CONTROLLED-RELEASE NITROGEN FERTILIZER RELEASE CHARACTERIZATION AND ITS EFFECTS ON POTATO (*Solanum tuberosum*) PRODUCTION AND SOIL NITROGEN MOVEMENT IN NORTHEAST FLORIDA

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2004

This thesis is dedicated to my loving wife, Jerami, and three daughters, Sarah, Rachel, and Elisabeth, for following me wherever I needed to go.

ACKNOWLEDGMENTS

I thank my advisor, Dr. Chad Hutchinson, for his mentor-like spirit. He provides guidance y*et al*lows me room to teach myself. I thank my other committee members Dr. George Hochmuth, Dr. Rao Mylavarapu, Dr. Johan Scholberg, and Dr. Michael Dukes for their support of this work.

I thank my sweetheart, Jerami, for her patience and unwavering support and ennobling confidence as well as my children, Sarah, Rachel, and Elisabeth, and those yet unborn, for trusting and simple love. We can only get through this together.

Finally, I thank our Father for agency to choose, opportunities to grow, truth to guide us home, and a veil of forgetfulness to allow it to come from within.

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December 2004

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Major Department: Horticultural Science

The Tri-County Agricultural Area of northeast Florida is home to nearly 8,000 ha of potato (*Solanum tuberosum* L.) production, valued at approximately $64M annually. The combination of sandy soils, perched water tables, and unpredictable rainfall together with nitrogen fertilizer applications as high as 390 kg ha^{-1} N increases the potential for nutrient loading into local watersheds, including the St. Johns River. As mandated by the 1987 Florida SWIM Act, the St. Johns River Water Management District directs the development of agricultural best management practices (BMP) for the area. Within the BMP program the potential of controlled-release fertilizers (CRF) as alternative fertilizers was evaluated. The specific research objectives were to 1) characterize nutrient release from CRF under laboratory and field conditions, 2) determine potato production and nutrient recovery efficiency for soluble fertilizer and CRF treatments, and 3) estimate soil nutrient levels in the potato bed and in the perched water table.

Seven CRF products (polymer coated ureas) were compared to ammonium nitrate (AN). Lab and field experiments evaluated nutrient release both at controlled temperature and under field conditions. Field experiments evaluated CRF products at three application rates (112, 168, and 224 kg ha^{-1} N); 224 kg ha^{-1} N is the current potato BMP rate, adopted from the University of Florida's Institute of Food and Agricultural Sciences Extension Service's recommendation. Two CRF products and AN blends were included to evaluate ideal combinations. Leaching studies evaluated nitrate (NO_3-N) and ammonium (NH_4-N) movement into nearby wells and lysimeters under field conditions.

Results from the nutrient release experiments revealed that CRF2b, CRF4, CRF5, and CRF6 all exhibited temperature-based, complete release over time. While initial release from CRF products was somewhat higher under field conditions compared to lab conditions, subsequent sustained release from the two experiments was similar.

From the field production experiments, CRF fertilized plants produced comparable total and marketable potato yields to AN fertilized plants. Plants within CRF2 (224 kg ha^{-1} N) and CRF4 (224 kg ha^{-1} N) had the highest total and marketable yields and specific gravity (SG) of all treatments. Applications of 224 kg ha^{-1} N did not result in yield or SG increases over the 168 kg ha^{-1} N rate, independent of N source. For percent AN:CRF blends evaluated with two CRF products, no blend was advantageous for either 'Atlantic' or 'Red LaSoda' potato production.

NO_3-N and NH_4-N movement into the perched water table was significantly lower with CRF than with AN treatments, particularly early in the season. Potatoes fertilized with CRF products have similar yields and quality to AN fertilized potatoes while soil nitrogen movement into watersheds is significantly reduced.

CHAPTER 1
INTRODUCTION

Agricultural associations with Florida usually involve images of orange trees full of fruit. However, Florida produces a wide variety of fruit and vegetable crops, not the least of which is potatoes. Florida potatoes (*Solanum tuberosum* L.) are grown primarily for the fresh market and chip market, with 'Atlantic' variety being the most widely grown. In northeast Florida, potato production approaches 8,000 ha at approximately $64M per year in value.

The soils in northeast Florida are sandy with a shallow perched water table. In combination with unpredictable rainfall and high fertilizer rates, this increases the potential movement of nutrients into local watersheds, thus degrading the environment. Local endeavors under mandate from state and federal law have encouraged cultural practices called BMPs or best management practices which aim to allow farmers to maintain high yielding and high-value crops while protecting the environment.

This research project evaluates the suitability of controlled-release fertilizers (CRF) as an alternative nitrogen (N) fertilizer source to commonly utilized ammonium nitrate (AN) for potato production in northeast Florida. It evaluates the effects of CRF products on potato production including tuber yields and quality as well as their effects on nutrient leaching into local watersheds. It further examines the release characteristics of selected CRF products under controlled and field conditions. Our hypothesis is that appropriate use of CRF products may provide an alternative to AN fertilizer sources including equal or improved potato tuber yields with less negative impacts on the environment.

CHAPTER 2
LITERATURE REVIEW

Potato (*Solanum tuberosum* L.) nitrogen (N) fertilization strategies to improve tuber yield and/or quality have greatly evolved during the past century. Methods have included additions of organic fertilizer amendments like manures and green manures; the application of N in various soluble forms (e.g., ammonium, nitrate, and urea), alone and in blends; the application of N in slowly soluble forms (e.g., urea formaldehyde, methylene urea, and isobutylidene diurea); and the application of coated soluble N (e.g., sulfur-coated urea, polymer-coated urea). Research has explored the timing of application (e.g., pre-plant, at planting, at hilling), placement (e.g., banded, broadcast, surface applied, incorporated, side-dressed), application method (e.g., solid prills, liquid through irrigation lines), rate, and virtually every combination thereof. Research has evaluated the growth characteristics of the plant and linked this to nitrogen accumulation patterns—little N demand very early, to heavy N demand during vegetative growth and bulking stages, to little N demand during maturation and senescence. New, N-efficient cultivars have been compared to reliable favorite varieties. Climate (e.g., rainfall, temperature), soil conditions (e.g., texture, structure, CEC), and seasons have been linked to fertilizer management. Nitrogen management is increasingly subject to market demands, legal constraints, and economic considerations. N fertilization of potatoes has become a highly specialized science, with different applications for any given set of conditions.

However, as society advances, so does the need to adapt to new circumstances, new needs, new laws, new considerations, etc. Increasing concerns over fossil fuel supplies, polluted water supplies, and environmental degradation have forced the agricultural industry to re-evaluate how it manages production inputs. It has been obliged to seek out more environmentally responsible methods of production while striving to remain profitable with an increasingly competitive economy and ever more environmentally conscious public.

This review will discuss the evolution and implementation of best management practices (BMP) across the United States with special reference to Florida. It will then outline the basic potato plant growth cycle and strategies to maximize production efficiency. It will then narrow its focus to potato fertilizer research, particularly with slow- or controlled-release fertilizers. Finally, it will present the research justification and objective of the current project.

Best Management Practices

Agricultural best management practices (BMP) are scientifically-based cultural farming practices that should maintain or increase crop yields and/or profits while protecting the environment (Simonne *et al*., 2003). One common BMP goal is to reduce the contamination of water bodies by chemicals or other pollutants, such as nitrogen. Nitrogen (N), particularly in the form of nitrate (NO_3^-), is the most common contaminant in aquifer systems (Freeze and Cherry, 1979). Hallberg (1989) states that agriculture is the largest human-caused source of nitrate and Keeney (1986) suggests that this is caused by activities associated with crop and animal production. Burkart and Stoner (2002) report that shallow unconfined aquifers associated with agricultural systems, particularly under irrigation, are the most susceptible watersheds to nitrate contamination.

Individual BMPs differ according to specific regional, climatic, geographic, governmental, and growing requirements. Though BMPs differ, the following aspects commonly appear in BMP programs: 1) soil or tillage management to reduce runoff and erosion of nutrients and/or nutrient coated soils, 2) irrigation management to reduce runoff, deep percolation, and soil salinization, 3) mulching practices to reduce soil losses and, in the case of some organic mulches, partially or completely replace fertilizer applications, reduce evaporation rates, and enhance soil water storage, and 4) fertilizer scheduling to apply only the types and quantities of nutrients required by crops at the right time to produce optimal yields and minimize negative environmental impacts.

Florida BMPs

In 1987, the Florida legislature, under the mandate of the Federal Clean Water Quality Act of 1977, passed the Florida Surface Water Improvement and Management (SWIM) Act (Florida, 2004). The SWIM Act created a program that focused on the preservation and/or restoration of the state's water bodies through the development and implementation of Best Management Practices (BMPs) (Simonne *et al*., 2003). Since its passage, state and local regulatory agencies have worked to improve water bodies in need of restoration throughout the state.

The St. Johns River watershed in northeast Florida has been identified as a water body in Florida in need of restoration. Nitrate leaching into the river has generated concern. The lower St. Johns River basin is encompassed by three counties: St. Johns, Putnam, and Flagler counties. These counties comprise the Tri-County Agricultural Area (TCAA) and feature predominate agricultural land use. The major crop in the TCAA is potato, and this area produces nearly half of Florida's annual 15,000 hectare crop with a value of $130M (Bronson, 2003). Soils in the area are generally sandy with low water-

holding capacity. This, together with the shallow root system of potatoes and the possibility of excessive seasonal rains, increases the potential for movement of water soluble plant nutrients into the surrounding watersheds, including the St. Johns River.

State and local regulatory agencies in cooperation with growers in the TCAA have developed a BMP program which has been in place for over three years. The BMP program is the TCAA Water Quality Protection Cost Share Program which is managed by the St. Johns River Water Management District (SJRWMD). The TCAA Water Quality Protection Cost Share Program encourages growers to adopt environmentally responsible practices by partially offsetting the implementation costs of those practices (Livingston-Way, 2000).

The nitrogen BMP rate for potato production in the TCAA ranges from 224 to 280 kg ha^{-1} N. This contrasts with growers in the TCAA, who apply an average of 280 kg ha^{-1} N, ranging from 195 kg ha^{-1} N on fresh market potato to 390 kg ha^{-1} N for some chipping potatoes. The base rate of 224 kg ha^{-1} N was adopted from the University of Florida's Institute of Food and Agricultural Science (IFAS) recommended rate (Hochmuth and Cordasco, 2000; Hochmuth *et al.*, 2003). The IFAS recommended BMPs for potato production also suggest split application of N fertilizer. Approximately 30% of the total N should be applied at planting and the remainder banded 35-40 days after planting. N rates should be based on plant nutrient status analysis. IFAS recommendations also include the installation and monitoring of water table observation wells, control structures to trap sediment from the field, and conservation crop rotations (Hutchinson *et al.*, 2002).

Nutrient Use Efficiency

One possible benefit of BMPs is an improvement in production efficiencies. As system efficiency increases, productivity per unit of energy increases while loss and environmental impacts decrease. The efficient use of nutrients is referred to in this thesis as "nutrient use efficiency" (NUE), and refers to the percentage recovery of an applied nutrient.

NUE has different definitions depending on the goals of the research program. Prihar *et al.* (2000) divided NUE into the following categories: Agronomic NUE is expressed as the amount of yield increase obtained per unit of fertilizer applied when compared to the yield of an unfertilized crop. Economic NUE refers to the returns on investment in added nutrients, where the cost of the last unit of fertilizer applied equals the value of the yield increase obtained by that addition. Apparent nutrient recovery is the amount of nutrient taken up by the crop and divided by the amount applied as fertilizer, independent of the source from which the nutrient may have been obtained. Actual NUE is similar to apparent NUE in that it measures the amount of fertilizer taken up by a crop. However, actual NUE differs from apparent NUE in that actual NUE measures the amount of fertilizer-supplied nutrients that are actually taken up by the crop using tracers like depleted ^{15}N or phosphorus-32 (^{32}P) in the fertilizer source (Prihar *et al*., 2000).

In some cases where the amount of nutrients available for movement from the site is of interest, the nutrient recovery efficiency (RE) is calculated (Zvomuya *et al.*, 2003; Westermann *et al.*, 1988). Nutrient RE is defined as the fraction of an applied nutrient that is recovered or removed from the site, usually in the form of a product.

Baligar *et al.* (2001), reviewed several factors affecting NUE including soil characteristics, fertilizer types and quantities, plant uptake and use mechanisms, agronomic considerations such as tillage, crop rotation, and cover crop usage, biological contributions of mycorrhizal fungi symbiosis and rhizobial nitrogen fixation, and climate factors. Their review also stressed that highest NUEs (apparent, agronomic, economic, etc.) can only be obtained through the appropriate integration of all of these factors.

Potato Growth Stages

In order to maximize productivity and NUE, it is useful to review the life cycle of the potato plant. This is because by understanding the life cycle of the plant, its uptake capacity, peak uptake periods, etc., fertilizer products can be designed to maximize NUE and minimize waste.

The life cycle of a potato plant can be divided into five general growth stages during each of which, the plant will carry on generally different metabolic activities (Rowe, 1993). Once understood, effective practices can be implemented which work together with the plant maximizing production and uptake efficiency.

Growth Stage I

Growth stage I is characterized by sprout development. During this stage sprouts form from eyes on seed tubers and grow upward to emerge from the soil. No photosynthesis takes place during this stage as the entire plant is underground and all of the plant nutritional requirements are supplied by the seed tuber. Because the plant has only begun developing functional roots during this stage, little or no nitrogen uptake occurs.

Growth Stage II

Growth stage II is characterized by vegetative growth. The plant begins to photosynthesize and products of photosynthesis provide energy to the plant as the seed tuber becomes depleted of both energy and nutrients. Leaves and branch stems develop from aboveground nodes along emerged sprouts and roots and stolons develop at below-ground nodes. Growth stages I and II are reported to last from 15 to 30 days (Ojala *et al.*, 1990) to as long as 60 or 70 days (Kleinkopf, 1983; Westermann, 1993) depending on planting date, planting depth, soil temperature and other environmental factors, the physiological age of the seed tubers, and the characteristics of particular cultivars. Approximately 15% of the total nitrogen uptake by 'Russet Burbank' occurs during stages I and II (Ojala *et al.*, 1990). Nitrogen deficiency during this stage is easily corrected without appreciable yield losses if addressed early. Nutrient excesses during this stage promote assimilate partitioning to vines, prolonging this vegetative growth stage and delaying tuber initiation and expansion.

Growth Stage III

Growth stage III is characterized by tuber initiation and typically lasts from 10 to 14 days (Westermann, 1993; Ojala *et al.*, 1990). During this stage, tubers form at the end of stolons but are not yet enlarging. Marketable-sized tubers at harvest are usually initiated at this time. The end of this stage typically coincides with early flowering. Approximately 30% of the total plant nitrogen uptake occurs by the middle of this stage of growth (Ojala *et al.*, 1990). Nitrogen stress during this stage reduces leaf area and canopy development but may stimulate early tuber initiation; excess nitrogen stimulates vegetative growth and may delay the initiation of stage IV tuber growth for up to ten days (Allen and Scott, 1980; Ojala *et al.*, 1990).

Growth Stage IV

Growth stage IV is characterized by tuber bulking (expansion) and lasts from 30 to 60 days (Kleinkopf, 1983) to as high as 120 days (Ojala *et al.*, 1990). During this stage tuber cells expand and become the major sinks for photosynthetic products, water, and nutrients. Much of the total nitrogen uptake (58 to 71%) by the crops occurs through early and mid tuber bulking, respectively (Ojala *et al.*, 1990), and most of the nutrients used by the plant are taken up during growth stage IV (Westermann, 1993). Westermann *et al.* (1988) reported that the nitrogen taken up during this stage is initially concentrated in the stems and leaves and later translocated to the tubers. Nitrogen deficiencies during this stage reduce tuber yield and size; excesses decrease tuber specific gravity, delay vine senescence, and hamper tuber maturation (Ojala *et al.*, 1990).

Growth Stage V

Growth stage V is the maturation stage, and little additional nitrogen is taken up from the soil. During this stage, representing the final 10 to 24 days of growth, mobile nutrients are translocated from vegetative plant portions into the enlarging tubers [for N, up to 90% or more is translocated to the tubers (Westermann, 1993)]. Also during this stage, tuber dry weight reaches its highest level, canopy photosynthesis decreases, and above-ground parts senesce and die, and tuber skin matures (Rowe, 1993). Excessive nitrogen during this stage can promote late-season vegetative growth and delay tuber maturity and also result in poor net development of tuber skins, which is a concern for russet-type potato growers (Ojala *et al.*, 1990). Early season cultivars reach maturity in 90-100 days while late season cultivars may take 150 or more days (Kleinkopf, 1983). 'Atlantic' potatoes grown for chip production in Florida mature between 85 and 110 days (Hochmuth *et al*., 2003).

Cultural Practice Influences on N Fertilization Efficacy

By understanding the life cycle of the potato plant, effective fertility management and fertility related cultural practices can be adopted. As stated by Westermann (1993), "…the goal in managing potato crop nutrition is to promote uniform and continuous growth of plants and tubers throughout all growth stages." Most soils need nitrogen applications to produce maximum yields of potatoes. However, the efficacy of that application may be highly dependent on the control of other soil and environmental factors. Cultural practices that influence uniform, continuous growth are in turn influenced by nitrogen, and include N application timing, irrigation management, N source, and N placement.

N Application Timing

Westermann and Kleinkopf (1985) showed that on 'Russet Burbank' potatoes, for maximum early tuber growth, the above ground portion of the plant should contain 79 to 100 kg ha^{-1} N at the start of tuber bulking (growth stage IV), and that a preplant N fertilizer application between 67 and 134 kg ha^{-1} would provide adequate N, while excessive preplant N would delay tuber formation and result in lower marketable yield (Westermann and Kleinkopf, 1985). Errebhi *et al.* (1998) reported that as the percentage of total N applied pre-plant increased, total marketable yield decreased while total yields remained the same on 'Russet Burbank' potatoes grown on a sandy loam in Minnesota. They also reported that split applications of N fertilizer reduced nitrate leaching and increased recovery because less fertilizer was applied preplant. Stark *et al*. (1993) showed that split biweekly N applications produced higher marketable tuber yields than did weekly applications. Depending on potato variety and local conditions, fertilizer applications should be terminated from two or three weeks (Ojala *et al.*, 1990) to four to

six weeks (Westermann, 1993), before the start of maturation (stage V) growth to avoid tuber immaturity at harvest.

Irrigation Management

Ojala *et al.* (1990) reported that when growing 'Russet Burbank' potatoes with reduced irrigation and seasonal water application rates ranging from 160 mm (severely water-stressed) to 590 mm (adequate water) were applied, that maximum tuber yields were attained with 247 kg ha^{-1} N. They also reported that under optimal irrigation, specific gravity was greatest at the lowest N application rate whereas higher N levels decreased specific gravity. For excessive irrigation (1.2 and 1.4 times the estimated evapotranspiration rate), Stark *et al.* (1993) reported no significant plant N uptake effects, or late-season tuber or plant dry weight differences, but did find significant reductions in marketable yields in two seasons, and reduced total yields in one season.

N Source

Nitrogen source is important for optimal potato growth. Commonly used N fertilizer sources are nitrate, urea, and ammonium, though plants only take up N as either NO_3-N or NH_4-N (Westermann, 1993). N applied as urea is converted into NH_4-N by the ubiquitous enzyme urease (Benson and Barnette, 1939). This is a rapid process, reaching a rate up to 90% conversion within 4 days of application at soil temperatures of 21°C (Benson and Barnette, 1939). Francis and Haynes (1991) reported similar results with urea transforming to NH_4-N within 48 hours under field conditions in New Zealand. Polizotto *et al.* (1975), testing 'Red Pontiac' and PU 66-142 potatoes in solution cultures found that growth of tops, roots, and tubers was greatest with N supplied as NO_3, intermediate with $NH_4 + NO_3$, and least with NH_4, for both cultivars. Davis *et al.* (1986) reported similar findings for 'Russet Burbank' potatoes. Changing the N source from

NO_3 or $NH_4 + NO_3$ to NH_4 reduced both shoot and root growth while changing the N source from NH_4 to $NH_4 + NO_3$ improved growth. They concluded that some NO_3-N should be available to potatoes for proper growth and development and that when NH_4-N was the sole form of N available to the plant, it was detrimental to potato growth, regardless of stage of development (Davis *et al.*, 1986).

N Placement

Nitrogen placement can influence the N use efficiency, plant health, and tuber yields in potatoes. In Idaho, Westermann and Sojka (1996) reported for 'Russet Burbank' potato production, that banding N increased average plant dry weight 6.4%, total tuber yield 9%, and N uptake 28% compared with broadcast N. They reasoned that these results were consistent with predictions because potato roots would be unable to exploit a certain percentage of broadcasted N due to spatial limitations, whereas banded applications would tend to be in a region of the soil accessible to plant roots. This would be consistent regardless of irrigation method. Waddell *et al.* (1999), working with 'Russet Burbank' potato in central Minnesota, reported no significant tuber yield differences except for lower yields with buried drip irrigation and the control treatment regardless of irrigation and N source treatments.

CRF Products

One approach to potato fertilization that may limit nutrient leaching involves the use of slow- or controlled-release fertilizers (CRF). These are products that theoretically reduce nitrogen leaching by limiting the solubility and availability of a fertilizer (e.g., sulfur-coated urea (SCU), isobutylidene diurea (IBDU), polymer-coated urea (PCU), others) or by limiting its conversion to mobile forms (e.g., nitrification inhibitors (NI)).

These slow- or controlled-release strategies have been used successfully to reduce nitrogen applications in numerous crops. These include 'Yolo Wonder' bell peppers (*Capsicum annuum* L.) with IBDU and SCU (Locascio *et al.,* 1981), 'Jupiter' bell peppers with resin-coated-urea/potassium nitrate blends (Csizinszky, 1994), green bell peppers with PCU, SCU, or AN (Guertal, 2000), tomatoes (*Lycopersicon esculentum* Mill.) with IBDU or SCU/ammonium nitrate blends (Locascio *et al.*,1984), strawberries (*Fragraria x ananassa* Weston), with SCU and IBDU (Locascio and Martin, 1985), potted chrysanthemums (*Chrysanthemum x morifolium*) with "Osmocote" (a PCU) (Hershey and Paul, 1982), and barley (*Hordeum vulgare* L.) with PCU and NI (Shoji *et al.*, 2001). These products have been evaluated for potato production over the years in different parts of the country with varying degrees of success.

Sulfur-Coated Urea

In studies conducted over several years in three locations in California, Lorenz *et al.* (1972, 1974) showed that ammonium sulfate was generally superior to SCU or urea-formaldehyde (a slowly available N source) for 'White Rose' potatoes, and that while in some cases SCU produced yields equal to ammonium sulfate, in no case were yields greater with SCU. In both studies, the lower yields of CRF treatments were attributed to too-slow release of the fertilizer products.

Cox and Addiscott (1976) using SCU on 'King Edward' potatoes in Rothamsted, England, determined that for rates up to 200 kg ha^{-1} N, potato tuber yields were greater for ammonium nitrate than for SCU and at higher rates no significant difference between nitrogen sources was found. They attributed these findings to incomplete or too slow release of SCU over the potato growth period.

Liegel and Walsh (1976) in Hancock, Wisconsin reported that 'Russet Burbank' potatoes, grown on a loamy sand with SCU, produced higher tuber yields than plants grown with urea or AN. However, this was attributed to excessive rainfall in May which leached the water soluble fertilizer and reduced yields for the entire year.

In central Minnesota, Waddell *et al.* (1999), growing 'Russet Burbank' potatoes on a sandy loam soil, found that SCU applied at a rate of 224 kg ha^{-1} N resulted in lower tuber yields than did urea under either drip or sprinkler irrigation. This was attributed to slow availability of the SCU product.

Elkashif *et al.* (1983) reported similar results in Florida where yields of 'Atlantic' potatoes grown on two sandy soils fertilized with SCU or a SCU/ammonium nitrate (AN) blend were lower than treatments with only AN. These results were consistent for rates from 134 to 201 kg ha^{-1} N and either as preplant or split applications. Maynard and Lorenz (1979), in reviewing the work done on SCU, concluded that N release rates from SCU are too slow to meet the high N demand of the potato crop early in the growing season.

Isobutylidene Diurea and Nitrification Inhibitors

Though evaluated, isobutylidene diurea (IBDU) and nitrification inhibitors (NI) have not been adopted for commercial potato production. Under potato production in Florida, Elkashif *et al*. (1983) reported lowest total tuber yields and 25% lower marketable yields using IBDU as the N source compared to either AN or IBDU/AN blends. NI evaluated in five studies on potato in Northeast Florida gave no tuber yield increases in four of the five tests. As a result, the researchers did not recommend NI for potato production on hyperthermic, irrigated, sandy soils (Martin *et al.*, 1993).

Polymer-Coated Urea

One relatively new CRF technology that has shown promising preliminary results for potato production and reduced leaching is polymer-coated water soluble fertilizers. Polymer-coated ureas (PCU) are CRFs with a polymer coating.

Zvomuya and Rosen (2001), growing 'Russet Burbank' potatoes on a sandy soil in Minnesota, reported higher marketable yields using PCU applied at planting compared to urea applied at emergence and hilling for application rates ranging from 110 to 290 kg ha^{-1} N. In other research involving a three-year study, Zvomuya *et al.* (2003) reported that at 280 kg ha^{-1} N, NO_3-N leaching was 34 to 49% lower with PCU treatments than three split applications of urea while nitrogen recovery efficiency (RE) for PCU averaged 50%, 7% higher than urea (43%). Total and marketable tuber yields with the CRF treatments were between 12 and 19% higher than three applications of urea under leaching or excessive irrigation conditions. This was attributed to a prolonged N release period and reduced leaching of PCU treatments compared to urea treatments under excessive irrigation conditions.

Shoji *et al.* (2001) demonstrated that PCU could markedly increase the NUE and tuber yields of 'Centennial' russet potatoes, reporting that a single basal application of 112 kg ha^{-1} N PCU at planting produced total tuber yields comparable to traditional fertilizer practices totaling 269 kg ha^{-1} N in 9 split applications. They also reported that plant nitrogen NUE values of CRF products were nearly doubled compared to that of urea N. These results were attributed to the ability of CRF products to supply N synchronously with plant requirements.

In northeast Florida on 'Atlantic' potatoes, Hutchinson *et al.* (2003) reported that at low N rates (112 kg ha^{-1} N), marketable tuber yields and nutrient use efficiency (NUE)

were higher for PCU than AN, though marketable yields were lower than acceptable local levels. At higher rates (168 to 224 kg ha^{-1} N), tuber yields and NUE were similar.

PCU Release

One characteristic of PCU that has made it a successful fertilizer is the degree of control of nutrient release. The controlled-release is obtained through varying either the thickness or composition of the fertilizer coating. Though the specifics of coating composition are held by individual manufacturers and are proprietary secrets, the general list of chemicals is similar. Polymer-coating films are typically composed of blends of water permeable and impermeable resins and surfactants (e.g. polyolefin or polyethylene), ethylene vinyl acetate, and talc occurring as layered plates (Shoji, 1999). Regulating the composition of the coating gives it a controlled moisture permeability and release rate (Fujita *et al*., 1983).

Shoji (1999) and Gandeza *et al*. (1991) characterized the release mechanism as following three general steps: 1) Water moves into the fertilizer granule by osmotic potential, 2) the water soluble fertilizer inside the granule dissolves, and 3) the nutrient solution diffuses out of the granule due to a chemical concentration gradient. The rate of water penetration is proportional to the differences in water vapor pressures between the inside and outside of the capsule. This gradient potential determines the rate of release of the nutrient (Kochba, 1990). The talc component of the coating aids in control over the rate of nutrient diffusion because the talc forms voids in the polymer coating. These voids become larger with increasing talc content, increasing the distance which the water must move through, slowing diffusion (Shoji, 1999). Talc can also be used to adjust the Q_{10} (the rate increase of a reaction over a 10º C rise) of release. As the talc content of the coating increases, the Q_{10} of diffusion decreases (Shoji, 1999). Generally, fertilizers are

formulated to maintain a Q_{10} of around 2, matching typical Q_{10} values for chemical reactions occurring in plants and microbial activity in many soils (Shoji, 1999).

Soil temperature and moisture affect nutrient release rates. Maeda (1990) studied the contributions of various soil factors affecting N release of one particular PCU product and found that temperature accounted for about 83% while moisture content, about 11%. Other soil factors such as microbial activity, pH, etc., and their interactions accounted for less than 1% each. Having a nutrient release rate that is highly dependent on one variable enables good prediction of release. Gandeza *et al.* (1991) showed that N release from PCU was primarily affected by temperature. In that study, cumulative air temperature (CAT) and cumulative soil temperature (CST) were highly correlated (r^2= 0.99) so either could be used for predicting nutrient release rates. This is useful because soil temperature data is not always readily available, air temperature data can be used instead. Fujita *et al.* (1983) and Fujita (1989) reported that the rate of PCU release is affected most by moisture when soil moisture is less than the incipient plant wilting point of the plant (10 kPa). This was addressed by Shoji (1999) who reported that at any soil moisture content greater than wilting point, the relative humidity of the soil is 100%. He did report that some observed values from a PCU product were somewhat lower than temperature-predicted values in some coarse-textured upland soils, possibly due to reduced diffusion under exceedingly dry soil conditions.

Summary and Research Objectives

Polymer-coated CRFs have the potential to revolutionize the way potato crops are being grown. With predictable release rates, polymer-coated CRFs are very suitable for BMP programs by allowing growers to produce acceptable crop yields while eliminating the need for frequent applications of water soluble nutrients, thus reducing excessive

fertilizer applications and labor costs as well as the potential for nutrient movement. As nutrient release rates could be formulated to match crop requirements, nutrients would be available at times and in quantities required by the plant. This would result in potential reduction in nutrient losses associated with high intensity rainfall events and thereby also enhance nutrient use efficiency.

