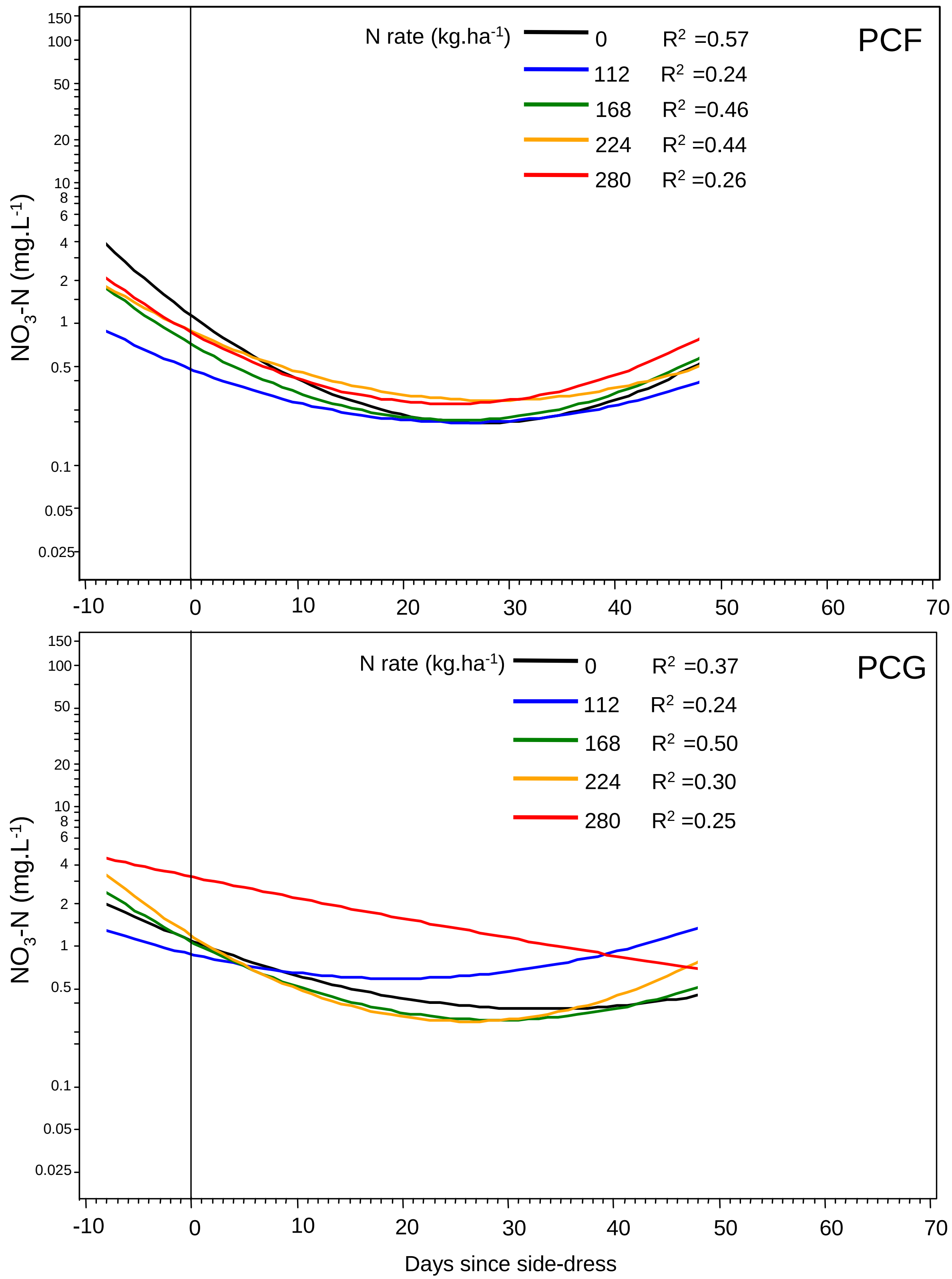


Figure 2-4a. Predicted NO_3-N concentration in the water table under four crop rotations and five N rates during the second year. PCF=Potato-Cowpea-Fallow, PCG=Potato-Cowpea-Green bean

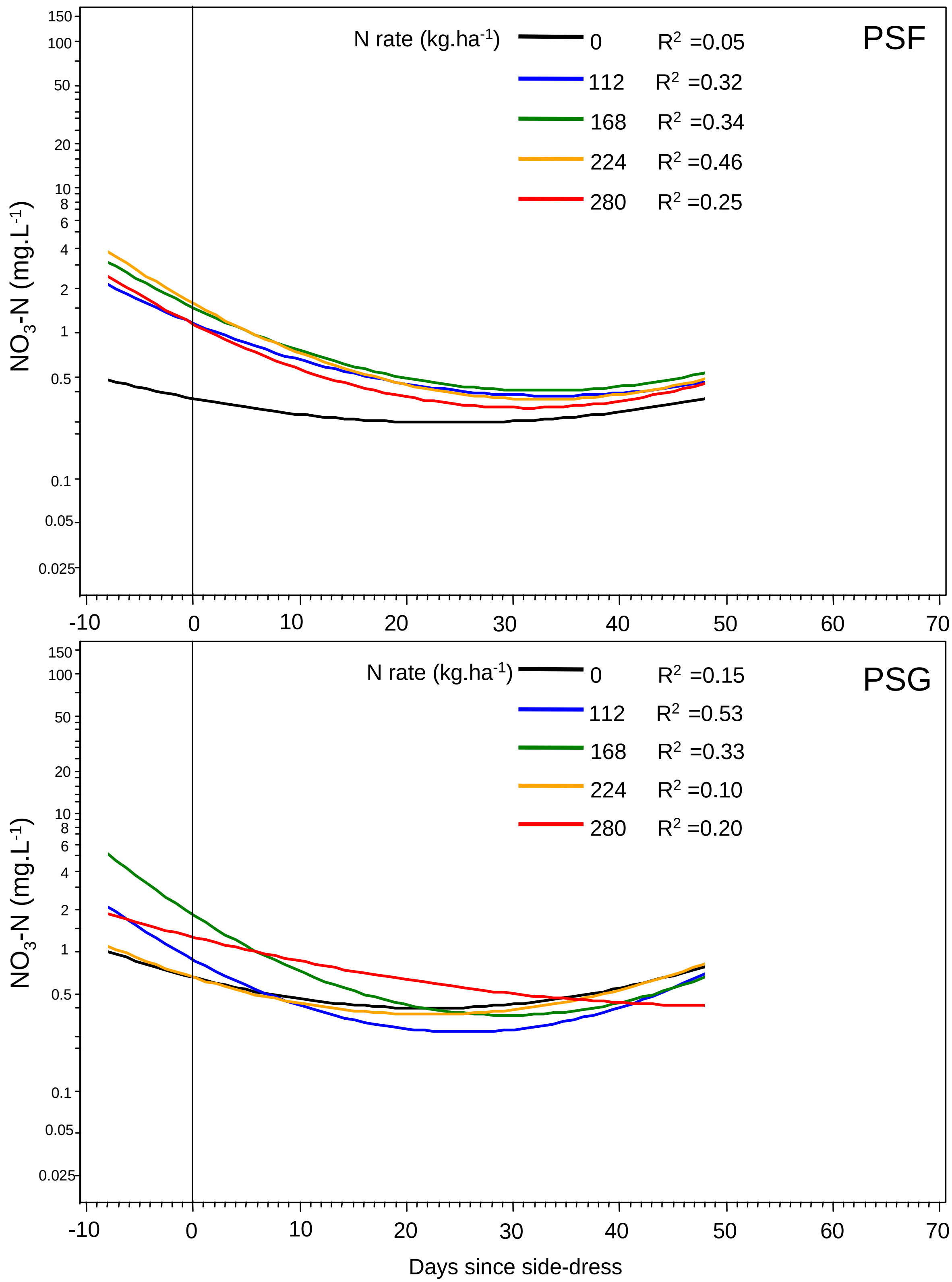


Figure 2-4b. Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the second year. PSF=Potato-Sorghum-Fallow, PSG=Potato-Sorghum-Green bean

were close to the analytical method detection limit (0.5 mg·L^{-1} of NO_3-N).). Even though, the low coefficients of determination a similar overall pattern was observed in the water table NO_3-N concentration under the four crop rotations (Fig. 2-4a, b). A probable explanation for the low NO_3-N concentration values was the low rainfall in the period between potato planting and N side-dressing in 2002 compared with the high rainfall in 2001 and 2003 (Table 2-2).

In the third year, water samples from wells were taken only from the plots fertilized with 0, 168, and 280 kg·ha^{-1} of N. As in the first year, the NO_3-N concentration in the

fertilized plots followed a decreasing pattern. The predicted values for fertilized plots in the first sampling (2 days after side-dressing of N) were between 11.0 and 54.6 mg·L^{-1} of NO_3^-N (Fig. 2-5). These values are similar to the predicted values at the first sampling during the first year. The only difference being sampling time which was 3 days before side-dressing in the first year (Fig. 2-3). Predicted NO_3-N concentration values in the water table under fertilized plots treated with different fertilizer rates tended to be similar and unfertilized plots showed low NO_3-N concentration values (0.8 to 2.0 mg.L^{-1}) except in PCG rotation (Fig. 2-5a) where the effect of the two legumes in rotation with potato could explain the relatively high NO_3-N concentration in the water table under the control plot for this rotation. Similarly to the second year, the relatively low NO_3-N concentration in the water table under unfertilized plots produced low R^2 and low adjustment to the regression model (Fig. 2-5a, b). The main difference between the first and third year is that the predicted values for the unfertilized plots in the first year were higher compared with the low values for the same plots in the third year. The difference

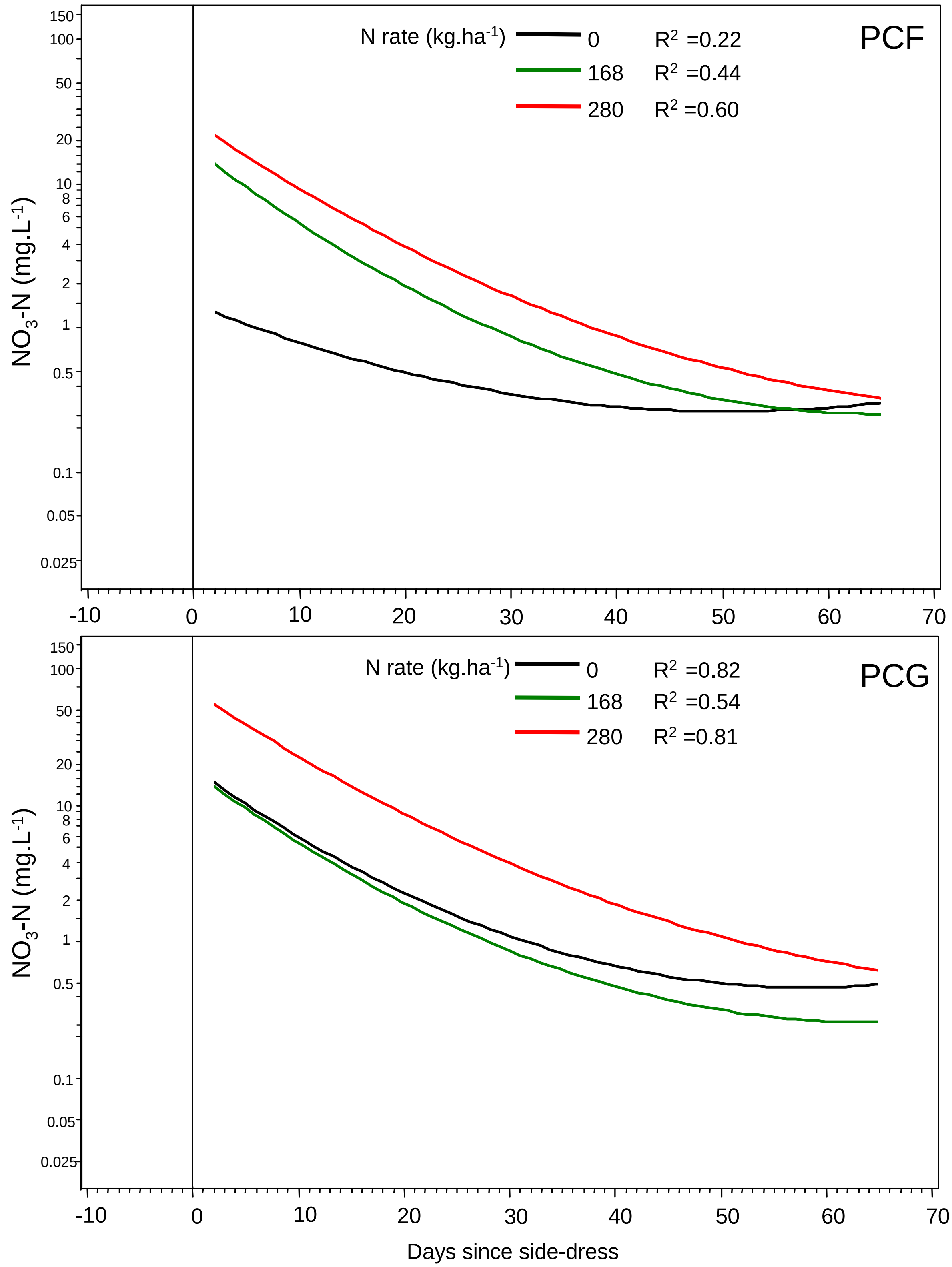


Figure 2-5a. Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the third year. PCF=Potato-Cowpea-Fallow, PCG=Potato-Cowpea-Green bean

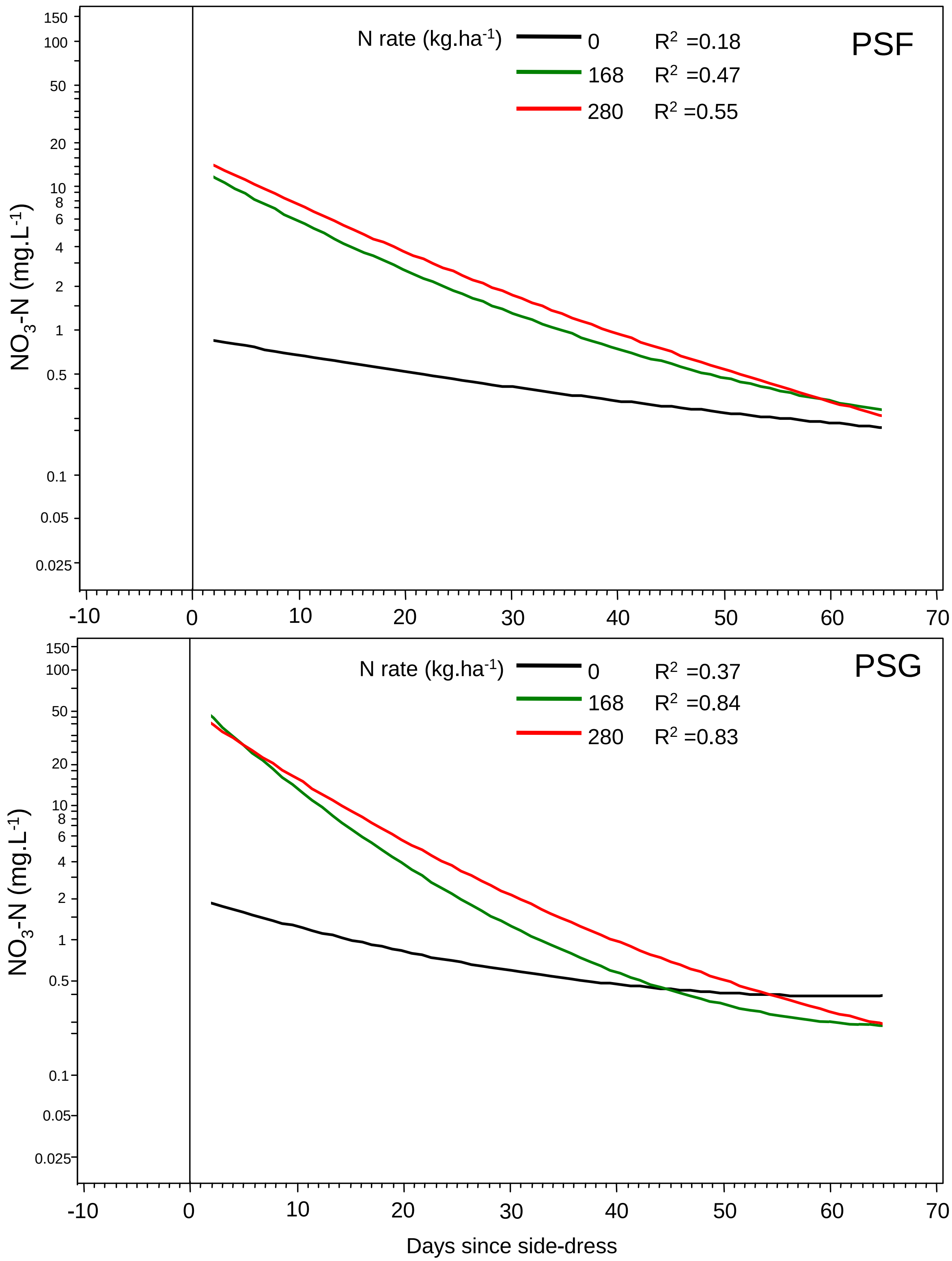


Figure 2-5b. Predicted NO_3-N concentration in the water table under two crop rotations and five N rates during the third year. PSF=Potato-Sorghum-Fallow, PSG=Potato-Sorghum-Green bean

among unfertilized plots in the first and third year was due to high residual effect of N in the field from the past season.