Release rates of nitrogen from polymer-coated fertilizers have not been determined for TCAA growing conditions. Neither have the effects of various current commercially-available PCU CRFs on potato production been examined. Once these are established, fertilizer blends can be formulated to match crop uptake requirements, reducing excesses of fertilizer being applied. The objectives of this work were to: 1) determine nutrient release characteristics of various controlled-release fertilizers under controlled and field conditions, 2) determine potato production and nutrient recovery efficiency data for soluble and controlled-release fertilizer treatments, and 3) estimate soil nutrient levels in potato beds and underlying perched water tables.

CHAPTER 3
MATERIALS AND METHODS

This chapter describes the materials and methods of the various experiments conducted. In broad categories, the experiments can be broken down into three sections, each of which addresses one of the three objectives of this research project. The three categories are: 1) CRF release through the incubator and meshbag experiments, 2) field production of potatoes in the CRF production and replacement experiments, and 3) soil nitrogen movement in the leaching experiment utilizing wells and lysimeters.

The fertilizer products evaluated through all of the experiments performed are shown in Table 3-1. The CRF products utilized for these experiments were labeled CRF1 through CRF6 with CRF2 being broken into CRF2a and CRF2b. CRF2 was sub-divided because in the production experiment, "CRF2" was a blend of two fertilizer products, CRF2a, and CRF2b. AN and urea were provided by Gator Fertilizer (Hastings, FL), CRF1, CRF2a, and CRF2b were provided by Scotts Chemical Company (Marysville, OH), and CRF5 and CRF6 were provided by Pursell Technologies, Inc. (Sylacauga, AL). The University of Florida has signed a secrecy agreement with the manufacturers of CRF3 and CRF4.

CRF Release from the Incubator and Meshbag Experiments

Incubator Experiment

The goal of the incubator experiment was to evaluate the release characteristics of selected CRF products under aqueous conditions at controlled temperatures over a 13

Table 3-1. Characteristics of fertilizer products evaluated in the various CRF release, production, and leaching experiments.

Fertilizer	Formulation	Manufacturer	N Form	Characteristics
AN	30-0-0	Gator Fertilizer	16% NH_4, 14% NO_3	water soluble
Urea	46-0-0	Gator Fertilizer	Urea	water soluble
CRF1	44-0-0	Scotts Chemical Co.	Urea	45-day release
CRF2a	37-0-0	Scotts Chemical Co.	Urea	120-day release
CRF2b	43-0-0	Scotts Chemical Co.	Urea	75 day release
CRF3	42-0-0	Product 3[1]	Urea	CRF, unknown
CRF4	41-0-0	Product 4[1]	Urea	CRF, unknown
CRF5	44-0-0	Purcell Technologies, Inc.	Urea	CRF, unknown
CRF6	43-0-0	Purcell Technologies, Inc.	Urea	CRF, unknown

[1] – The manufacturer of these products has a secrecy agreement with the University of Florida to remain anonymous.

week period. Weekly and cumulative release were measured together with residual fertilizer, Q_{10} values, and total recovery.

CRF fertilizer products

The incubator experiment had a total of ten fertilizer treatments: a no fertilizer control (No N), ammonium nitrate (AN), urea, and seven CRF products. The two products in CRF2 were separated for individual characterization.

Incubators

Six cooled incubators (Sanyo Electric Biomedical Co., Ltd., Osaka, Japan) were set at constant temperatures of 5, 10, 15, 20, 25, and 30°C. A seventh incubator was set at variable temperatures based on the average soil temperature (10 cm depth) for a given week of a typical growing season. The variable temperatures were established using 25 years (1975 to 2000) of historical soil temperature data for the area (Table 3-2). Each week, prior to sampling, the temperature of each incubator was recorded as well as that of an American Society for Testing and Materials (ASTM) certified thermometer inside

Table 3-2. Incubator 7 temperature settings used for the incubator experiment.

Average soil temperature for week beginning	Incubator setting (°C)
25-Jan	15
1-Feb	15
8-Feb	15
15-Feb	16
22-Feb	18
1-Mar	18
8-Mar	19
15-Mar	19
22-Mar	21
29-Mar	21
5-Apr	23
12-Apr	22
19-Apr	23
26-Apr	24

each incubator for temperature verification. The variable temperature incubator was adjusted for the next week's temperature after sampling.

Duration

The experiment lasted for 13 consecutive weeks, with samples taken each week.

Setup and procedure

Three grams of nitrogen (varying amounts of fertilizer based on formulation) were placed inside 200 ml sterile glass bottles with screw caps and added to 100 ml of deionized (DI) water. These bottles were then placed inside each incubator. At one week intervals, the bottles were shaken to ensure solution homogeneity and a 20 ml sample aliquot removed. The fertilizer prills were filtered out of the remaining solution and returned to the sampling bottle; the excess solution was discarded. The bottles were then refilled with 100 ml of fresh DI water. After 13 weeks, the filtered fertilizer prills were

ground with a mortar and pestle and residual fertilizer was dissolved in 100 ml DI water and an aliquot taken.

Sample analysis

Aqueous samples were stored at -5°C prior to analysis. Solution from weekly samplings was analyzed at the University of Florida Analytical Research Laboratory (ARL) for nitrogen by TKN and for EC using standard protocols (Mylavarapu and Kennelley, 2002). The TKN method used measures NH_4-N but not NO_3-N, so the AN treatment percent recovery was based on 1.6% applied N. Residual fertilizer samples were analyzed by Waters Analytical Laboratories (Camilla, GA) for N by the Dumas method (Dumas, 1831; Watson and Galliher, 2001).

Statistical design and analysis

Treatments were arranged in a completely randomized design with three replicates. Data were treated in three major categories: weekly and cumulative release, residual fertilizer, and total N recovery.

Weekly and cumulative release data were analyzed factorially for sampling date, incubator temperature, and fertilizer source main effects and their interactions. Further factorial analysis was performed on weekly and cumulative release samples by analysis of fertilizer product main effect N release within each temperature setting, analysis of temperature main effect release within each fertilizer product, and analysis of fertilizer product main effect release for each sampling date.

Residual fertilizer can be defined as the amount of N which would be available after plants had been harvested or ceased nutrient uptake. In this experiment it was the amount of N remaining in prills after 13 weeks of release. Residual fertilizer was

evaluated for fertilizer main effects at each temperature setting and for temperature main effects with each fertilizer.

Total N recovery evaluated the fertilizer products at each incubator temperature setting. All statistical analyses were performed using SAS ANOVA and software (SAS, 1999). Treatment significance and mean separation were performed using ANOVA and the Tukey's mean separation tests with $\alpha = 0.05$.

Meshbag Experiment

CRF fertilizer treatments

The meshbag experiment consisted of eight fertilizer treatments: AN, and seven CRF products (CRF1 through CRF6). CRF2 was divided into CRF2a and CRF2b.

Setup and procedure

Meshbags were prepared by mixing approximately 200 g of soil with 3 g of fertilizer (varying amounts of N). The mix was then tied into porous cheesecloth bags, and labeled at the end of an attached string. The bags were then buried at 10 cm depth from the top of the potato row at the research farm at the Plant Science Research and Education Unit (PSREU) in Hastings, FL with no potato plants present. The meshbags were subject to the same temperature and moisture conditions as plants. They were buried on 13 Feb 2003 with samplings at 20, 35, 48, 62, 76, 91, and 104 days. Due to limited space, meshbags were placed at approximately 20 cm in-row spacing and 100 cm between-row spacing. At two week intervals, three replicates of each fertilizer material were removed from the ground and air-dried. Once dry, the soil was sieved (30-mesh) to remove soil and to retain the fertilizer prills. Prills were ground with a mortar and pestle and any fertilizer was dissolved with DI water. The solution was filtered with #3

Whatman (Whatman International, LTD, Middlesex, UK) filter paper and diluted to 100 ml with DI water in class A volumetric flasks.

Sample analysis

Aqueous samples were stored at -5°C prior to analysis. Samples were analyzed at the University of Florida Analytical Research Laboratory (ARL) for nitrogen by TKN and for EC according to standard protocol (Mylavarapu and Kennelley, 2002).

Statistical analysis

Treatments were arranged in a randomized complete block design with three replicates. Data were analysed factorially for fertilizer product and sampling date main effects. Fertilizer source main effects were analyzed both over all sampling dates as well as for each sampling date. Sampling date main effects were analyzed over all fertilizer products.

All analyses were performed using SAS ANOVA software (SAS, 1999). Treatment significance and mean separation were performed using ANOVA and the Tukey's mean separation tests with $\alpha = 0.05$.

Field Production

Two field experiments were conducted at the University of Florida's Hastings Plant Science Research and Education Unit (PSREU). The first experiment was a CRF production experiment evaluating tuber yield, tuber quality, and plant nutritional status over the course of the season as affected by six different CRF products plus ammonium nitrate (AN) all at three nitrogen application rates together with a no fertilizer control. The second experiment was a replacement experiment in which two potato varieties were evaluated for tuber yield and tuber quality and plant nutritional status, as affected by applying two different CRF products in combination with AN at different ratios (100:0,

75:25, 50:50, 25:75, and 0:100). Weather data was collected and recorded with the Florida Agricultural Weather Network (FAWN) weather station located on the research farm. As production was essentially the same for both experiments with the exception of N fertilization, the production practices described below apply to both experiments except as specified.

General Production

Soils

Soil at the field site is an Ellzey fine sand (sandy, siliceious, hyperthermic Arenic Ochraqualf; sand 90-95%, <2.5% clay, <5% silt, 1% OM).

Irrigation

Subsurface irrigation was used during the season for irrigation. A perched water table was maintained by flooding the growing field with water pumped from wells. A clay hardpan approximately 1 meter below the soil surface prevented deep percolation of this water. The water level was maintained at historical cultural levels (45-60 cm) by controlling the drainage of water from the growing beds in ditches (18.3 m apart) at the bottom of the field.

Planting

Seed potatoes for both trials were cut to approximately 71 g (2.5 oz) pieces and dusted with fungicide (1.1 g (0.04 oz) a.i. fludioxonil and 21.8 g (0.77 oz) a.i. mancozeb per 45.4 kg (100 lb) seed pieces; Maxim MZ, Syngenta Crop Protection, Inc. Greensboro, N.C.) prior to planting.

In the CRF production trial, ‘Atlantic’ potatoes were planted on 13 Feb 2003 and in the replacement experiment, ‘Atlantic’ and ‘Red LaSoda’ potatoes were planted on 20 Feb 2003. Seed potatoes were planted using 20-cm in-row spacing with 24 seed potatoes

per row in each plot of the production experiment and 36 seed potatoes per row in each plot of the replacement experiment. Plots in both trials were four rows wide with between-row spacing of 102 cm. The CRF trial plots were 4.6 m long with 1.2 m in-row border space between plots and the replacement experiment plots were 7.3 m long with 1.8 m in-row border space between plots.

Fertilizer treatments

In the CRF production experiment, treatments consisted of a no nitrogen control (No N) and 7 nitrogen sources (6 CRFs and AN) at three rates (112, 168, and 225 kg ha^{-1} N), representing 50%, 75%, and 100% of the recommended IFAS (or BMP) rate. CRF2 was a blend of CRF2a and CRF2b with 50% of the N coming from each fertilizer source. In the replacement experiment, fertilized treatments consisted of a no nitrogen control (No N) and two CRF products (CRF4 and CRF6) blended with AN at AN:CRF percent N applications of 100:0, 75:25, 50:50, 25:75, and 0:100 totaling 168 kg ha^{-1} N. The nitrogen source in all CRF products was urea. All fertilizer treatments were incorporated into the plot the day of planting. Thirty-four kg ha^{-1} P (76 kg ha^{-1} P_2O_5) and168 kg ha^{-1} K (202 kg ha^{-1} K_2O) were incorporated into all plots prior to planting.

Seasonal management

Pesticide applications were made during the growing season following IFAS extension recommendations (Aerts and Nesheim, 2000; Weingartner and Kucharek, 2004). Soil was fumigated with 1,3-dichloropropene (Telone II, 56 L ha^{-1}, Dow Chemical Company, Indianapolis, IN) in early January prior to planting. Aldicarb (Temik 22.5 kg ha^{-1}, Bayer Chemical Company, Kansas City, MO) was applied at planting. Metribuzin (Sencor, 2.9 L ha^{-1}, Bayer Chemical Company, Kansas City, MO) was broadcast at hilling (approximately 21 days after planting) for weed control. Fungicides were applied

as needed for control of early and late blight following integrated pest management practices.

Soil analysis

A composite soil sample (20 cores of the upper 30 cm) from the entire potato bed was taken on 5 Feb 2003, before planting and prior to fertilizer application. Soil was air-dried, sieved through a 30-mesh sieve, and analyzed by the University of Florida's ARL for pH, nitrate (NO_3-N) and ammonium (NH_4-N) concentrations, phosphorus, calcium, magnesium, electrical conductivity (EC), and soil organic matter (OM) according to standard protocol (Mylavarapu and Kennelley, 2002). Soil samples (8 cores of the upper 30 cm) were taken from each plot in the production experiment at two-week intervals over the growing season at 15, 29, 41, 55, 69, 84, and 97 days after planting (DAP). The final soil samples (97 DAP) were taken one day before final harvest. The replacement experiment was sampled pre-plant and after harvest. All soil samples were dried and sieved as described above. Mid-season soil samples were tested for the same parameters as pre-plant soil samples.

Tissue Sampling and Analysis

Tissue samples consisting of both the leaflets and petiole of the most recently matured (expanded) leaf which had reached full size and had turned a dark-green color (Hochmuth, 1991) were sampled in the production experiment at bi-weekly intervals at 36, 47, 64, and 82 DAP. Six samples from each plot were dried at 70º C until a constant weight was measured. They were then ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass through a 20 mesh sieve, and analyzed for total Kjeldahl nitrogen (TKN) at the ARL. Petiole/leaflet tissue samples were not taken from the replacement experiment.

At full flower, at 64 days after planting (DAP), one plant taken at random from each plot in both the production and the replacement experiments was cut at the soil surface. Leaves and stems were separated, dried, and ground. Samples were then submitted to the ARL for TKN analysis using a standard protocol (Mylavarapu and Kennelley, 2002). Data were used to calculate percent leaf and stem TKN, and leaf, stem, and leaf + stem ("total") dry matter accumulation (DM).

At harvest in both the production and the replacement experiments, four marketable tubers from each plot were skinned. The remaining center was then diced into 1 cm cubes, dried, and ground. Tuber samples were analyzed for TKN at the ARL using standard procedures (Mylavarapu and Kennelley, 2002).

Nitrogen Recovery Efficiency

Nitrogen recovery efficiency reflects the amount of applied nitrogen recovered from the field in tubers. Nitrogen recovery efficiency (NRE) was calculated after the method used by Zvomuya *et al*. (2003) by the following equation:

$$NRE = 100 * (N_{treat} - N_{control}) / N_{applied}$$

where N_{treat} represents the amount of nitrogen removed in the tubers of a given fertilizer treatment, $N_{control}$ is that removed in the tubers of the no fertilizer control plot, and $N_{applied}$ is the amount of nitrogen applied as fertilizer.

Harvest

The center two rows of each plot were mechanically harvested on 28-29 May 2003 at 106 DAP in the production experiment and 2 Jun 2003 at 103 DAP in the replacement experiment using commercial equipment.

Potatoes were washed and graded into five size classes (size 1 ≤ 4.8 cm, 4.8 cm ≤ size 2 ≤ 6.4 cm, 6.4 cm ≤ size 3 ≤ 8.3 cm, 8.3 cm ≤ size 4 ≤ 10.2 cm, size 5 ≥10.2 cm) based on USDA standards (USDA, 1991). Potatoes were grouped according to total yield and marketable yield. Total potato yield is defined as all tubers harvested from the field, independent of size or defects. Marketable yield is defined as no.1 tubers with diameters between 4.8 and 10.2 cm (USDA, 1991) and without any visible blemishes (rotten, green, misshapen, or containing growth cracks).

Specific gravity was measured by the weight in air/weight in water method (Edgar, 1951). Specific gravity is a ratio of water to solid content in a potato tuber. Because 'Atlantic' potatoes are used primarily for chipping, a high specific gravity is desired. Specific gravities of at least 1.078 are considered good for production at the PSREU research farm in Hastings, FL (Hutchinson *et al*., 2002).

Plant physiological disorders reduce tuber yields and quality. Tubers unfit for storage or consumption were removed from the total yields and quantified. Tuber external disorders that reduce marketability include sunburned (green) potatoes, misshapen potatoes, growth crack potatoes, and otherwise rotten potatoes . Tuber internal disorders monitored include hollow heart or brown center, and internal heat necrosis. Also evaluated were disease-induced tuber disorders include corky ring spot and brown rot.

Statistical Analysis

The CRF production experiment was arranged in a randomized complete block design with four replications. Data in the CRF production experiment were analyzed factorially by fertilizer source and rate main effects. Where interactions were significant, simple effects were analyzed. This was followed for total and marketable yields, specific

gravity, tuber quality, plant biomass, nutrient uptake, and nutrient recovery efficiency. In the case of plant tissue analyses, data were also analyzed across all and at each of the sampling dates, and where interactions existed, simple effects were evaluated.

The replacement experiment was arranged in a split plot design with four replications. Statistical analysis involved the evaluation of the various fertilizer blends for each CRF product, though not between products or across potato varieties. This was done for yields, specific gravity, tuber quality, plant biomass, and nutrient recovery efficiency. Linear regression analysis was performed within each fertilizer product and potato variety across all AN:CRF blends.

All analyses for both the production and the replacement experiments were performed using SAS ANOVA software (SAS, 1999, Gary NC). Treatment significance and mean separation were performed using ANOVA and the Tukey's mean separation tests with $\alpha = 0.05$.

Nitrogen Leaching Experiment

The nitrogen leaching experiment was performed within the CRF production experiment mentioned above. One lysimeter and one well were buried in each plot (described below). Samples from both lysimeters and wells were taken at 29, 41, 64, and 78 DAP. Lysimeter and well samples were stored at -5°C until analyzed. All water samples were analyzed at the ARL for NO_3-N and NH_4-N concentrations following standard procedures (Mylavarapu and Kennelley, 2002).

Lysimeters

Suction lysimeters, consisting of a PVC tube having a porous ceramic cup affixed to one end and a rubber stopper affixed to the other, were buried in each plot to a 30 cm depth below the top of the potato row. At two-week intervals over the season, a vacuum

of approximately 40 kPa, was applied to each lysimeter. After 24 hrs, a water sample was removed from the lysimeter. Excess water from the lysimeter was removed and discarded.

Wells

Well casings (PVC pipe, 10 cm diameter by 120 cm long) were buried in each plot at a depth of 90 cm below the soil surface from the top of the potato row to access water in the perched water table. Wells were removed from the field at 104 DAP in order to harvest plots.

Statistical Analysis

As with the CRF production experiment, data were arranged in a randomized complete block design, though with three replicates. Data were analyzed factorially by fertilizer product, rate, and sampling date main effects. Where significant interactions were found, simple effects were evaluated. With the sampling date effects, fertilizer source and rate were analyzed both for each and across all dates.

All statistical analyses were performed using SAS ANOVA software (SAS, 1999). Treatment significance and mean separation were performed using ANOVA and the Tukey's mean separation tests with $\alpha = 0.05$.

CHAPTER 4
RELEASE CHARACTERISTICS OF CONTROLLED-RELEASE NITROGEN FERTILIZERS UNDER CONSTANT TEMPERATURE AND FIELD CONDITIONS

The laboratory and field release experiments were conducted to evaluate the rate of release of nutrients from various controlled-release fertilizer (CRF) products. Hypothetically, if release were predictable, fertilizer blends could be formulated that would match crop uptake requirements. To that end, nitrogen CRF products from various manufacturers were analyzed for rate of N release. These products were analyzed in two experiments: 1) nitrogen (N) release from CRF in DI water inside incubators at constant temperature and fluctuating temperature and 2) N release from CRF in buried meshbags under field conditions. In the incubator experiment, 3 g of N (variable amounts of fertilizer depending on formulation) were mixed with 100 ml DI water. The prills were filtered weekly for thirteen weeks with aqueous samples taken each week, and fresh DI water added, replacing water from each previous week. Residual fertilizer in prills after thirteen weeks was submitted for quantification. Incubator temperatures were 5°C, 10°C, 15°C, 20°C, 25°C, 30°C and a variable temperature incubator which was adjusted weekly to match average soil temperatures over successive weeks of a typical north Florida growing season. In the meshbag experiment, meshbags containing 3 g of CRF (varying amounts of N) mixed with approximately 200 g of soil were buried in the growing field at planting, and were successively removed at two week intervals over the potato growing season and analyzed for residual fertilizer remaining in the prills.

Incubator Experiment Results

Ten fertilizer treatments were analyzed: a no fertilizer control (No N), ammonium nitrate (AN), urea, and seven CRF products (CRF1, CRF2a, CRF2b, CRF3, CRF4, CRF5, and CRF6). CRF2 was split into two products because in the production and leaching experiments (Chapters 5 and 6, respectively) CRF2 was a blend of two fertilizer products, each contributing half of the N applied. For this experiment, these two products were analyzed separately to determine the release profile of each. Although AN and urea are water soluble, they were included as controls. These are currently the local prevailing fertilizer sources for potato production. Table 4-1 shows the various incubator settings with readings taken weekly over the experimental period.

Incubator Experiment Weekly and Cumulative N Release

The weekly release data were analyzed factorially for rate, sampling date, and fertilizer source main effects; the ANOVA table is shown in Table 4-2. Over all temperature settings, fertilizer products, and sampling dates, all main effects were significant as were their interactions: temperature by fertilizer ($p < 0.0001$), temperature by sampling date ($p < 0.0001$), fertilizer by sampling date ($p < 0.0001$), and the third-order interaction, temperature by fertilizer by sampling date ($p < 0.0001$). Thus, further analyses were performed within each effect to evaluate the reasons for these results. As the primary purpose of this experiment was to evaluate the release characteristics of certain fertilizer products and to relate that release to field conditions, each fertilizer product was evaluated for differences of release at each temperature for each sampling date and the various fertilizers were evaluated for differences of release in the variable temperature incubator, also for each sampling date.

Table 4-1. Incubator temperatures during the incubator experiment.

Week	Incubator 5°C		Incubator 10°C		Incubator 15°C		Incubator 20°C		Incubator 25°C		Incubator 30°C		Incubator Variable		Incubator 7 setting (°C)
0[1]	5.0[2]	5.5	10.0	10.5	14.5	14.6	19.5	19.0	24.5	24.5	30.0	30.6	14.0	15.4	15
1	4.3	4.7	9.8	10.4	14.9	15.2	20.0	19.7	24.9	25.3	30.1	30.0	14.2	14.5	15
2	5.0	5.7	10.0	10.1	15.0	15.1	20.0	20.4	25.0	25.4	30.0	30.2	14.0	15.2	15
3	4.0	5.1	9.7	10.3	14.6	14.4	20.0	20.3	25.0	25.5	30.0	30.3	15.6	15.9	16
4	4.3	5.2	9.9	10.2	14.8	14.9	20.0	20.6	24.8	25.2	30.0	30.4	17.3	18.3	18
5	4.5	5.6	10.0	10.0	14.5	15.2	19.5	19.8	25.0	25.5	30.0	29.9	16.9	17.4	18
6	4.0	4.5	9.8	9.4	14.5	15.3	20.0	20.3	24.9	25.2	30.3	30.1	18.2	18.5	19
7	4.2	4.5	10.0	9.6	14.6	15.2	20.0	20.5	24.6	25.4	30.0	30.0	18.0	18.7	19
8	4.1	5.3	10.0	9.8	14.6	14.9	19.8	19.4	24.9	25.4	29.5	30.0	20.8	21.5	21
9	4.1	5.3	10.0	10.0	14.8	15.2	20.0	20.5	25.0	25.2	29.8	30.0	20.6	20.9	21
10	4.3	4.6	10.0	9.7	14.9	15.3	20.0	20.1	24.3	25.0	30.0	30.0	22.5	23.2	23
11	4.3	4.5	10.0	10.2	14.8	15.3	20.0	20.4	25.0	25.4	30.0	30.4	21.5	22.2	22
12	4.2	5.4	10.0	9.8	14.7	15.2	20.0	19.8	24.5	24.6	29.7	30.0	23.4	23.4	23
13	4.3	5.2	9.8	10.0	14.6	14.7	19.9	20.3	24.8	25.5	29.8	30.0	23.9	23.8	24

[1] At week zero, the samples were placed in the incubator after equilibrating, but no sample was submitted for testing.
[2]First temperature represents a water-submerged alcohol thermometer inside incubator; second represents the incubator digital reading.

Table 4-2. ANOVA table for CRF incubator release by sampling date, temperature setting and fertilizer product main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Date	12	1849142746	154095229	3352.85	< 0.0001
Temp	6	83822647	13970441	303.97	< 0.0001
Fert	8	625969804	78246226	1702.5	< 0.0001
Rep	2	30250	15125	0.33	0.7196
Temp*Fert	48	118597592	2470783	53.76	< 0.0001
Date*Temp	72	104261826	1448081	31.51	< 0.0001
Date*Fert	96	1681062415	17511067	381.01	< 0.0001
Date*Temp*Fert	576	237509519	412343	8.97	< 0.0001
Error	1636	75189704	45959		
Corrected Total	2456	4775586503			

Ammonium Nitrate

The release profile of ammonium nitrate (AN) is shown in Table 4-3 and in Figure 4-1. As would be expected for a water-soluble fertilizer, release from AN was characterized by a "flush" of nutrients at the first sampling date, with little N recovery at subsequent samplings. Further, as AN has no temperature-based release, there was little statistical separation between N in the various sample at any of the sampling dates. There was a significant difference in N found in samples taken at 7 DAP, though this would not be expected, and could be due to experimental error. Significant differences found between samples taken at 57 and 64 DAP were not considered of particular use because the concentration of nutrients at this time was practicably zero and within the background range for this experiment.

Urea

The release profile of urea is shown in Table 4-4 and in Figure 4-2. Similar to ammonium nitrate, urea had high initial N release with little residual fertilizer in subsequent samplings. This is not surprising as urea is a water-soluble product. While there was a significant difference in N concentration between samples from the variable

Table 4-3. N release from ammonium nitrate at various incubator settings for each sampling date.

	Days (TKN, mg L^{-1})													
Temperature (°C)	7		14	21	28	35	42	49	57		64		71	78	85	92
5	9471	ab[1]	621	7	4	5	3	5	2	a	3	a	2	2	1	0
10	9432	ab	238	11	3	2	1	1	1	b	1	b	1	0	0	0
15	9721	ab	280	5	3	2	1	3	1	b	1	b	2	0	0	0
20	9656	ab	282	3	4	3	1	2	1	b	1	b	1	0	0	0
25	10185	a	242	7	2	1	1	31	1	b	1	b	2	1	0	0
30	9550	ab	376	7	2	2	1	1	1	b	1	b	2	3	0	0
Variable	9136	b	329	7	2	1	1	2	1	b	1	b	2	0	0	0
ANOVA p-value	0.0232		0.4397	0.2096	0.7104	0.0773	0.0619	0.4915	0.0371		< 0.0001		0.3242	0.0726	0.3126	0.4682
Tukey LSD	817		ns	ns	ns	ns	ns	ns	0.6		0		ns	ns	ns	ns

[1] - Means in columns followed by same letters not significantly different.

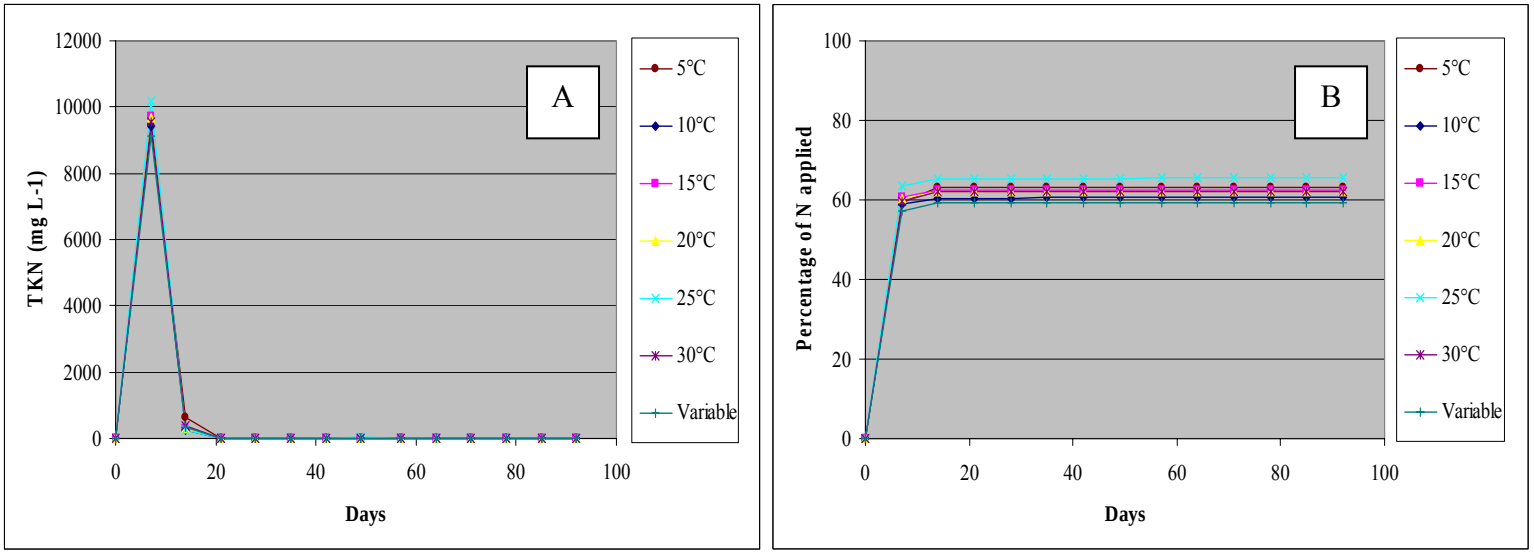


Figure 4-1. Release profile of ammonium nitrate at each incubator setting over the duration of the CRF release experiment. A) Weekly release, B) Cumulative release.