In each year, a declining pattern in NO_3-N concentration starting with higher values prior to side-dressed application of N was a common observation under all rotations and N rates. This was evidently due to the application of 112 kg ha-1 of N through readily soluble ammonium nitrate to all the potato plots that received N treatments at planting when the root development is limited leading to inefficient fertilizer uptake and higher NO_3-N concentration in the water table. This hypothesis is supported by the steady decline in NO_3-N concentration after side-dress fertilization through the potato season in the fertilized plots. In the 3-year period NO_3-N concentration in the water table under the four different crop rotations exhibited a similar pattern within season but different trends were observed during different seasons. In the second year, NO_3-N concentrations in the water table between planting and side-dressing N fertilizations under all rotations were lower than 5 $mg \cdot L^{-1}$ compared with the same period on the first and third years when the highest concentrations were close to 50 $mg \cdot L^{-1}$ of NO_3-N (Figs 2-3 and 2-5). High amounts of rainfall received during those years (Table 2-2) have resulted in higher leaching of NO_3-N. During the first and third years, precipitation received during the month of planting was 47% and 51% higher respectively than the historic 25-yr average (NOAA, 2004) with occurrence of leaching rain Kidder *et al*. 1992) before the first

Table 2-2. Precipitation during crops and intercrops periods during the study period.

Year	Potato		Crops in rotation with potato				
	Planting to N side-dress	N side-dress to harvest	Inter crop	Sorghum/ Cowpea	Inter crop	Green bean	Inter crop
	Rainfall (cm)						
2001	15.98	5.86	16.32	27.37	5.97	54.24	5.87
2002	8.24	7.56	1.79	30.05	13.10	23.81	26.55
2003	22.30	11.18	12.19	38.75	14.48	22.46	6.32

water sampling. The second year was not a typical year with a received precipitation 45% below the average. Therefore, less NO_3^- could have leached from the potato beds in the second year compared to the first and third years.

Concentrations of NO_3-N in the Soil Solution

The concentration of NO_3-N in the soil solution under four crop rotations and five N rates during the second year (Fig. 2-6a. b), was explained by the quadratic regression model with coefficients of determination ranging between 0.47 and 0.89 (Fig. 2-6a,b) . Eight days before N side-dressing, predicted values fluctuating between 156.0 and 63.4 $mg \cdot l^{-1}$ of NO_3-N were estimated for fertilized plots planted with PCG (Fig. 2-6a) and PSG (Fig. 2-6b) rotations, and predicted values for the non-fertilized plots planted under the same rotations were 40.4 and 25.0 $mg \cdot l^{-1}$ of NO_3-N respectively. In the plots with crop rotations including fall as a fallow period predicted values for fertilized plots were between 27.1 and 85.6 $mg \cdot l^{-1}$ of NO_3-N. Predicted values for non-fertilized plots with the same rotations were around 16.0 $mg \cdot L^{-1}$ of NO_3-N (Fig. 2-6a, b). Also, a comparison of predicted NO_3-N concentrations at first sampling in PSF and PSG under fertilization showed that the concentration in plots with green bean in fall was twice as the concentration in fallow plots. A similar trend was observed when PCF and PCG were compared. Factors such as residual N from green bean fertilization, increase in the soil N due to the biological N fixation and/or mineralization of crop residues from green bean could have resulted in such a difference in the NO_3-N concentration in the soil solution.

An elevation in NO_3-N concentration in the soil solution was detected between 40 to 60 days after N side-dress (Fig. 2-6a, b). A similar elevation in NO_3-N concentration in water samples from the water table beginning 30 days after N side-dress (Fig. 2-6a, b) was detected. These elevations in NO_3-N concentration in the soil solution and water

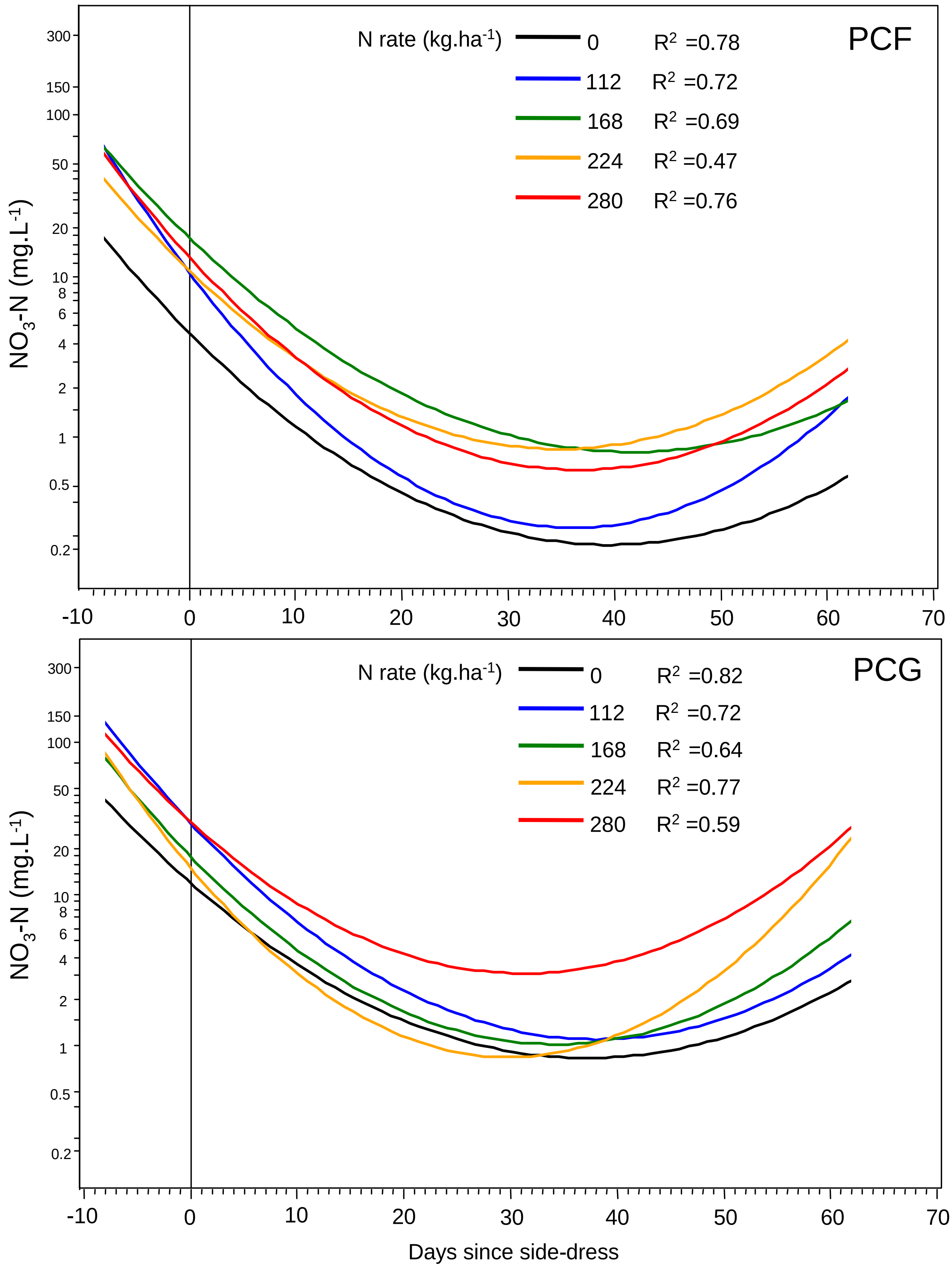


Figure 2-6a. Predicted NO_3-N concentration in the soil solution under two crop rotations and five N rates during the second year. PCF=Potato-Cowpea-Fallow, PCG=Potato-Cowpea-Green bean

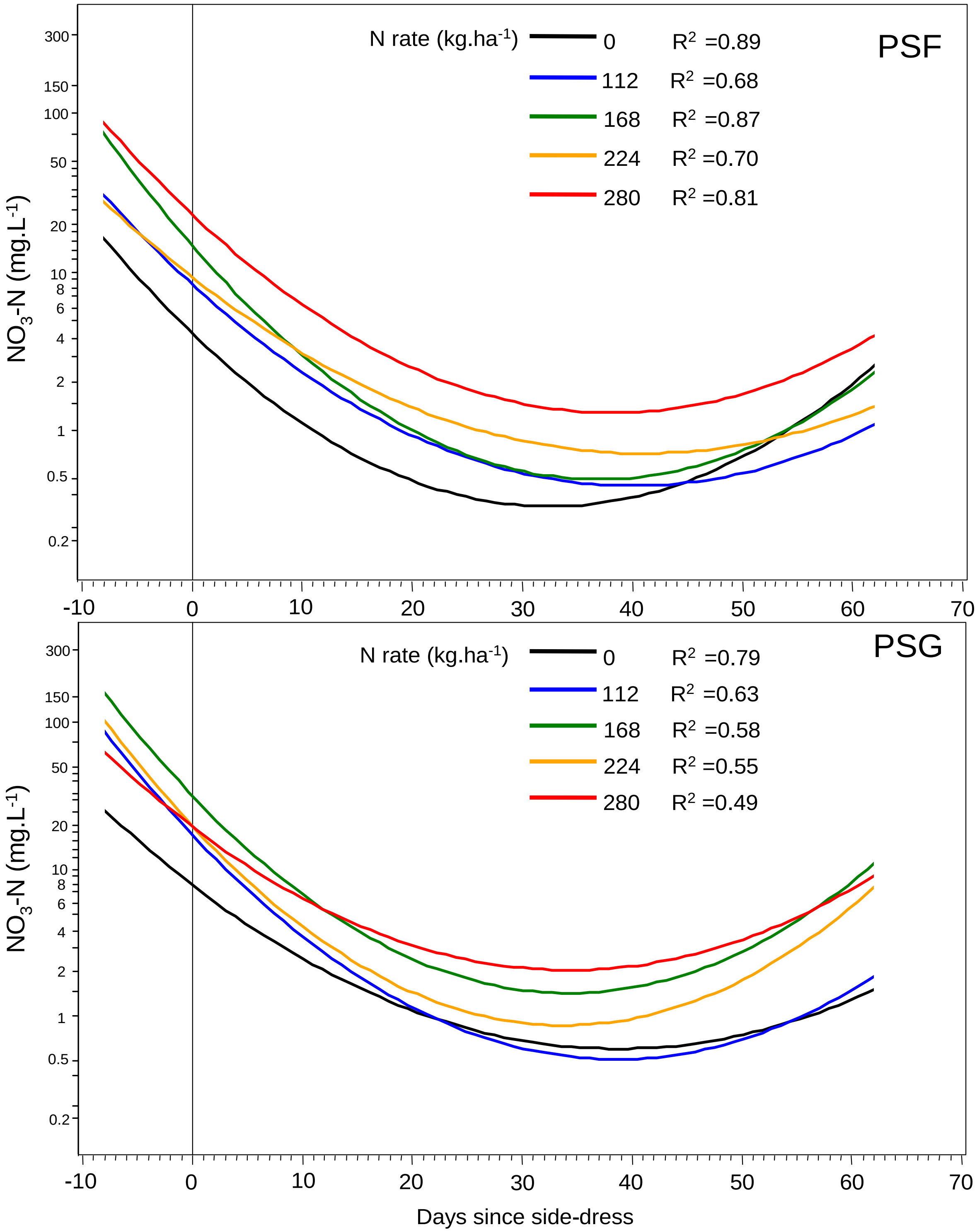


Figure 2-6b. Predicted NO_3-N concentration in the soil solution under two crop rotations and five N rates during the second year. PSF=Potato-Sorghum-Fallow, PSG=Potato-Sorghum-Green bean

table close to potato harvest coincide with the suggestion of increased nitrification of the NH_4^+ applied at N side-dress fertilization (Fig. 2-8 and 2-9). The coincidence in the elevation of NO_3-N concentration in the soil solution at 30 cm from the top of the ridge with the elevation in NO_3-N concentration in the water table 40 cm below of the lysimeter cup suggest leaching of NO_3-N.

Concentrations of NO_3-N in the Water Table under Cowpea and Sorghum

In summer 2003, three bi-weekly samplings from the water table under plots planted with cowpea and green bean were taken in order to study the residual effect of the

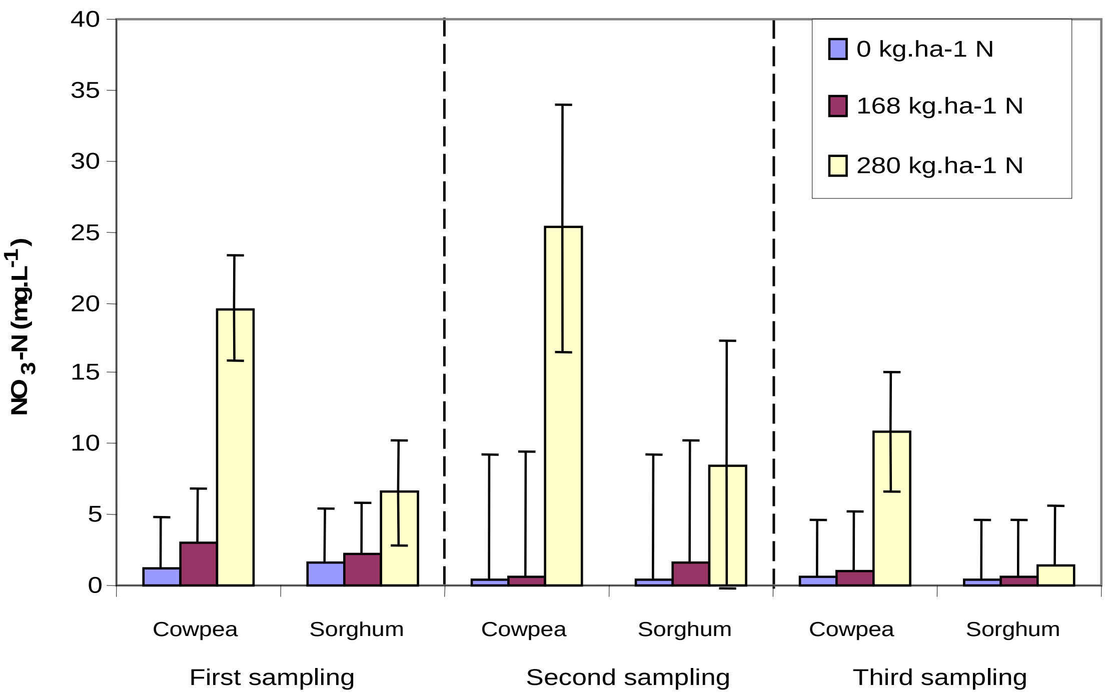


Figure 2-7. NO_3-N concentrations in the water table under sorghum and cowpea. Vertical whiskers are confidence intervals at 0.95 level.

fertilizer applied to potato in spring. At first sampling NO_3-N concentrations in the water table under cowpea showed a significant increase when the N rate applied to potato in spring was increased from 168 to 280 kg.ha^{-1} and there was no difference between plots fertilized with 0 and 168 kg.ha^{-1} of N (Fig. 2-7). Also at the first sampling there was no difference in the NO_3-N concentrations in the water table under plots planted with sorghum. The NO_3-N concentrations in water table under sorghum were significantly lower than the NO_3-N concentrations under cowpea in plots fertilized with 280 kg.ha^{-1} of N but there was no difference with cowpea planted in plots where potato was no-fertilized or fertilized with 168 kg.ha^{-1} of N (Fig. 2-7). These results showed that sorghum was a better NO_3-N catch crop compared to cowpea. Including sorghum as a summer cover crop in the potato production rotation was found to have a significant potential in reducing applied N rates, improving N efficiency and minimizing leaching.