Table 4-4. N release from urea at various incubator settings for each sampling date.

	Days (TKN, mg L^{-1})												
Temperature (°C)	7	14		21	28	35	42	49	57	64		71	78		85	92
5	2491	440	a[1]	11	3	4	4	3	2	2	a	2	3	a	4	0
10	2529	389	a	10	3	4	3	1	1	1	b	1	1	b	0	0
15	2679	400	a	7	4	2	3	2	2	1	b	2	1	b	0	0
20	2626	355	a	7	4	3	3	3	1	2	a	2	1	b	0	0
25	2682	377	a	23	21	5	2	41	1	1	b	3	1	b	0	0
30	2665	359	a	9	6	6	1	3	1	1	b	2	1	b	0	0
Variable	2714	217	b	8	3	7	1	2	0	1	b	2	0	b	3	0
ANOVA p-value	0.0842	<0.0001		0.2220	0.4017	0.6317	0.4166	0.4235	0.2320	0.0003		0.5848	<0.0001		0.1909	0.4682
Tukey LSD	ns	93		ns	ns	ns	ns	ns	ns	0.6		ns	1		ns	ns

[1] - Means in columns followed by same letters not significantly different.

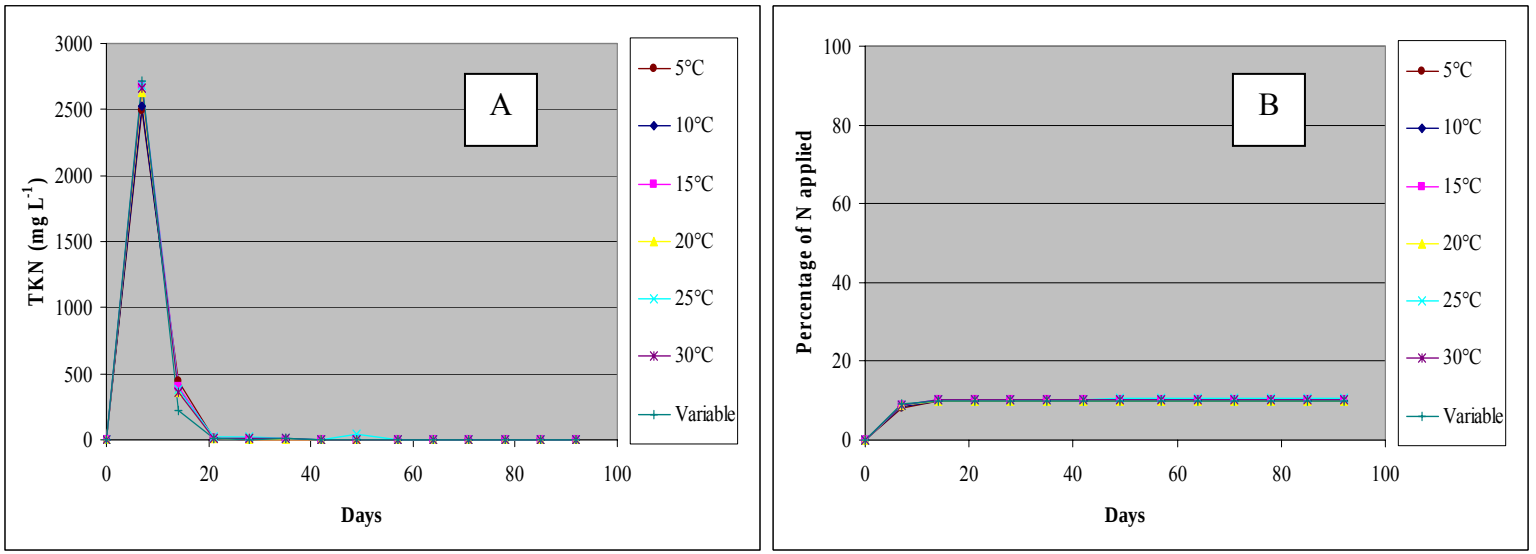


Figure 4-2. Release profile of urea at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

temperature incubator and all other incubators, this is likely due to sample error. The significant separations at 64 and 78 days are artifacts of samples with background concentrations of N and rounding errors rather than actual differences in N. The low percent release (recovery of applied) of N is discussed below (see Total N recovery).

CRF1

The release profile of CRF1 is shown in Table 4-5 and in Figure 4-3. While there was significant separation in N release at the first two sampling dates, CRF1 had a generally similar release profile to urea and AN—high initial release with little subsequent release. As with urea and AN, significant separations at 28, 64, and 78 days are likely due to background levels of N coupled with low-level contamination in random samples causing some statistical differences. While N release at the first sampling date was greater in the 25°C, 30°C, and variable temperature incubators than in the 5°C and 10°C incubators, this temperature-influenced release was not continued at subsequent samplings. This would tend to indicate an initial temperature-based release, though not over time.

CRF2a

The release profile of CRF2a is shown in Table 4-6 and Figure 4-4. Like the water-soluble fertilizer products, CRF2a exhibited little temperature-based release. No significance was found for the first four sampling dates for N concentration from samples in the various incubators, and the differences found at 35 and 64 days were small. In contrast to AN, urea, and CRF1, CRF2a had continued nutrient release over the entire season, albeit at low levels. This would tend to indicate that nutrient inside the fertilizer prills was not entirely depleted and slowly available.

Table 4-5. N release from CRF1 at various incubator settings for each sampling date.

	Days (TKN, mg L^{-1})																			
Temperature (°C)	7		14		21	28		35	42	49	57	64		71	78		85	92
5	2438	d[1]	371	ab	17	2	b	1	7	7	4	2	b	1	14	b	0	0
10	2531	cd	343	ab	17	2	b	1	6	8	3	10	a	27	2	b	0	0
15	2624	bc	419	ab	17	3	b	1	4	8	11	1	c	13	1	b	0	0
20	2588	b-d	424	ab	17	2	b	1	4	11	5	1	c	13	1	b	0	0
25	2704	a	516	a	24	3	b	2	5	7	1	1	c	14	7	b	0	0
30	2646	ab	383	ab	16	20	a	9	10	6	1	1	c	14	84	a	0	0
Variable	2841	b	259	b	19	3	b	10	6	5	3	1	c	16	4	b	0	0
ANOVA p-value	< 0.0001		0.0117		0.3834	0.0182		0.2218	0.4983	0.2928	0.2128	< 0.0001		0.4558	< 0.0001		0.3168	--
Tukey LSD	170		183		ns	16		ns	ns	ns	ns	0		ns	14		ns	ns

[1] - Means in columns followed by same letters not significantly different.

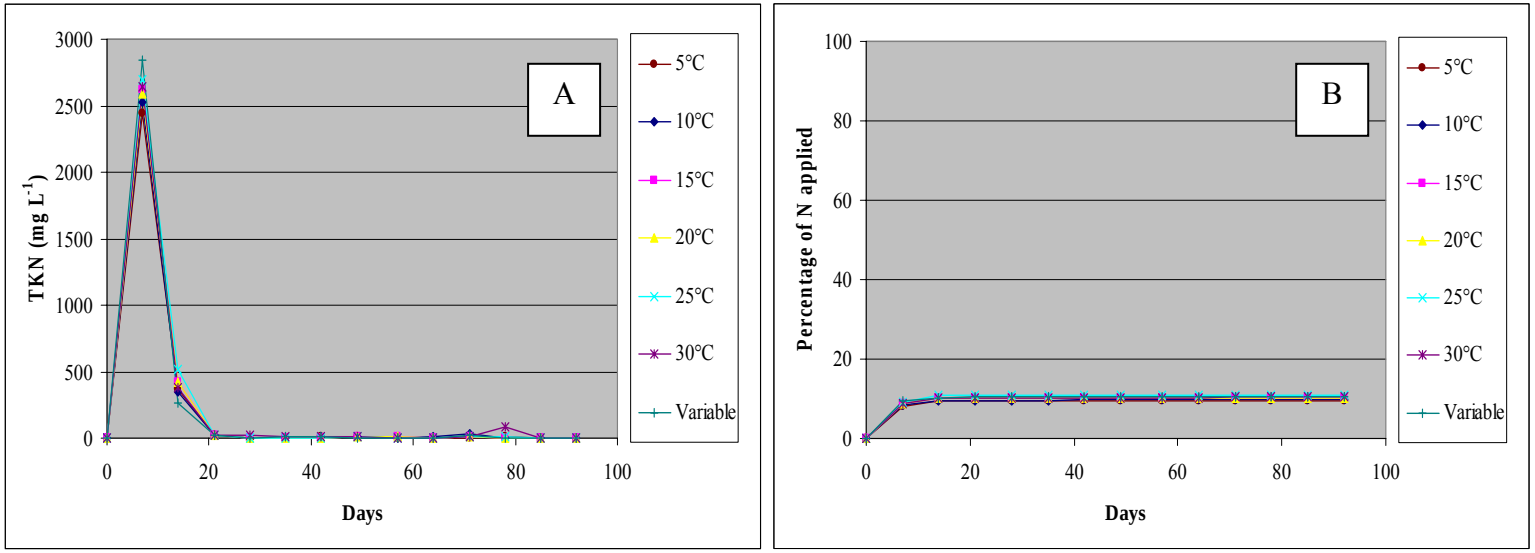


Figure 4-3. Release profile of CRF1 at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

Table 4-6. N release from CRF2a at various incubator settings for each sampling date.

	Days (TKN, mg L^{-1})													
Temperature (°C)	7	14	21	28	35		42	49	57	64		71	78	85	92
5	4043	1183	540	355	317	ab[1]	251	226	195	220	ab	284	226	207	272
10	4231	1084	529	490	411	ab	250	260	281	260	a	369	196	208	176
15	4065	1052	414	514	332	ab	347	284	351	191	ab	246	262	194	195
20	4543	1288	574	534	473	a	424	243	320	180	ab	183	131	247	153
25	5160	1221	562	457	413	ab	270	238	216	162	b	146	103	150	150
30	4890	1267	714	415	315	ab	239	292	457	165	b	123	126	191	141
Variable	4996	1172	454	379	236	b	198	216	180	142	b	190	131	123	157
ANOVA p-value	0.1711	0.5554	0.1555	0.0765	0.0565		0.1424	0.6871	0.4608	0.0047		0.2080	0.1142	0.6138	0.2041
Tukey LSD	ns	ns	ns	ns	233		ns	ns	ns	82		ns	ns	ns	ns

[1] - Means in columns followed by same letters not significantly different.

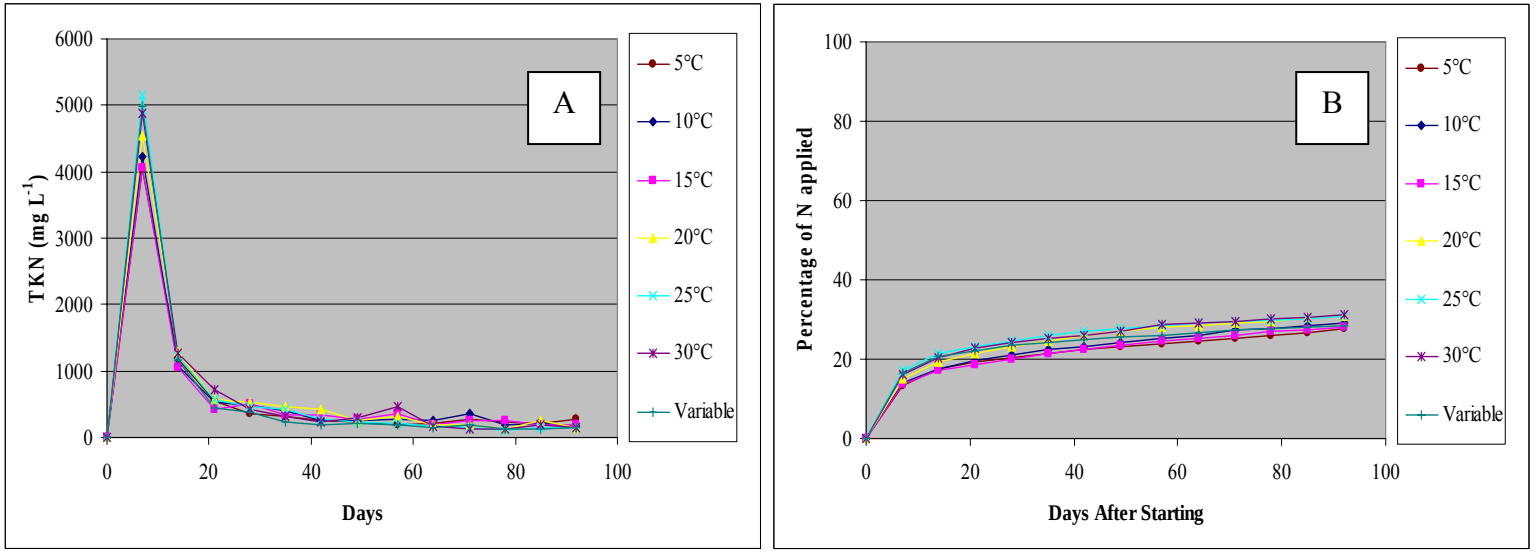


Figure 4-4. Release profile of CRF2a at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

CRF2b

The nutrient release profile for CRF2b is found in Table 4-7 and Figure 4-5. While CRF2b had the spike of initial N release at the first sampling date, it also continued sustained nutrient release throughout the majority of the testing period. Of particular interest, at the first sampling date (7 days), an increase in incubator temperature resulted in an increase in N release, thus indicating temperature-based release characteristics. As would be predicted, N release from the variable incubator was comparable to that from the 15°C and 20°C incubators. Also of note, total release by the end of the study was similar for fertilizer in incubators set at 20°C, 25°C, 30°C, and the variable temperature incubator, in that they had all approached 90% release of total nutrients during the testing period.

CRF3

CRF3 exhibited characteristics between those of CRF and water-soluble products (Table 4-8 and Figure 4-6). At the first sampling date, a large flush of N was observed, while at 14 days, only samples from the 10°C and 30°C incubators had substantially comparable release to the first sampling date. At 21 and 28 days, N release followed a temperature-based trend where significantly greatest release was obtained from samples in the 30°C incubator and least release from the 5°C incubator. Between 42 and 57 days, nutrient release from all samples was substantially higher than from previous samplings, a phenomenon not seen with either the water-soluble or CRF products. At and after 64 days no trend appeared to describe the data, though N concentrations at 71, 78, 85, and 92 days had significant differences.

Table 4-7. N release from CRF2b at various incubator settings for each sampling date.

	Days (TKN, mg L^{-1})																									
Temperature (°C)	7		14		21		28		35		42		49		57		64		71		78		85		92	
5	1870	de	1000	e	620	e	537	c	576	e	522	c	515	d	553	e	550	c	530	c	594	de	548	c	514	bc
10	1758	e	1303	de	953	de	946	bc	866	de	828	bc	776	d	971	de	820	c	838	c	855	cd	783	b	792	ab
15	2416	cd	1722	cd	1379	d	1529	a-c	1654	cd	1618	b	1633	bc	1947	bc	1540	b	1618	b	1470	ab	1228	a	1098	a
20	2684	c	2251	bc	2108	c	2220	a-c	2372	bc	2603	a	2480	a	2566	a	1956	ab	1622	b	1183	bc	811	b	663	b
25	4578	b	2420	b	3482	b	3406	a	3623	a	1524	b	2102	ab	1502	cd	894	c	631	c	413	de	278	d	220	cd
30	5741	a	4530	a	5749	a	2818	ab	2744	ab	1377	b	1072	cd	751	e	412	c	317	c	199	e	156	e	112	d
Variable	2364	cd	1770	cd	1400	cd	1666	a-c	1814	b-d	1621	b	2436	ab	2250	ab	2163	a	2633	a	1768	a	1250	a	812	ab
ANOVA p-value	< 0.0001		< 0.0001		< 0.0001		0.0036		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001	
Tukey LSD	587		552		714		2008		1014		853		827		545		488		703		527		90		371	

[1] - Means in columns followed by same letters not significantly different.

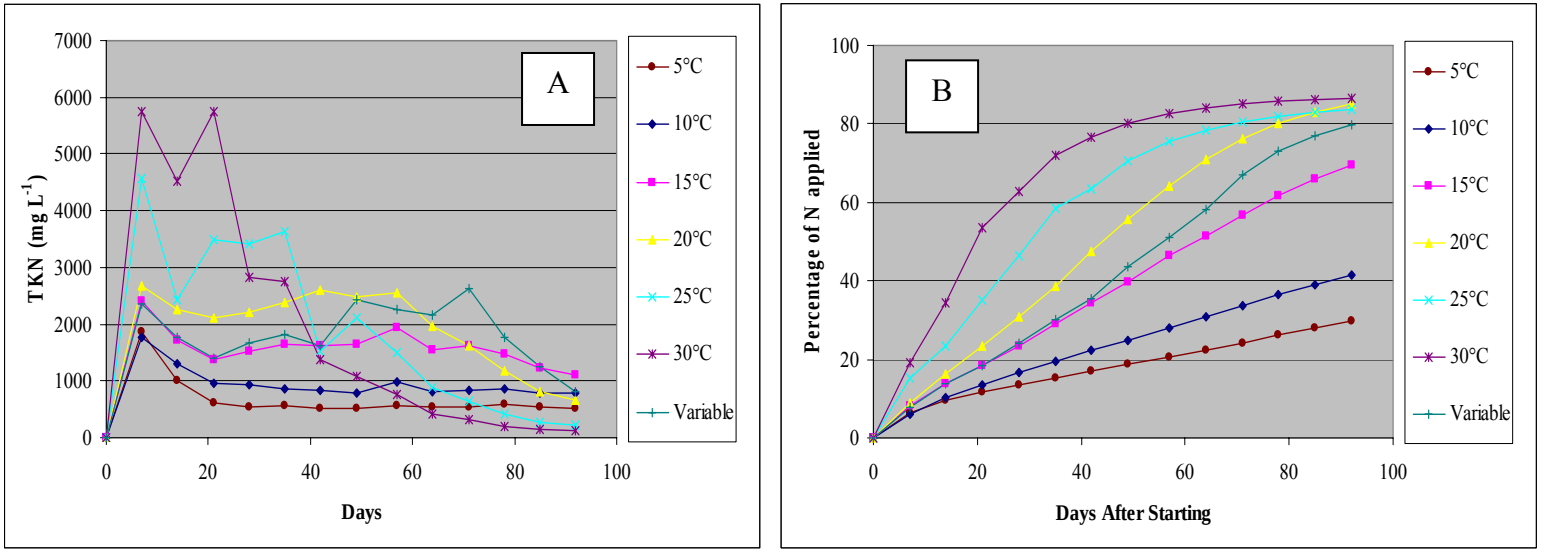


Figure 4-5. Release profile of CRF2b at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

Table 4-8. N release from CRF3 at various incubator settings for each sampling date.

Temperature	Days (TKN, mg L^{-1})																									
(°C)	7	14	21		28		35		42		49		57		64	71		78		85		92				
5	1701	654	94	d[1]	45	c	34	c	228	d	202	c	191	c	75	14	c	135	a	37	c	113	cd			
10	1756	1784	100	d	59	bc	39	c	345	cd	290	bc	272	bc	20	205	a-c	91	a-c	183	ab	155	bc			
15	1859	460	138	c	78	b	59	c	453	a-c	371	ab	350	b	102	233	ab	79	a-c	215	a	189	ab			
20	1926	480	141	c	81	b	80	c	556	ab	439	a	558	a	30	227	ab	100	a-c	173	ab	135	cd			
25	1394	522	180	ab	148	a	86	c	501	a-c	383	ab	32	d	22	271	ab	20	bc	116	bc	102	de			
30	1968	1362	184	a	132	a	600	a	360	b-d	262	c	19	d	14	92	bc	3	c	76	c	62	e			
Variable	1713	315	148	bc	127	a	186	b	648	a	445	a	375	b	39	365	a	132	ab	241	a	220	a			
ANOVA p-value	0.7682	0.2372	< 0.0001		< 0.0001		< 0.0001		0.0002		< 0.0001		< 0.0001		0.3431	0.0008		0.0081		< 0.0001		< 0.0001				
Tukey LSD	ns	ns	34		32		54		204		103		141		ns	194		112		84		46				

[1] - Means in columns followed by same letters not significantly different.

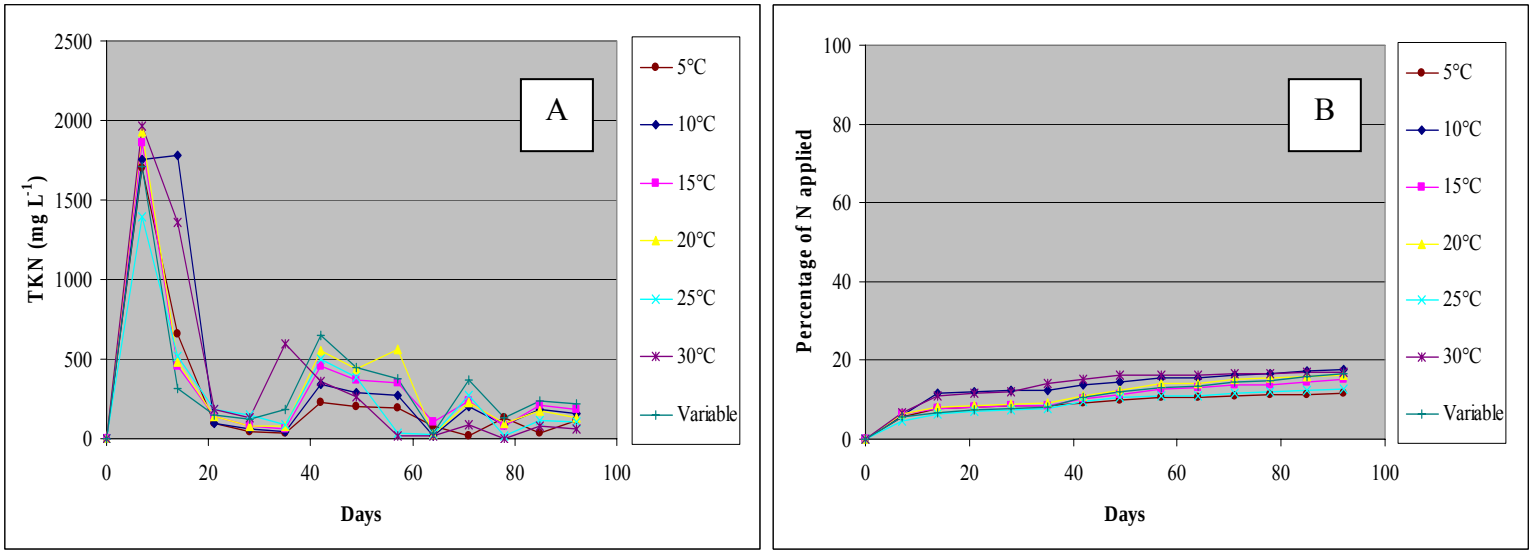


Figure 4-6. Release profile of CRF3 at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

CRF4

The CRF4 release profile is shown in Table 4-9 and Figure 4-7. At the first two sampling dates, no significant difference was found in N concentration between the various incubator temperatures. There was, however, at these early sampling dates, a high initial pulse of N release, as seen with both the water-soluble and the CRF products previously evaluated. At 21 and 28 days, N release followed temperature-based release patterns; highest N release was obtained from samples in the 25°C, 30°C, and variable temperature incubators while least release was obtained from the 5°C and 10°C incubators. After 28 days, though differences were found, N concentrations did not appear to follow a strong temperature-based trend. As with CRF2b, by 92 days, total N release samples in the 20°C, 25°C, 30°C, and the variable temperature incubators was roughly equal. As samples from the third and fourth samplings exhibited temperature-controlled release, it is possible that temperature-based control was also controlling release at the first two samplings, with those effects being masked by a large initial N release.

CRF5

The release profile and sample N concentrations for CRF5 at each sampling date are found in Table 4-10 and Figure 4-8. Of all of the CRF products evaluated, CRF5 exhibited the greatest degree of temperature-based release as evidenced by the significant decrease in N concentrations from samples taken at the first sampling date. This controlled-release trend continued through 49 days, where samples from warm-temperature incubators, generally had greater nutrient release than from cool-temperature incubators. The only exception to this was at 14 days, where none of the samples were statistically different from one another. This is likely due to a lack of precision in

Table 4-9. N release from CRF4 at various incubator settings for each sampling date.

Temperature	Days (TKN, mg L^{-1})																					
(°C)	7	14	21		28		35		42		49		57		64	71		78		85		92	
5	1701	654	94	d[1]	45	c	34	c	228	d	202	c	191	c	75	14	c	135	a	37	c	113	cd
10	1756	1784	100	d	59	bc	39	c	345	cd	290	bc	272	bc	20	205	a-c	91	a-c	183	ab	155	bc
15	1859	460	138	c	78	b	59	c	453	a-c	371	ab	350	b	102	233	ab	79	a-c	215	a	189	ab
20	1926	480	141	c	81	b	80	c	556	ab	439	a	558	a	30	227	ab	100	a-c	173	ab	135	cd
25	1394	522	180	ab	148	a	86	c	501	a-c	383	ab	32	d	22	271	ab	20	bc	116	bc	102	de
30	1968	1362	184	a	132	a	600	a	360	b-d	262	c	19	d	14	92	bc	3	c	76	c	62	e
Variable	1713	315	148	bc	127	a	186	b	648	a	445	a	375	b	39	365	a	132	ab	241	a	220	a
ANOVA p-value	0.7682	0.2372	< 0.0001		< 0.0001		< 0.0001		0.0002		< 0.0001		< 0.0001		0.3431	0.0008		0.0081		< 0.0001		< 0.0001	
Tukey LSD	ns	ns	34		32		54		204		103		141		ns	194		112		84		46	

[1] - Means in columns followed by same letters not significantly different.

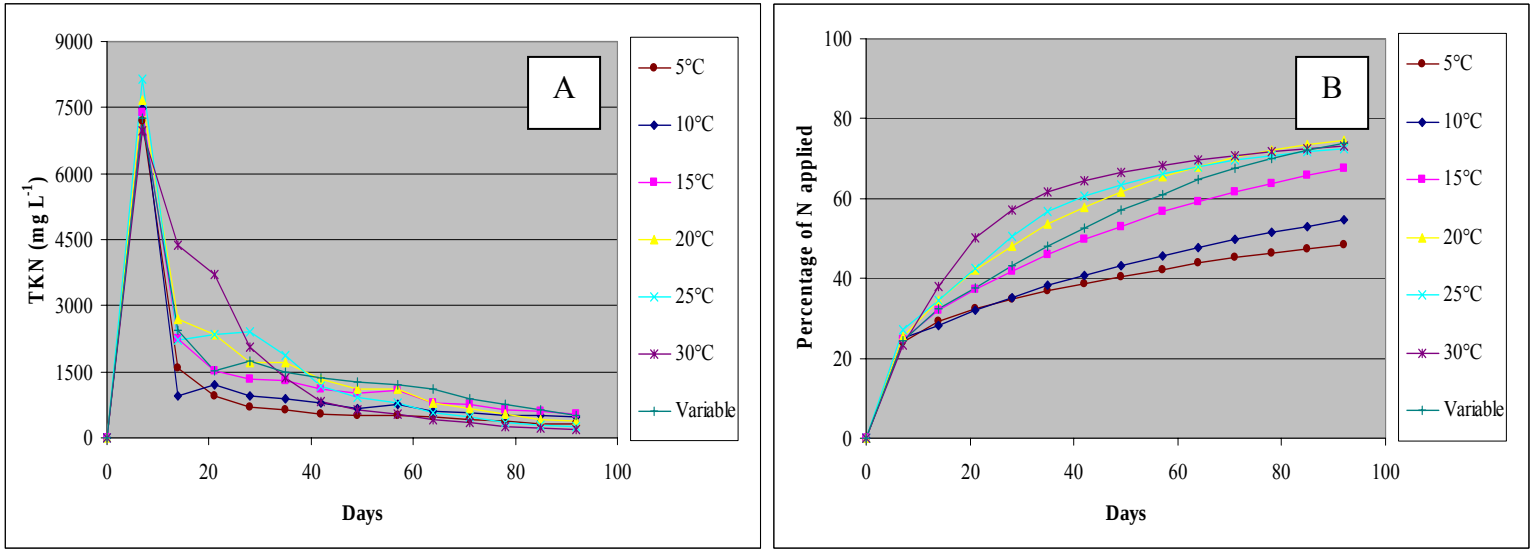


Figure 4-7. Release profile of CRF4 at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

Table 4-10. N release from CRF5 at various incubator settings for each sampling date.

Temperature	Days (TKN, mg L^{-1})																									
(°C)	7		14		21		28		35		42		49		57		64		71		78		85		92	
5	720	c[1]	679	a	391	c	407	d	593	d	576	c	701	d	860	d	810	cd	763	d	790	cd	477	cd	683	b
10	848	c	614	a	530	c	926	d	1027	d	986	bc	1041	c	1231	c	947	c	925	d	841	cd	810	bc	696	b
15	960	c	1114	a	1390	bc	1591	c	1681	c	1445	ab	1307	b	1463	b	1078	bc	1116	c	944	bc	784	bc	801	b
20	1518	bc	2158	a	2354	ab	2414	b	2494	b	1960	a	1760	a	2059	a	1292	ab	1319	b	1060	b	849	b	723	b
25	2648	b	3135	a	3382	a	3396	a	3202	a	1731	ab	1834	a	1578	b	1113	bc	909	d	683	d	583	bc	471	c
30	4530	a	3554	a	3468	a	3492	a	2601	b	1378	a-c	1104	bc	877	d	586	d	467	e	324	e	197	d	228	d
Variable	895	c	1267	a	1592	bc	1847	bc	1847	c	1713	ab	1651	a	1625	b	1607	ab	1550	a	1492	a	1375	a	1239	a
ANOVA.p-value	< 0.0001		0.0224		0.0001		< 0.0001		< 0.0001		0.0010		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001	
Tukey LSD	1240		2986		1721		614		509		815		232		218		342		187		167		357		157	

[1] - Means in columns followed by same letters not significantly different.

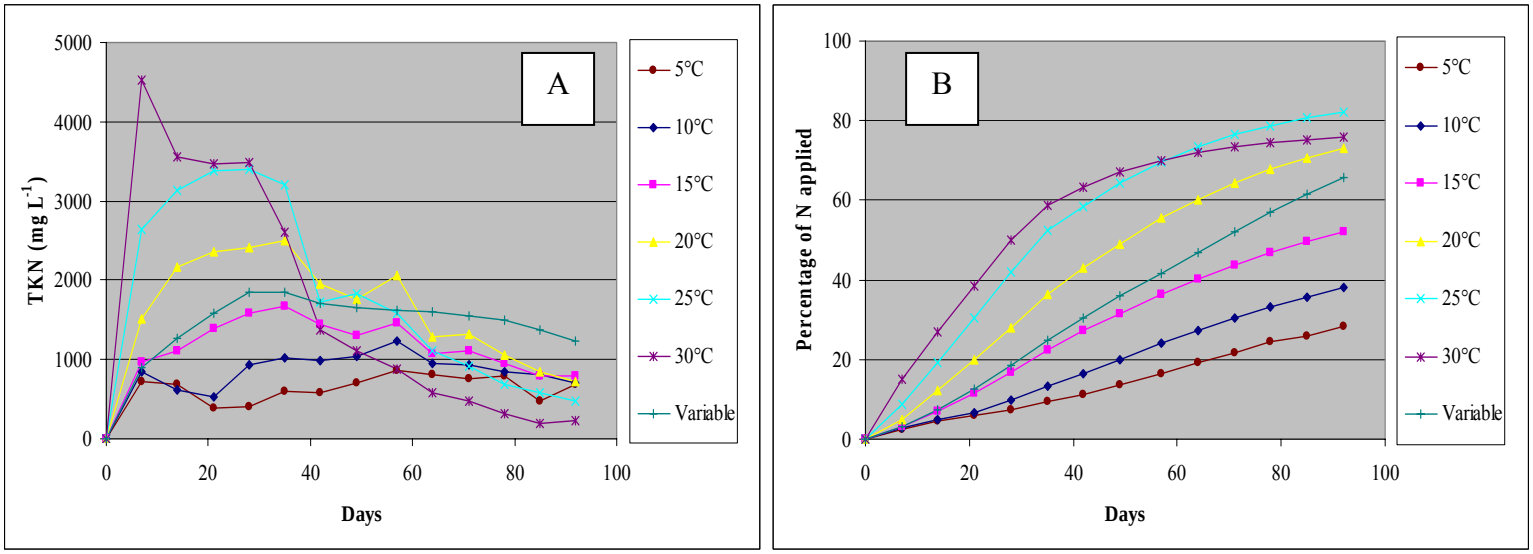


Figure 4-8. Release profile of CRF5 at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

samples taken from the 30°C incubator where concentrations of the three replicates were 358, 4700, and 5500 mg L^{-1} N; it is likely that the first value is a transcriptional error and not a true value. Thus the absence of statistical differences is an error and true separation would have likely followed trends set both before and after that sampling date, as evidenced by the decreasing N concentration in successively cooler incubators. Of note with CRF5, however, was that independent of temperature, this product never reached greater than 90% release over the course of the experiment. Under field conditions, it would be desirable to have a greater rate of release, so as to be useful to the plant during the growing season. It should be noted that nutrient release from this product may have been incomplete as substantial N was released even after 92 days, and illustrated by the positive slope of the cumulative release curves in Figure 4-8, B.

CRF6

The release profile for CRF6 with accompanying N concentrations from the various incubators at each sampling date are shown in Table 4-10 and Figure 4-9. CRF6 was the only fertilizer product evaluated that did not have a substantial initial release of N. Like CRF5, it exhibited good temperature-based release. From the data, it appears that this product had somewhat of a sigmoidal-type release—a period of no nutrient release followed by a linear release curve, finally tapering off as the product was depleted. This is illustrated by the S-pattern in the cumulative release curve for CRF6 (Figure 4-9, B). Of note with this product was its continued release of substantial quantities of nutrients through the end of the experiment period. Also, after 92 days of release, only product in the 30°C incubator had released even 70% of its nutrients; all other temperature regimes had resulted in 60% or less total N release. As with CRF5, the positive slope of the cumulative release curve between 85 and 92 days tends to indicate that further release

Table 4-11. N release from CRF6 at various incubator settings for each sampling date.

Temperature	Days (TKN, mg L^{-1})																									
(°C)	7	14		21		28		35		42		49		57		64		71		78		85		92	
5	331	295	b	113	b	104	e	137	c	134	e	99	d	118	c	150	d	155	e	185	e	193	f	232	d
10	208	270	b	60	b	91	e	149	c	151	e	197	d	289	c	277	d	322	e	322	e	315	e	342	d
15	301	350	b	168	b	229	de	369	c	501	d	647	c	918	b	837	c	912	d	886	d	822	d	900	bc
20	377	451	b	438	b	750	c	998	b	1031	c	1157	b	1664	a	1197	b	1185	c	1113	c	970	c	968	b
25	481	466	b	1179	ab	1826	b	2034	a	1637	b	1777	a	1919	a	1636	a	1540	a	1350	ab	1150	b	989	b
30	650	1591	a	1598	a	2562	a	2466	a	2072	a	1893	a	2028	a	1639	a	1472	ab	1239	bc	1000	c	789	c
Variable	562	198	b	237	b	342	d	551	bc	700	d	907	bc	1100	b	1274	b	1350	bc	1436	a	1400	a	1383	a
ANOVA p-value	0.1037	< 0.0001		0.0022		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001	
Tukey LSD	ns	434		1127		231		448		218		283		477		175		177		163		112		159	

[1] - Means in columns followed by same letters not significantly different.

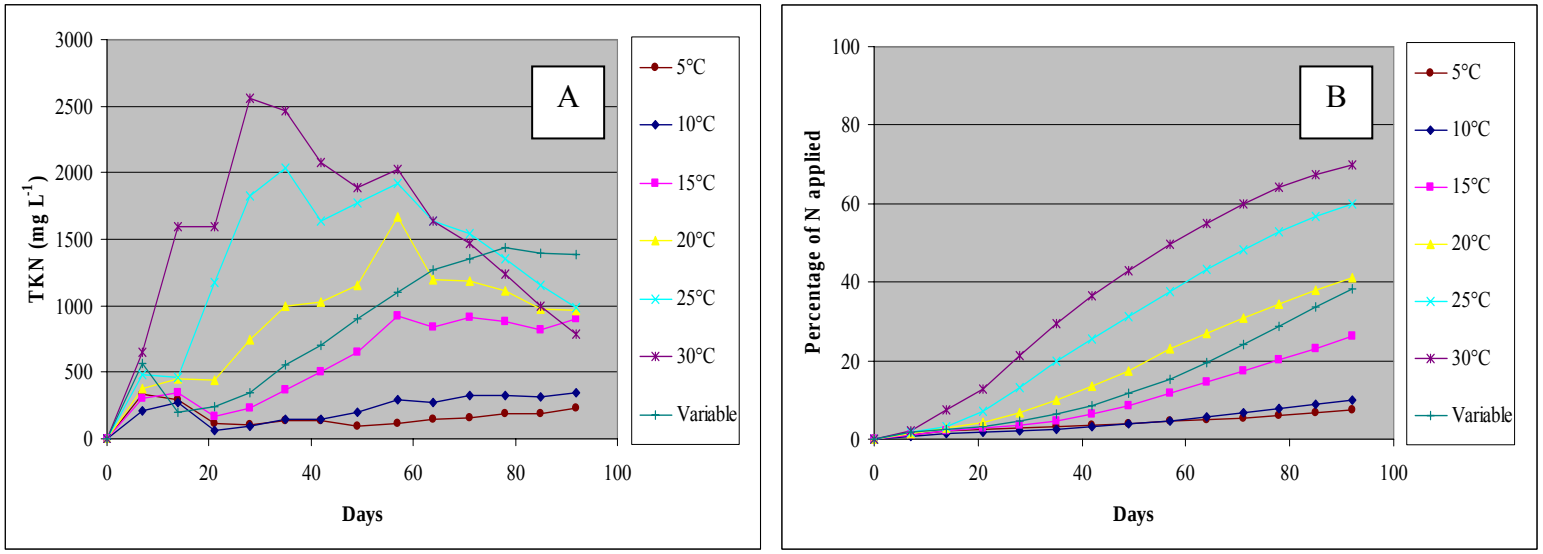


Figure 4-9. Release profile of CRF6 at each incubator setting over the duration of the incubator experiment. A) Weekly release, B) Cumulative release.

would occur, although it would be useless with respect to the typical 'Atlantic' potato growth cycle.

No N Control

N found from the no fertilizer control at the various sampling dates is illustrated in Figure 4-10. It serves to illustrate the background degree of contamination that occurred throughout the sampling dates of the experiment. Early in the experiment, as high quantities of N were found in the various samples, contamination in the control was higher than late in the season when many of the CRF products had been depleted and the water-soluble products had been removed.

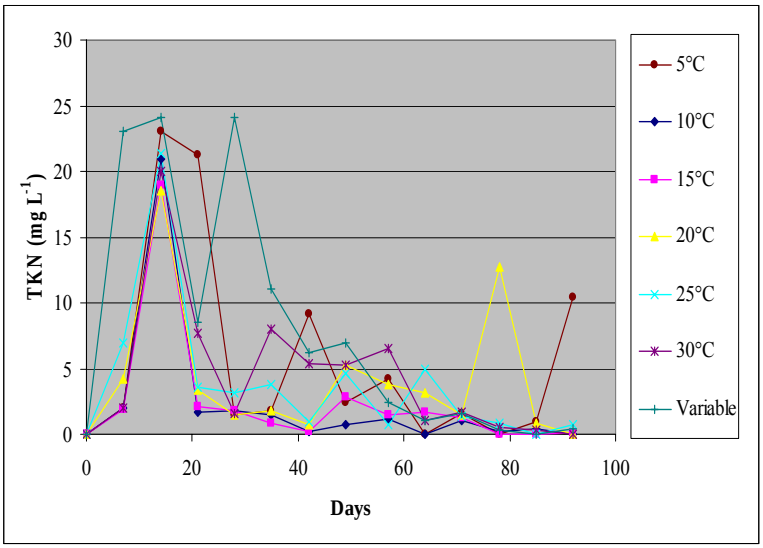


Figure 4-10. N found in the no fertilizer control within each incubator for various sampling dates.

Variable Temperature Incubator Release

As one of the purposes of this experiment was to evaluate the release of various CRF products under simulated field conditions, the nutrient release of the fertilizer products under varying temperature conditions was evaluated. The release profiles and nutrient release from each fertilizer at each sampling date are shown in Table 4-12 and in Figure 4-11. As noted previously with each individual fertilizer, all products with the

Table 4-12. N release from fertilizer products in the variable temperature incubator for each sampling date.

	Days (TKN, mg L^{-1})																							
Fertilizer	7		14		21		28		35		42		49		57		64		71		78		85		92	
AN	9136	a	329	d	7	e	2	b	1	b	1	c	2	e	1	h	1	d	2	e	0	c	0	f	0	d
Urea	2714	d	217	d	8	e	3	b	7	b	1	c	2	e	0	i	1	d	2	e	0	c	3	f	0	d
CRF1	2841	d	259	d	19	e	3	b	10	b	6	c	5	e	3	g	1	d	16	e	4	c	0	f	0	d
CRF2a	4996	c	1172	c	454	c	379	b	236	b	198	c	216	e	180	f	142	d	190	e	131	c	129	e	157	d
CRF2b	2364	de	1770	b	1400	b	1666	a	1814	a	1621	a	2436	a	2250	a	2163	a	2633	a	1768	a	1250	b	812	b
CRF3	1713	e	315	c	148	de	127	b	186	b	648	b	445	de	375	e	39	d	365	de	132	c	241	d	220	d
CRF4	7270	b	2451	a	1533	ab	1728	a	1475	a	1357	a	1278	bc	1200	c	1109	c	900	cd	751	b	636	c	494	c
CRF5	895	f	1267	c	1592	a	1847	a	1847	a	1713	a	1651	b	1625	b	1607	b	1550	b	1492	a	1375	a	1239	a
CRF6	562	f	198	d	237	de	342	b	551	b	700	b	907	cd	1100	d	1274	bc	1350	bc	1436	a	1400	a	1383	a
ANOVA p-value	< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001	
Tukey LSD	786		168		182		443		859		438		645		1		403		585		464		53		260	

[1] - Means in columns followed by same letters not significantly different.

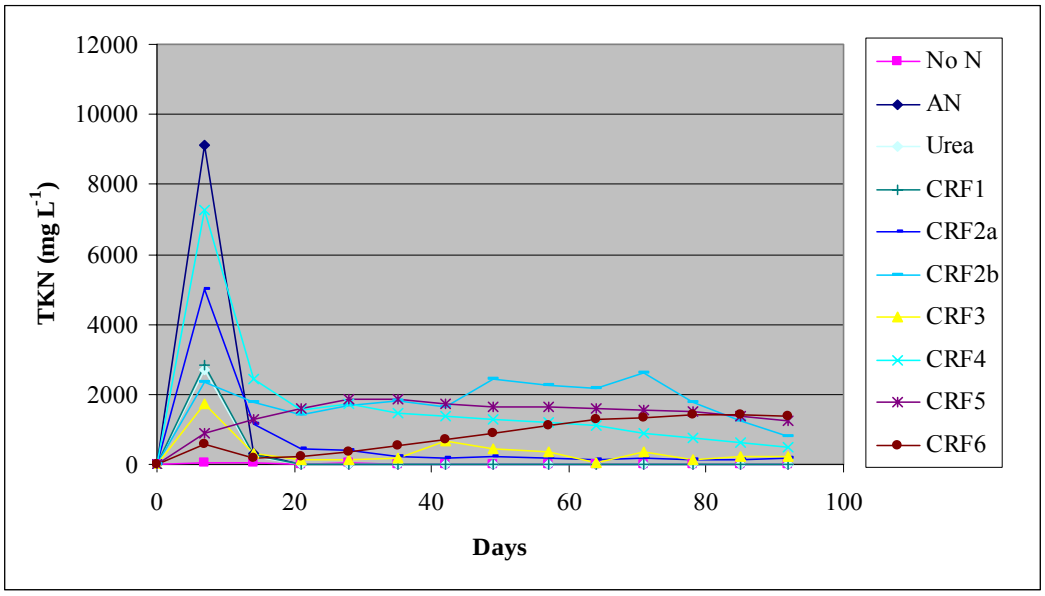


Figure 4-11. Release profile of fertilizer product at the variable incubator setting over the duration of the CRF release experiment

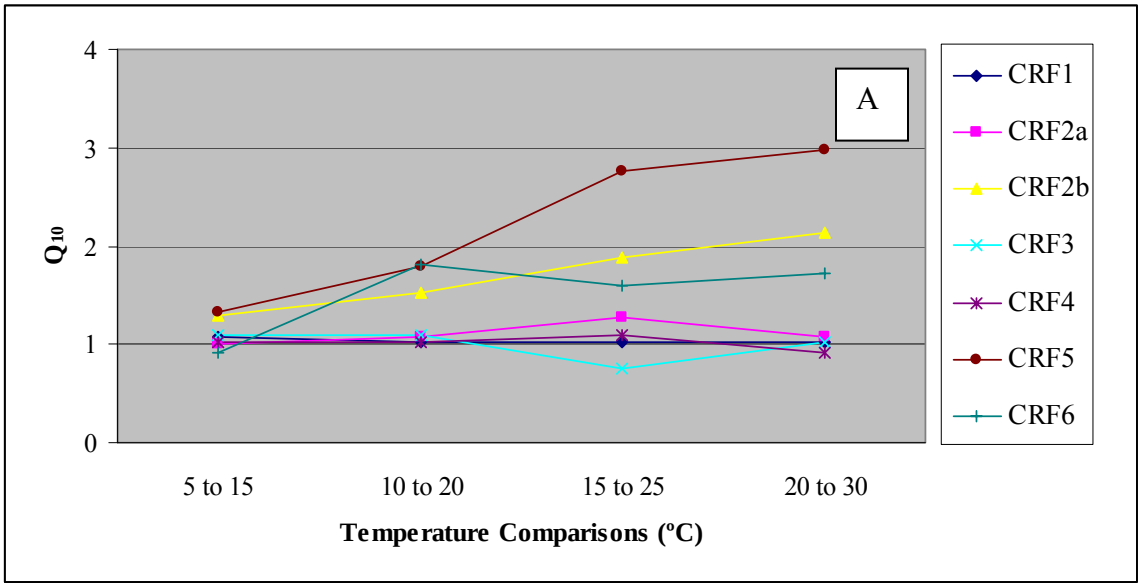
exception of CRF6 had substantial release at the first sampling date. Of the fertilizer products evaluated, CRF2b, CRF4, and CRF6 had the greatest degree of sustained release over the entire experiment.

When compared against each other, AN and CRF4 had significantly the greatest N release at the first sampling dated, while sustained release from 14 through 49 days was highest with CRF2b, CRF4 and CRF5. Late in the experiment, as CRF4 was depleted, CRF2b, CRF5, and CRF6 had highest release. With the exception of the first two sampling dates, AN, urea, and CRF1 had essentially zero N release, typical of a water-soluble fertilizer product.

Q_{10}

Early in the experiment (7 and 14 day sampling dates), the release of each fertilizer with respect to incubator temperature provided a good estimate of Q_{10} values for each product. CRF1 and CRF2a, together with the water soluble fertilizers, AN and urea, had a single flush of N release which was independent of temperature, hence Q_{10} values for

these products were roughly 1. Q_{10} values were greatest for CRF5, both at the 7 and 14 day samplings across all temperature comparisons (Figure 4-12, A and B). Also from these data, Q_{10} values varied considerably over the biological range depending on where one was within that range. For example, CRF5 at the 7 day sampling has a Q_{10} of 1.3 between 5 and 15°C, but a Q_{10} of 3.0 between 20 and 30°C. Q_{10} values for sampling dates beyond 14 days were not calculated because of a "depletion" effect that could occur



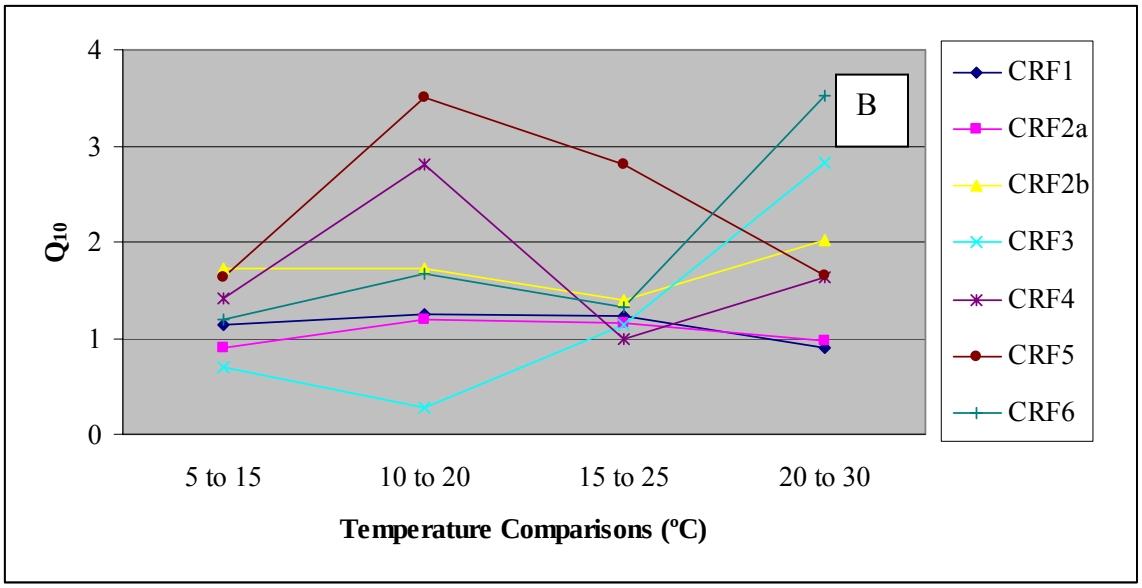


Figure 4-12. Q_{10} values for various CRF products. A) at 7 days, B) at 14 days.

where future fertilizer release if affected by differing amounts of fertilizer previously released and correspondingly different remaining concentrations.

Residual Fertilizer

After 13 weeks of release, the fertilizer products were ground and the residual fertilizer dissolved and submitted for TKN analysis. No residual analysis was run for urea or AN because of zero residual recovery. The ANOVA table for factorial analysis of incubator temperature and fertilizer source is shown in Table 4-13. As there was a significant interaction ($p < 0.0001$) between the main effects and it was not of interest to evaluate each product and temperature setting with all other product-temperature combinations, differences in residual N from the fertilizer products was evaluated at each temperature setting (Table 4-14) and the effects of the various temperature settings on N release were evaluated for each CRF product (Table 4-15).

Table 4-13. ANOVA table for residual N by incubator temperature and fertilizer product main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Temp	6	17647	2941	333.63	< 0.0001
Fert	6	68808	11468	1300.86	< 0.0001
Rep	2	24	12	1.38	0.2565
Temp*Fert	36	14063	391	44.31	< 0.0001
Error	96	846	9		
Corrected Total	146	101389			

Within the coolest three incubators (5, 10, and 15°C), both CRF2a and CRF6 had the greatest amount of residual fertilizer after 13 weeks while CRF1 had significantly the least residual N of all products (Table 4-14). Within the warmest constant-temperature incubators (20, 25 and 30°C), significantly greatest residual was found in CRF2a while CRF1 continued with the least residual N. The lack of residual N in CRF1 and, to a

Table 4-14. Residual N recovery (% of applied) from CRF products after 13 weeks of release for each incubator.

	TKN (% of applied)											
Fertilizer	5°C		10°C		15°C		20°C		25°C		30°C		Variable	
CRF1	1.2	e[1]	1.1	f	1.5	d	1.1	e	2.0	d	0.9	c	1.0	f
CRF2a	65.5	b	64.6	b	66.4	a	64.9	a	68.1	a	65.8	a	67.2	a
CRF2b	62.2	b	47.6	c	21.5	c	9.0	de	4.3	cd	1.8	c	7.9	de
CRF3	14.4	d	10.4	e	14.3	cd	4.6	de	4.0	cd	3.2	c	4.5	ef
CRF4	36.4	c	28.6	d	19.3	c	12.0	cd	7.3	c	7.3	c	12.5	d
CRF5	63.9	b	52.2	c	39.7	b	20.9	c	8.5	c	3.7	c	22.4	c
CRF6	79.4	a	64.6	a	60.5	a	49.7	b	28.2	b	18.3	b	47.1	b
ANOVA *p*-value	0.0001		0.0001		0.0001		0.0001		0.0001		0.0001		0.0001	
Tukey LSD	10.5		9.0		12.8		9.4		4.6		7.6		5.3	

[1] - Means in columns followed by same letters not significantly different.

Table 4-15. Residual N recover (% of applied) from CRF products after 13 weeks of release at each temperature setting.

	TKN (% of applied)													
Temperature (°C)	CRF1		CRF2a		CRF2b		CRF3		CRF4		CRF5		CRF6	
5	1.2		65.5		62.2	a[1]	14.4	a	36.4	a	63.9	a	79.4	a
10	1.1		64.6		47.6	b	10.4	a	28.6	b	52.2	b	64.6	a
15	1.5		66.4		21.5	c	14.3	a	19.3	c	39.7	c	60.5	b
20	1.1		64.9		9.0	d	4.6	b	12.0	d	20.9	d	49.7	c
25	2.0		68.1		4.3	d	4.0	b	7.3	d	8.5	e	28.2	d
30	0.9		65.8		1.8	d	3.2	b	7.3	d	3.7	f	18.3	e
Variable	1.0		67.2		7.9	d	4.5	b	12.5	d	22.4	d	47.1	c
ANOVA *p*-value	0.657		0.9782		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001	
Tukey LSD	ns		ns		10.1		5.8		5.9		4.8		9.7	

[1] - Means in columns followed by same letters not significantly different.

lesser degree, CRF3, independent of temperature, is of concern because they imparted no nutrient retentive advantage over AN or urea. Having noted a high initial nutrient release, hope might have been maintained all of the fertilizer was not lost, merely locked into the prill. However, with little residual, it becomes apparent that all N was released at the first sampling date. At 30°C, CRF2a and CRF6 had 65.8% and 18% residual N, respectively. This is of concern because after 90-100 days, most potato plants have ceased uptake and even been harvested. This residual fertilizer would remain in the field though with no crop to take it up, again potentially leading to leaching conditions. Residual N from samples in the incubator temperature fell perfectly between that found in the 15°C and 25°C incubators, the predicted response as temperatures in the variable temperature incubator were always between these two values.

Considering each CRF across temperature settings (Table 4-15, Figure 4-13), both CRF1 and CRF2b had little change in nutrient release as temperature was changed. This indicates no temperature-based control. Conversely, CRF2b, CRF4, CRF5, and CRF6 had significant reductions in residual fertilizer as incubator temperature setting was increased, tending to indicate varying degrees of temperature-based control. CRF3 had intermediate characteristics between CRF and water-soluble products in that residual N was not significantly different for the lower temperature settings or for the higher settings, though a significant decrease

in residual was found between the two sets of temperatures. With the exceptions of CRF2a and CRF6, the CRF products had very little residual fertilizer at either 25°C or 30°C.

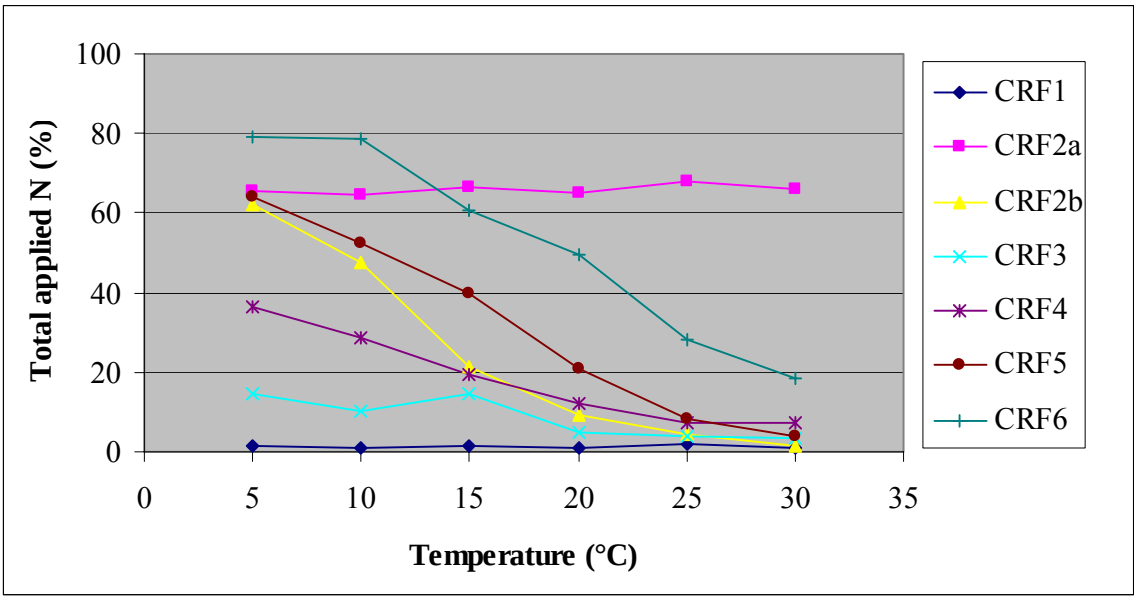


Figure 4-13. Residual TKN (% of applied) for various CRF products as affected by temperature.

Total N Recovery

The total amount of N recovered from the 13 weeks of release added to the amount of N recovered from the residual found still inside the fertilizer prills constitutes the total recovery of fertilizer. The percentages recovered are found in Table 4-16 and illustrated in Figure 4-14 and Figure 4-15. CRF2a, CRF2b, CRF4, CRF5, and CRF6 all had total recoveries greater than 80%, with CRF2a having total recoveries greater than 90%, across all temperatures.

Meshbag Experiment

The meshbag experiment consisted of eight fertilizer products thoroughly mixed with soil and buried in the growing field. The fertilizers consisted of ammonium nitrate (AN) and the seven CRF products as were evaluated in the incubator experiment. In preparing the meshbags, three grams of fertilizer (varying amounts of N) were applied to approximately 100 g of field soil, mixed, and placed into a cheesecloth “bag”, labeled,

Table 4-16. Total N recovery (% of applied) from fertilizer treatments from solution and residual sources for each temperature setting.

	TKN (% of applied))																				
	5°C			10°C			15°C			20°C			25°C			30°C			Variable		
Fertilizer	Soln[1]	Res	Tot	Soln	Res	Tot	Soln	Res	Tot	Soln	Res	Tot	Soln	Res	Tot	Soln	Res	Tot	Soln	Res	Tot
AN[2]	68	0	68	61	0	61	63	0	63	62	0	62	65	0	65	62	0	62	59	0	59
Urea	13	0	13	10	0	10	10	0	10	10	0	10	11	0	11	10	0	10	10	0	10
CRF1	10	1	11	10	1	11	10	2	12	10	1	11	11	2	13	11	1	12	11	1	12
CRF2a	27	65	92	28	65	93	28	66	94	31	65	96	31	68	99	31	66	97	28	67	95
CRF2b	28	62	90	39	48	87	70	21	91	85	9	94	84	4	88	87	2	88	69	8	77
CRF3	11	14	26	18	10	28	15	14	30	16	5	21	13	4	17	17	3	20	21	4	25
CRF4	47	36	83	55	29	83	68	19	87	75	12	87	73	7	80	73	7	80	71	13	84
CRF5	25	64	89	38	52	90	52	40	92	73	21	94	82	8	91	76	4	80	58	22	80
CRF6	7	79	86	10	79	89	26	61	87	41	50	91	56	28	84	67	18	85	32	47	79

[1] Soln = solution; Res = residual; Tot = total. All values in % of applied.