Concentrations of NO_3-N and NH_4-N in the Soil

In 2001 and 2003, 3 weeks after side-dress N was applied soil NO_3-N concentration across N rates showed a positive relationship described by linear and quadratic regressions respectively (Fig 2-8a) Twelve weeks later, at planting of sorghum and cowpea a corresponding trend was detected (Fig 2-8b). The persistence of the N fertilizer in the soil indicated N over-fertilization to potato. Similarly to 2003, at seven weeks after N side-dressing soil NO_3-N concentration increased linearly across N rates (Fig 2-8b)

Ammonium-N concentration 3 weeks after N side-dressing exhibited a positive relationship described by a quadratic regression in both years (Fig. 2-9a). Prior to side-dressing, concentrations of NH_4-N in unfertilized plots (0 N) and plots with fertilization only at planting (112 kg.ha^{-1} N rate) showed similar values possibly due to both high nitrification rate and/or leaching and runoff due to the high amount of rainfall after potato planting in 2001 and 2003 (Table 2-2). Predicted soil NH_4-N concentrations at planting of sorghum and cowpea (12 weeks after N side-dressing) in 2001 and 2002, and 7 weeks after N side-dress in 2003 (Fig. 2-9b) decreased to similar concentration values observed

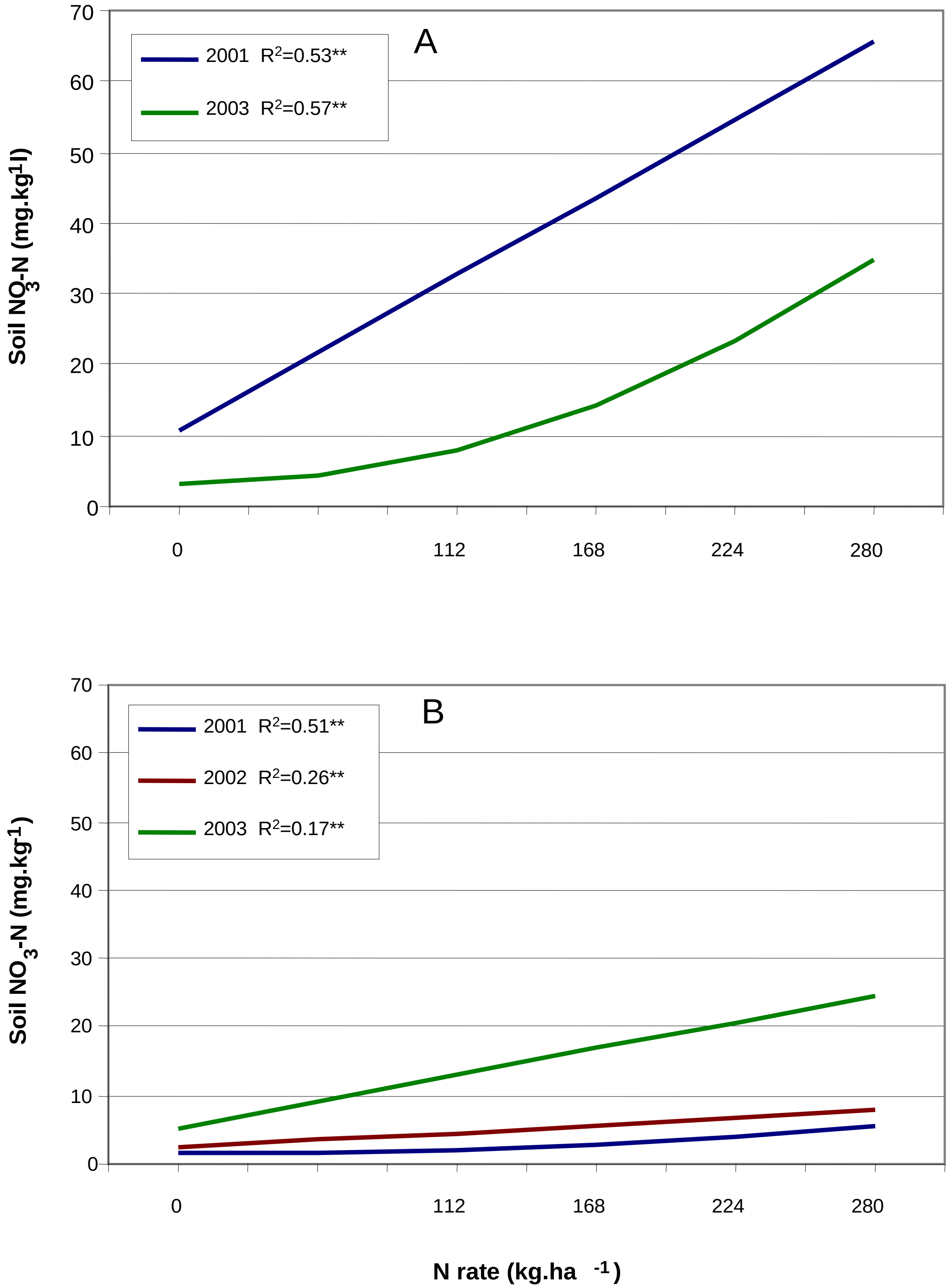


Figure 2-8. Predicted NO3-N concentration in the soil by effect of five N rates. A- Three weeks after N side-dressing. B-At sorghum and cowpea planting in 2001 and 2002, and three weeks before potato harvest in 2003. Coefficient of determination significance: * p <0.05 and **p<0.01

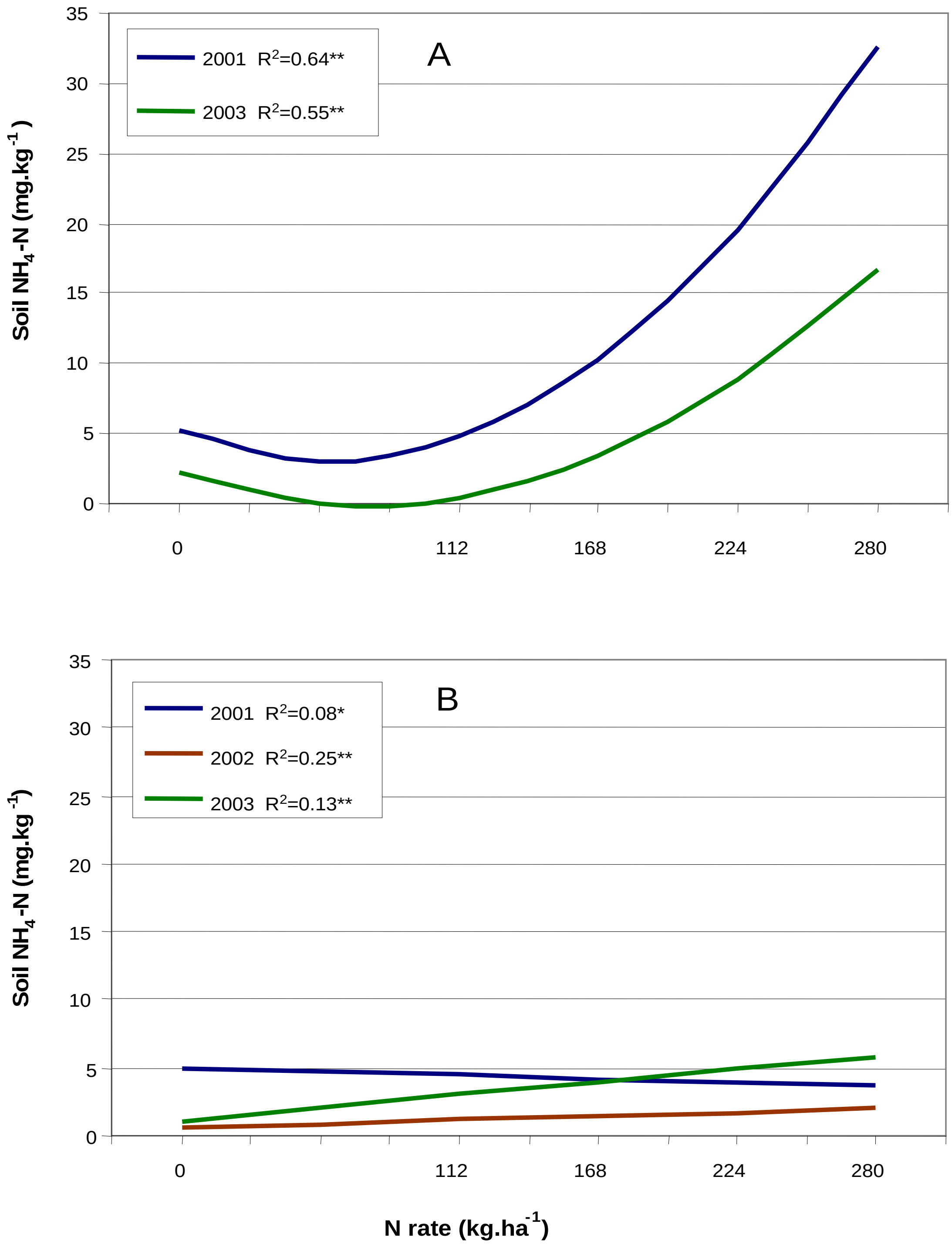


Figure 2-9. Predicted NH4-N concentration in the soil by effect of five N rates. A-Three weeks after N side-dress. B-At sorghum and cowpea planting in 2001 and 2002, and 3 weeks before potato harvest in 2003 . Coefficient of determination significance: * p <0.05 and **p<0.01.

in unfertilized plots 3 weeks after side-dressing (Fig. 2-9a). In 2003, the decrease in soil NH_4-N concentration between N side-dressing (Fig. 2-9a) and potato harvest (Fig. 2-9b), during a relatively low rainfall period (Fig. 2-2), along with increased NO_3-N in the seventh week after N side-dressing in 2003 (Fig. 2-8b), showed that increase in NO_3-N concentration at the end of the potato season was caused by nitrification of the NH_4^+ contained in the ammonium nitrate side-dressed to potato. The increase in NO_3-N concentration in the soil solution at 30 cm from the top of the ridge between 40 and 60 days after N side-dressing in 2002 (Fig. 2-6a, b) supports the suggestion of increased nitrification before potato harvest. The accumulation of NO_3-N in the potato beds at the end of the potato cycle could be explained by the relatively low rainfall between time of side-dress fertilization and harvest of potato compared with the high rainfall between potato planting and side-dress N application (Table 2-2). Furthermore, as seepage irrigation relies on upward capillary movement of water instead of the downward movement of the water under conventional overhead irrigation NO_3^- accumulated in the relatively dry soil on the surface potato beds. Also aerobic conditions on top of the potato beds could result in an increased nitrification favoring build up of soil NO_3-N.

In 2003, the soil sampling at 3 weeks prior potato harvest revealed increased NO_3-N concentration along with the increase in N rate (Fig. 2-8b). Three months later, at sorghum and cowpea incorporation, soil NO_3-N concentration dropped close to 0.5 $mg{\cdot}kg^{-1}$ and no statistical differences were detected among crop rotation or N treatments. Most of the residual NO_3-N detected before potato harvest was evidently captured up by sorghum as was found in its increased N uptake values (Fig. 2-10) and/or leached to the water table from cowpea plots as depicted in Fig 2-7.

In 2001 at green bean harvest, there was no difference in soil NO3-N concentration among crop rotations (Table 2-3). Two months later, at potato planting 2002, soil NO3-N concentration in plots planted with green bean in fall was significantly higher than plots left as fallow (Table 2-3). Soil NO3-N concentration in the rotation with cowpea in summer and fallow in fall (PCF) was significantly higher than soil NO3-N concentration

Table 2-3. Effect of crop rotation on soil NO_3-N concentration at potato planting

Crop Rotation	G. bean harvest	Potato planting	G. bean harvest	Potato planting
	11-29-01	02-04-02	11-15-02	02-03-03
	mg.kg-1			
PCG	3.90 a	10.58 a	5.11 a	1.94 a
PCF	3.00 a	5.29 b	3.90 a	1.30 c
PSG	2.96 a	9.91 a	2.86 a	1.56 b
PSF	2.55 a	3.99 c	2.12 a	0.95 d

Means in the same column followed by different letter are statistically different ($p<0.01$)

in plots with sorghum in summer and left as fallow in fall (PSF) suggesting increased soil NO3-N concentration due to mineralization and nitrification of cowpea residues incorporated in summer into the soil (Table 2-3). Cowpea residues have an average C/N ratio of 15:1 (Havlin et al. 1999) which should enhance N mineralization. In summer 2001, soil incorporation of sorghum in PSF rotation could result in an initial immobilization of N due to its high C:N ratio (60:1) (Havlin et al. 1999). Six months later at potato planting in 2002, soil NO3-N concentration in PSF plots increased suggesting late mineralization of sorghum residues incorporated in summer 2001 (Table 2-3).

In 2002 at green bean harvest, similarly to 2001, there were no statistical differences in soil NO3-N concentration (Table 2-3). However, in a couple of months at potato planting 2003, a decreased soil NO3-N concentration was observed (Table 2-3). Declining in soil NO3-N concentration at potato planting in 2003 was due to rainfall during the intercrop period at the end of 2002 which was five times higher than the rainfall during the similar intercrop period at the end of 2001 (Table 2-2). These results show that the beneficial effect of enhanced N availability by rotation with legumes easily can be eliminated in sandy soils by effect of rainy periods. Therefore, the increase in N available to potato grown in the following spring season from the rotation with green bean should be taken in account to calculate the fertilization rate for the following potato crop but the amount of rainfall should be considered also.

Nitrogen Uptake by the Crops

Sorghum

Rotation did not significantly affect N uptake by sorghum. Significant linear response in the first year and quadratic in the second and third years of N uptake to residual soil NO_3-N from the five N rates applied to potato 70 days before summer cover-crops (SCC) planting were observed (Fig 2-10). Overall decreasing sorghum N uptake during the 3-year period was observed (Fig. 2-10). An initial data exploratory study showed sorghum biomass highly correlated (0.91, $p<0.0001$) with sorghum N uptake, therefore, vegetative growth determined its N uptake. Decreasing N uptake by sorghum in spite of the trend to increased residual NO_3-N across N rates through the study period suggests that growth of sorghum was limited by other factors, possibly in combination. Differences in sorghum N uptake among years could be explained in part by the combined effect of different length of the period between planting and soil incorporation and the amount of residual N from potato fertilization. In the first, second, and third years sorghum stayed in the field for 57, 77 and 48 days, respectively. These results reveal sorghum as an efficient NO_3-N catch-crop and showed that sorghum grown for an extended period in the field leaving only a short time between potato harvest and

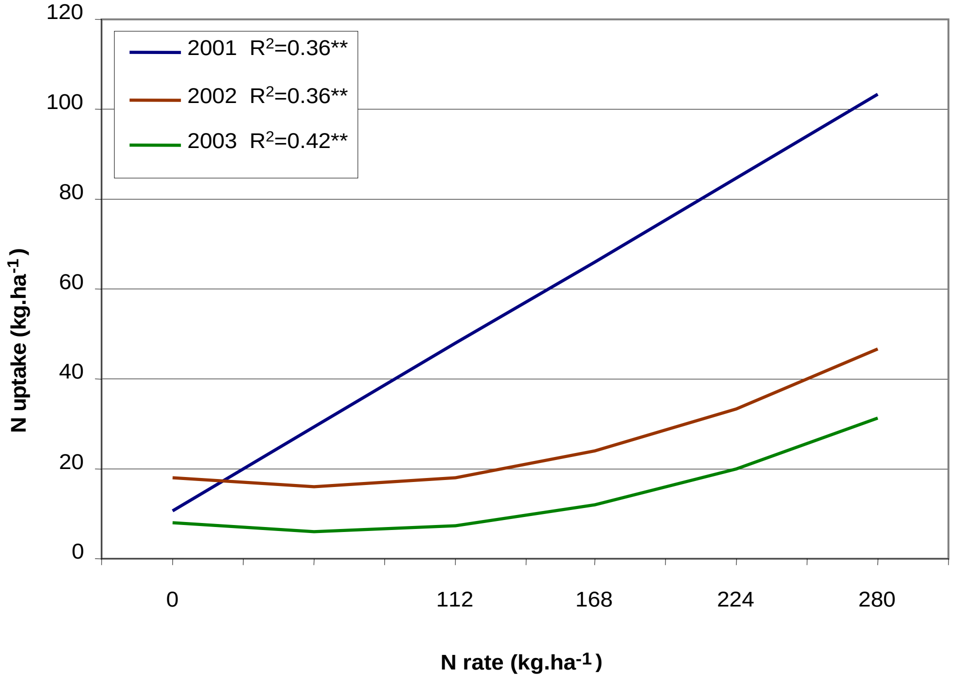


Figure 2-10. Nitrogen uptake of sorghum by residual effect of the fertilizer applied to potato. Coefficient of determination significance: * $p < 0.05$ and ** $p < 0.01$.

sorghum planting as feasible measures to reduce potential leaching of residual NO_3-N from potato fertilization. The effect of a sorghum crop as an efficient N scavenger will be particularly apparent during the wet summer season (Fig. 2-2) as was showed by the significant less NO_3-N leaching under sorghum plots compared with cowpea plots (Fig. 2-7).

Cowpea

Crop rotation and residual N from potato fertilization had no significant effect on N uptake of cowpea. N uptake of cowpea in control plots (0 N) was similar to N uptake in plots with residual N from fertilization to potato in spring (Table 2-4). This response was expected from a leguminous plant like cowpea, which can meet its N requirement through biological fixation with minimal dependence on soil N availability. Low demand for soil N by cowpea explains the occurrence of the second flux of NO_3-N to the water

Table 2-4. Nitrogen uptake of cowpea by year at incorporation time.

N rate ($kg{\cdot}ha^{-1}$)	($kg{\cdot}ha^{-1}$)		
	2001	*2002*	*2003*
0	213 a	225 a	59 a
112	204 a	214 a	66 a
168	225 a	163 a	68 a
224	199 a	221 a	68 a
280	191 a	186 a	61 a

Means followed by the same letter are not statistically different.

table detected after potato harvest in 2003 (Fig. 2-7) when the summer rainfall peak occurred (Fig. 2-2). Nitrogen uptake in 2003 was significantly reduced compared to the corresponding values in 2001 and 2002. However, no difference among N rates persisted (Table 2-4) suggesting that there was another limiting factor at play other than N fixation. Similar to the reduced N uptake observed in sorghum (Fig. 2-10) and potato (Fig. 2-11) in 2003 compared with 2001 and 2002, the reduced N uptake of cowpea suggests the occurrence of a growth limiting factor affecting any crop.

Potato

Nitrogen rate affected significantly N uptake by potato shoots at full flowering all the three years (Table 2-5). Effect of crop rotation on N uptake of potato was not significant in any of the 3 years suggesting a short term effect of crop rotation (Table 2-

Table 2-5. ANOVA of the annual potato N uptake over the 3 year period

Source of variation	Type III Mean Square[2]					
	DF	2001	DF	2002	DF	2003
Replication[1]	2	22179.39*	2	3861.55	3	5004.21
Rotation[1]	3	1610.55	3	6456.90	3	7750.47
Main Plot Error	6	3312.78	6	2250.81	6	3818.49
N rate	4	21837.80**	4	24594.45**	4	44526.97**
Rotation*N rate	12	3509.94	12	1310.37	12	1723.61
Error	59	3878.20	59	1466.22	79	1311.33

[1] Main plot effects tested using main plot error.
[2] *=significant at type I error <.05. **=Significant at type I error <0.01

5). In 2001, potato N uptake was described by a linear regression and was higher than N uptake in 2002 and 2003 (Fig. 2-11). In 2002 and 2003 potato crop N uptake was described for quadratic and linear regressions respectively, with similar overall N uptake (Fig. 2-11). The linear increase in N uptake across N rates 2001 and 2003 (Fig. 2-11) without response in marketable yield (Fig. 2-12) confirmed luxury consumption of N by potato after it has reach its maximum yield.

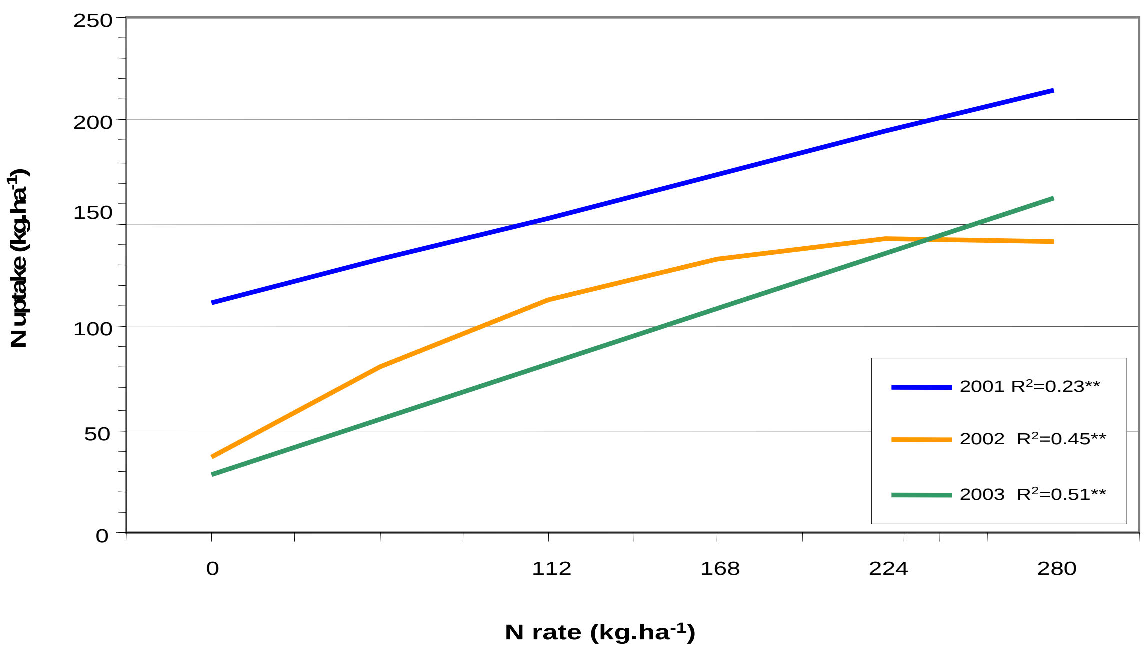


Figure 2-11. Potato N uptake at full flowering during the study period. Coefficient of determination significance: * $p < 0.05$ and ** $p < 0.01$

Potato Yield

An initial exploratory analysis showed that marketable yield in the N fertilized treatments were highly and significantly correlated with yield of potato sizes A2 and A3. Therefore, these two sizes were the main components of the potato yield. In 2001, N rate affected significantly most of the yield components (Appendix B). In 2002 and 2003 there was a significant interaction between crop rotation and N rate (Appendix B). Yields

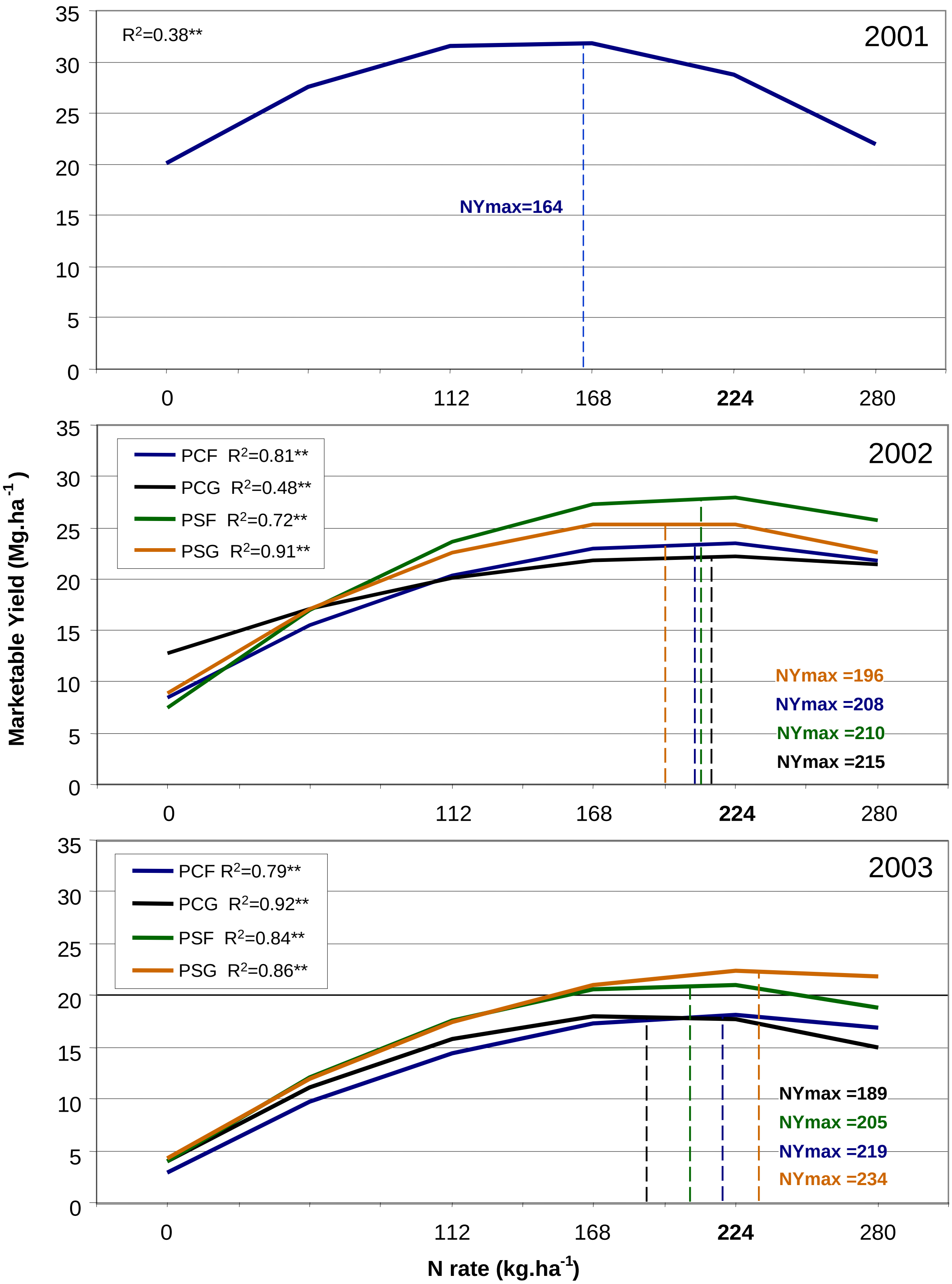


Figure 2-12. Predicted N rate for maximum marketable potato yield. NYmax= N rate for maximum yield. Coefficient of determination significance: * p <0.05 and **p<0.01.

increased quadratically with increasing N rate. In 2001, there was no interaction between crop rotation and N rate (Appendix B) and The predicted N rate required for potato to reach maximum marketable yield (NYmax) was 164 kg.ha^{-1} of N for all four crop rotations(Fig. 2-12). In 2002, the predicted NYmax for the four crop rotations was between the range of 196 to 215 kg.ha^{-1} of N (Fig. 2-12). In 2003, the NYmax ranged between 189 and 234 kg.ha^{-1} of N (Fig. 2-12). The annual increase in the spread of the range containing the predicted NYmax indicated the effect of crop rotations over-time. A decline in yield with N rates higher than NYmax was observed in the study period (Fig. 2-12). These results were similar to reports of 168 to 196 kg.ha^{-1} for maximum yield and decreased yields above 280 kg.ha^{-1} of N in the same site (Hochmuth and Cordasco, 2000). In 2002 and 2003, rotations including sorghum in summer produced higher marketable yield than rotations with cowpea (Fig 2-12) suggesting late mineralization of sorghum residues from the past season as a possible source of N during the initial stages of the potato crop. In 2002, PSG rotation had the lowest NYmax among the rotations studied (Fig. 2-12). This event could be explained by a decreased overall C:N ratio in the PSG rotation caused by the inclusion of green bean which resulted in increased mineralization of sorghum residues and finally more N could be available at potato planting in 2003 reducing in this way the dependence of soluble fertilizers to reach the NYmax. Furthermore, in the intercrop period between green bean harvest-2001 and potato N side-dressing 2002 rainfall was three times less than the same period between 2002 and 2003 (Table 2-2), favoring the persistence in the soil of the mineralized N from sorghum and green bean residues (Table 2-3). In the same period in 2003, under a three times increased rainfall, the PSG rotation exhibited the highest requirement of N for maximum yield (Fig. 2-12) suggesting increased N leaching-runoff (Fig 2-12).

Maximum marketable yield decreased over-time from 32 $Mg.ha^{-1}$ in 2001 to 22 $Mg.ha^{-1}$ in 2003 (Fig. 2-12). The NYmax reported here (Fig. 2-12) are close to the current recommended N rate of 224 $kg.ha^{-1}$ for maximum yield in the TCAA (Hochmuth

Table 2-6. Marketable and Total yield of potato under rotation by N rate.

Rotation	N rate	Marketable yield ($Mg{\cdot}ha^{-1}$)	Total yield ($Mg{\cdot}ha^{-1}$)
PCF	0	8.68 d	11.02 d
PCF	112	21.31 bc	25.48 ab
PCF	168	25.57 ab	29.73 a
PCF	224	23.45 abc	27.22 ab
PCF	280	22.63 abc	26.30 ab
PCG	0	13.92 d	16.52 c
PCG	112	23.25 abc	26.73 ab
PCG	168	24.34 abc	28.00 ab
PCG	224	24.49 abc	28.21 ab
PCG	280	20.06 c	23.26 b
PSF	0	8.46 e	11.06 d
PSF	112	25.88 ab	29.09 a
PSF	168	26.79 a	30.26 a
PSF	224	24.83 abc	28.31 ab
PSF	280	25.58 ab	28.79 a
PSG	0	12.93 d	15.24 cd
PSG	112	24.62 abc	28.08 ab
PSG	168	26.18 ab	29.83 a
PSG	224	26.71 a	30.52 a
PSG	280	23.25 abc	26.65 ab

Means followed by different letter are significantly different. Marketable yield ($p<0.0004$). Total yield ($p<0.0004$).

and Cordasco, 2000). The small difference in yield observed among the plots with only fertilization at planting (112 $kg.ha^{-1}$ N) and plots with additional side-dressed fertilization plots (Fig 2-12) support previous reports that most of the N used for potato under subsurface irrigation in Hastings comes from the fertilization at planting (Elkashif and Locascio, 1983). That report suggests upward movement of soluble salts as water evaporated during dry periods reducing the need of side-dress fertilization. In this study, the increased residual effect of the side-dressed fertilization on soil NO_3-N concentration close to potato harvest (Fig. 2-8b) produced increase in sorghum N uptake in summer (Fig. 2-10) supporting the suggestion that a sufficient side-dressed N fertilization would decrease the risk of NO_3-N leaching-runoff without negatively affect potato marketable yield. Higher yield with commercial N fertilization programs using only one side-dress application compared with experimental fertilization programs including fertilization at planting and side-dress fertilization have been reported (Hochmuth and Cordasco, 2000). This observation suggest the possibility of reach higher potato yields with only one side-dressed fertilization with optimum timing placement and N rate.

The inclusion of green bean in the crop rotations increased significantly marketable and total yield of unfertilized plots as compared to unfertilized plots planted with cowpea and sorghum in summer and left as fallow in fall. There was no effect of N rate on marketable and total yield of potato grown under the different crop rotations (Table 2-6). The observed increase in yield by inclusion of green bean in fall and the lack of response of yield to N rates confirmed the potential of incorporating legumes in fall as a possible measure to reduce the application rates of soluble fertilizers.

The export of N by total yield of potato tubers decreased significantly in unfertilized plots along the three-year period. There were however no differences in exported N from plots that received N rates during the three years (Table 2.7). Along with the decrease in exported N from unfertilized plots a general increase in the % TKN was observed throughout the period of study (Table 2-7). In a preliminary exploratory statistical analysis these two variables were negatively correlated (r^2=-0.28, $p<0.0001$) explaining why in spite of the reduction of yield over the three years the exported N in tuber remained statistically the same. Specific gravity (Table 2-7) of fertilized plots was not affected by N rate through the 3-year period.

Table 2-7. Tuber exported N, % TKN, and specific gravity of potato under year by N rate interaction.

Year	N rate	N exported ($kg \cdot ha^{-1}$)	% TKN	Specific gravity
1	0	40.39 e	0.99 h	1.071 bc
1	100	79.65 cd	1.15 gh	1.078 ab
1	150	89.20 abc	1.23 fg	1.078 ab
1	200	82.15 bcd	1.22 fg	1.079 ab
1	250	85.71 bcd	1.42 ef	1.079 ab
2	0	27.27 e	1.20 fg	1.065 c
2	100	90.07 abc	1.63 de	1.074 abc
2	150	95.51 abc	1.71 de	1.075 abc
2	200	104.68 a	1.84 bcd	1.075 ab
2	250	99.08 ab	1.82 bcd	1.075 ab
3	0	16.93 f	1.75 cd	1.077 ab
3	100	69.01 d	1.79 cd	1.077 ab
3	150	90.85 abc	1.96 bc	1.078 ab
3	200	94.84 abc	2.05 ab	1.079 ab
3	250	99.62 a	2.25 a	1.080 a

Means followed by different letter are significantly different. N exported ($p<0.0001$), %TKN ($p<0.0003$), Specific gravity ($p<0.0001$).

Conclusions

Fertilization at potato planting generated increase in NO_3-N concentration in the water table under potato beds. A similar pattern of the NO_3-N concentration under N fertilized treatments was caused by the even N rate applied at potato planting.

The amount of rainfall between potato planting and N side-dress determined the increase in NO_3-N concentration in the water table. Rainy periods between potato planting and N side-dressing caused increased NO_3-N concentration in the water table under fertilized potato beds.

Nitrate and nitrification of ammonium from ammonium nitrate side-dress fertilization could generate a potential second flux of NO_3-N leaching/runoff by effect of the rainfall peak in summer.

Summer cover crops with high demand of N could act as N catch crops diminishing the possibility of NO_3^- leaching in summer. On the contrary, legume crops due to their low dependence on soil N could not be efficient N catch crops especially when more than 168 $kg.ha^{-1}$ of N are applied to potato.

Bush green bean as fall crop increased soil NO_3-N at potato planting but the amount of rainfall between its harvest and potato planting in spring determined how much NO_3-N persisted in the soil.

In 2001 and 2003, potato N uptake increased linearly even after potato reached its maximum marketable yield. Potato yield under the four rotations responded quadratically to N rate with maximum marketable yield under the recommended N rate for the region. Rotations including sorghum in summer produced higher marketable yield than rotations including cowpea.

CHAPTER 3
POTATO ROOT DISTRIBUTION STUDY

Introduction

The potato root system began to be studied many years ago. Pictorial descriptions of the potato root system (Weaver, 1926) and the effect of fertilizer placement and soil compaction (De Roo and Waggoner, 1961) have been reported. Research reports on the relationship between the potato plant root characteristic water use and uptake of nutrients are scarce. Total root length of potato in the field has been used to calculate inflow rates of N, P, K and water into the plant. These studies demonstrate that roots below 30 cm were more active in uptake of nitrate and water than those nearer the soil surface (Asfary *et al*. 1982). In another study, two potato cultivars differing in their N acquisition rate from the soil demonstrated the importance of root length and surface area to estimate N uptake over root dry weight. This study suggested that the larger root system of one variety enabled it to absorb more nitrate when it was limited, which allowed it to produce its optimum yield at lower soil N availability compared with a second variety (Sattelmacher *et al*. 1990). However; these approaches may underestimate the influx rate because not all the root length and root surface area have equal nutrient uptake capacity. The region immediately behind the meristem has greater uptake activity than older segments, but these segments maintain some uptake capacity (Gao *et al*. 1998; Robinson *et al*. 1991). The improvements in technology have now enabled roots to be analyzed in detail. Root characterization studies have great potential to elucidate the role of root structure in N management.

Enhanced N use and uptake are likely results of proposed strategies to minimize nitrate leaching, including diminished fertilizer rates. In the short term, this could be accomplished by timely and precise placement of the fertilizer in soil regions where it could be quickly and efficiently absorbed by the roots. In the long term, the development of potato cultivars with high uptake and use efficiencies by plant breeding would be part of the solution to nitrate leaching from potato fields (Errebhi *et al*. 1998). In both cases a detailed knowledge of the root system is required. The precise placement of fertilizer in time and space is especially important for nutrients such as nitrate that have high mobility in the soil. Root distribution studies are important to enhance the understanding of nutrient and water uptake in order to improve irrigation and nutrient management programs (Asfary *et al*. 1983).