[2] AN values are corrected for total recovery based on 1.6 g N applied as NH_4-N.

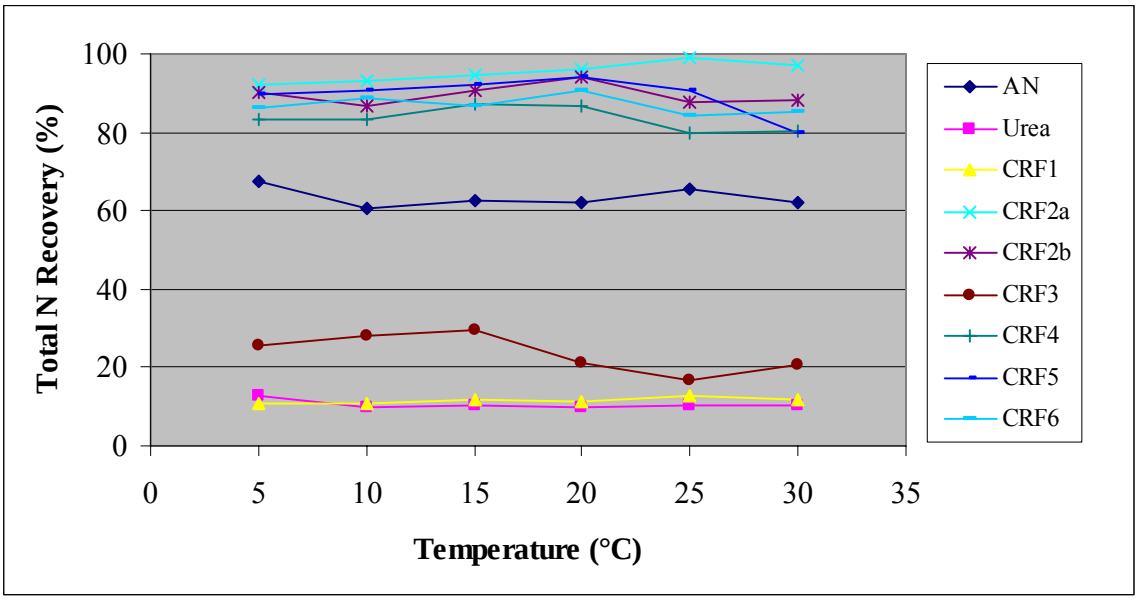


Figure 4-14. Total N recovery from dissolution and residual analysis across all temperatures.

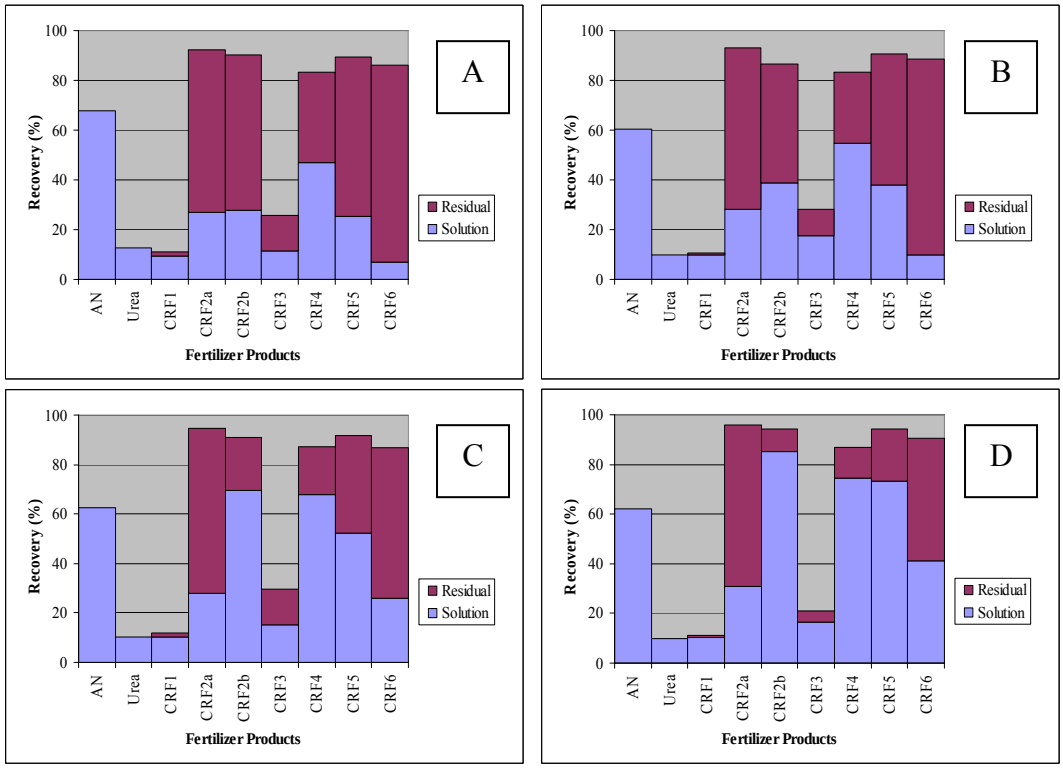


Figure 4-15. Graphical breakdown of the total recovery of fertilizer treatments at various temperatures. A) 5°C, B) 10°C, C) 15°C, D) 20°C, E) 25°C, F) 30°C, G) variable temperatures.

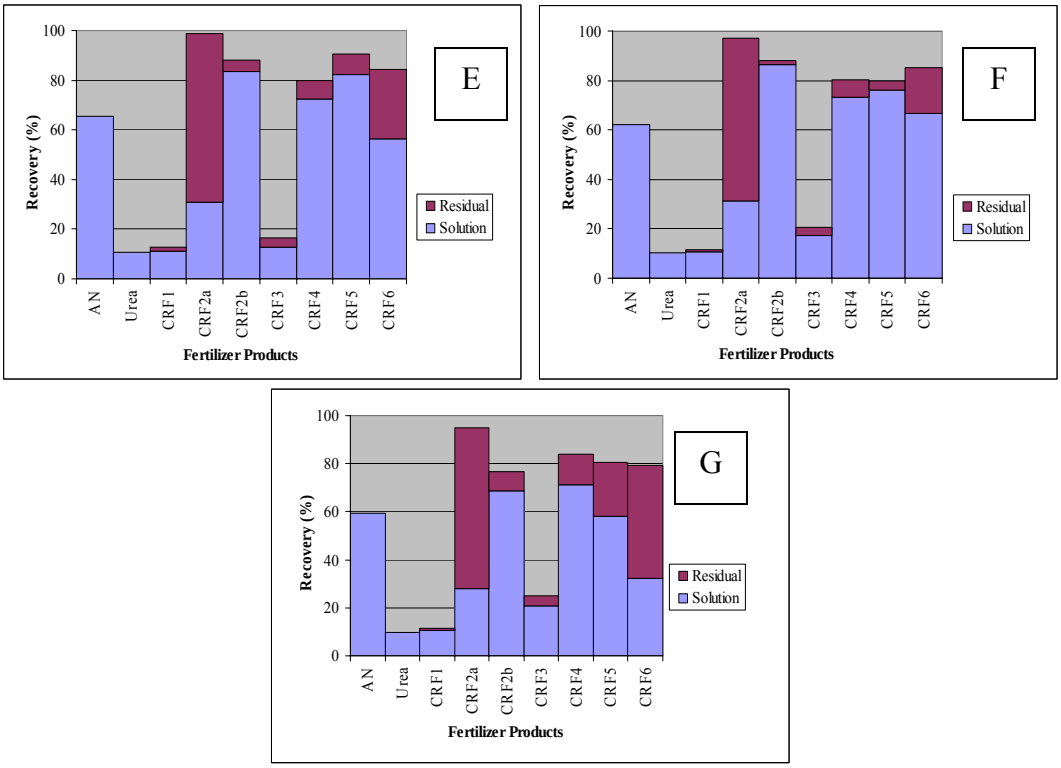


Figure 4-15. Continued.

and tied with twine. Enough bags were prepared for three replicates of each product to be removed from the field every two weeks over the growing season (7 total samplings at 20, 35, 48, 62, 76, 91, and 104 DAP). At two-week intervals, meshbags were removed from the field, air-dried, and sieved with a 20-mesh sieve to remove soil particles. The prills were then ground to disrupt the polymer coating and the residual fertilizer dissolvedand analyzed by TKN analysis. Also analyzed were pure fertilizer prills to give a baseline of total available N before field application.

Meshbag Experiment Results

ANOVA testing for the treatment and sampling date main effects revealed a significant interaction between the effects (Table 4-17). As it was not of interest to evaluate every fertilizer product and sampling date combination, the various fertilizer products were evaluated at each sampling date (Table 4-18, Figure 4-16). For each of the

Table 4-17. ANOVA table for released N (% of applied) by fertilizer treatment and sampling date main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Trt	5	1.6801	0.336	95.6	< 0.0001
Date	6	2.1965	0.366	104.16	< 0.0001
Rep	2	0.007	0.0035	0.99	0.3743
Trt*Date	30	0.463	0.0154	4.39	< 0.0001
Error	82	0.2882	0.0035		
Corrected Total	125	4.6347			

sampling dates, AN, a water-soluble fertilizer, and CRF1, a product that breaks up into tiny granules, were not recovered. Accordingly, no residual analysis was performed. CRF3 had the greatest release of N by day 20, statistically higher than all other CRF products except CRF2b. However, CRF3 at subsequent samplings released only 10% of applied more, similar to a water soluble product. At 20 DAP, CRF2a had released only 31% of its N, yet by the 104 DAP, it had released a total of 72% of its total contents—28% was still in the prills after 104 days. CRF6, at 20 DAP, had released less fertilizer than any other product, 23%. However, it continued to release steadily throughout the season and by 104 DAP it had released 90% of its contents. For potato production in Florida, it is desirable to have around 70 to 80 % release by full flower which occurs around 60 days after planting. Of the CRF products evaluated, CRF2b, CRF3, CRF4, and CRF5 all met that criteria, though CRF3 would likely not perform well for potato production because after its initial high release, little fertilizer was subsequently released for plant use. Figure 4-17 converts Figure 4-16 from a DAP to a degree-day basis, using a base temperature of 5°C. This is useful for calculating nutrient release based on physiological age of the plant and adjusts for seasonal temperature variations.

Table 4-18. Cumulative N release (%) from CRF products at each sampling date for each fertilizer.

	DAP[1]						
Fertilizer	20	35	48	62	76	91	104
CRF2a	31 cd[2]	57 b	63 b	60 c	70 d	70 c	72 c
CRF2b	63 ab	86 a	93 a	94 a	99 a	98 a	99 a
CRF3	85 a	89 a	89 a	90 ab	91 ab	96 a	95 ab
CRF4	48 bc	72 ab	72 ab	81 b	84 bc	88 b	92 ab
CRF5	41 b-d	62 b	75 ab	87 ab	89 a-c	94 a	94 ab
CRF6	23 d	57 b	55 b	65 c	78 cd	84 b	89 b
ANOVA *p*-value	0.0001	0.0002	0.0010	0.0001	0.0001	0.0001	0.0001
Tukey LSD	24	19	23	11	11	5	8

[1] - DAP = Days after planting.

[2] - Means in columns followed by same letters not significantly different.

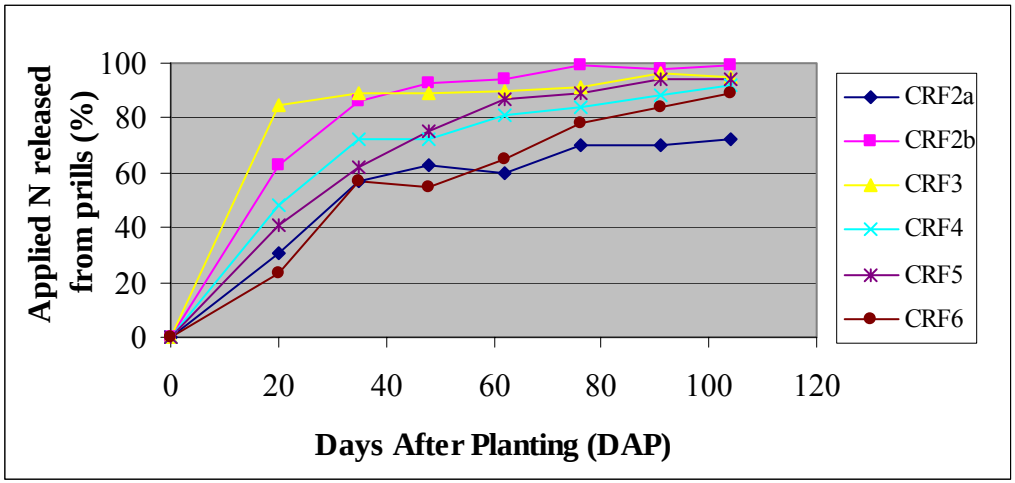


Figure 4-16. Cumulative N release (% of applied) from CRF products at each sampling date.

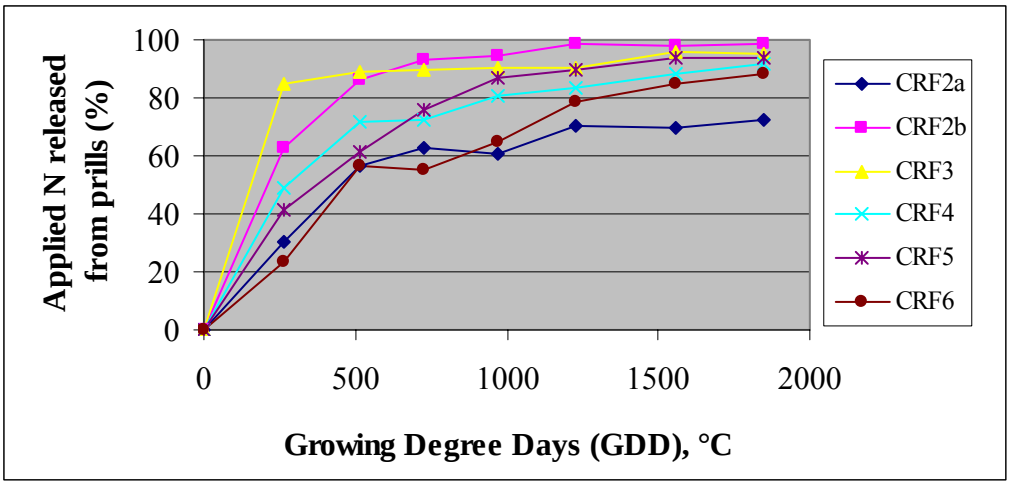


Figure 4-17. Cumulative N release (% of applied) of each fertilizer product as a function of growing degree days with 5°C base temperature.

CRF Release Discussion

Incubator CRF Release and Meshbag Experiment Correlation

When the various CRF release, residual, total recovery, and Q_{10} data from the incubator experiment are considered together with the data obtained from the meshbag experiment, the general release characteristics of the evaluated CRF products can be readily ascertained for both controlled-temperature and field conditions. As a general rule, the fertilizer products had similar release patterns relative to each other between the CRF release experiment and the meshbag study.

A comparison of the six CRF products that were evaluated in both the meshbag and CRF release experiments is shown in Figures 4-18. As the temperature patterns experienced by the CRF products between 2003 (when the meshbag study was run) and the 30 year average (the temperature regime used in the variable temperature incubator experiment) varied, the release of each of the products was converted to growing degree days to obtain a common reference point. As mentioned previously, the base temperature for growing degree day conversion was 5°C, which is the temperature most often used for

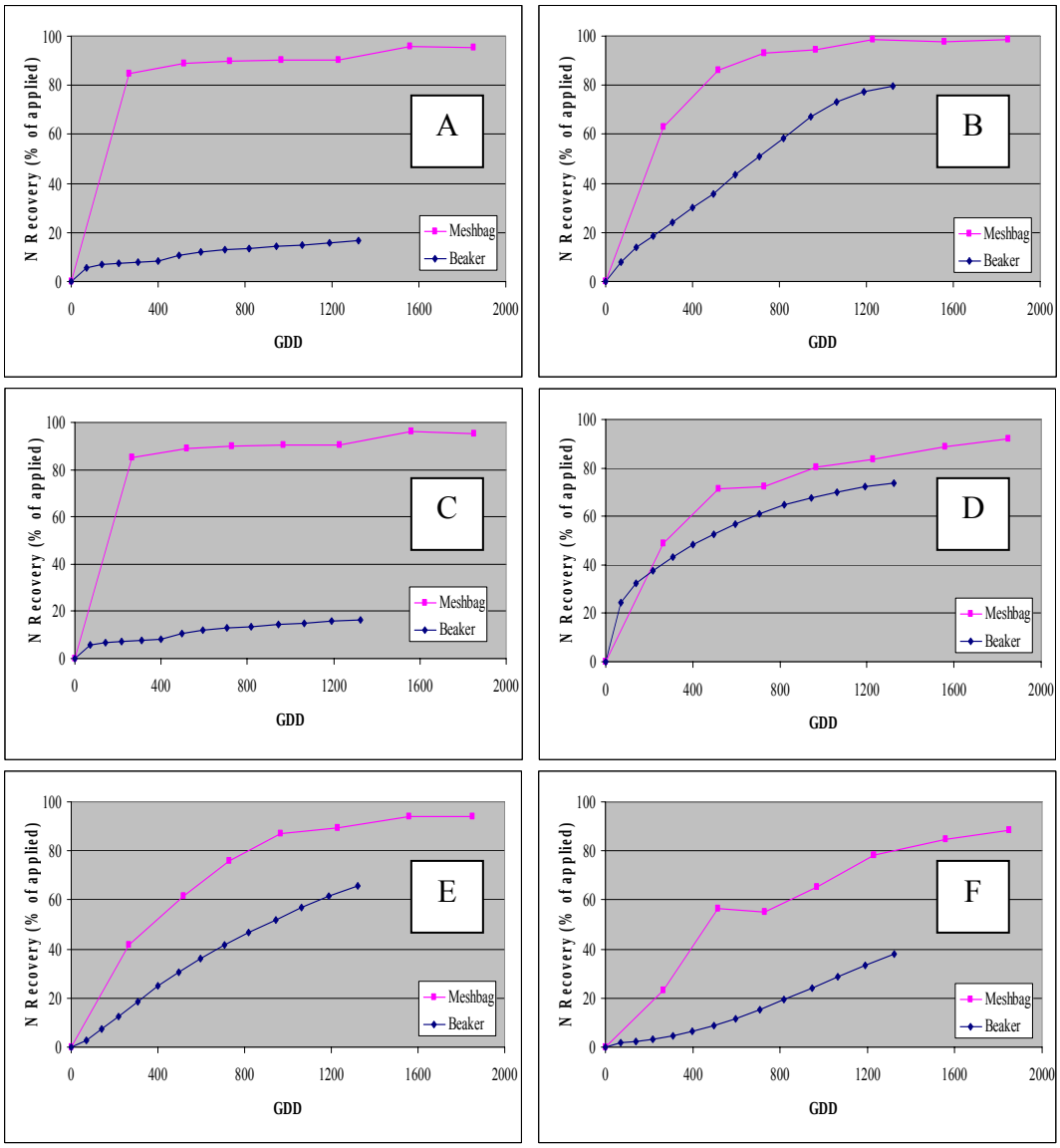


Figure 4-18. Comparison of release rates of CRF products between the CRF release experiment and the meshbag experiment on a degree day basis, base temperature of 5°C. A) CRF2a, B) CRF2b, C) CRF3, D) CRF4, E) CRF5, F) CRF6.

potato growth equations. The incubator experiment received a total of 13 samplings compared to 7 in the meshbag experiment, though the total number of degree days accumulated in the CRF release experiment was only 1323 compared to the 1850 accumulated in the meshbag experiment.

On the surface, the release rates of the CRF products under the two sampling regimes appear dissimilar. However, if the first sampling date from each experiment were removed, and the slopes of the remaining lines compared (representing sustained nutrient release over time), the slopes are remarkably similar with the exception of CRF2b. The initial sampling date was observed to have a high release, likely due primarily to broken, partially-coated, or otherwise incompletely sealed fertilizer prills. So in removing these, the relative release of the fertilizer products can be evaluated. Also from this data, it is encouraging that, after an initial release, the beaker experiment adequately charts the release of coated materials.

The higher total release rates observed in the meshbag study compared to the beaker experiment, particularly in the first sampling, may be explained by the physical environment in which each was found. In the meshbag study, the fertilizer prills would have been subjected to physical abrasion and pressure from surrounding soil particles together with microbiological action found in the soil environment on the prill coatings. In the beaker experiment, fertilizer prills were maintained in a pool of water with little physical abrasion, and would not have been subjected to a full soil-like environment.

Fertilizer Release Characteristics

AN and urea

AN and urea can be used as baseline indicators for the behavior of water soluble N products—near 100% release (though not necessarily recovery) early in the season with little recovery and no residual thereafter. The poor total recovery of urea is probably due to analytical difficulties in digesting the matrix resulting in low recoveries. As shown in Figure 4-2, A, fertilizer release occurred in one burst. Together with the lack of residual fertilizer (as illustrated in Figure 4-13), these data reveal that most of the fertilizer was

released at the first sample date. The laboratory performing the analyses reported extensive difficulty performing digestions on these samples. The lab further reported that upon digestion, the samples formed a brownish semi-gelatinous/semi-crystalline gel. This had never previously been seen by the laboratory (Elisabeth Kennelley, personal communication). Repeated dilutions were necessary to process the samples. It is possible that the low recoveries of these samples were due to an incomplete digestion, together with a compounding dilution factor.

The reduced recovery of AN is also somewhat enigmatic. The actual recovery, based on a 3 g sample of N was approximately 33%. However, TKN analysis will detect NH_4 and urea nitrogen, but the method used does not convert NO_3 nitrogen to NH_4. Thus, instead of a full 3 g potential N recovery, only 1.6 g (that applied in the NH_4 form) was potentially recoverable by the TKN method used. If the recovered N was calculated against the amount recoverable by the analysis utilized, recovery values rose to an average of 63% across all sampling dates for AN. As all of the fertilizer had dissolved into the first sample and would have been subjected to high dilutions, the difference in theoretical and actual recovery may possibly be attributed to dilution error as with urea.

CRF1

In the incubator experiment, CRF1 had a high release at 7 days (80% of total released) and by 14 days had released 96% of total released. This, coupled with no residual fertilizer and a constant Q_{10} value of 1 leads one to the conclusion that this product behaves like a water soluble fertilizer rather than a CRF. The poor total recovery likely follows the pattern set by urea—difficulty in analysis coupled with high dilutions. As no residual fertilizer was recovered from the meshbag, no meaningful comparisons were performed between the two experiments.

CRF2a

Similar to CRF1, CRF2a in the incubator experiment gave a release characteristic of a water-soluble fertilizer in that initial release was high with little subsequent release. CRF2a also had a high initial release of about 50% of total release by 7 days. Though some amount of fertilizer continued to release over the successive weeks, this fraction was small. The constant Q_{10} value of 1 reveals limited response to temperature, and the high residual fertilizer found after 92 days reveals that the coating of this product accounts for a large percentage of "lockout" which is permanently (over the lifecycle of the plant) unavailable fertilizer to the growing crop. Because of the high residual and low release, it is likely that the early fertilizer flush was due to fertilizer prills that either had damaged coatings or were incompletely coated.

In the meshbag experiment, CRF2a followed a similar release pattern to that observed in the incubator experiment. At 20 DAP, total N release was approximately 30% and by 104 days, total N release was only 72%. Thus, even under field conditions, substantial nutrient was retained in the fertilizer prills, unavailable for nutrient uptake.

Correlation between the two experiments (Figure 4-18, A), revealed a similar release pattern after the first two samplings within each. The difference in initial release may be due to prill degradation/abrasion under field conditions.

CRF2b

CRF2b proved to be one of the best candidates for further research. The initial fertilizer release from the incubator experiment was moderate except for high levels at the 25°C and 30°C temperatures while continued release occurred over a number of weeks. Its total cumulative release was near 80% by 92 days (for the variable temperature incubator) and residual fertilizer at the higher temperatures was around 10%

or less. Q_{10} values ranged from 1.3 between 5°C and 15°C to 2.1 between 20°C and 30°C.

In the meshbag experiment, greater than 60% of the product had been released by 20 DAP, while by 104 days, greater than 99% had been released. CRF2b was the only CRF product evaluated in both release experiments where a different shaped release curve was obtained for each. The reason for this difference is unknown, though different products may have different responses field conditions. Thus, the involvement of biological activity on fertilizer prills or soil abrasion, both of which were absent in the incubator experiment, may be factors.

CRF3

CRF3 appeared to have similar release patterns as CRF1 and CRF2a in the incubator experiment—a spike of release early in the growing season and limited response to temperature (Q_{10} constant at 1). Unlike CRF1 or CRF2a, it had a period of release between 35 and 57 days. The lack of residual fertilizer, especially at warmer temperatures, reveals limited problem with lockout. Q_{10} values for this product ranged around 1 for all temperature comparisons, indicating that release was not temperature controlled.

From the meshbag experiment, CRF3 had released 85% of applied N by the first sampling date (20 DAP), while 10% was released over the succeeding 84 days. Correlation between the two experiments revealed that except for the first sampling date at which samples in the meshbag experiment had nearly 8 times as much fertilizer released as in the incubator experiment, sustained release of the product was very similar between the two experiments.

CRF4

CRF4 had a high initial release (day 7), but exhibited continued steady release up to nearly 40 days. The product had a Q_{10} of 1 across all temperature comparisons; thus release was not influenced by temperature. Residual fertilizer ranged from nearly 40% at 5°C to about 8% at 30°C.

In the meshbag experiment, CRF4 had released nearly half (48%) of its nutrient by the first sampling date, though an additional 44% was released fairly consistently over the successive weeks. Correlation between the two experiments was very similar with the exception of the amount of N recovered at the first sampling—a phenomenon seen with all of the products.

CRF5

CRF5 had a moderate nutrient release at day 7, but even higher release (with the exception of the 30°C temperature) in subsequent weeks. Total release approached 80% by 92 days, but the positive slope of the cumulative release and the positive value on the weekly release curves indicate that more fertilizer would have been released had the trial period extended for a longer span. Of all of the CRF products evaluated, CRF5 also exhibited the greatest Q_{10} values—about 1.4 between 5°C and 15°C to nearly 3 between 20°C and 30°C. Thus, the product release could closely pattern temperature-related plant growth, though release rates varied with temperature. Because of its high Q_{10} value, amount of residual fertilizer also indicated a strong relationship to temperature. At 5°C, residual fertilizer was nearly 64% while at 30°C residual fertilizer was only 4%. In the variable temperature incubator, total residual N was approximately 22%.

In the meshbag experiment, CRF5 had released 41% of its contents by 20 DAP while by 104 DAP, it had released 94%. As with the incubator experiment, the lack of

residual is promising in that it was nearly all available during the plant growing season. Further, with nearly 60% of the fertilizer remaining in the prills after 20 DAP, substantial N was available through the middle and late parts of the season.

Correlation between the two experiments was generally good with the exception of higher initial release in the meshbag experiment. Release from the incubator experiment was not yet completed during the time period evaluated whereas it was largely complete in the meshbag experiment after the same number of degree days.

CRF6

CRF6 exhibited desirable release characteristics. Of all of the CRF products evaluated, it was the only one that did not have a high initial fertilizer release at day 7, and it continued to have slow and controlled-release over the duration of the experiment. This fertilizer in the variable temperature incubator had peak release at 78 days, resulting in less than 30% total release to date. This is less than half of the desired 75% release desired by 60 DAP. Q_{10} values averaged 1 between 5 and 15°C and approximately 1.6 over between 10°C and 20°C through 20°C and 30°C. Residual fertilizer showed a correspondingly sharp decline with increasing temperature with nearly 80% residual fertilizer in the 5°C and 10°C incubators down to less than 20% in the 30°C incubator; residual fertilizer in the variable temperature incubator was 47%.

In the meshbag experiment, total N release was 23% at 20 DAP which gradually increased to 89% release by 104 DAP. This, resulted in substantial release during the middle and late portions of the season, though likely too slowly to be useful to plants during peak growth.

Correlation between the two experiments was generally good after two samplings. In the field (meshbag experiment) substantial release was observed until 35 DAP, after

which sustained slow release was observed, whereas in the incubator experiment, substantial initial release never occurred. Rather, slow steady release was observed throughout the entire experiment.

Nitrification and denitrification

The possibility of N being nitrified or even denitrified and hence unavailable for recovery by TKN was evaluated by analyzing a subset of samples for NH_4 and NO_3 content. Since the N in all of the CRF products is from urea, the ubiquitous urease enzyme would be necessary to convert urea to ammonium and the bacteria *Nitrosomonas* spp. and *Nitrobacter* spp. would be necessary to convert ammonium to nitrite then nitrate, respectively. For denitrification, N would have been required to be converted to either nitrate or nitrite by the previously mentioned bacterium species and then reduced by various denitrifying bacteria, converting nitrite to nitrous oxide or nitrogen gas. In the cases of either nitrification or denitrification, bacteria would have to be introduced into the environment and they would require a carbon source—neither of which is likely in a sterile bottle with DI water and no substantial carbon supply. From the analysis of the CRF samples, no significant quantity of ammonium was found (the maximum amount in one sample was 100 mg L^{-1} with the rest being baseline), and no nitrate was found (data not shown). Thus, some small amount of ammonification may have occurred in some samples, but no nitrification or subsequent denitrification likely followed afterwards. Therefore, most of the N in the CRF samples would have been in a chemical form available for TKN analysis, except for NO_3-N in AN as previously discussed.