Nitrate leaching from potato crops has been considered one of the possible causes of water eutrophication in the St. John's River watershed, therefore improved knowledge about the potato root system under northeast Florida conditions is needed to enhance N uptake. In order to begin the collection of information about the potato root system, a study of potato root distribution was initiated. The information obtained about root distribution could be used to develop fertilization regimes based on controlled release fertilizers in order to synchronize N release with plant demand. Knowledge of the root system distribution could be used as well to model the N cycle in the potato production system.

Based in the above considerations the following objectives were stated: i) to design and test a new methodology to obtain a representative sample from the potato root system in order to study vertical and horizontal root distribution. ii) to study the effect of sufficient fertilization rates on the root distribution of the Atlantic potato variety used extensively by the farmers in the TCAA located in the St. John's River watershed. iii) generate information that could be used as part of strategies to enhance fertilizer placement in order to maximize N uptake and minimize leaching and/or runoff of nitrate from the potato beds.

Materials and Methods

Site Description

This study was conducted at the Hastings Research and Education Center's Yelvington Farm in Hastings, Florida. Soil and other details about the experimental site were described in chapter 2 of this dissertation.

Statistical Design

The plots containing the potato-sorghum-fallow rotation under the three highest N rates (168, 224, and 280 $kg \cdot ha^{-1}$ in the crop rotation experiment (Fig 2-1) were used to study potato root distribution at full flowering (60 DAP) in the third year. At this time, Atlantic reaches its maximum vegetative growth and rooting depth (Stalham and Allen, 2001). The plots used in this study were set as a randomized complete block design with three replications and the treatments were arranged under a split-split plot design where nitrogen rate was the main-plot (Fig. 2-1), slice was the split-plot, and position into the slice was the split-split plot (Fig. 3-2).

Root Sampling Methodology

A device to sample a representative portion of the potato root system was designed based on a sampler used by Vos and Groenwold (1986). The device, a "slicer", was composed of two sharp-edged metal sheets of 101.6 cm long (distance between rows) x 50.8 cm height (Fig 3-1a). Three wooden blocks keep the sheets in place with an even separation of 10.2 cm (half the distance between plants) and three “C” clamps firmly held the pieces together (Fig 3-1a).

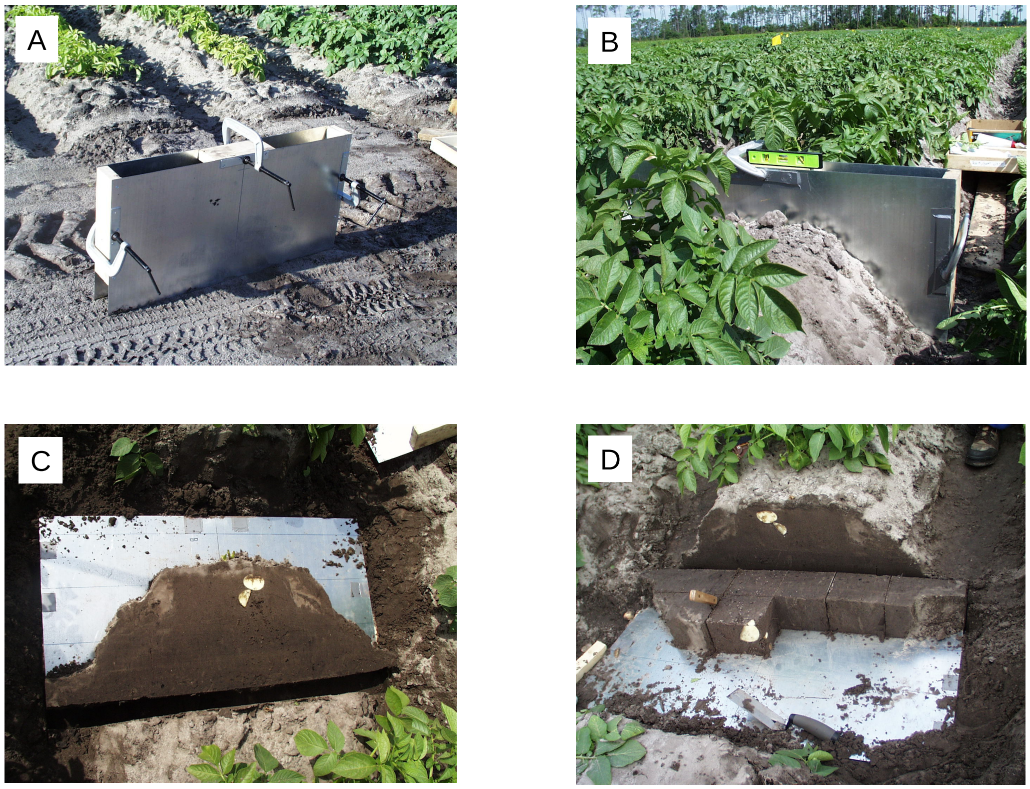


Figure 3-1. Procedure to take the root samples. (a) Root sampler; (b) leveled and buried into the ridge; (c) slice of ridge; (d) splitting sub-samples.

The “slicer” was driven into the soil (Fig 3-1b), keeping it horizontal (Fig. 3-1c). Subsequently, part of the ridge was removed and the slicer containing the slice of soil was flipped on the ground and the upper sheet removed to access the ridge slice (Fig. 3-1d) Afterward, each slice was split in 14 sub-samples (environments) arranged in three layers (top, middle, and bottom). Each environment was coded by the first letter of the layer where it came from followed by a number to identify the position in the layer (Fig. 3-2). Soil samples containing roots where weighed individually. Two slices, one including a plant and another one between plants, were taken in each plot in order to get a representative sample of the potato root system under each N rate.

Root Washing

The roots were separated from the soil by washing them on a screen while removing organic matter debris. The soil samples containing roots were stored in a cooler at 7 °C during the washing process. In the laboratory, roots were spread on white trays to enhance contrast and sorted from thin residues of organic matter. Afterward, roots were refrigerated in plastic bags containing a solution of sodium azide (0.01%) as preservative.

Root Scanning and Image Analysis

In order to enhance the image contrast and prior to scanning, roots were stained by immersion in a solution of methylene blue (1 g L^{-1}) for at least 24 hr. Roots were spread on translucent Plexiglas trays containing water and scanned on a HP Scanner at resolution of 300 dpi. Images acquired by this method were loaded and saved in Adobe PhotoDeluxe in format PDD. Root images stored as PDD were converted to grayscale BMP format as is required by GSRoot (Guddanti and Chambers, 1993) specialized software for root analysis. GSRoot was set up to classify roots by diameters, and estimate root length and surface area.

Root Variables

After the scanning process, the root samples were oven dried at 105 °C and weighed to estimate root dry weight (RDW) on an analytical scale Sartorius Model 1712 MP8 with readability of 0.00001 g. GSRoot was set up to measure seven diameter classes (<0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0, 1.0-1.2, >1.2 mm) to get root length and root surface area for the individual root diameter classes. Total root length (TRL) in cm and total root surface area in cm^2 (TRSA) were calculated and reported as the total sum of length and surface area of the individual root diameter classes and expressed as meters of root per square meter of soil (m root · m^{-2} soil) and square centimeters of root surface per square meter of soil (cm^2 root surface m^{-2} soil) respectively. Using the calculated soil volume (SVOL) for each sample (see next section) root length density (RLD) expressed as cm root · cm^{-3} soil and root surface area density (RSAD) expressed as mm^2 root surface·cm^{-3} soil were calculated. RLD and RSAD intended to describe the exploratory capacity of the root system in terms of length and root surface by unit of soil volume, respectively. High values of RLD and RSAD mean high capacity of the root system to explore the soil. Specific root length (SRL) expressed as cm root · mg^{-1} root dry matter and specific root surface area (SRSA) expressed as cm^2 root surface · mg^{-1} root dry matter were calculated in order to estimate the resources invested by the plant in terms of length and root surface area by unit of root dry matter. Therefore, high values of SRL and SRSA indicate high efficiency of the root system in the assignment of resources. Total and marketable tuber yield of the plots where the root study was done were measured and analyzed in conjunction with all of the plots in the crop rotation experiment (chapter 2).

Soil Strength, Bulk Density, and NO_3-N concentration by Depth

Two days before root sampling, a study of the soil strength in the plots was done. A Delmi penetrometer with a 30° cone-shaped tip was pushed into the soil 60 cm deep from the top of the ridge in each sampled plot. The measure was taken in the same ridge where the root sampling was performed. The penetrometer provided a continuous plot (on a standard 7.6 by 12.7 cm card) of soil strength in megapascals (MPa). Using the method of undisturbed soil cores, soil samples were collected and used to estimate soil bulk density and soil moisture content in each one of the three layers. The soil volume (SVOL) of each one of the 14 sub-samples was calculated using their estimated soil dry weight and the estimated soil bulk density of the layer from which each one of the 14 sub-samples came from. The calculated values were plugged into the following relationship:

$$V = W \cdot D$$

where:

V= Soil volume of each sub-sample, W= Soil Dry Weight of each sub-sample, and D= Bulk density of the layer (top, middle, or bottom) and applied to the data from each sub-sample. Along with the sampling to estimate bulk density, soil samples were taken to estimate NO_3-N concentration in the three layers of each slice.

Statistical Analysis

Root sampler

The soil wet-weight (SWW) of each sub-sample recorded at sampling time, the soil dry weight (SDW) estimated from the bulk density sampling, and the estimated sub-sample soil volume (SVOL) were used as response variables to evaluate the performance of the designed root sampling device. Replication (bed) and slice were considered random effects and their contribution to the total variance of the dependent variables was estimated using the VARCOMP procedure of SAS (SAS Institute, 2004).

Soil strength, bulk density, and NO_3-N concentrations by depth.

Soil strength values obtained with the penetrometer and NO_3-N concentration by depth were analyzed under a Split Plot Design using the GLM procedure of SAS (SAS Institute, 2004). Nitrogen level was the main plot factor and depth from 0 to 36 cm in increments of 12 cm from the top to bottom of the ridge was the subplot. Bulk density was analyzed as a RCB design for the same depths sampled with the penetrometer. The LSMEANS option with Tukey adjustment was used to separate soil strength and NO_3-N concentration by depth. A regular Tukey test was used to separate bulk density means.

Roots

As exploratory analysis, scatter plots of the studied variables to search possible association were plotted using the GOPTION procedure of SAS/GRAPH (SAS Institute, 2004). Four different models using the MIXED procedure and considering common pooled variance, heterogeneous variances for bed (replication) by N treatment, spatial correlations within slice for each slice, and spatial correlations within and between slices were evaluated. Furthermore, the same four models were re-evaluated using root dry weight (RDW) and soil volume (SVOL) as covariates. After the evaluation process, RLD and RSAD were analyzed using the model considering spatial correlations within and between slices, SRL was analyzed using the model considering heterogeneous variances, and SRA was analyzed with the model considering spatial correlations within and between slices. The LSMEANS option was used to perform means separation. Means of SRL and SRA were separated with the Bonferroni adjustment and SRL and SRA by the Fisher test with alpha=0.001.

Results and Discussion

Root Sampler Device

The variance attributable to the sampling technique (slice) was relatively low compared with the variance of environments. This result could be caused by the irregular shape of the sub-samples coming from the external part of the ridge (Fig. 3-2). Soil volume was used to evaluate the root sampler performance. This effect was evaluated using the soil volume of each one of the subsamples taken in each slice. Average soil volume (cm^3) and horizontal and vertical dimensions for each environment are included in Figure 3-2. Soil volume for each environment is the overall mean estimated through out all the soil slices sampled.

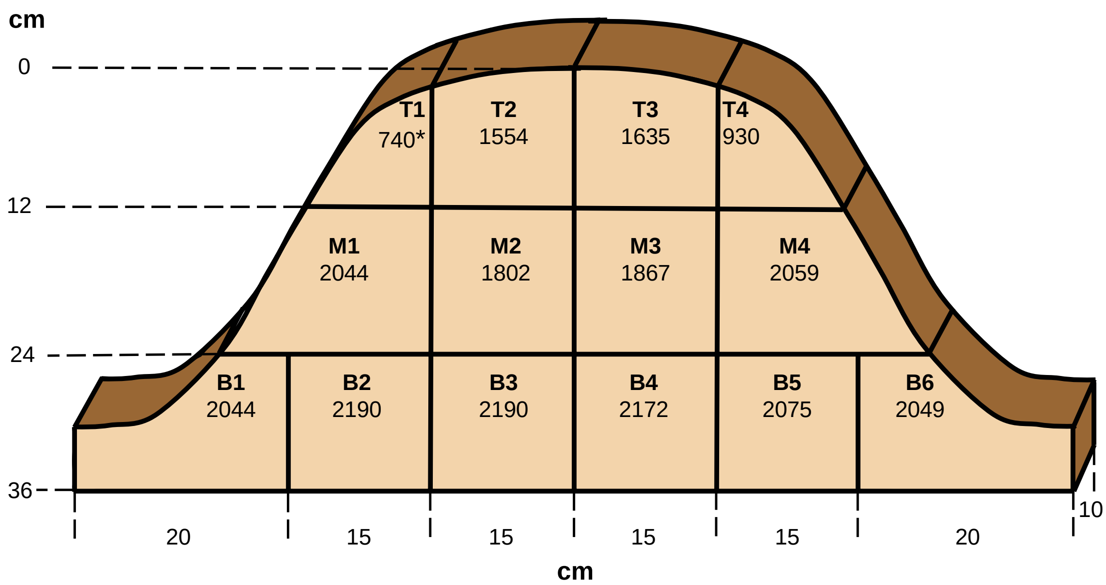


Figure 3-2. Distribution and sample size into the slice. Soil volume (cm^3), dimensions (cm), T1 to B6 = Environment code for identification.

Soil Strength and Bulk density

Soil strength differences among blocks (beds) were observed. Nitrogen treatment had no effect on soil strength. Highly significant differences were observed among all of the three layers studied (Table 3-1). The increase of soil resistance from the top to the bottom layer coincided with a significant increase in the observed bulk density of the bottom layer compared with the top and middle layers (Table 3-1). In some root samples coming from the 12 to 24 and 24 to 36 cm layers a pronounced thickness of the

Table 3-1. Soil strength, Bulk density, and Soil NO_3-N by depth.

Soil depth (cm)	Soil strength (MPa)	Bulk density ($g \cdot cm^{-3}$)	Soil NO_3-N ($mg \cdot kg^{-1}$)
0-12	0.024 a	1.28 a	10.22 a
12-24	0.105 b	1.45 b	14.15 a
24-36	0.203 c	1.50 b	2.71 b

Soil strength ($p<0.0001$); Bulk density ($p<0.0001$); Soil NO_3-N ($p<0.0082$).

roots were observed (Fig. 3-3). A similar pattern of thickness was reported for tomato roots impeded by a column of glass beads (Waisel, 2002). Inhibition of the elongation of the main axis and enhanced formation of lateral roots in young barley plants grown in fields with high bulk density also have been reported (Scott-Russell *et al.* 1974). Also, accumulation of ethylene in roots under mechanical stress and anaerobic conditions have been reported as the possible cause of aerenchyma formation in the root cortex of waterlogged maize roots (Drew *et al.* 1979). In the case of the potato roots, a combination of these two conditions could have been responsible for the increase in diameter of roots in the middle and bottom layer (Fig 3-3). Soil NO_3-N concentration from 24 to 36 cm was lower than the concentration observed at the 0 to 12 and 12 to 24 cm depths. There was no difference between the two top layers (Table 3-3). The low concentration of NO_3-N in the deepest layer could be explained by increased denitrification due to the anaerobic conditions in the bottom layer and/or upward capillary flux of water causing concentration of nitrate in the two top layers as have been reported in a study with lysimeters (Patel, 2001).

Rooting Depth, Root Length, and Root Surface Area

The deepest roots were observed in the bottom layer (24-36 cm) and never exceed 36 cm. This is a shallow rooting depth compared to the maximum rooting depth of 60 cm reported for Atlantic on a deep sandy clay loam soil under overhead irrigation in the UK (Stalham and Allen, 2001). At that time 16 varieties of varying determinacy were tested and some of them reached rooting depths close to 1 meter. Atlantic was one of the varieties with a shallower root system. Even though that observation was under different conditions, it could be taken as evidence that Atlantic has a restricted root system growth in Hastings.

The observed total root length (TRL) for Atlantic in Hastings was 0.763 km roo t · m^2 soil (Table 3-2). Although in the literature there are no data on TRL of Atlantic it is a very low value as compared with reported values as high as 24 km root · m^2 for the cultivar Norin 1 (Iwama *et al.* 1999), 11.4 km root · m^2 for Russet Burbank (Lescyznki and Tanner, 1976), and even still lower than 1.4 to 4.6 km root · m^2 for White Rose (Bishop and Grimes, 1978). The vertical distribution of Atlantic TRL (Table. 3-2) shows that 94% of the TRL was in the two upper layers (0 to 24 cm) but 63% of the TRL was concentrated in the middle layer (12 to 24 cm) and just 6% was in the bottom layer (24 to 36 cm). The region from 12 to 24 cm could be the place where most of the NO_3^- uptake is taking place under Hastings conditions. Seventy-six percent of the TRL was comprised by roots less than 0.4 mm in diameter suggesting this fraction was a important part of the Atlantic root system (Table 3-2).

Figure 3-3. Detail of potato roots thickening

The observed total root surface area (TRSA) for Atlantic was 838.41 cm^2 root · m^2 with 92 % of this area in the upper 24 cm of the ridge (Table 3-2) and 64.4 % in the middle layer (12 -24 cm). The fraction of roots with diameter less than 0.4 mm represented 76 % of the TRL but just 45 % of the TRSA. This observation shows one of the inconveniences when TRL is used to estimate the apparent inflow rates of nutrients. Therefore, approaches using TRL could underestimate the true values of nutrient uptake

(Robinson *et al.* 1991). Determination of the root diameter class active in nitrate uptake will be a key factor to adjust fertilizer placement in order to improve its uptake.