Plant uptake requirements

In order for N release characterizations to be useful, the general shape of the N uptake curve for the life cycle of potato should be understood. Thus, the ideal nutrient

release curve for a fertilizer product can match the ideal uptake curve. As plants very early in the season (0-10 days) rely solely upon nutrients contained in the seed tuber (no roots have formed in this time), no outside fertilizer nutrients are necessary. After approximately 10 days, when the plant has emerged from the soil and has begun forming a root system, active soil nutrient uptake begins. This rate of uptake rapidly increases and continues for nearly 60 days in 'Atlantic' potato. By full flower, which occurs around 60 days in northeast Florida, approximately 75% of the fertilizer nutrients should have been released and available for uptake. During the next 20 days of the season, the remaining 25% of nutrients should be released, as nutrient uptake after around 85 days is minimal (Ojala *et al*., 1990; Westermann, 1993).

Of the CRF products evaluated, all except CRF6 had high nutrient release very early in the release periods, right when N uptake capacity of the plant is minimal. CRF2b, CRF4 and CRF5 exhibited the best release profiles under field conditions (meshbag experiment), although all could be improved if initial release was delayed for 10-14 days to allow the emerging plant to become established. CRF6 exhibited sustained release over the experiment though total release was too delayed to be of maximal use to the plant. This product could be improved if initial release occurred earlier in the season, followed by greater sustained release rates through 80 DAP.

Methodology improvement

As already discussed, urea, CRF1, CRF2a, and CRF3 all had low total N recoveries. These products also had little or no residual fertilizer and a single large flush of nutrients at day 7. This likely created difficulties in analysis by TKN. This could be solved by analyzing all samples by combustion by the Dumas method. No digestions or dilutions are necessary with this method. Further, the Dumas method reads N whether in

the nitrate, ammonium, or urea form (all N is atomized), so would read AN as well (Watson and Galliher, 2001).

Another possible point of improvement in methodology could be accomplished by adding field soil to the beakers. This could possibly introduce a more abrasive environment for greater polymer coating disruption and a supply of microorganisms. It would however complicate the taking of weekly samples because of the difficulty of keeping soil out of the sample aliquot. However, if these CRF release data were found to correlate well to data from similar tests performed in the field, such adjustments would be unnecessary.

Summary

Of the CRF products evaluated, CRF2b, CRF4, CRF5, and CRF6 showed characteristics most favorable to potato production. They all released in increasing quantities with temperature ($Q_{10} > 1$), had release periods over a period of many weeks, and released a high percentage of fertilizer (low residual) indicating low levels of "lockout". Though none of the fertilizer products released 75% of total N by full flower in the incubator experiment, CRF2b, CRF3, CRF4 and CRF5 all met that criteria in the meshbag experiment. In the incubator experiment, CRF2b, CRF4, and CRF5 appeared to release excessive amounts of N early in the experiment (7 days), while CRF6 had comparatively little release early. All four of them also appeared to have too long of longevity in the incubator experiment. In the meshbag experiment, these four products had even a higher initial release of nutrients, though continued release appeared similar to the beaker experiment. CRF1, CRF2a, and CRF3 appeared to release available fertilizer quickly (by day 7), leaving little available nitrogen for subsequent weeks. With CRF1 and CRF3, all of the nitrogen was released in this first week, while CRF2a had large

quantities of N that remained in the prills over the entire duration of the experiment. In the meshbag experiment, both CRF2a and CRF3 had higher initial releases of nitrogen when compared to the incubator experiment at the first sampling date, with no subsequent difference in slope.

Of the CRF products evaluated, CRF2b, CRF4, CRF5, and CRF6 would be good products for further evaluation. If the coating characteristics of the prills were modified or if blends were created to bring total N release more in line with crop uptake requirements, the products could provide nutrients to plants at times and in quantities needed.

CHAPTER 5
COMPARISON OF CONTROLLED-RELEASE NITROGEN FERTILIZERS TO AMMONIUM NITRATE ON POTATO PRODUCTION

If controlled-release fertilizers (CRF) are to be adopted for use in potato production, they must not compromise either yield quantity or quality. Two field experiments were conducted to evaluate the influence of CRF on potato production. These include the "CRF Production Experiment" and the "Replacement Experiment". Both experiments evaluated the effect of CRFs on total and marketable yields, tuber quality, plant nutritional status, and nutrient recovery.

CRF Production Experiment

The CRF production experiment evaluated the potential use of CRFs in place of traditionally-used ammonium nitrate (AN), and was set up with six CRF products (CRF1 through CRF6). This experiment was designed to determine if N from CRF materials remained in the soil longer than a similar rate of a "soluble" fertilizer source. The CRF products were also evaluated to determine optimal N rates by evaluating yield response to N applications at rates of 112 kg ha^{-1} N, 168 kg ha^{-1} N, and 225 kg ha^{-1} N, corresponding to 50%, 75%, and 100% of the current BMP rate for the area. The CRF products evaluated were chosen because they represented a broad product diversity with respect to N release patterns and were preliminary products from manufacturers aiming to design a fertilizer that meets the specific needs of potato growers. The AN treatment cannot be considered a grower standard treatment because all N was applied at the beginning of the season, whereas growers apply AN in split applications.

Total and Marketable Yields

The data were analyzed factorially by fertilizer product and rate main effects. ANOVA tables for total and marketable yields are shown in Table 5-1 and Table 5-2, respectively. Because the rate by product main effect was significant for both total and marketable yields, their simple effects were evaluated (Table 5-3). Total and marketable yields with the CRF production experiment were highest with plants in CRF2 (224 kg ha^{-1} N) at 38.3 and 33.8 Mg ha^{-1}, respectively, and with plants in CRF4 (224 kg ha^{-1} N) at 37.8 and 32.8 Mg ha^{-1}, respectively. Marketable yields from both of these treatments were significantly higher than those achieved from any of the AN treatments. Figure 5-1 illustrates the total and marketable yields obtained for each fertilizer treatment as well as the no fertilizer control. All plants in fertilized treatments resulted both in higher total and marketable yields than those in the no fertilizer control (No N).

Total yields from CRF fertilized plants were not higher than with any of the plants fertilized in the AN treatments (see AN, 224 kg ha-1 N, 33.4 Mg ha-1; Table 5-3). When

Table 5-1. ANOVA table for total yields by fertilizer and rate main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Fert	6	106091	17682	14.86	< 0.0001
Rate	2	73169	36584	30.75	< 0.0001
Rep	3	10904	3635	3.05	0.0304
Rate*Fert	12	140439	11703	9.84	< 0.0001
Error	144	171350	1190		
Corrected Total	167	501952			

Table 5-2. ANOVA table for marketable yield by fertilizer rate and main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Fert	6	112144	18691	19.03	< 0.0001
Rate	2	100820	50410	51.33	< 0.0001
Rep	3	14375	4792	4.88	0.0029
Rate*Fert	12	129788	10816	11.01	< 0.0001
Error	144	141415	982		
Corrected Total	167	498542			

Table 5-3. Total and marketable yield simple effects.

Fertilizer	N rate kg ha^{-1}	Total yield Mg ha^{-1}		Marketable yield[1] Mg ha^{-1}	
AN	112	23.2	fg[2,3]	16.7	hi
AN	168	28.9	b-f	19.8	f-h
AN	224	33.4	a-d	24.9	c-g
CRF1	112	28.9	b-f	22.6	d-h
CRF1	168	29.5	b-f	25.6	c-e
CRF1	224	16.7	g	13.0	i
CRF2	112	29.7	b-f	22.2	d-h
CRF2	168	34.4	a-c	28.4	a-d
CRF2	224	38.3	a	33.8	a
CRF3	112	25.6	ef	19.2	g-i
CRF3	168	34.1	a-d	28.5	a-d
CRF3	224	30.7	b-e	26.5	b-e
CRF4	112	28.3	c-f	22.1	e-h
CRF4	168	32.6	a-e	26.7	b-e
CRF4	224	37.8	a	32.8	ab
CRF5	112	28.0	c-f	22.5	d-h
CRF5	168	31.8	a-e	26.3	c-e
CRF5	224	35.5	ab	30.0	a-c
CRF6	112	27.1	d-f	21.2	e-h
CRF6	168	32.5	a-e	26.5	b-e
CRF6	224	34.8	a-c	30.3	a-c
ANOVA *p*-value		< 0.0001		< 0.0001	
Tukey LSD		6.3		5.7	

[1] - Marketable Yield: size classes 2 to 4.
[2] - Means in columns followed by same letters not significantly different.
[3] – Plants in the control treatment yielded 6.0 and 3.8 Mg ha^{-1} for total and marketable yields, respectively.

compared to AN fertilized plants at the BMP rate (224 kg ha-1 N), potatoes with all six CRF products with the 168 kg ha^{-1} N rate had 3 to 14% higher marketable yields. Marketable yields with five of the CRF treatments (CRF1 excluded) at the 224 kg ha^{-1} N rate were 7 to 36% higher than marketable yield with the AN at the BMP rate. Low yields with CRF1, 224 kg ha^{-1} N are due to poor stand establishment with that treatment.

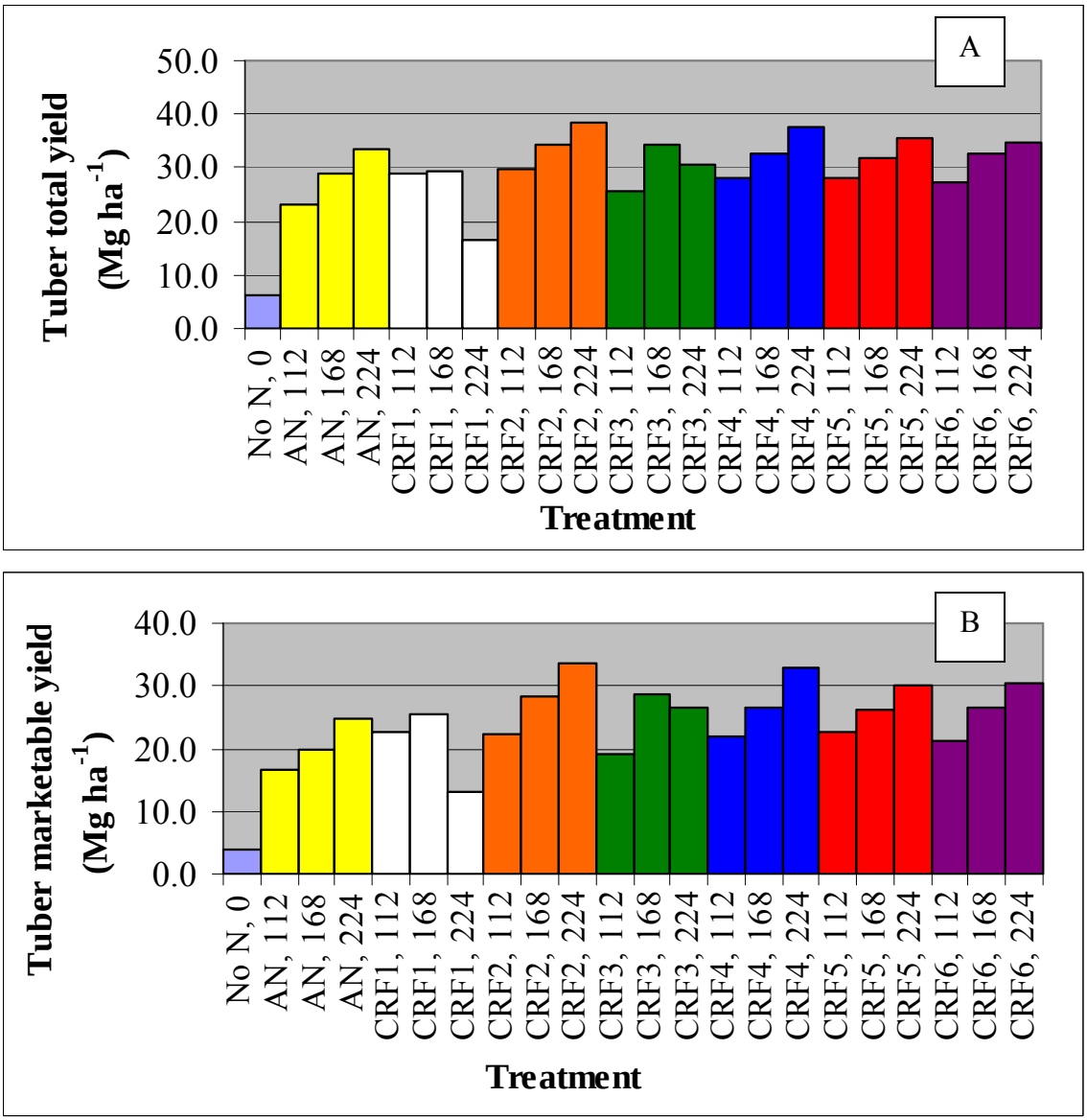


Figure 5-1. Total and marketable tuber yields by treatment. A) total yield, B) marketable yield.

Specific Gravity

The ANOVA table for specific gravity by product and rate main effects indicates a significant rate by product interaction (Table 5-4). Simple effects analysis for specific gravity (SG) ranged from a low of 1.074 with AN (112 kg ha^{-1} N) to a high of 1.084 with CRF2 (224 kg ha^{-1} N) (Table 5-5, Figure 5-2). Only plants fertilized with CRF2 with 224

kg ha^{-1} N had SG significantly higher than plants fertilized with any of the AN treatments. The control treatment (no N) had a SG of 1.065.

Table 5-4. ANOVA table for specific gravity by rate and fertilizer source main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Fert	6	0.00059	0.0001	11.52	< 0.0001
Rate	2	0.0001	0.00005	6.11	0.0028
Rep	3	0.00063	0.00021	24.73	< 0.0001
Rate*Fert	12	0.00027	0.00002	2.61	0.0036
Error	144	0.00122	0.00001		
Corrected Total	167	0.00281			

Table 5-5. Potato tuber specific gravity by simple effects.

Fertilizer	N rate kg ha^{-1}	Specific gravity	
AN	112	1.074	c[1,2]
AN	168	1.075	c
AN	224	1.077	bc
CRF1	112	1.081	ab
CRF1	168	1.081	ab
CRF1	224	1.077	bc
CRF2	112	1.079	a-c
CRF2	168	1.082	ab
CRF2	224	1.084	a
CRF3	112	1.080	a-c
CRF3	168	1.081	ab
CRF3	224	1.079	a-c
CRF4	112	1.077	bc
CRF4	168	1.081	ab
CRF4	224	1.081	ab
CRF5	112	1.078	a-c
CRF5	168	1.079	a-c
CRF5	224	1.079	a-c
CRF6	112	1.075	c
CRF6	168	1.078	bc
CRF6	224	1.079	a-c
ANOVA *p*-value		< 0.0001	
Tukey LSD		0.005	

[1] - Means in columns followed by same letters not significantly different.
[2] - Tubers from the control treatment had a specific gravity of 1.065.

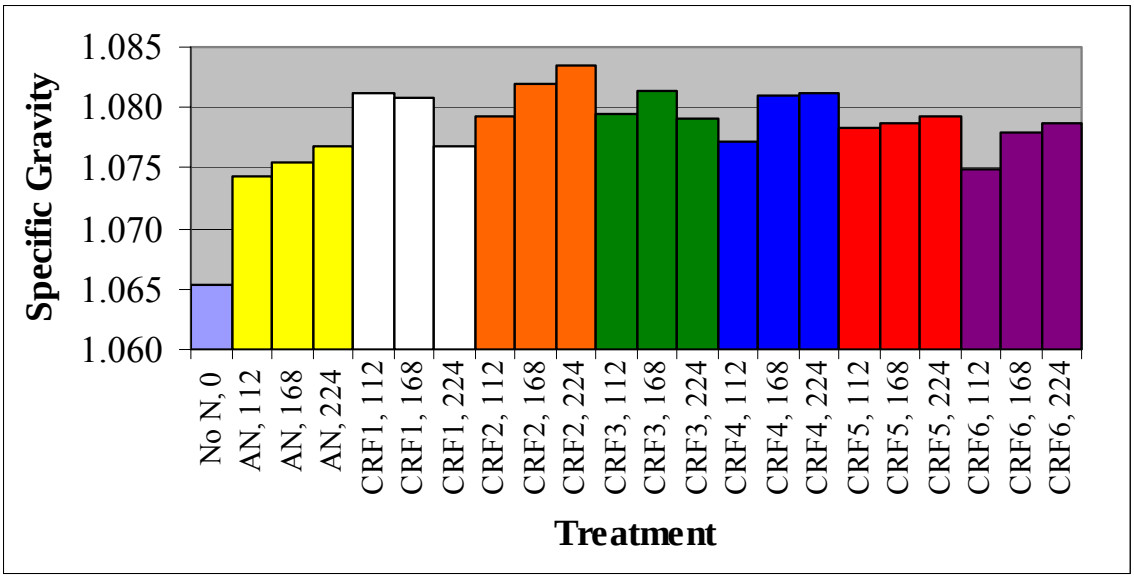


Figure 5-2. Potato tuber specific gravity by treatment.

SG values were relatively high for the production site in 2003. Potatoes with most treatments had SG of 1.078 or greater, with the highest gravities as high as 1.084. Notably, the tubers in treatments with highest SG were also the highest yielding plants.

Tuber Quality

In the CRF production experiment, no significant rate by product interaction was found for the tuber quality parameters of percent green, percent growth crack (GC), percent rotten (Rot), percent hollow heart (HH), percent brown rot (BR), and percent corky ring spot (CRS). Accordingly, main effect analysis results for these parameters is shown for fertilizer products (Table 5-6) and for N rates (Table 5-7). Within the fertilizer product main effect, none of the parameters tested were significantly different either within CRF products or compared to AN. However, within the rate main effect, a significantly greater percentage of green and growth crack potatoes was observed with potatoes grown at higher N rates than at the 112 kg ha^{-1} N rate.

Table 5-6. Potato tuber quality by fertilizer source main effect.

Fertilizer	Green[1] %	GC %	Rot %	HH %	BR %	CRS %
AN	1.8	0.6	4.2	4.4	0.2	0.0
CRF1	2.4	1.1	3.5	4.4	0.0	0.0
CRF2	1.1	0.5	3.7	1.7	0.0	0.0
CRF3	2.3	0.4	4.1	3.3	0.0	0.2
CRF4	1.0	0.4	3.9	2.7	0.2	0.0
CRF5	1.1	1.0	4.3	1.3	0.0	0.0
CRF6	1.1	0.2	4.1	1.0	0.0	0.0
ANOVA *p*-value	0.0323	0.0491	0.9755	0.019	0.5327	0.4278
Tukey LSD	ns	ns	ns	ns	ns	ns

[1] - Green = green, GC = growth cracks, Rot = rotten, HH = hollow heart, BR = brown rot, CRS = corky ring spot.

Table 5-7. Potato tuber quality by rate main effect.

N rate kg ha^{-1}	Green[1] %	GC %	Rot %	HH %	BR %	CRS %
112	0.7 b[2]	0.3 b	5.3 a	2.7	0.1	0.0
168	1.7 a	0.5 ab	3.9 b	2.9	0.1	0.0
224	2.3 a	0.9 a	2.8 b	2.5	0.0	0.1
ANOVA *p*-value	0.0002	0.0109	0.0001	0.9008	0.6012	0.3704
Tukey LSD	0.8	0.5	1.4	ns	ns	ns

[1] - Green = green, GC = growth cracks, Rot = rotten, HH = hollow heart, BR = brown rot, CRS = corky ring spot.
[2] - Means in columns followed by same letters not significantly different.

Significant rate by product interactions were found for percent misshapen (MS, p = 0.0059) and percent internal heat necrosis (IHN, p = 0.0115). Results of simple effects analysis are presented in Table 5-8. For MS potatoes, greatest percentages resulted from AN fertilized treatments at 224 kg ha^{-1} N, and was statistically similar only to plants fertilized with AN at 168 kg ha^{-1} N. All CRF products independent of rate resulted in tubers with similar quantities of misshapes. IHN was highest in tubers with AN fertilized plants at 168 kg ha^{-1} N at 30.0%. This was significantly higher than all other treatments except AN with 224 kg ha^{-1} N and CRF6 at 112 kg ha^{-1} N. None of the CRF products were significantly different from each other in incidence of IHN.

Table 5-8. Potato tuber quality by treatment.

Fertilizer	N rate kg ha^{-1}	Mis[1] %		IHN %	
AN	112	0.2	b[2,3]	11.3	bc
AN	168	1.0	ab	30.0	a
AN	224	2.0	a	20.0	ab
CRF1	112	0.5	b	6.9	bc
CRF1	168	0.0	b	5.0	bc
CRF1	224	0.5	b	10.0	bc
CRF2	112	0.3	b	7.5	bc
CRF2	168	0.0	b	3.1	bc
CRF2	224	0.3	b	7.5	bc
CRF3	112	0.3	b	10.0	bc
CRF3	168	0.2	b	7.6	bc
CRF3	224	0.0	b	5.6	bc
CRF4	112	0.0	b	5.0	bc
CRF4	168	0.3	b	8.8	bc
CRF4	224	0.4	b	2.5	c
CRF5	112	0.3	b	10.6	bc
CRF5	168	0.8	ab	8.1	bc
CRF5	224	0.0	b	3.8	bc
CRF6	112	0.4	b	16.9	a-c
CRF6	168	0.1	b	6.9	bc
CRF6	224	0.0	b	5.6	bc
ANOVA *p*-value		0.0009		< 0.0001	
Tukey LSD		1.4		17.4	

[1] - Mis = misshapen potatoes, IHN = internal heat necrosis.
[2] - Means in columns followed by same letters not significantly different.
[3] - Tubers from the control treatment had 0.4% Mis and 52.4% IHN.

Stand Establishment

The CRF production experiment had variable stand establishment, which was influenced by fertilizer treatment (Table 5-9). Plants fertilized with CRF1 with 224 kg ha^{-1} N had the lowest establishment of all treatments with 47.9% emergence, while those fertilized with CRF4 with 168 kg ha^{-1} N had the highest establishment of all at 100%. Other notable treatment-affected stands were with CRF1 with 168 kg ha^{-1} N at 69.2%

Table 5-9. Potato stand establishment for the CRF production experiment.

Fertilizer	N rate kg ha^{-1}	Stand %
No N	0	98.3
AN	112	97.1
AN	168	97.1
AN	224	95.4
CRF1	112	87.1
CRF1	168	69.2
CRF1	224	47.9
CRF2	112	96.3
CRF2	168	95.4
CRF2	224	96.7
CRF3	112	92.1
CRF3	168	87.5
CRF3	224	72.1
CRF4	112	98.3
CRF4	168	100.0
CRF4	224	96.3
CRF5	112	95.0
CRF5	168	97.1
CRF5	224	97.9
CRF6	112	98.3
CRF6	168	97.1
CRF6	224	96.3

emergence and with CRF3 with 224 kg ha^{-1} N at 72.1% emergence. With the exception of these three low stand treatments, most plants in treatments had stand establishment >95% while two (CRF1, 112 kg ha^{-1} N and CRF3, 168 kg ha^{-1} N) had < 90% stand establishment. The reduced stand counts, especially for CRF1 at the high rate likely account directly for the low observed marketable and total yields. Though not analyzed statistically, it should be noted that this product appeared to reduce plant stands and yields independent of the rate applied, and even at the lowest fertilizer rate (112 kg ha^{-1}

N), the stand was only at 87.1%, considerably lower than the 96.1% average stand for all of the other fertilizers at the same rate.

Plant tissue

Most recently matured (MRM) leaf tissue samples consisting of petioles and leaflets were taken bi-weekly from plants in the CRF production experiment and tested for total Kjeldahl nitrogen (TKN). The ANOVA table for sampling date, rate, and fertilizer source main effects (Table 5-10) revealed a significant third-order interaction between sampling dates, fertilizer products, and rates, as well as a significant second-order interaction between fertilizer products and sampling dates. As there was no interest in evaluating each of the simple effects of these three factors individually, the rate and product effects were evaluated at each sampling date. Rate by product interactions were not significant at 36 DAP or 64 DAP, though they were at 47 DAP ($p = 0.0240$) and 82 DAP ($p = 0.0010$). Accordingly, main effect analysis was performed for leaf TKN at 36 DAP and 64 DAP, and results are shown for fertilizer product (Table 5-11) and rate (Table 5-12) main effects. Simple effects analysis results for leaf TKN at 47 DAP and 82 DAP are shown in Table 5-13.

Table 5-10. ANOVA table for most recently matured leaf TKN by rate and fertilizer product main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Date	3	48470762397	16156920799	1209.9	< 0.0001
Rate	2	3340874028	1670437014	125.09	< 0.0001
Fert	6	765897038	127649506	9.56	< 0.0001
Rep	3	425253010	141751003	10.61	< 0.0001
Rate*Fert	12	254254195	21187850	1.59	0.0957
Date*Rate	6	139699796	23283299	1.74	0.1115
Date*Fert	18	1498614386	83256355	6.23	< 0.0001
Date*Fert*Rate	36	830795456	23077652	1.73	0.0087
Error	249	3325127378	13353925		
Corrected Total	335	59051277683			

Table 5-11. Most recently mature leaf percent TKN of potato plants by fertilizer source main effect at 36 and 64 DAP.

Fertilizer	TKN (x 10^4 g kg^{-1}) 36 DAP[1]	64 DAP
AN	5.7 c[2]	4.8 ab
CRF1	6.3 ab	5.1 a
CRF2	6.7 a	4.4 bc
CRF3	6.5 ab	4.5 bc
CRF4	6.5 ab	4.3 c
CRF5	6.5 ab	4.4 bc
CRF6	6.2 b	4.3 c
ANOVA *p*-value	< 0.0001	< 0.0001
Tukey LSD	0.5	0.4

[2] - DAP = Days after planting.
[3] – Means in columns followed by same letters not significantly different.

Table 5-12. Most recently mature leaf percent TKN of potato plants by rate main effect at 36 and 64 DAP.

N rate kg ha^{-1}	TKN (x 10^4 g kg^{-1}) 36 DAP[1]	64 DAP
112	6.1 c[2]	4.1 c
168	6.4 b	4.6 b
224	6.6 a	5.0 a
ANOVA *p*-value	< 0.0001	< 0.0001
Tukey LSD	0.2	0.2

[1] - DAP = Days after planting.
[2] - Means in columns followed by same letters not significantly different.

Leaf TKN at 36 DAP was significantly higher in the CRF treatments than in AN treatments. However, at 64 DAP, leaf TKN was significantly highest in CRF1. Also at 64 DAP, leaf TKN in AN treatments was among the highest of all fertilizer products.

As might be expected, leaf TKN was affected by fertilizer rate main effect both at 36 and 64 DAP; it was significantly highest with 224 kg ha^{-1} N across all fertilizer products for both dates. Leaf TKN was also significantly different between plants in 168 and 112 kg ha^{-1} N treatments, with the lowest rate having the lowest average TKN concentration at both 36 and 64 DAP.

Table 5-13. Most recently mature leaf tissue percent TKN of potato plants by fertilizer and rate simple effects.

Fertilizer	N rate kg ha^{-1}	TKN (x 10^4 g kg^{-1}) 47 DAP[1]		82 DAP	
AN	112	4.9	fg[2,3]	2.8	d-f
AN	168	5.0	e-g	3.4	a-e
AN	224	5.5	a-f	3.7	a-c
CRF1	112	5.4	a-f	2.5	f
CRF1	168	5.9	ab	3.6	a-d
CRF1	224	5.7	a-f	4.2	a
CRF2	112	5.1	d-g	2.5	ef
CRF2	168	5.7	a-e	3.0	c-f
CRF2	224	5.7	a-f	3.1	b-f
CRF3	112	5.1	c-g	2.4	f
CRF3	168	5.7	a-f	3.0	c-f
CRF3	224	5.9	a-d	3.9	ab
CRF4	112	5.0	e-g	2.4	f
CRF4	168	5.3	a-f	2.8	d-f
CRF4	224	5.9	a-c	3.1	b-f
CRF5	112	5.2	b-f	2.9	c-f
CRF5	168	5.5	a-f	3.4	a-e
CRF5	224	6.1	a	3.1	c-f
CRF6	112	4.4	g	2.8	d-f
CRF6	168	5.4	a-f	3.1	b-f
CRF6	224	5.5	a-f	3.2	b-f
ANOVA *p*-value		< 0.0001		< 0.0001	
Tukey LSD		0.8		0.9	

[1] - DAP = Days after planting.
[2] - Means in columns followed by same letters not significantly different.
[3] - Plants in the control treatment had average TKN of 3.6 and 2.6 x10^4 g kg^{-1}, at 47 and 82 DAP, respectively.

Leaf TKN simple effects at 47 DAP and 82 DAP indicate that highest leaf TKN at the earlier date was found in plants with CRF5 with 224 kg ha^{-1} N and lowest with CRF6 with 112 kg ha^{-1} N. At 82 DAP highest leaf TKN was found in plants with CRF1 with 224 kg ha^{-1} N and significantly lowest in both CRF1 and CRF4, both with 112 kg ha^{-1} N.

Plant Biomass

Factorial analysis of plant biomass for rate and fertilizer source main effects provides useful information. No significant interactions between rate and product were observed for leaf TKN, stem TKN, leaf dry matter (DM), stem DM, or total (leaf + stem) DM. Accordingly, fertilizer product main effect analysis results are shown in Table 5-14 and rate main effect analysis results are shown in Table 5-15.

Table 5-14. Plant biomass and tissue nitrogen at full flower (61 DAP) by fertilizer source main effect.

Fertilizer	Leaf TKN 10^4 g kg^{-1}	Stem TKN 10^4 g kg^{-1}	Leaf DM[1] g plt^{-1}	Stem DM g plt^{-1}	Total DM g plt^{-1}
AN	4.8 ab[2]	2.2 ab	28.4	12.1 ab	40.5
CRF1	5.1 a	2.3 a	28.4	13.6 ab	41.9
CRF2	4.4 bc	1.7 cd	24.3	13.1 ab	37.4
CRF3	4.5 bc	2.0 bc	35.1	18.5 a	53.6
CRF4	4.3 c	1.5 d	27.3	15.3 ab	42.7
CRF5	4.4 bc	1.8 b-d	28.4	16.5 ab	44.8
CRF6	4.3 c	1.7 cd	22.2	11.2 b	33.5
ANOVA *p*-value	< 0.0001	< 0.0001	0.0819	0.0279	0.0713
Tukey LSD	0.4	0.4	ns	6.9	ns

[1] - DM = Dry matter; Total DM = Leaf DM + Stem DM.
[2] - Means in columns followed by same letters not significantly different.

Table 5-15. Plant biomass and tissue nitrogen at full flower (61 DAP) by rate main effect.

N rate kg ha^{-1}	Leaf TKN 10^4 g kg^{-1}	Stem TKN 10^4 g kg^{-1}	Leaf DM[1] g plt^{-1}	Stem DM g plt^{-1}	Total DM g plt^{-1}
112	4.1 c[2]	1.5 c	22.4 b	12.7	35.0 b
168	4.6 b	2.0 b	30.6 a	16.1	46.7 a
224	5.0 a	2.2 a	30.3 a	14.2	44.5 ab
ANOVA *p*-value	< 0.0001	< 0.0001	0.0037	0.0753	0.0138
Tukey LSD	0.2	0.2	6.4	ns	9.8

[1] - DM = Dry matter; Total DM = Leaf DM + Stem DM.
[2] - Means in columns followed by same letters not significantly different.

Fertilizer source main effects influenced leaf and stem TKN and plant dry weight accumulation. Leaf and stem TKN were significantly higher in plants with the AN and CRF1 treatments than from plants with all other treatments. No significant difference

was found between fertilizer sources for leaf DM or total DM. Plants fertilized with CRF3 had significantly greater stem DM (18.5 g) than CRF6 (11.2 g) (Table 5-14).

Within the rate main effect, leaf and stem TKN from plants with the 224 kg ha^{-1} N rate (5.0 and 2.2 x 10^4 g kg^{-1}, respectively) plots were significantly higher than from plants in the 112 kg ha^{-1} N rate (4.1 and 1.5 x 10^4 g kg^{-1}, respectively) but neither were significantly different from those fertilized at the 168 kg ha^{-1} N rate (4.6 and 2.0 x 10^4 g kg^{-1}, respectively) (Table 5-15). Fertilizer rate did not influence stem dry weight accumulation. Conversely, leaf dry weights with the 168 and 224 kg ha^{-1} N (30.6 and 30.3 g, respectively) plots were significantly higher than with 112 kg ha^{-1} N (22.4 g) plots. Total dry weight accumulation was statistically higher within the 168 kg ha^{-1} N (46.7 g) plots compared to plants in the 112 kg ha^{-1} N (35.0 g) plots (Table 5-15).

Tuber Nitrogen Uptake and Recovery Efficiency (NRE)

ANOVA tables for total tuber N uptake (kg ha^{-1}) and NRE are shown in Table 5-16 and Table 5-17, respectively. Factorial analysis of the fertilizer source and rate main effects revealed a significant interaction on total tuber N uptake ($p < 0.0001$) and NRE ($p = 0.0012$). Thus, the simple effects for each rate by product combination were evaluated (Table 5-18).

Treatments having plants with the highest N removal were CRF4 (224 kg ha^{-1} N), CRF2 (224 kg ha^{-1} N) and CRF5 (224 kg ha^{-1} N) with 139.1, 134.8, and 132.3 kg ha^{-1} N, respectively. The greater N uptake in these treatments was a function of the higher yields of potatoes, and not a function of more N in tubers in those treatments (data not shown). These results would be expected because if there is more nitrogen present, more would be available for uptake by plants and eventually movement into tubers. Lowest tuber N uptake was by plants within the no fertilizer control with 16.2 kg ha^{-1} N.

Table 5-16. ANOVA table for N recovery (kg ha^{-1} N) by fertilizer product and rate main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Fert	6	7144	1191	6.25	< 0.0001
Rate	2	20206	10103	53.06	< 0.0001
Rep	3	530	177	0.93	0.4329
Rate*Fert	12	11898	992	5.21	< 0.0001
Error	60	11424	190		
Corrected Total	83	51203			

Table 5-17. ANOVA table for NRE by fertilizer product and rate main effects.

Source	DF	Type III SS	MS	F Value	Pr > F
Fert	6	0.1727	0.0288	4.12	0.0016
Rate	2	0.2740	0.1370	19.59	< 0.0001
Rep	3	0.0254	0.0085	1.21	0.3134
Rate*Fert	12	0.2722	0.0227	3.24	0.0012
Error	60	0.4196	0.0070		
Corrected Total	83	1.1638			

When N recovery values were expressed as a percentage recovery of applied N [$(N_{tubers} - N_{control}) * 100 / N_{applied}$], there were no significant differences with the exception of CRF1 (224 kg ha^{-1} N) which had the lowest nutrient recovery efficiency (NRE) of 19.5%, when compared to NRE values of all other treatments (44.5 to 65.8%). This is related to it having the highest rate of applied N and low yields due to poor stand establishment.

Replacement Experiment

The replacement experiment was performed separate from the CRF production experiment to evaluate the feasibility of blending CRF products with AN. One of the purposes of this is to partially alleviate the higher of costs of CRF products (compared to AN) by applying a percentage of N as the cheaper AN. Theoretically, AN would provide a rapid early N supply to potato plants followed by controlled N release by the CRF over the remainder of the season.

Table 5-18. Tuber nitrogen uptake and nutrient recovery efficiency by treatment.

Fertilizer	N rate kg ha^{-1}	Tuber N uptake kg ha^{-1}		NRE[1] %	
AN	112	71.0	gh[2,3]	49.0	a
AN	168	103.5	a-g	52.0	a
AN	224	117.4	a-d	45.0	a
CRF1	112	87.2	c-h	63.3	a
CRF1	168	106.1	a-g	53.5	a
CRF1	224	59.8	h	19.5	b
CRF2	112	89.9	b-h	65.8	a
CRF2	168	118.6	a-c	61.0	a
CRF2	224	134.8	a	53.0	a
CRF3	112	77.2	f-h	54.3	a
CRF3	168	113.6	a-f	58.0	a
CRF3	224	115.5	a-e	44.5	a
CRF4	112	81.5	d-h	58.3	a
CRF4	168	108.3	a-f	55.0	a
CRF4	224	139.1	a	54.8	a
CRF5	112	84.3	c-h	61.0	a
CRF5	168	109.2	a-f	55.3	a
CRF5	224	132.3	a	51.8	a
CRF6	112	80.1	e-h	57.0	a
CRF6	168	112.8	a-f	57.5	a
CRF6	224	124.1	ab	48.3	a
ANOVA *p*-value		< 0.0001		< 0.0001	
Tukey LSD		36.4		22.0	

[1] - NRE = Nutrient recovery efficiency.
[2] - Means in columns followed by same letters not significantly different.
[3] - Plants in the control treatment had a total N uptake of 16.2 kg ha^{-1}.

Two CRF products, CRF4 and CRF6 were used in the replacement experiment. These CRF products were blended with AN at AN:CRF percent ratios of 0:100, 25:75, 50:50, 75:25, and 100:0. All fertilizer material was broadcast in the field at a constant N rate (168 kg ha^{-1} N) at planting and does not represent a grower standard treatment, because growers typically apply N in split applications. 'Red LaSoda' and 'Atlantic' potatoes were used to determine CRF influences with different potato varieties.

No factorial analysis was performed with the replacement experiment. Results from the experiment for the two potato varieties were analyzed separately as there was no interest in comparing the two varieties themselves. Consequently, all analyses were simple treatment comparisons within each potato variety.

Total and Marketable Yields

Total and marketable yields for 'Atlantic' potatoes were highest with CRF4 in the AN:CRF4 25:75 plots at 29.7 and 21.0 Mg ha^{-1}, respectively, though differences were not significant from other blends in either case (Tables 5-19). CRF6 had highest 'Atlantic' total yields in the AN:CRF6 75:25 blend at 27.9 Mg ha^{-1}, though not significantly different from the other CRF6 blends. Highest CRF6 marketable yields were observed in the AN:CRF6 25:75 blend at 19.4 Mg ha^{-1}, which was significantly higher than the AN treatment (AN:CRF 100:0) (Table 5-20). The reason for this apparent lack of yield response to CRFs may be due to overall lower stand counts (compared with the production experiment) (Table 5-23), possibly due to an overabundance of water observed in that field which may have caused excessive N leaching and/or seed rot. No significant total or marketable yield differences were observed in the 'Red LaSoda' plots between 100% AN and any of the blends for either of the CRF products (Table 5-19 and 5-20, respectively). Highest total and marketable yields for plants with CRF4 were with 100% AN (24.7 Mg ha^{-1}) and AN:CRF4 75:25 (14.2 Mg ha^{-1}) treatments, respectively. Highest total and marketable yields for plants with CRF6 were with AN:CRF6 25:75 (25.4 Mg ha^{-1}) and AN:CRF6 50:50 (14.4 Mg ha^{-1}) treatments, respectively. No significant regression equation was found for either total or marketable yields as a function of percent CRF for either CRF product or potato variety (Figure 5-3, A and B).

Table 5-19. Total and marketable yields of 'Atlantic' and 'Red LaSoda' potatoes by CRF4 blend.

	'Atlantic'				'Red LaSoda'			
AN:CRF4	Total yield	Marketable yield			Total yield	Marketable yield		
blend[1]	Mg ha^{-1}	Mg ha^{-1}	%No N	%100:0	Mg ha^{-1}	Mg ha^{-1}	%No N	%100:0
100:0	22.6	13.1	400	100	24.7	11.8	704	100
75:25	25.7	16.1	492	123	24.5	14.2	845	120
50:50	22.6	14.8	452	113	23.9	13.6	815	116
25:75	29.7	21.0	641	160	21.3	8.5	506	72
0:100	23.8	14.6	445	111	20.8	10.6	636	90
ANOVA *p*-value	0.0937	0.0641			0.7094	0.4989		
Tukey LSD	ns	ns			ns	ns		

[1] - CRF4 = 41-0-0. Blends are % of N applied as AN and CRF, respectively.

Table 5-20. Total and marketable yields of 'Atlantic' and 'Red LaSoda' potatoes by CRF6 blend.

	'Atlantic'				'Red LaSoda'			
AN:CRF6	Total yield	Marketable yield[2]			Total yield	Marketable yield[2]		
blend[1]	Mg ha^{-1}	Mg ha^{-1}	%No N	%100:0	Mg ha^{-1}	Mg ha^{-1}	%No N	%100:0
100:0	22.6	13.1 b[2]	400	100	24.7	11.8	704	100
75:25	27.9	17.3 ab	530	132	22.4	11.6	693	98
50:50	27.2	17.9 ab	546	136	23.7	14.4	860	122
25:75	27.7	19.4 a	593	148	25.4	14.0	839	119
0:100	27.1	15.9 ab	487	122	24.7	13.5	803	114
ANOVA *p*-value	0.2517	0.0566			0.8812	0.9206		
Tukey LSD	ns	6.0			ns	ns		

[1] - CRF6 = 43-0-0. Blends are % of N applied as AN and CRF, respectively.

[2] - Means in columns followed by same letters not significantly different.

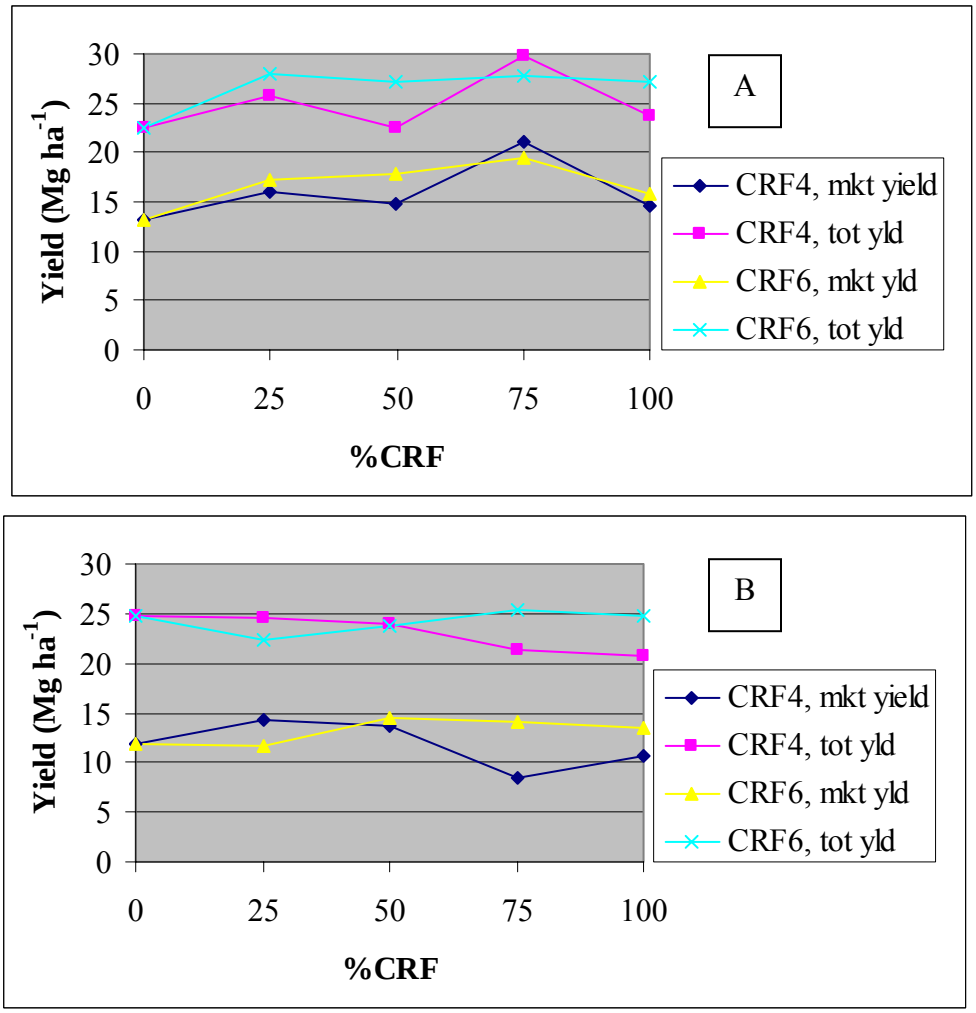


Figure 5-3. Total and marketable potato tuber yields by AN:CRF ratio by variety. A) 'Atlantic', B) 'Red LaSoda'.

Specific Gravity

Tuber SG values from tubers with CRF4 blends ranged from 1.078 to 1.080 for 'Atlantic' potatoes and from 1.064 to 1.067 for 'Red LaSoda' potatoes (Table 5-21). SG from tubers with CRF6 blends ranged from 1.075 to 1.081 for 'Atlantic' potatoes and 1.062 to 1.065 for 'Red LaSoda' potatoes (Table 5-22).

No significant tuber SG difference was observed with either CRF product for any blend within a potato variety. No significant regression equation for tuber SG was found for either of the CRF products or potato varieties tested, though an apparent increasing SG

trend was observed with CRF6 as the percentage of AN in the blend increased for both varieties of potatoes (Figure 5-4). 'Atlantic' tuber specific gravities were within the accepted grade range for northeast Florida production.

Table 5-21. 'Atlantic' and 'Red LaSoda' tuber specific gravity by CRF4 blend.

AN:CRF4 blend[1]	Specific gravity 'Atlantic'	'Red LaSoda'
100:0	1.079	1.064
75:25	1.078	1.067
50:50	1.080	1.067
25:75	1.080	1.065
0:100	1.078	1.066
ANOVA *p*-value	0.7414	0.1562
Tukey LSD	ns	ns

[1] - CRF4 = 41-0-0. Blends are % of N applied as AN and CRF, respectively.

Table 5-22. 'Atlantic' and 'Red LaSoda' tuber specific gravity by CRF6 blend.

AN:CRF6 blend[1]	Specific gravity 'Atlantic'	'Red LaSoda'
100:0	1.079	1.064
75:25	1.081	1.065
50:50	1.076	1.065
25:75	1.078	1.062
0:100	1.075	1.062
ANOVA *p*-value	0.1428	0.2395
Tukey LSD	ns	ns

[1] - CRF6 = 43-0-0. Blends are % of N applied as AN and CRF, respectively.

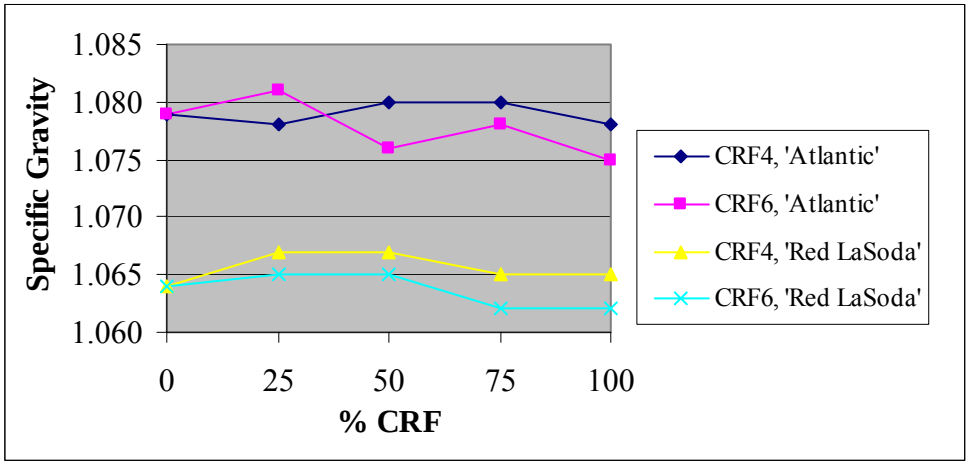


Figure 5-4. 'Atlantic' and 'Red LaSoda' tuber specific gravity by fertilizer treatment.

Tuber Quality

In the replacement experiment, no significant difference in tuber quality was observed for any internal or external tuber disorders for either CRF product, AN:CRF blend, or for either of the potato varieties, with the exception of percent growth cracks. The AN:CRF4 0:100 treatment had a significantly higher percentage of 'Atlantic' tubers with growth cracks (5.2%) than did the 50:50 (1.3%) and 25:75 (0.9%) blends. The AN:CRF4 100:0 (3.2%) and 75:25 (2.3%) blends were not significantly different from any of the CRF4 treatments.

Stand Establishment

'Atlantic' potato stands ranged from 61.1% CRF4 (AN:CRF 50:50) to 79.2% CRF6 (AN:CRF 25:75). 'Red LaSoda' stand count ranged from 67.4% CRF4 (AN:CRF 25:75) to 90.3% CRF6 (AN:CRF 25:75) (Table 5-23). Lower stand counts observed may in part be explained by the fact that this potato bed is very slightly downhill and relatively wetter than other areas of the farm. Higher water may lead to more rotting of the seed tuber and, in turn, reduced stands.

Table 5-23. Plant stand establishment data in the replacement experiment.

Treatment	AN:CRF blend[1]	'Atlantic' % stand	'Red LaSoda' % stand
No N	--	64.6	75.0
AN	100:0	63.2	69.4
CRF4	75:25	66.7	76.4
CRF4	50:50	61.1	84.0
CRF4	25:75	77.8	67.4
CRF4	0:100	66.0	70.8
CRF6	75:25	69.4	81.9
CRF6	50:50	69.4	77.8
CRF6	25:75	79.2	90.3
CRF6	0:100	77.1	84.7

[1] - CRF4 = 41-0-0, CRF6 = 43-0-0. Blends are % of N applied as AN and CRF, respectively.

Tissue Analysis

No periodic tissue sampling was performed in the replacement experiment.

Plant Biomass

Whole plant samples were only taken from the 'Atlantic' plots. No significant difference in leaf TKN or leaf, stem, or total (leaf + stem) dry weight was observed between plants within the AN:CRF blends for either of the CRF products (Table 5-24 and 5-25). No significant difference was found in stem TKN with CRF6, though with CRF4, plants with AN:CRF 100:0 had significantly higher TKN concentrations (1.7×10^4 g kg^{-1}) than for with AN:CRF 25:75 blend (1.1×10^4 g kg^{-1}). No significant linear regression equation was found for leaf or stem TKN, or leaf, stem, or total dry weight for either of the CRF blends or potato varieties evaluated.

Tuber Nitrogen Recovery Efficiency

There were no significant differences among treatments for the amount of N removed by the tubers. Total N recoveries for CRF4 ranged from 57.9 (AN:CRF 0:100) to 82.9 kg ha^{-1} N (AN:CRF 25:75) (Table 5-26) and from 65.0 (AN:CRF 0:100) to 89.1 kg ha^{-1} N (AN:CRF 25:75) for CRF6 (Table 5-27).

Table 5-24. Plant biomass and tissue nitrogen by CRF4 blend.

AN:CRF4 blend[1]	Leaf TKN 10^4 g kg^{-1}	Stem TKN 10^4 g kg^{-1}	Leaf DM[2] g plt^{-1}	Stem DM g plt^{-1}	Total DM g plt^{-1}
100:0	4.0	1.7 a[3]	24.7	15.6	40.3
75:25	3.9	1.5 ab	33.7	22.2	55.9
50:50	3.4	1.6 ab	35.7	20.0	55.7
25:75	3.0	1.1 b	33.0	20.8	53.7
0:100	3.3	1.3 ab	28.6	16.0	44.7
ANOVA *p*-value	0.1106	0.0049	0.3866	0.2917	0.3772
Tukey LSD	ns	0.6	ns	ns	ns

[1] - CRF4 = 41-0-0. Blends are % of N applied as AN and CRF, respectively.
[2] - DM = Dry matter; Total DM = Leaf DM + Stem DM.
[3] - Means in columns followed by same letters not significantly different.

Table 5-25. Plant biomass and tissue nitrogen by CRF6 blend.

AN:CRF6 blend[1]	Leaf TKN 10^4 g kg^{-1}	Stem TKN 10^4 g kg^{-1}	Leaf DM[2] g plt^{-1}	Stem DM g plt^{-1}	Total DM g plt^{-1}
100:0	4.0	1.7	24.7	15.6	40.4
75:25	3.8	1.4	36.5	22.7	59.2
50:50	3.5	1.3	26.9	16.1	43.0
25:75	3.6	1.1	29.2	18.2	47.4
0:100	3.1	1.2	23.4	15.1	38.5
ANOVA *p*-value	0.1449	0.1182	0.0559	0.1238	0.066
Tukey LSD	ns	ns	ns	ns	ns

[1] - CRF6 = 43-0-0. Blends are % of N applied as AN and CRF, respectively.
[2] - DM = Dry matter; Total DM = Leaf DM + Stem DM.

Table 5-26. Tuber nitrogen uptake and nutrient recovery efficiency by CRF4 blend.

	'Atlantic'		'Red LaSoda'	
AN:CRF4 blend[1]	N uptake kg ha^{-1}	NRE[2] %	N uptake kg ha^{-1}	NRE[2] %
100:0	71.9	42.8	57.2	34.1
75:25	73.5	43.7	56.7	33.7
50:50	62.5	37.2	59.4	35.3
25:75	82.9	49.3	52.8	31.4
0:100	57.9	34.5	52.3	31.1
ANOVA *p*-value	0.1629	0.1629	0.9588	0.9588
Tukey LSD	ns	ns	ns	Ns

[1] - CRF = controlled-release fertilizer; CRF4 = 41-0-0. Blends are % of N applied as AN and CRF, respectively.
[2] - NRE = Nutrient recovery efficiency.

Table 5-27. Tuber nitrogen uptake and nutrient recovery efficiency by CRF6 blend.

	'Atlantic'		'Red LaSoda'	
AN:CRF6 blend[1]	N uptake kg ha^{-1}	NRE[2] %	N uptake kg ha^{-1}	NRE[2] %
100:0	71.9	42.8	57.2	34.1
75:25	76.6	45.6	60.1	35.8
50:50	74.6	44.4	56.7	33.7
25:75	82.1	48.9	58.4	34.7
0:100	65.0	38.7	55.3	32.9
ANOVA *p*-value	0.5224	0.5224	0.9896	0.9588
Tukey LSD	ns	ns	ns	Ns

[1] - CRF6 = 43-0-0. Blends are % of N applied as AN and CRF, respectively.
[2] - NRE = Nutrient recovery efficiency.

No significant differences in NRE were observed. Percent NRE values for 'Atlantic' tubers 34.5 to 49.3% recovery with CRF4 and 38.7 to 48.9% recovery with CRF6. 'Red LaSoda' NRE results were similar to 'Atlantic results'—NRE percentages ranged from 31.1% (AN:CRF 0:100) to 35.3% (AN:CRF 50:50) with CRF4, and from 32.9% (AN:CRF 0:100) to 35.8% (AN:CRF 75:25) with CRF6 (Table 5-26 and 5-27, respectively). No significant linear regression equation for N uptake was found for either of the CRF product blends or potato varieties evaluated.

CRF Production Studies Discussion

CRF Production Experiment

The effects of the CRF fertilizers on potato production generally were better than those of AN. There were, however, situations where production parameters were either unimproved or worse with CRF than with AN. These are outlined by fertilizer product.

Ammonium nitrate

Marketable yields for plants with AN ranged from 16.7 to 24.9 Mg ha^{-1} for the 112 to 224 kg ha^{-1} N rates. Overall these yields were somewhat low for the area (Hutchinson *et al*., 2003). Specific gravity with AN was also lower than area averages at 1.077, 1.075, and 1.074 for decreasing fertilizer rates. Plants with AN did not have substantially higher amounts of green, growth cracked, or rotten potatoes, or potatoes with hollow heart, brown rot, or corky ring spot than plants fertilized with CRF. Plants with AN at 224 kg ha^{-1} N had significantly more misshapen potatoes than with CRF, and tubers with AN at 168 kg ha^{-1} N had significantly more internal heat necrosis than with CRF, with the exception of CRF6 (112 kg ha^{-1} N). Stand counts averaged 96% for the three N rates. Leaf tissue N and plant biomass were not greatly different from CRF treatments. Tuber N uptake and NRE was similar with CRF products.

CRF

The CRF products as a whole resulted in higher yields than AN. CRF2 and CRF4, both with 224 kg ha^{-1} N, had the highest total and marketable yields of all treatments, while CRF1 (112 kg ha^{-1} N) had lowest yields (total and marketable) of all fertilized treatments. Other products of note were CRF5 and CRF6, both of which had statistically comparable marketable yields with CRF2 and CRF4, at similar rates of application.

Specific gravity followed a similar trend to yields. Highest SG were found with CRF2 (224 kg ha^{-1} N) with 1.084, though most of the other CRF and rate combinations were statistically similar to this. Lowest SG among CRF fertilized plants was with CRF1 (224 kg ha^{-1} N).

Tuber quality from CRF fertilized plots was similar to AN fertilized plots for all measured parameters except misshapen potatoes and potatoes with internal heat necrosis. In the case of these, no CRF product or rate resulted in higher incidence than another combination, though all CRF-rate combinations had lower incidence than AN.

Stand establishment for the various CRF products averaged 68% for CRF1, 96% for CRF2, 84% for CRF3, 98% for CRF4, 96% for CRF5, and 97% for CRF6. Some possible reasons for the low stands of CRF1, especially at the higher rates, may be that the material may have induced dormancy of the seed tubers, or the fertilizer may have burned back the leading buds and it was not until the fertilizer levels were reduced that the plant could successfully emerge from the soil. One observation was that late in the season some of the potatoes finally emerged—indicating that at least some of the seed tubers had not rotted, though emergence was delayed. The low observed yields from CRF1 are thus a result of fewer plants producing tubers as opposed to fewer tubers per plant.

As mentioned for AN, plant tissue taken during the growing season was not outstandingly different between CRF fertilized plants and AN fertilized plants. A trend was observed that early in the season, plants with CRF had higher tissue N than AN, whereas late in the season, this trend was reversed. However, considering tuber yield, SG, and quality, it would appear that early tissue N concentration is more important to the desirable plant outcome than tissue N concentration late in the season.

It is useful to link the various sampling dates to physiological plant age, with sampling date 1 approximately when plants are 20-30 cm tall, sampling date 2 shortly before first flower, sampling date 3 at full flower, and sampling date 4 three weeks before harvest. In terms of physiological age, the data from the current study correlate well to work done by Hochmuth *et al*. (1991), which indicated that at sampling date 1, the most recently matured (MRM) leaf (leaflets + petioles) should have a TKN concentration between 3-6 x 10^4 g kg^{-1}, at sampling date 2, between 3-4 x 10^4 g kg^{-1}, at sampling date 3, between 2.5-4 x 10^4 g kg^{-1}, and at sampling date 4, between 2-4 x 10^4 g kg^{-1}. From this information, the MRM leaf tissue samples taken from the various treatments during the production experiment were somewhat high early in the season and fell to within sufficiency ranges towards the end of the growing season.

The increase in leaf TKN concentrations of CRF1 could possibly indicate a late release of that product, fertilizing plants late into the season. The decrease in leaf TKN over the course of the growing season is likely due to a depletion of N from the soil coupled with a re-translocation of nutrients from above ground tissues into developing tubers.

Plant biomass as measured by leaf and stem N, and by leaf, stem, and total DM, revealed that plants with CRF2 through CRF6 were relatively comparable across all rates (the rate by product interaction was not significant), though they were different than plants with CRF1 and AN. This may be related to the similar observation with plant tissue. In the case of both, it may be due to the late emergence and growth of plants seen with CRF1, though the reason for this with AN is unknown.