Table 3-2. Root length and root surface area by diameter class and soil depth.

	Depth (cm)	Diameter class (mm)							Total
		<0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	>1.2	
Root Length* m root · m^2 soil	0-12	93.38* 39.4%	94.33 39.8%	24.89 10.5%	13.51 5.7%	6.16 2.6%	2.61 1.1%	2.37 1.0%	237.01 31.0%
	12-24	142.93 29.7%	219.92 45.7%	69.30 14.4%	25.51 5.3%	12.03 2.5%	5.77 1.2%	5.29 1.0%	481.23 63.0%
	24-36	10.48 22.9%	20.77 45.4%	8.05 17.6%	3.52 7.7%	1.56 3.4%	0.69 1.5%	0.69 1.5%	45.75 6.0%
	Total	246.65 32.3%	335.24 43.9%	102.14 13.4%	42.77 5.6%	20.04 2.6%	8.93 1.2%	8.23 1.1%	763.99 100%

	Depth (cm)	Diameter class (mm)							Total
		<0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	>1.2	
Root Surface Area* cm^2 root · m^2 soil	0-12	25.82* 8.7 %	64.32 27.4%	50.0 21.3%	42.72 18.2%	24.41 10.4%	11.74 5.0%	15.73 6.7%	234.73 28.0%
	12-24	43.74 8.1%	189.00 35.0%	130.14 24.1%	77.22 14.3%	45.36 8.4%	25.38 4.7%	29.70 5.5%	540.00 64.4%
	24-36	3.88 6.1%	21.65 34.0%	16.62 26.1%	10.00 15.7%	5.54 8.7%	2.67 4.2%	3.44 5.4%	63.68 7.6%
	Total	73.14 8.7 %	274.99 32.8%	196.62 23.5%	130.03 15.5%	75.37 9.0%	39.41 4.7%	48.86 1.0%	838.41 100.0%

Root Length Density

No significant differences in RLD were observed under the three N rates applied to potato. Significant differences in RLD among environments ($p<0.0001$) and between slices ($p<0.05$) were observed (Fig. 3-4). The slice containing the plant had higher RLD than the slice between plants (Fig. 3-4). RLD values in the environments M2 and M3 were higher than all of the values observed in other environments except from the values of T2 and T3 where the difference was not significant. M2 and M3 were the environments where the seed piece was located making them the center of origin of the potato root system (Fig. 3-4). There were no differences among the environments covering M2 and M3. The environments in the bottom layer (B1 to B6) had significantly lower values than the environments in the middle layer (M1 to M4), suggesting that soil exploration by the potato root system is evidently reduced at more that 24 cm depth (Fig. 3-4).

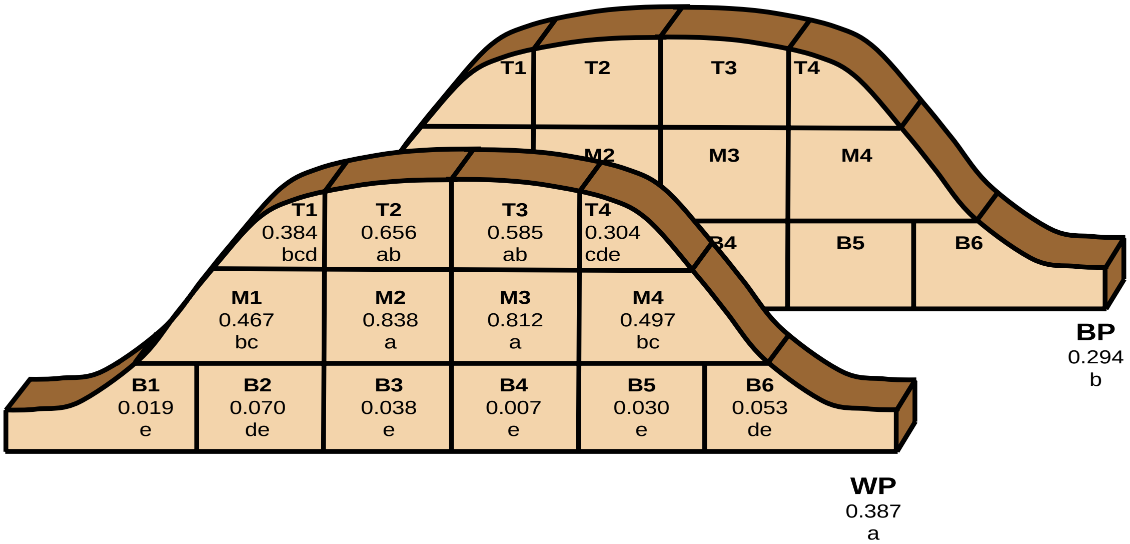


Figure 3-4. Root length density distribution (cm root · cm $^{-3}$ soil). P= Slice containing the plant; B= Slice between plants. T1 to B6 = Environment identification. Means with same lowercase letter are not statistically different. Environments (p<0.0001); Slices (<0.025).

Root Surface Area Density

No significant differences on RSAD under N rates were observed. This variable was highly correlated with RLD (0.95, p<0.0001). Differently from RLD, a significant interaction environment by slice was observed (Fig. 3-5). RSAD had higher values for environments M2 and M3 in the slice containing the plant but the difference was not significant with T2. The difference between M3 and T3 was significant. The differences in RSAD in T2 and T3 as compared with M2 and M3 could be the result of the position of the seed piece in the two central M environments and the position of the stem in the two central T environments. A lot of adventitious roots were originated from the stem when part of it was soil covered at the time of hilling and N side-dressing. That means that in terms of root surface the potato plant could have its maximum uptake capacity in

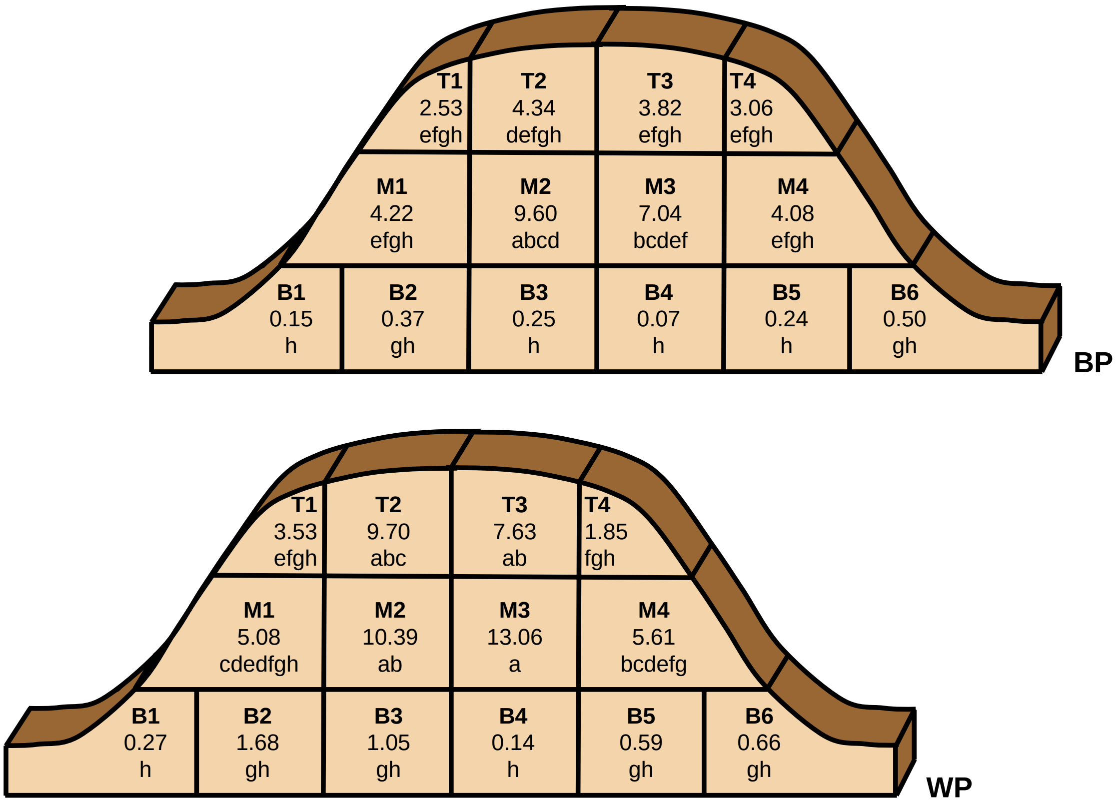


Figure 3-5. Root surface area density distribution (mm^2 root · cm^{-3} soil). WP= Slice containing the plant; BP= Slice between plants. T1 to B6 = Environment identification. Means with same lowercase letter are not statistically different ($p<0.0059$). Possible comparisons between slices.

the central two M environments. Along with the greater RSAD in the two central M environments, higher soil moisture and higher NO_3^- concentration were observed in the middle layer than in the top layer (Fig. 3-5). In chapter 2 was shown that the residual effect of the side-dressed fertilizer applied 40 DAP remained in the soil even after potato harvest. The dryness of the top layer could be limiting NO_3^- uptake by the potato roots. Even though the difference among environments in different slice was not significant except when the environments were compared with M2 and M3 in both slices it is possible suggest that roots in the region between plants could have less capacity to scavenge NO_3^- from the soil. In the slice between plants all of the environments around M2 and M3 were not different among them, even though high differences among the RDA values for environments in the bottom layer compared with the two environments at both sides of the middle layer and all of the environments in the top layer were observed but not statistically detected by the model (Fig. 3-5).

Specific Root Length

There were no significant differences by slice and N treatment in SRL. Highly significant differences were detected among environments. No significant differences were observed for the interactions among factors. The highest values for SRL were observed in the environments T1 and T4 without significant difference between them (Fig. 3-6). The high values of SRL in the environments T1 and T4 are indication of very fine roots in this part of the ridge. The stem coverage with loose soil at N side-dress and hilling time (40 DAP) could be the explanation for the development of a system of fine adventitious roots in these environments (Fig. 3-6). On the contrary, the low SRL values observed in B3 and B4 (Fig. 3- 6) could be the result of the increase in diameter caused by the combination of the high bulk density in B3 and B4 environments and by the water rising by capillary effect from the water table. Saturated soil conditions could increase root diameter by stimulation of aerenchyma formation (Drew *et al.* 1979), and saturated conditions could be motivated by a high capillary flux from the water table as reported in presence of a plow pan (van Loon and Bouma, 1978). The higher SRL values observed in the environments beside B3 and B4 suggest that the compacted zone could be localized just in the two central environments of the bottom layer. In terms of SRL the environments T2 and T4 are the places where the potato plant has its most fine fraction of roots and probably where high nutrient uptake could take place but it also could be limited by the fluctuant soil moisture on the top of the ridge. If RLD values (Fig. 3-4) for T1 and T4 are compared with the values for M2 and M3 (Fig. 3-4) it is possible to notice that the two environments on the top of the ridge have significantly lower values than M2 and M3 in the middle of the ridge. It is explained by the high concentration of roots in the central environments (M2 and M3) where the seed piece was placed. On the other hand,

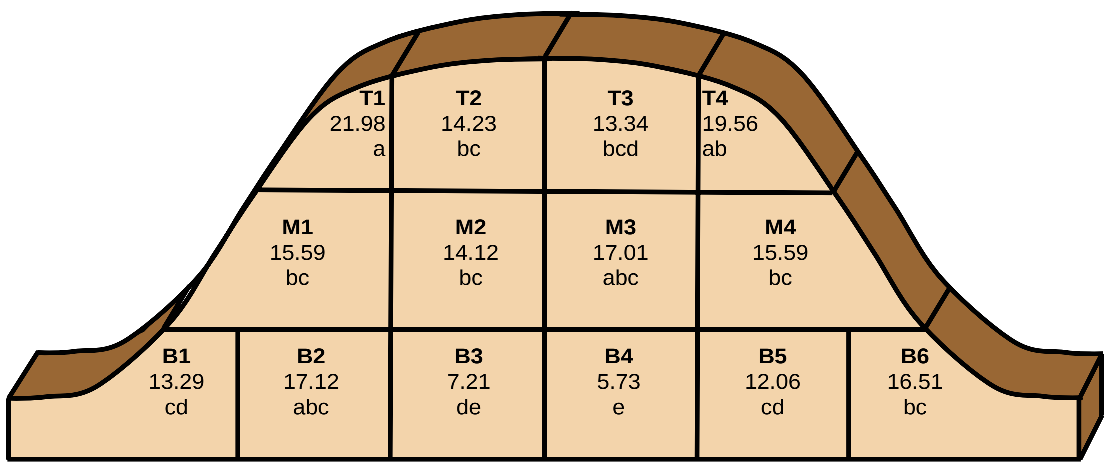


Figure 3-6. Specific root length distribution (cm root · mg^{-1}root dry weight). T1 to B6 = Environment identification. Means with same lowercase letter are not statistically different. ($p<0.0001$).

the significant lower SRL values observed in M2 and M3 compared with T1 and T4 are indication of the presence of roots with high diameter close to the root piece. Generally, finest roots are more efficient in nutrient uptake than coarse roots, therefore would be possible suggest that roots in T1 and T4 could be more active in NO_3^- uptake when soil moisture is not limiting it.

Specific Root Surface Area

SRSA was analyzed using RDW as a covariate ($p <0.0004$). The interaction environment by slice was significant. The scarce difference observed among SRSA suggests that the potato root system has a very homogeneous configuration in terms of.the amount of biomass allocated by unit of root surface area (Fig. 3-7). Significant low SRSA values were observed in B3 and B4 environments located in the slice between plants, however, these values were not statistically different from many higher values in the same slice and in the slice including the potato plant (Fig. 3-7). The lack of sensitivity of the model to detect high differences among SRSA could be attributed to the high

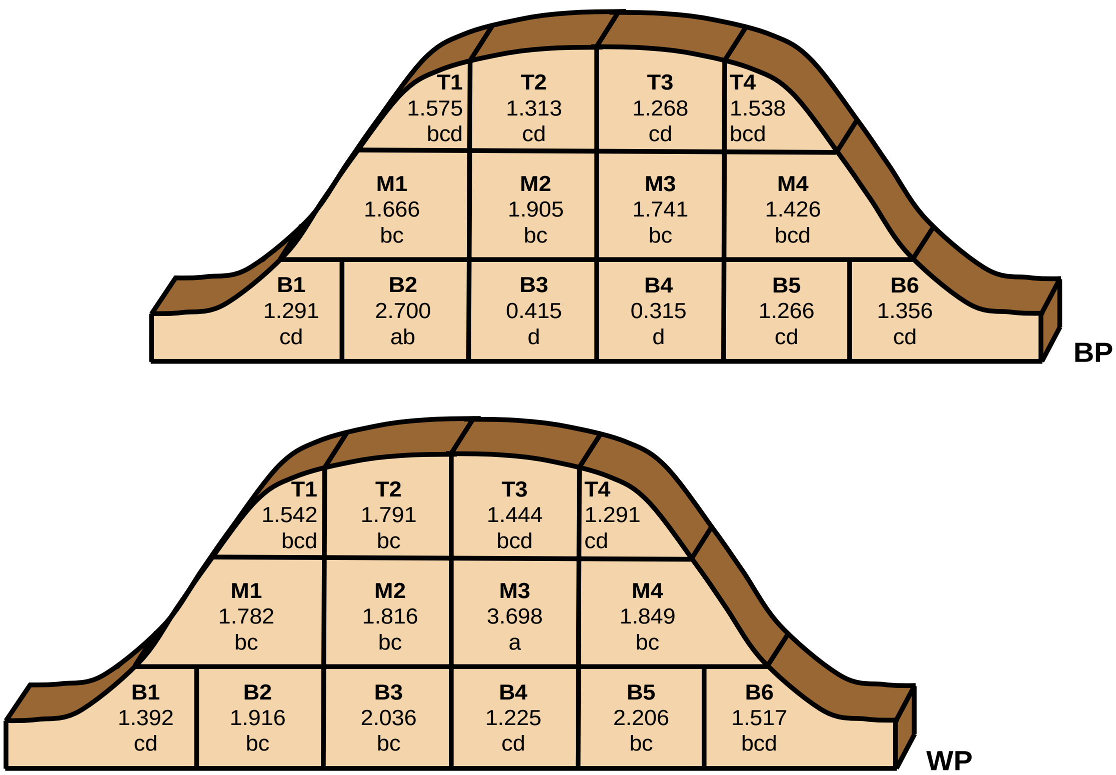


Figure 3-7. Specific root surface area distribution (cm^2 root · mg^{-1} root dry weight). WP= Slice containing the plant; BP= Slice between plants. T1 to B6 = Environment identification. Means with same lowercase letter are not statistically different (p<0.0395). Comparisons possible between slices.

variability produced by the relatively low resolution (300 dpi) used to capture the root images; therefore, low resolution maybe affected more area than length estimation. Based on the results of SRL where the lowest values were observed in the same environments (B3 and B4), it would be possible suggest that the low values of SRSA observed in the corresponding environments in the slice between plants could be really different from higher values in both of the slices. If this idea is correct the theory of increased thickness due to soil impedance and/or flooded conditions could be supported by these results.

Conclusions

This study was developed to propose a new methodology to study the potato root system under Hastings conditions and to describe spatially the potato root distribution as affected by N rates currently used in commercial potato production.

The proposed sampling methodology performed satisfactorily and is suitable for future root studies in the TCAA or agricultural areas with similar conditions. The ridge slicing methodology allowed to recover most of the roots from a representative sample of the potato root system and spatially classify sub-samples around the potato plant.

The potato root distribution was not affected by N rate. RLD, SRL, RSAD, and SRSA were affected by their spatial position in the soil profile. Soil exploration capacity (RLD and RSAD) was maximized into 15 cm around the potato plant at a depth of 24 cm from the top of the ridge. Significant lower soil exploration capacity was detected under 24 cm from the top of the ridge. The invested biomass by unit of root length or unit of surface area (SRL and SRSA) were relatively homogeneous except in the environments under the potato plant (B3 and B4) where low values were probably caused by root thickening caused by a combination of increased soil strength and saturated conditions. High bulk density and water saturation at the bottom layer of the ridge could be a limiting factor for potato root development.

Observed differences in root parameters could be used as base to plan fertilizer placement strategies in order to enhance nutrient uptake. To optimize fertilizer placement a detailed study of the water movement in the root zone should be done.

CHAPTER 4
SUMMARY, OVERALL CONCLUSIONS AND FUTURE RESEARCH

Some years ago nutrient loses from agricultural production systems were considered as a purely agronomic problem limited productivity and negatively affected the economic profitability of agricultural producers. Currently in Florida, the negative effect of nutrient enriched water bodies is turning on a great concern in endangered zones where nutrient mobility is expedited by the low capacity of the soil to retain them in exchangeable form and for the sandy nature of the soils. This is the case of most of the Florida soils where the low content of mineral colloids results in a pH dependent exchange capacity. The TCAA in northeast Florida is a region where potatoes and cabbage are the dominant crops. Due to the relatively high N demand by potato, farmers apply more N fertilizer than is needed for optimum production generating nitrate non-source pollution from the potato fields. The over-fertilization problem could be enhanced by the current irrigation system used for agricultural production. It consist in a perched water table that is controlled by pumping water from deep wells into irrigation-drainage furrows running parallels to the raised potato beds. The concern by the potential environmental impact of agricultural practices have generated a growing interest to develop Best Management Practices (BMPs) that allow sustainable crop productivity without negatively affecting the environment. Inclusion of legumes as green manure or as a second cash crop in rotation with potatoes has been considered a viable way to supply part of the relatively high N requirement of soluble fertilizers applied to potatoes.

Synchronizing N availability in the soil and plant uptake is another proposed approach that require good knowledge of the root system in order to enhance fertilizer uptake by an optimum placement in the region of the root zone where uptake will be maximized.

Based on the previous considerations this dissertation included in the Chapter 2 the sequential study of NO_3-N concentration in the water table, soil solution, soil, and plant tissue as affected by four different crop rotations and five N rates over a three-year period. Chapter 3 reports the study of the potato root system in order to describe quantitatively and spatially its distribution in the soil in terms of root length and root surface area under three rates of nitrogen. Each one of these chapters had specific objectives and their results are summarized below.

Summary

Crop Rotation and N rates

Concentrations of NO_3-N in the water table under potato

In the first year NO_3-N concentration in the water table was increased up to 54.6 $mg \cdot L^{-1}$ under effect of fertilization at planting. Predicted values for non-fertilized plots were in the range of 8.2 to 18.2 $mg \cdot L^{-1}$. Decreasing patterns of the regressions describing NO_3-N concentration in the water table were observed from potato planting to harvest.

In the second year predicted values for NO_3-N concentration were below 10 $mg \cdot L^{-1}$ and a light increase were predicted close to the harvest time. There was no noticeable difference among fertilized and unfertilized plots. The low rainfall after potato planting could be addressed as the cause of the low NO_3-N in the water table.

In the third year a similar pattern to the first year was observed with the difference that unfertilized plots exhibited lower NO_3-N concentration than the first year. Side-dressed nitrogen at 40 DAP did not affect the decreasing pattern of NO_3-N concentration in the water table in the first an d third years suggesting fertilization at potato planting as the main source of the increased NO_3-N concentration in the water table.

Concentrations of NO_3-N in the soil solution

It was possible to study this variable just in the second year due to insufficient information from the first year and problems with the installation of the lysimeters in the third year. Even though 2002 was a year with low rainfall after potato planting NO_3-N concentration values as high as 156.0 $mg \cdot L^{-1}$ were observed after fertilization. The unaffected decreasing pattern after side-dress fertilization suggests low effect of it on NO_3-N concentration in the water table.

Concentrations of NO_3-N in the water table under cowpea and sorghum

Concentration of NO_3-N in the water table under cowpea plots under effect of residual N from potato fertilized with 280 $kg.ha^{-1}$ was significantly higher than concentration under plots fertilized with 168 $kg.ha^{-1}$. There was no difference in NO_3-N concentration in the water table under cowpea planted in unfertilized plots and under cowpea planted in plots fertilized with 168 $kg.ha^{-1}$ of N. NO_3-N concentration in the water table under sorghum was significantly lower than under cowpea in plots fertilized with 280 $kg.ha^{-1}$ except in the second sampling when high variability was observed.

Concentrations of NO_3-N and NH_4-N in the soil

Soil NO_3-N concentration was increased after side-dressing N and exhibited a rising pattern across the N rates applied. The same pattern persisted in the soil for 3 months and was detected before potato harvest and at planting of sorghum and cowpea in summer. The concentration of NO_3-N at planting of the cover crops showed variation among years. This variation could be attributable to the amount of rainfall between potato harvest and sorghum and cowpea planting. Soil concentration of NH_4-N across the N rates was described by a quadratic pattern 3 weeks fertilizer side-dressing and there was no difference between unfertilized plots and plots with only fertilization at planting suggesting that nitrification occurred. In 2003 , coincident high concentration of NO_3-N and low concentration of NH_4-N 3 weeks before potato harvest suggest a late nitrification of the side-dressed fertilizer. Increased soil NO_3-N concentration in plots planted with green bean in fall as compared with plots left as fallow was noticed.

Nitrogen recovery by the summer cover crops

Residual N from the fertilizer applied to potato produced increased nitrogen recovery by the sorghum from the fertilized plots. Nitrogen accumulation in sorghum biomass was described by similar regressions describing soil NO_3-N concentration after N side-dress, at potato harvest, and at summer cover crops planting. Cowpea N accumulation was not affected by the N rate applied to potato. Cowpea N accumulation in biomass in fertilized plots was not different from nitrogen accumulation in unfertilized plots. This event supports the observation that the residual fertilizer from potato side-dressed fertilization could be generating a second flux of nitrate leaching from the plots planted with cowpea in summer. These results suggest sorghum as an effective N catch crop that should be planted as close as possible to the potato harvest. Low soil N uptake by cowpea could generate leaching-runoff when potato is fertilized with more than 168 $kg.ha^{-1}$ of N.

Potato N uptake at full flowering

Nitrogen rate affected significantly potato N uptake over the 3-year period. Nitrogen uptake was described by linear regressions in 2001 and 2003, and by a quadratic regression in 2002. The continuous increment in N uptake even after potato reach its maximum yield suggest luxury consumption of N when higher N rates than needed for maximum marketable yield were applied. In 2002, the overall potato N uptake showed closer to N rate needed for maximum yield.

Potato yield

Quadratic increase by effect of N rate was observed in each year. In 2001, there was a relatively similar response of the four rotations to N rate. This year was considered a transition year where the effect of crop rotation with legumes was not evident. In 2002 and 2003 rotations including sorghum as summer cover crop yielded more than rotations with cowpea. The difference in the N rate required for maximum yield by the four crop rotations was increased from 2002 to 2003. A period with heavy rainfall at the end of 2002 maybe propitiated leaching of the mineralized N from the cover crop residues generating different potato N requirement for maximum yield in 2003.

Exported N as total yield of tubers in fertilized plots remained statistically the same within year throughout the three-year period without statistically differences among N rates except in the third year when the treatment with just fertilization at planting (112 $kg \cdot ha^{-1}$ of N) exported significantly less N than plots with side-dressed fertilizer. These results suggest that fertilization at planting could be enough to supply the N needed to reach optimum yield under Hastings conditions.

A generalized increase of %TKN along with total yield decreasing during the three-year period was observed explaining the relatively unaffected exportation of N by the decrease in yield.

Potato Root Distribution Study

Root sampler

The root sampler device was an efficient method to sample the potato root system in the ridges used for potatoes production in Hastings.

Soil strength, bulk density, and NO3-N by depth

Significant increase in the soil strength from the top to the bottom layer of the ridge was observed. Bulk density followed the same trend but there were no differences between the middle (12-24 cm) and the bottom (24-36 cm) layers. Soil NO_3-N concentration by layer was significantly higher in the top and middle layers as compared with the bottom layer. This observation coincide with the observed persistence of the side-dressed fertilizer in the soil in the top of the ridge.

Rooting depth, root length, and root surface area

The deepest roots were observed between 24 and 36 cm. This is a very shallow rooting depth as compared with 60 cm reported for Atlantic in well drained soils. The total root length observed was 0.763 km root m2 soil This is also a low value as compared with the reported values for some potato varieties. Ninety four percent of the total root length was in the 2 top layers. The total root surface area was 838.41 $cm^2 \cdot m^2$ soil and 92% of the root surface area was in the 2 top layers. There were no reported values of potato root surface area to compare.

Root length density and specific root length

Root Length Density (RLD) was not affected by nitrogen rate. Differences wereobserved among different environments and between slices. Significant higher values of RLD were observed in the central environments of the middle and top layers. Very low RLD values were observed in the bottom layer. RLD in the slice was significantly lesser than RLD in the slice containing a plant. Specific Root Length (SRL) was not affected by N rate. There were no differences between slices. The highest values for SRL were observed in the external environments of the top layer maybe caused by the fine adventitious root system generated by the stem coverage with soil at side-dress fertilization. In order to predict placement of fertilizer to enhance nitrogen uptake values of RLD should be compared with SRL in order to select the environments with coincident highest values for these two variables.

Root surface area density and specific root surface area

RSAD and SRSA were not affected by, nitrogen rate and were highly correlated with RLD and SRL. Differently from RLD significant interaction environment by slice was observed. RSAD in the central environments in the two top layers of the slice containing the plant exhibited the highest RSAD values maybe because in those environments was located the seed piece and the stems generated from it. SRSA was relatively homogeneous among environments and between slices suggesting that potato has a homogeneous configuration in terms of the amount of biomass allocated by unit of root surface. Significant low SRSA values were observed in the central environments of the bottom layer in the slice between plants. This is the result of the thickening observed in some of the root samples recovered from those environments.

Overall Conclusions

Fertilization at potato planting generated increase in NO_3-N concentration the water table with a steady decreasing pattern through the time under the four rotations evaluated. The little difference among fertilized plots (2-3a to 2-5b) was maybe caused by the even N rate applied at planting to fertilized plots (Table 2-1). The influence of the rainfall on the magnitude of the increase in NO_3-N concentration in the water table was evident in 2002 when an atypical low rainfall period between potato planting and N side-dress (Table 2-2) caused lower NO_3-N concentration in the water table before N side-dressing (Fig. 2-4a and 2-4b) compared with the same period in 2001 and 2003. Fertilization at planting, when potato has not established its root system could increase the risk of nitrate leaching/runoff. Therefore, fertilization at crop emergence could be more effective to reduce the chance of N leaching/runoff by increasing the N uptake. Fertilizer placement should be considered also in order to enhance N uptake. Based in the description of the potato root distribution is possible suggest T2, T3, M2, and M3 as the optimal environments to locate fertilizers at planting or potato emergence. These environments comprise a zone of 15 cm around the potato plant with a depth of 24 cm from the top of the ridge. In these environments the potato seed piece was located; therefore, in this soil region nutrient uptake will take place first. The environments T2, T3, M2, and M3 comprise the root zone where coincided high RLD and high SRL showing that in these environments was concentrated the maximum exploratory capacity of the potato root system (Fig. 3-4) along with high density of fine roots (Fig. 3-6). A detailed study of the water movement in the potato root zone should be done in order to optimize nutrient placement into the root zone. Previous reports in the region (Elkashif and Locascio, 1983) and in lysimeters (Patel *et al*. 2001) have reported ascendant movement of nitrates due to water evaporation and plant uptake during dry periods. Therefore, low placement of the fertilizers on dry periods like after potato side dressing, or placement of controlled release fertilizers under the potato seed at planting, programmed to liberate nutrients when the dry period after N side-dressing begins could be an alternative to enhance plant uptake N uptake. Controlled release fertilizers could be placed closer to the potato seed with lesser risk of seed damage than conventional soluble fertilizers.

Optimized fertilizer placement at potato planting could help to minimize the need of side-dress N fertilization turning it in an optional practice when seasons with heavy rains occur. Minimal side-dressed fertilization would diminish the risk of a potential second flux of NO_3-N leaching-runoff originated in the residues of the side-dressed application of N by effect of the rainfall peak in summer (Fig. 2-7).

Summer cover crops with high demand of N planted as soon as possible after potato harvest should be planted in order to recover any residual N from the potato fertilization. In this study sorghum exhibited higher capacity to recover residual N than cowpea when the N rate applied to potato was higher than 168 $kg.ha^{-1}$. Potato in rotation with sorghum in summer yielded more than rotations with cowpea suggesting sorghum as a better crop to storage N to be used in the next potato season specially when heavy rains occur at the end of the year.

Bush green bean as fall crop increased soil N at potato planting but the amount of rainfall between harvest of the fall crop and potato planting in spring (Table 2-2) determined how much N persisted in the soil until potato planting (Table 2-3). The relatively large difference in the N rate required for maximum potato yield of the rotation PSG between 2002 and 2003 (Fig. 2-12) suggests that green bean could be decreasing the overall C/N ratio of the soil organic matter, therefore increased N mineralization and nitrification could enhance N availability for the next potato crop but also could increase the risk of nitrate leaching/runoff in years with heavy rains between green bean harvest and potato planting.

Finally it is possible to conclude that an improved N management of the potato production system in order to reach optimum marketable yield minimizing at the same time the risk of N leaching/runoff could be achieved by improved fertilization practices including optimized fertilizer timing, placement, and N sources. These practices should be complemented by rotation with cover crops that allow recover residual N from the potato season and transfer it in an efficient manner to the next potato crop.

Future Research

Based on the results of this dissertation is possible suggest some topics to be addressed by future research work.

- The water movement toward and from the water table as influenced by the rainfall and the sub-irrigation system should be studied in order to estimate its role on nitrate movement.

- Different non-leguminous nitrogen catch crops after potato harvest should be tested in order to ensure a maximum recovery of the possible residual nitrogen fertilizer.

- Depending on the catch crop and its C/N ratio different incorporation times in order to match available nitrogen from the mineralized residues with potato uptake should be tested.

- Based on the results of this dissertation the effect of reduced nitrogen rates or controlled nitrogen sources allocated in the sites of the root zone with high scavenging capacity should be studied.

- Determination of the fraction of potato root diameters implied in nitrogen uptake should be investigated.

APPENDIX A
REGRESSION PARAMETERS

NO_3-N concentration in the water table (Figs. 2-3a to 2-5b)

Year	Crop Rotation	N rate kg.ha^{-1}	Conc. mg.L^{-1}	Intercept	Linear term	Quadratic term	R^2
2001	PCF	0	Ln[NO_3-N]	= 1.750575	- 0.077125*dss		0.79**
2001	PCF	112	Ln[NO_3-N]	= 2.310352	- 0.111002*dss	+ 0.000350*dss^2	0.78**
2001	PCF	168	Ln[NO_3-N]	= 2.335808	- 0.120305*dss	+ 0.000710*dss^2	0.77**
2001	PCF	224	Ln[NO_3-N]	= 2.477959	- 0.118539*dss	+ 0.000821*dss^2	0.73**
2001	PCF	280	Ln[NO_3-N]	= 2.871943	- 0.176226*dss	+ 0.001600*dss^2	0.77**
2001	PCG	0	Ln[NO_3-N]	= 1.893703	- 0.102081*dss	+ 0.000360*dss^2	0.81**
2001	PCG	112	Ln[NO_3-N]	= 2.37892	- 0.105337*dss	+ 0.000485*dss^2	0.66**
2001	PCG	168	Ln[NO_3-N]	= 2.36447	- 0.104694*dss		0.80**
2001	PCG	224	Ln[NO_3-N]	= 2.79625	- 0.077589*dss		0.77**
2001	PCG	280	Ln[NO_3-N]	= 2.529325	- 0.058704*dss		0.67**
2001	PSF	0	Ln[NO_3-N]	= 2.546013	- 0.102689*dss		0.76**
2001	PSF	112	Ln[NO_3-N]	= 2.592968	- 0.025896*dss	- 0.000878*dss^2	0.74**
2001	PSF	168	Ln[NO_3-N]	= 2.801359	- 0.040917*dss	- 0.000700*dss^2	0.81**
2001	PSF	224	Ln[NO_3-N]	= 3.157429	- 0.087921*dss		0.72**
2001	PSF	280	Ln[NO_3-N]	= 3.140889	- 0.050690*dss		0.78**
2001	PSG	0	Ln[NO_3-N]	= 2.529126	- 0.122880*dss		0.64**
2001	PSG	112	Ln[NO_3-N]	= 3.077667	- 0.072097*dss		0.87**
2001	PSG	168	Ln[NO_3-N]	= 3.69064	- 0.108683*dss		0.79**
2001	PSG	224	Ln[NO_3-N]	= 3.08599	- 0.076067*dss		0.84**
2001	PSG	280	Ln[NO_3-N]	= 3.127979	- 0.033881*dss	- 0.000947*dss^2	0.81**
2002	PCF	0	Ln[NO_3-N]	= 0.125753	- 0.126270*dss	+ 0.002298*dss^2	0.57**
2002	PCF	112	Ln[NO_3-N]	= -0.74375	- 0.067456*dss		0.25^{ns}
2002	PCF	168	Ln[NO_3-N]	= -0.33049	- 0.098137*dss	+ 0.001950*dss^2	0.46**
2002	PCF	224	Ln[NO_3-N]	= -0.12305	- 0.079519*dss	+ 0.001408*dss^2	0.44**
2002	PCF	280	Ln[NO_3-N]	= -0.13962	- 0.094500*dss	+ 0.001928*dss^2	0.26^{ns}
2002	PCG	0	Ln[NO_3-N]	= 0.078867	- 0.067357*dss		0.37*
2002	PCG	112	Ln[NO_3-N]	= -0.14726	- 0.040648*dss	+ 0.001036*dss^2	0.24^{ns}
2002	PCG	168	Ln[NO_3-N]	= 0.060474	- 0.088368*dss	+ 0.001519*dss^2	0.50**
2002	PCG	224	Ln[NO_3-N]	= 0.16497	- 0.107891*dss	+ 0.002066*dss^2	0.30*
2002	PCG	280	Ln[NO_3-N]	= 1.123871	- 0.036187*dss	+ 0.000097*dss^2	0.26^{ns}
2002	PSF	0	Ln[NO_3-N]	= -1.04924	- 0.031680*dss	+ 0.000662*dss^2	0.05^{ns}
2002	PSF	112	Ln[NO_3-N]	= 0.146383	- 0.068382*dss		0.32*
2002	PSF	168	Ln[NO_3-N]	= 0.394715	- 0.080456*dss		0.34*
2002	PSF	224	Ln[NO_3-N]	= 0.456274	- 0.092204*dss	+ 0.001404*dss^2	0.46**
2002	PSF	280	Ln[NO_3-N]	= 0.13171	- 0.085000*dss		0.25^{ns}
2002	PSG	0	Ln[NO_3-N]	= -0.42654	- 0.046118*dss	+ 0.001040*dss^2	0.15^{ns}

NO_3-N concentration in the water table. Continued.										
Year	Crop Rotation	N rate $kg.ha^{-1}$	Conc. $mg.L^{-1}$		Intercept		Linear term		Quadratic term	R^2
2002	PSG	112	Ln[NO_3-N]	=	-0.12776	-	0.094905*dss	+	0.001872*dss^2	0.53*
2002	PSG	168	Ln[NO_3-N]	=	0.609595	-	0.112335*dss	+	0.001897*dss^2	0.33*
2002	PSG	224	Ln[NO_3-N]	=	-0.42545	-	0.055495*dss	+	0.001258*dss^2	0.10^{ns}
2002	PSG	280	Ln[NO_3-N]	=	0.243151	-	0.043875*dss	+	0.000418*dss^2	0.20^{ns}
2003	PCF	0	Ln[NO_3-N]	=	0.382195	-	0.067770*dss	+	0.000672*dss^2	0.22^{ns}
2003	PCF	168	Ln[NO_3-N]	=	2.866326	-	0.129757*dss	+	0.000995*dss^2	0.44**
2003	PCF	280	Ln[NO_3-N]	=	3.289673	-	0.113775*dss			0.60**
2003	PCG	0	Ln[NO_3-N]	=	2.928474	-	0.127533*dss	+	0.001098*dss^2	0.82**
2003	PCG	168	Ln[NO_3-N]	=	2.873487	-	0.131558*dss			0.54**
2003	PCG	280	Ln[NO_3-N]	=	4.226966	-	0.117990*dss			0.81**
2003	PSF	0	Ln[NO_3-N]	=	-0.11973	-	0.030667*dss	+	0.000130*dss^2	0.18^{ns}
2003	PSF	168	Ln[NO_3-N]	=	2.59872	-	0.093499*dss	+	0.000520*dss^2	0.47**
2003	PSF	280	Ln[NO_3-N]	=	2.771621	-	0.082717*dss	+	0.000289*dss^2	0.55**
2003	PSG	0	Ln[NO_3-N]	=	0.73014	-	0.055740*dss	+	0.000460*dss^2	0.37*
2003	PSG	168	Ln[NO_3-N]	=	4.118405	-	0.166594*dss	+	0.001241*dss^2	0.84**
2003	PSG	280	Ln[NO_3-N]	=	3.925743	-	0.124762*dss			0.83**

dss= Days since side-dress

^{ns} = No significant

* = Significant to 0.05

** = Significant to 0.01

NO_3-N concentration in the soil solution (Figs. 2-6a, b)

Year	Crop Rotation	N rate kg.ha^{-1}	Conc. mg.L^{-1}		Intercept		Linear term		Quadratic term	R^2
2002	PCF	0	Ln[NO_3-N]	=	1.4963	-	0.1526*dss	+	0.0019*dss^2	0.78**
2002	PCF	112	Ln[NO_3-N]	=	2.3555	-	0.2012*dss	+	0.0028*dss^2	0.72**
2002	PCF	168	Ln[NO_3-N]	=	2.8498	-	0.1464*dss	+	0.0018*dss^2	0.69**
2002	PCF	224	Ln[NO_3-N]	=	2.3856	-	0.1461*dss	+	0.0021*dss^2	0.47**
2002	PCF	280	Ln[NO_3-N]	=	2.5739	-	0.1652*dss	+	0.0023*dss^2	0.76**
2002	PCG	0	Ln[NO_3-N]	=	2.4596	-	0.1420*dss	+	0.0019*dss^2	0.82**
2002	PCG	112	Ln[NO_3-N]	=	3.3709	-	0.1716*dss	+	0.0023*dss^2	0.72**
2002	PCG	168	Ln[NO_3-N]	=	2.8677	-	0.1660*dss	+	0.0024*dss^2	0.64**
2002	PCG	224	Ln[NO_3-N]	=	2.6941	-	0.1917*dss	+	0.0032*dss^2	0.77**
2002	PCG	280	Ln[NO_3-N]	=	3.3876	-	0.1467*dss	+	0.0023*dss^2	0.59**
2002	PSF	0	Ln[NO_3-N]	=	1.4101	-	0.1532*dss	+	0.0024*dss^2	0.76**
2002	PSF	112	Ln[NO_3-N]	=	2.1226	-	0.1455*dss	+	0.0018*dss^2	0.89**
2002	PSF	168	Ln[NO_3-N]	=	2.6749	-	0.1821*dss	+	0.0025*dss^2	0.87**
2002	PSF	224	Ln[NO_3-N]	=	2.2218	-	0.1242dss	+	0.0015*dss^2	0.70**
2002	PSF	280	Ln[NO_3-N]	=	3.1244	-	0.1497*dss	+	0.0020* dss^2	0.81**
2002	PSG	0	Ln[NO_3-N]	=	2.0610	-	0.1320*dss	+	0.0017* dss^2	0.79**
2002	PSG	112	Ln[NO_3-N]	=	2.8405	-	0.1818*dss	+	0.0024* dss^2	0.63**
2002	PSG	168	Ln[NO_3-N]	=	3.4428	-	0.1793*dss	+	0.0026* dss^2	0.58**
2002	PSG	224	Ln[NO_3-N]	=	2.9767	-	0.1836*dss	+	0.0027* dss^2	0.55**
2002	PSG	280	Ln[NO_3-N]	=	2.9657	-	0.1306*dss	+	0.0019*dss^2	0.49**

dss= Days since side-dress
^{ns} = No significant
* = Significant to 0.05
** = Significant to 0.01

NO_3-N concentration in soil

Fig. 2-8a

Year	Conc. mg.kg		Intercept		Linear term		Quadratic term	R^2
2001	[NO_3-N]	=	10.8547	+	0.1953 Nrate			0.53**
2003	[NO_3-N]	=	3.2588	+	0.0049 Nrate	+	0.000042 Nrate^2	0.57**

Fig. 2-8b

Year	Conc. mg.kg		Intercept		Linear term		Quadratic term	R^2
2001	[NO_3-N]	=	1.7392	+	0.0077 Nrate	-	0.0077 Nrate^2	0.51**
2002	[NO_3-N]	=	2.0927	+	0.0263 Nrate	-	0.000023 Nrate^2	0.27**
2003	[NO_3-N]	=	5.2414	+	0.0691 Nrate			0.17**

NH_4-N concentration in soil

Fig. 2-9a

Year	Conc. mg.kg	Intercept	Linear term	Quadratic term	R^2
2001	$[NO_3\text{-}N]$ =	5.1498	- 0.0671 Nrate	+ 0.0006 $Nrate^2$	0.64**
2003	$[NO_3\text{-}N]$ =	2.1659	- 0.0558 Nrate	+ 0.00037 $Nrate^2$	0.55**

Fig. 2-9b

Year	Conc. mg.kg	Intercept	Linear term	Quadratic term	R^2
2001	$[NO_3\text{-}N]$ =	5.0331	- 0.0052 Nrate		0.08*
2002	$[NO_3\text{-}N]$ =	0.6143	+ 0.0049 Nrate		0.25**
2003	$[NO_3\text{-}N]$ =	1.0874	+ 0.0166 Nrate		0.13*

Nrate = N fertilization rate ($kg.ha^{-1}$)
^{ns} = No significant
* = Significant to 0.05
** = Significant to 0.01

Crops N uptake

Sorghum. Fig. 2-10

Year	N uptake $Kg.ha^{-1}$	Intercept	Linear term	Quadratic term	R^2
2001	TKN =	10.8858	+ 0.3293 Nrate		0.36**
2002	TKN =	17.9582	- 0.0659 Nrate	+ 0.00060 $Nrate^2$	0..36**
2003	TKN =	8.3331	- 0.0701 Nrate	+ 0.00054 $Nrate^2$	0.42**

Potato. Fig. 2-11

Year	N uptake $Kg.ha^{-1}$	Intercept	Linear term	Quadratic term	R^2
2001	TKN =	111.3804	- 0.3714 Nrate		0.23**
2002	TKN =	37.2222	+ 0.8693 Nrate	- 0.0018 $Nrate^2$	0.45**
2003	TKN =	28.0746	+ 0.4817 Nrate		0.51**

Nrate = N fertilization rate ($kg.ha^{-1}$)
TKN = Total Kjeldahl Nitrogen
^{ns} = No significant
* = Significant to 0.05
** = Significant to 0.01

Predicted N rate for maximum potato yield

Fig. 2-12

Year	Crop Rotation	NYmax ($kg.ha^{-1}$)		Intercept		Linear term		Quadratic term	R^2
2001	Pooled	NYmax	=	20.1574 Nrate	+	0.1640 Nrate	-	0.00050 $Nrate^2$	0.38**
2002	PCF	NYmax	=	8.4584 Nrate	+	0.1455 Nrate	-	0.00035 $Nrate^2$	0.81**
2002	PCG	NYmax	=	12.7438 Nrate	+	0.0884 Nrate	-	0.00021 $Nrate^2$	0.48**
2002	PSF	NYmax	=	7.4520 Nrate	+	0.1968 Nrate	-	0.00047 $Nrate^2$	0.72**
2002	PSG	NYmax	=	8.9293 Nrate	+	0.1701 Nrate	-	0.00043 $Nrate^2$	0.91**
2003	PCF	NYmax	=	2.9133 Nrate	+	0.1385 Nrate	-	0.00032 $Nrate^2$	0.79**
2003	PCG	NYmax	=	3.9586 Nrate	+	0.1506 Nrate	-	0.00040 $Nrate^2$	0.92**
2003	PSF	NYmax	=	3.9419 Nrate	+	0.1680 Nrate	-	0.00041 $Nrate^2$	0.84**
2003	PSG	NYmax	=	4.2412 Nrate	+	0.1553 Nrate	-	0.00033 $Nrate^2$	0.86**

NYmax = Predicted N rate for maximum yield ($kg.ha^{-1}$)
Nrate = N fertilization rate ($kg.ha^{-1}$)
^{ns} = No significant
* = Significant to 0.05
** = Significant to 0.01

APPENDIX B
ANOVA TABLES FOR POTATO YIELD PARAMETERS

In this appendix are reported ANOVA tables for potato yield variables during the study period. These tables include rot potatoes, classification by size, marketable yield, total yield, and specific gravity. Due to the size of the tables, they are included beginning in the next page.

Table B-1. 2001 ANOVA table for potato yield parameters

Source of Variation	DF	Type III Mean Square [2]									
		Rots	Damaged	B	A1	A2	A3	A4	Market Yield	Total Yield	Specific gravity
Replication [1]	3	15.68**	1.03	5.45*	63.59	609.01*	346.05	0.21	2489.32**	2126.80**	0.000030*
Rotation [1]	3	4.57*	13.60	3.94	42.14	29.65	246.05	0.59	213.48	312.33	0.000008
Main Plot Error	9	1.11	3.85	2.24	54.33	132.33	109.92	0.61	275.72	259.53	0.000006
N rate	4	5.85**	34.70**	1.04	192.09**	963.69	580.91	1.02	3662.42**	3891.34**	0.000174**
Rotation * N rate	12	0.58	2.69	2.42	36.95	168.39	37.32	0.61	301.46	275.77	0.000008
Error	79	1.40	2.75	1.44	32.25	75.78	46.89	0.47	172.48	179.87	0.00000462

[1] Main plot effects tested using main plot error

[2] *Significant at Type I error < 0.05

**Significant at Type I error < 0.01

Table B-2. 2002 ANOVA table for potato yield parameters

Source of Variation	DF	Type III Mean Square [2]									
		Rots	Damaged	B	A1	A2	A3	A4	Market Yield	Total Yield	Specific gravity
Replication [1]	2	13.49	1.63	5.97*	18.51	425.25	2.78	0.030	604.14	657.55	0.000005
Rotation [1]	3	16.31	1.64	4.49*	25.14	231.25	10.46	0.039	211.00	126.12	0.000027
Main Plot Error	6	6.17	5.39	2.80	55.42	313.14	6.71	0.067	191.18	227.68	0.000006
N rate	4	10.08*	12.04**	7.39**	765.81**	980.66**	7.30*	0.043	3676.50**	4266.38**	0.000234**
Rotation * N rate	12	5.52	0.74	1.10	49.25**	36.28	1.32	0.063	126.23**	152.94**	0.000004
Error	59	6.96	0.79	1.28	15.31	33.08	2.09	0.06	37.67	29.76	0.000004

[1] Main plot effects tested using main plot error
[2] *Significant at Type I error < 0.05
**Significant at Type I error < 0.01

Table B-3. 2003 ANOVA table for potato yield parameters

Source of Variation	DF	Type III Mean Square [2]									
		Rots	Damaged	B	A1	A2	A3	A4[3]	Market Yield	Total Yield	Specific gravity
Replication [1]	3	11.54	3.39	15.76*	101.77	129.12*	72.31*	----	188.22	342.64	0.000047**
Rotation [1]	3	17.10	0.54	2.44	101.99	111.12*	14.65	----	431.07*	346.41	0.000109**
Main Plot Error	9	11.75	4.03	2.56	77.01	27.97	12.61	----	102.88	101.65	0.000006
N rate	4	14.84**	3.73*	13.09**	192.09	533.78**	27.23**	----	5299.24**	6704.77**	0.000174**
Rotation * N rate	12	3.17	2.45*	1.00	36.95	29.85	4.75	----	67.15*	65.45*	0.000008
Error	79	2.42	1.08	0.63	14.67	16.29	3.80	----	32.18	32.55	0.000038

[1] Main plot effects tested using main plot error

[2] *Significant at Type I error < 0.05

**Significant at Type I error < 0.01

[3] In this year low production of potatoes A4 size did not allowed to analyze this variable

APPENDIX C
GREEN BEAN YIELD

Year	Potato N rate[2] ($kg.ha^{-1}$)	Previous crop	
		Sorghum[1]	Cowpea[1]
		Green bean yield ($kg.ha^{-1}$)	
2001	0	5428	7355
	100	5736	6653
	150	6175	6351
	200	5754	6705
	250	5196	7294
2002	0	2205	3519
	100	1909	3671
	150	1631	3467
	200	2119	3220
	250	1299	2540
2003	0	2860	2888
	100	3034	3095
	150	2839	3077
	200	3622	3513
	250	3287	3269

[1] Crop preceding green bean in the crop rotation.
[2] N rate applied to potato in spring.

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BIOGRAPHICAL SKETCH

Fernando Muñoz was born in Cali, Colombia, on December 19, 1959. In 1976, he completed high school at Colegio de Santa Librada. He attended the Universidad Nacional de Colombia, and at the end of his undergraduate work he had the opportunity to conduct his thesis in the Agronomy section of the International Center for Tropical Agriculture (CIAT) in Cali, Colombia. After earned his B.S. in agronomy he was hired by CIAT to work as Research Assistant in the Cassava Program. In 1991, he was awarded with a scholarship from the Dutch government to attend the Centro Agronomico Tropical de Investigacion y Enseñanza (CATIE) in Turrialba, Costa Rica. There, he developed his research work with the CATIE-GTZ Agroforestry Project earning his M.Sc. degree in agricultural production systems with emphasis in agroforestry. He went back to CIAT to work as Research Associate in the Plant Nutrition Section of the Bean Program. In 1998 he joined the research team of the Pathology Section at the Tropical Forages Program in CIAT. He joined the University of Florida, Gainesville, Florida, in summer 2001 to pursue a Doctor of Philosophy in soil and water science. After getting his degree, he plans to continue his professional career on agricultural research.