Tuber N uptake between the CRF products tended to decrease within a fertilizer product with a corresponding decrease in N rate. Highest N uptake in tubers was from CRF2, CRF4, and CRF5, all with 224 kg ha^{-1} N. NRE was not different for any of the fertilizer-rate combinations except for CRF1 (224 kg ha^{-1} N). This was likely due to the poor stands seen with plants in these plots, which resulted in poor yields, indirectly resulting in low NRE. This contrasts with results by Zvomuya *et al* (2003) who reported that nitrogen RE was on average higher with PCU (mean 50%) than urea (mean 43%). Hutchinson *et al*. (2003) reported comparable nutrient use efficiency between CRF and AN products at high rates, but significantly higher efficiencies of CRF products at low rates (112 kg ha^{-1} N). However, they reported that that year was fairly dry, resulting in less total fertilizer leaching away from the root zone for all of the products. In this study, the slow release of nutrients did not improve overall efficiency of use of N between CRF and AN products.

Fertilizer rate

Despite, many significant interactions resulting in simple effects analysis, yields, SG, and tuber quality from CRF products at 168 kg ha^{-1} N did not appear to be substantially less than from CRF products at 224 kg ha^{-1} N. Hutchinson *et al*. (2003)

reported similar results on ‘Atlantic’ potatoes. They found that total and marketable yield and SG were not significantly different between 168 and 224 kg ha^{-1} N.

Replacement Experiment

No AN:CRF blend from either of the CRF products utilized in the replacement experiment improved yields or SG significantly. CRF6 did increase marketable yields of ‘Atlantic’ potatoes some with a 25:75 AN:CRF6 blend, but this was not observed with ‘Red LaSoda’ potatoes. No significant effect on tuber quality was observed. No effect on stand establishment was observed. No significant effect on leaf TKN, leaf, stem, and total DM was observed. A slightly greater stem TKN level was observed with CRF4 on ‘Atlantic’ potatoes with 100:0 AN:CRF4. No significant regression equation was found for any of these parameters for either of the CRF products or either of the potato varieties. These results are enigmatic because the CRF products are supposed to improve nutrient use and therefore all aspects of the plant during its life cycle. This is especially the theoretical outcome under moist conditions. It may be that the absence of change when compared to 100% AN is that the fertilizer products did not in fact behave as such.

Summary

In general, all of the CRF products except CRF4 performed better than AN when total and marketable yields were averaged over rate. Presumably this is due to the extended period of availability of the CRF products. These findings are comparable to those of Zvomuya *et al*. (2003) who reported significantly higher total and marketable yields with PCU (polymer-coated urea, a CRF) at two rates (148 and 280 kg ha^{-1} N) than with urea (a water soluble fertilizer) applied in three split applications under excessive irrigation. Fertilization with PCU at 280 kg ha^{-1} N resulted in higher marketable yields in one study and in higher total and marketable yields in an excessive irrigation study

compared to five split applications of urea. Zvomuya and Rosen (2001) reported 3.9 and 3.3 Mg ha^{-1} total and marketable yield increase with POCU over urea alone, respectively. Hutchinson *et al*. (2003) reported highest total and marketable yields were obtained either with two different CRF combinations (one at 224 kg ha^{-1} N and one at 168 kg ha^{-1} N) or AN + urea (224 kg ha^{-1} N).

Although, tuber quality and quantity were greater with the CRF products than with the AN treatments, no comparison can be drawn by comparison to grower yields because the AN treatments did not constitute grower yields as they will typically split their N applications. Typical marketable yields for the area range around 36.9 Mg ha^{-1} (Hutchinson *et al*., 2002). Thus, for 2003, marketable yields were somewhat depressed compared to historical averages. However, as 2003 was a very wet year (see Precipitation, Chapter 6), it was observed that most growers had reduced yields and that the CRF program yielded better than grower programs.

Returning to the key question of this study, whether CRF products can be used to provide similar total and marketable yields of high-quality potatoes to traditionally-used AN products? It is concluded that CRF products offer no disadvantage to growers with respect to tuber yield or quality, and plant nutritional status, when compared to AN. In the recent studies outlined herein, some CRF-produced potatoes surpassed AN produced potatoes both in yields and quality. For Florida growers, CRF products provide an alternative to traditional AN fertilizer practices. As these products are improved to match crop uptake requirements, future research may find that they are superior to AN products under all growing conditions. This may be of particular interest during wet years when nutrient leaching pressures are greatest. As this technology is improved, CRF products

may help Florida growers to increase productivity and profits, thus benefiting the growers and society.

CHAPTER 6
NITROGEN MOVEMENT IN A SUB-SURFACE IRRIGATED POTATO PRODUCTION SYSTEM UTILIZING CONVENTIONAL AND CONTROLLED-RELEASE NITROGEN SOURCES

The hypothesis of this research is that controlled-release nitrogen fertilizers (CRF) offer a viable alternative to growers for producing potatoes by maintaining or increasing while reducing N contamination of watersheds. As part of that hypothesis, if CRF products release nutrients to plants in times and quantities required, little residual will be available for potential movement into water bodies. This chapter discusses the results of a field experiment designed to determine the timing of nitrogen release from CRF prills and its location in the soil (i.e., soil and water). Soil samples together with well and suction cup lysimeter samples were taken at regular intervals over the growing season. Since the amount of nitrogen found either in soil or aqueous samples represented only a "snapshot" of water and soil conditions at the specific time of sampling, it was impossible to quantify how much fertilizer had moved and to where. However, the successive measurements provided trends of amounts of nitrogen found in samples over the growing season.

Precipitation and Temperature

Precipitation

Precipitation quantity and timing coupled with temperature over the season, affect potato production and nitrogen fate. Total precipitation for the 2003 potato growing season (13 Feb through 28 May 2003) was 30.6 cm, above the historical average of 28.2 cm (Figure 6-1). Historical averages are based on a 47 year period from 1954 to 2001.

In the first 45 days of the 2003 season, the site received 23.3 cm of precipitation. Historical precipitation averages for this same time period are 13.7 cm. Thus, the first 45 days of the growing season were more wet than usual, creating an ideal environment for nutrient leaching. From 45 DAP to harvest at 105 DAP, the 2003 growing season was relatively dry (7.4 cm) compared to the historical average (14.2 cm) for the same period. The 7.4 cm precipitation was received mainly during three rain events at 71 DAP (0.9 cm), 77 DAP (1.6 cm), and 98 DAP (4 cm). The water table was maintained 56 to 69 cm below the top of the potato row based on historical cultural practices.

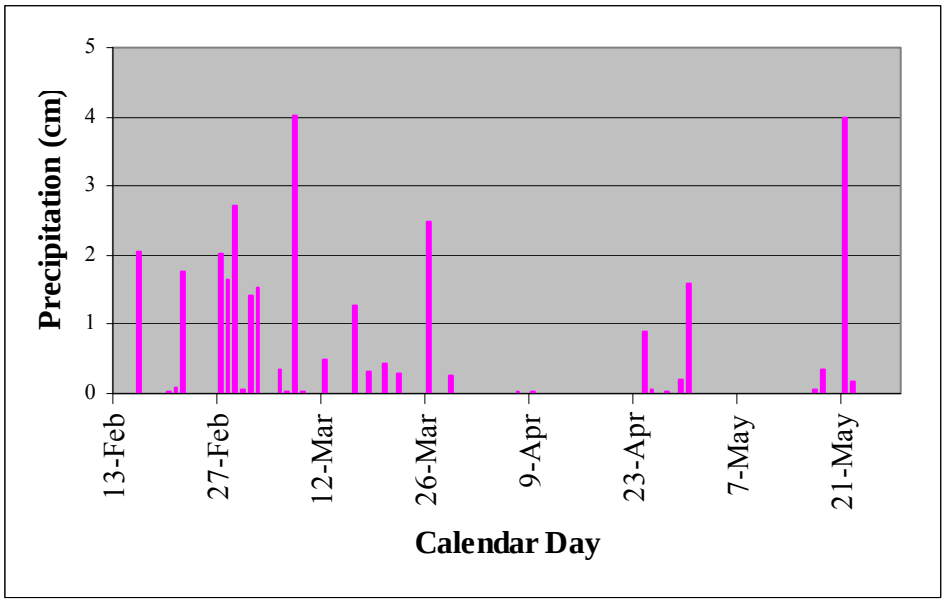


Figure 6-1. 2003 daily precipitation in Hastings, FL from 13 Feb to 28 May.

Temperature

Air temperatures for the 2003 growing season ranged from a low of 1.7°C on 31 Mar to a high of 35.7°C on 9 May with daily averages shown in Figure 6-2, A. These temperatures are roughly similar to historical averages, though with greater fluctuations, as would be expected for individual years. Of the two times that air temperatures dipped to near freezing over the season, the first occurred shortly after planting (14 Feb) before

plants had emerged, and was of little concern. The second event (30-31 Mar) occurred while plants were vigorously growing and could have been detrimental to the crop. However, plants appeared not to be affected, and no plant kill was observed.

Soil temperatures in 2003 ranged from a low of 12.7°C on 14 Feb to a high of 27.2°C on 26 May. As with air temperatures, 2003 average soil temperatures were roughly similar to historical averages (Figure 6-2, B).

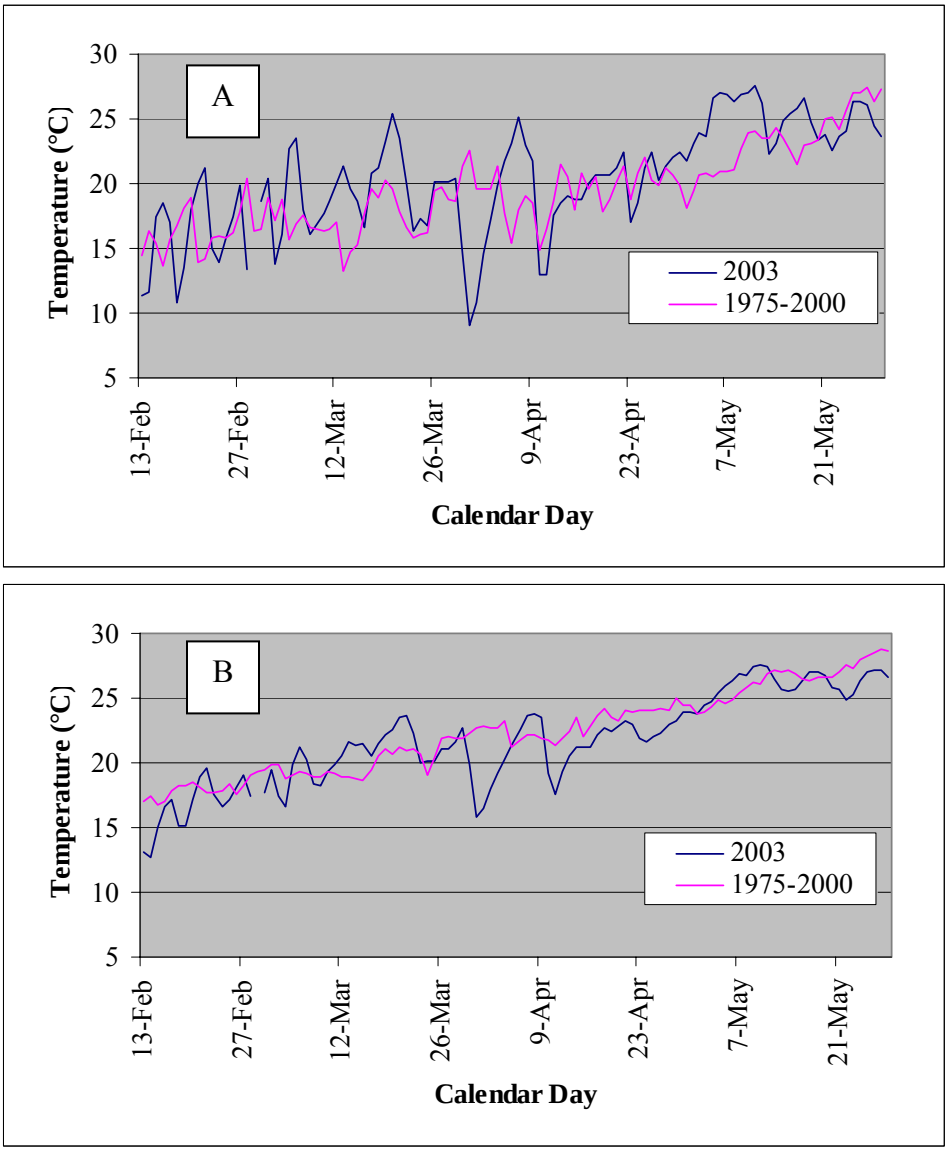


Figure 6-2. 2003 and historical air and soil temperatures in Hastings, FL over the potato growing season. A) air, B) soil.

Soil Nitrogen

Soil samples taken over the duration of the experiment can be separated into two groups: pre-plant soil samples reflecting the N content of the soil before treatments were implemented, and periodic growing season soil samples reflecting the relative changes in soil N content over the course of the growing season. Both are presented here and are summarized with water data at the end of the chapter.

Pre-plant Soil Nitrogen

Soils from the experiment area in 2003 contained total of 0.34 mg kg^{-1} ammonium nitrogen (NH_4-N) and 0.29 mg kg^{-1} nitrate nitrogen (NO_3-N) pre-plant. Soil OM levels were 1.06 x 10^4 g kg^{-1}, pH was 5.82, and the electrical conductivity of the soil was 0.04 dS m^{-1}. Based on those values the amount of N in the top 15 cm of a hectare, there would be about 0.7 kg NH_4-N and 0.6 kg NO_3-N per hectare of available nitrogen, plus that N tied up in the OM. The N in this OM is not available at proper times or in sufficient quantities to contribute substantially to the N requirement of the potato crop, as illustrated by the low yields of the non-fertilized control (No N) (see Table 5-3, footnote 4).

Seasonal Soil Nitrogen

Soil samples were analyzed factorially by sampling date, fertilizer source, and fertilizer rate. The ANOVA table for NH_4-N and NO_3-N are shown in Table 6-1 and Table 6-2, respectively. For NH_4-N, while the third-order interaction between sampling dates, fertilizer products, and rates, and the second-order interactions between sampling date and rate and between rate and fertilizer product were not significant, the sampling date by fertilizer product interaction was. For NO_3-N, all second-order interactions were significant while the third-order interaction was not. Accordingly, NH_4-N main effect

Table 6-1. ANOVA table for soil NH_4-N over all sampling dates.

Source	DF	Type III SS	MS	F Value	Pr > F
Date	6	1918	320	26.04	< 0.0001
Fert	6	908	151	12.33	< 0.0001
Rate	2	298	149	12.12	< 0.0001
Rep	3	200	67	5.44	0.0011
Date*Fert	36	1100	31	2.49	< 0.0001
Date*Rate	12	103	9	0.7	0.7525
Fert*Rate	12	220	18	1.49	0.1231
Date*Fert*Rate	72	599	8	0.68	0.9783
Error	438	5378	12		
Corrected Total	587	10724			

Table 6-2. ANOVA table for soil NO_3-N over all sampling dates.

Source	DF	Type III SS	MS	F Value	Pr > F
Date	6	4139	690	23.43	< 0.0001
Fert	6	3369	561	19.07	< 0.0001
Rate	2	5402	2701	91.76	< 0.0001
Rep	3	441	147	4.99	0.0020
Date*Fert	36	2528	70	2.39	< 0.0001
Date*Rate	12	1453	121	4.11	< 0.0001
Fert*Rate	12	2212	184	6.26	< 0.0001
Date*Fert*Rate	72	2721	38	1.28	0.0705
Error	438	12894	29		
Corrected Total	587	35159			

Table 6-3. Soil NH_4-N by fertilizer source main effect over all N rates and sampling dates.

Fertilizer	NH_4-N (mg kg^{-1})	
AN	2.30	e[1]
CRF1	2.62	de
CRF2	4.47	bc
CRF3	3.24	c-e
CRF4	3.94	b-d
CRF5	6.13	a
CRF6	4.83	ab
ANOVA p-value	0.0001	
Tukey LSD	1.56	

[1] - Means in columns followed by same letters not significantly different.

data is shown only for the various fertilizer sources across all sampling dates and rates (Table 6-3). Soils from all plots with CRF2, CRF4, CRF5, and CRF6 had higher

Table 6-4. Soil NO_3-N simple effects by fertilizer source and rate over all sampling dates.

Fertilizer	N rate kg ha^{-1}	NO_3-N mg kg^{-1}	
AN	112	1.10	h[1,2]
AN	168	2.27	gh
AN	224	4.14	e-h
CRF1	112	3.12	f-h
CRF1	168	9.35	cd
CRF1	224	15.44	ab
CRF2	112	3.45	f-h
CRF2	168	5.36	c-h
CRF2	224	10.44	bc
CRF3	112	3.15	f-h
CRF3	168	6.87	c-g
CRF3	224	18.34	a
CRF4	112	3.74	e-h
CRF4	168	4.61	d-h
CRF4	224	7.59	c-f
CRF5	112	3.36	f-h
CRF5	168	8.69	c-e
CRF5	224	10.14	c
CRF6	112	2.76	f-h
CRF6	168	3.61	e-h
CRF6	224	6.15	c-h
ANOVA *p*-value		< 0.0001	
Tukey LSD		5.21	

[1] - Means in columns followed by same letters not significantly different.
[2] - Soil from the control treatment had an average NO_3-N concentration of 0.82 over all sampling dates.

concentrations of NH_4-N over the entire season than AN fertilized plots. This may be an effect of prolonged CRF release over the entire growing season, despite numerous rain events that may have leached soil N. Simple effects of each fertilizer source by sampling date interaction on NH_4-N for each rate were not of interest and were not analyzed. For NO_3-N, rate by product interactions are shown in Table 6-4. NO_3-N was highest in soils with CRF3 at 224 kg ha^{-1} N over the entire season at 18.3 mg L^{-1}. This

was statistically comparable only to CRF1 at the 224 kg ha^{-1} N rate. These high soil N concentrations over the entire season are interesting because yields from these treatments were not the highest. This may be due to high salt concentrations around the seed tubers resulting in dieback of the sprouts.

In addition to analysis over all sampling dates, soils were also analyzed for differences within each sampling date. No significant interactions between fertilizer source and rate existed for NH_4-N at any sampling date during the season. However, interactions were significant at 55 ($p < 0.0001$), 69 ($p = 0.0150$), and 84 ($p = 0.0011$) DAP for NO_3-N. The fertilizer source main effects at each sampling date for NO_3-N and NH_4-N are shown in Table 6-5 and Table 6-6, respectively, while the simple effects for NO_3-N at 55, 69, and 84 DAP are shown in Table 6-7. As illustrated by the data, soil NH_4-N and NO_3-N were lowest in the AN fertilized plots early in the season when it might be expected to be highest. This effect may be due to the high mobility of AN which may have moved from the root zone with the numerous rainstorms that occurred early in the growing season.

Table 6-5. Soil NO_3-N by fertilizer source main effect for each sampling date.

	NO_3-N (mg kg^{-1})			
Fertilizer	15 DAP[1]	29 DAP	41 DAP	97 DAP
AN	2.38 b[2]	2.36 b	1.05 b	1.53
CRF1	6.59 ab	12.23 ab	8.37 a	4.35
CRF2	8.05 a	17.42 a	5.26 ab	2.61
CRF3	8.08 a	14.31 a	8.89 a	2.76
CRF4	8.15 a	13.33 a	3.42 ab	2.21
CRF5	8.00 a	16.72 a	6.50 ab	4.31
CRF6	3.95 ab	8.35 ab	3.12 ab	3.13
ANOVA *p*-value	0.0061	0.0003	0.0004	0.1028
Tukey LSD	5.53	10.07	6.56	ns

[1] - DAP = days after planting

[2] - Means in columns followed by same letters not significantly different.

Table 6-6. Soil NH_4-N by fertilizer source main effect for each sampling date.

	NH_4-N (mg kg^{-1})						
Fertilizer	15 DAP[1]	29 DAP	41 DAP	55 DAP	69 DAP	84 DAP	97 DAP
AN	1.04 b[2]	0.88 b	0.54	5.67	3.07 b	1.80 b	3.08 ab
CRF1	2.89 ab	1.89 b	1.03	5.81	2.57 b	2.08 b	2.05 b
CRF2	5.58 a	4.85 a	1.59	4.73	7.44 ab	4.29 ab	2.82 ab
CRF3	3.12 ab	2.52 ab	1.60	4.57	4.56 b	3.80 ab	2.49 ab
CRF4	3.29 ab	3.05 ab	0.93	5.67	6.80 ab	4.73 ab	3.13 ab
CRF5	4.15 ab	5.23 a	1.78	7.86	13.20 a	5.62 a	5.07 a
CRF6	1.90 ab	2.54 ab	1.21	5.65	12.47 a	6.13 a	3.89 ab
ANOVA *p*-value	0.0416	0.0004	0.0743	0.8634	0.0015	0.0005	0.0465
Tukey LSD	4.15	2.81	ns	ns	7.27	3.04	2.85

[1] - DAP = Days after planting.

[2] - Means in columns followed by same letters not significantly different.

Table 6-7. Soil NO_3-N by treatment for each sampling date.

Fertilizer	N rate kg ha^{-1}	NO_3-N (mg kg^{-1}) 55 DAP[1]		69 DAP		84 DAP	
AN	112	0.65	c[2,3]	1.04	c	0.79	c
AN	168	2.81	c	2.76	c	3.44	c
AN	224	9.37	bc	4.95	c	4.74	c
CRF1	112	1.27	c	1.23	c	0.89	c
CRF1	168	18.39	b	9.98	a-c	6.56	bc
CRF1	224	20.74	ab	23.32	a	18.35	ab
CRF2	112	3.24	c	1.46	c	1.75	c
CRF2	168	3.20	c	2.41	c	2.62	c
CRF2	224	8.97	bc	7.16	bc	3.91	c
CRF3	112	1.48	c	1.37	c	1.27	c
CRF3	168	6.95	bc	4.90	c	1.89	c
CRF3	224	33.57	a	21.80	ab	23.21	a
CRF4	112	1.62	c	1.38	c	1.63	c
CRF4	168	2.40	c	1.80	c	2.02	c
CRF4	224	9.75	bc	5.00	c	4.66	c
CRF5	112	2.05	c	1.62	c	1.39	c
CRF5	168	7.60	bc	4.89	c	5.52	bc
CRF5	224	9.61	bc	8.92	a-c	7.22	bc
CRF6	112	1.47	c	3.01	c	1.90	c
CRF6	168	1.54	c	2.47	c	3.23	c
CRF6	224	6.70	bc	5.62	c	6.05	bc
ANOVA *p*-value		< 0.0001		< 0.0001		< 0.0001	
Tukey LSD		14.35		14.89		13.38	

[1] - DAP = Days after planting.
[2] - Means in columns followed by same letters not significantly different.
[3] - Soils from the control treatments had 0.70, 1.03, and 0.92 mg kg^{-1} NO_3-N at 55, 69, and 84 DAP, respectively.

Plots fertilized with CRF5 and CRF6 consistently had the highest soil NH_4-N concentrations from 55 to 97 DAP, while from 41 to 97 DAP, soils in plots fertilized with CRF1 and CRF3 consistently had the highest NO_3-N concentrations. This latter phenomenon is particularly evident at the 224 kg ha^{-1} N rate (Table 6-7).

The rate main effects on soil NH_4-N and NO_3-N concentration are shown in Table 6-8 and Table 6-9, respectively, while NO_3-N rate effects at 55, 69, and 84 DAP were

discussed in Table 6-7 due to the significant rate by source interaction. As might be expected, higher NH_4-N and NO_3-N concentrations were found in soils as N rate increased. This trend continued throughout the season for NO_3-N, though it was not significant at 15 DAP. This is likely due to the recent rainfall which would have moved any available nutrients below the root zone, w/o providing subsequent time for later N release. Also noteworthy, early in the season, both for NH_4-N and NO_3-N, soil N was not significantly different between the 168 and 224 kg ha^{-1} N rates. Late in the season, the soils in treatments with the middle N rate had soil N concentrations not higher than those at the low rate. These results would tend to support reduced N application rates—considerable N was available early in the season while little residual remained late in the season.

Combining the soil data together, neither NH_4-N nor NO_3-N appeared to provide a clear indicator of tuber yields that would result at harvest. No strong trend in N concentration occurred over the season, though this may be due to greatly fluctuating environmental conditions.

Well Water Nitrogen

Seasonal Well Nitrogen

Well samples were analyzed factorially for sampling date, fertilizer source, and rate main effects. The ANOVA tables for NO_3-N and NH_4-N are shown in Table 6-10 and Table 6-11, respectively. As no main effects can be determined due to interactions, the fertilizer source by rate interaction is of most interest. Accordingly, source by rate simple effects are shown in Table 6-12. From this simple effect data, highest N concentrations were found in water below plots fertilized with AN. In the case of NO_3-N, highest concentrations were found in AN fertilized plots with 224 kg ha^{-1} N, while in the case of

Table 6-8. Soil NH_4-N by rate main effect for each sampling date.

Rate	NH_4-N (mg kg^{-1})											
kg ha^{-1} N	15 DAP[1]	29 DAP		41 DAP		55 DAP	69 DAP	84 DAP		97 DAP		
112	2.83	1.91	b[2]	0.71	b	5.23	5.23	2.92	b	2.60		
168	3.00	2.93	ab	1.38	a	5.57	7.43	3.83	b	3.37		
224	3.59	4.14	a	1.64	a	6.32	8.82	5.44	a	3.69		
ANOVA *p*-value	0.5791	0.0004		0.0014		0.7024	0.0681	0.0008		0.0974		
Tukey LSD	ns	1.28		0.60		ns	ns	1.53		ns		

[1] – DAP = Days after planting.

[2] – Means in columns followed by same letters not significantly different.

Table 6-9. Soil NO_3-N by rate main effect for each sampling date.

Rate	NO_3-N (mg kg^{-1})			
kg ha^{-1} N	15 DAP[1]	29 DAP	41 DAP	97 DAP
112	5.95	7.06 b[2]	1.69 c	1.35 b
168	6.70	12.65 a	4.85 b	2.64 b
224	6.71	16.6 a	9.15 a	4.97 a
ANOVA *p*-value	0.6942	< 0.0001	< 0.0001	< 0.0001
Tukey LSD	ns	4.34	2.88	1.72

[1] - DAP = days after planting.
[2] - Means in columns followed by same letters not significantly different.

Table 6-10. ANOVA table for well NO_3-N over all sampling dates.

Source	DF	Type III SS	MS	F Value	Pr > F
Date	4	1775	444	9.65	< 0.0001
Fert	6	4813	802	17.43	< 0.0001
Rate	2	328	164	3.57	0.0300
Rep	2	1438	719	15.63	< 0.0001
Date*Fert	24	9115	380	8.25	< 0.0001
Date*Rate	8	588	73	1.60	0.1272
Fert*Rate	12	2287	191	4.14	< 0.0001
Date*Fert*Rate	48	2083	43	0.94	0.5826
Error	208	9571	46		
Corrected Total	314	31999			

Table 6-11. ANOVA table for well NH_4-N over all sampling dates.

Source	DF	Type III SS	MS	F Value	Pr > F
Date	4	1857	464	106.37	< 0.0001
Fert	6	347	58	13.24	< 0.0001
Rate	2	143	71	16.36	< 0.0001
Rep	2	16	8	1.87	0.1568
Date*Fert	24	911	38	8.70	< 0.0001
Date*Rate	8	306	38	8.77	< 0.0001
Fert*Rate	12	113	9	2.16	0.0146
Date*Fert*Rate	48	233	5	1.11	0.2982
Error	208	908	4		
Corrected Total	314	4834			

NH_4-N, statistically highest N concentrations were found at 224 and 168 kg ha^{-1} N in AN fertilized plots as well as at 224 kg ha^{-1} N in CRF1 fertilized plots. These results are not surprising in that water soluble products like AN would be expected to be mobile in higher quantities than CRF products, and higher rates of such would tend to result in

Table 6-12. NH_4-N and NO_3-N concentrations in wells by treatment.

Fertilizer	N rate kg ha^{-1}	NH_4-N mg L^{-1}		NO_3-N mg L^{-1}	
AN	112	1.98	b-d[1,2]	8.20	bc
AN	168	4.64	ab	13.35	b
AN	224	5.68	a	23.47	a
CRF1	112	1.41	cd	0.82	c
CRF1	168	1.48	cd	6.97	bc
CRF1	224	3.88	a-c	6.36	bc
CRF2	112	0.51	d	6.71	bc
CRF2	168	1.18	cd	4.29	c
CRF2	224	1.37	cd	3.22	c
CRF3	112	0.71	d	1.06	c
CRF3	168	1.02	d	2.99	c
CRF3	224	2.16	b-d	4.51	bc
CRF4	112	0.60	d	6.84	bc
CRF4	168	0.67	d	2.91	c
CRF4	224	2.63	b-d	3.42	c
CRF5	112	0.77	d	4.15	c
CRF5	168	1.68	cd	3.30	c
CRF5	224	0.71	d	4.39	bc
CRF6	112	0.22	d	2.17	c
CRF6	168	1.58	cd	5.69	bc
CRF6	224	1.31	cd	2.07	c
ANOVA *p*-value		< 0.0001		< 0.0001	
Tukey LSD		2.76		8.96	

[1] - Means in columns followed by same letters not significantly different.
[2] - Wells in plots with the control treatment had NH_4-N and NO_3-N concentrations of 0.18 and 6.03 mg L^{-1}, respectively.

greater quantities of nutrient leached. No CRF product at a given rate was significantly different from any other CRF source by rate combination, except for higher NH_4-N in CRF1 fertilized plots at 224 kg ha^{-1} N. Table 6-12 is illustrated graphically in Figure 6-3 and visualizes the increased leaching of nutrients within plots fertilized by each product as rate increases. This is particularly well illustrated with NH_4-N (Figure 6-3, A).

Periodic Well Nitrogen

In addition to factorial analysis over the entire season, factorial analyses was also performed for each sampling date. Rate by product interactions were not significant for

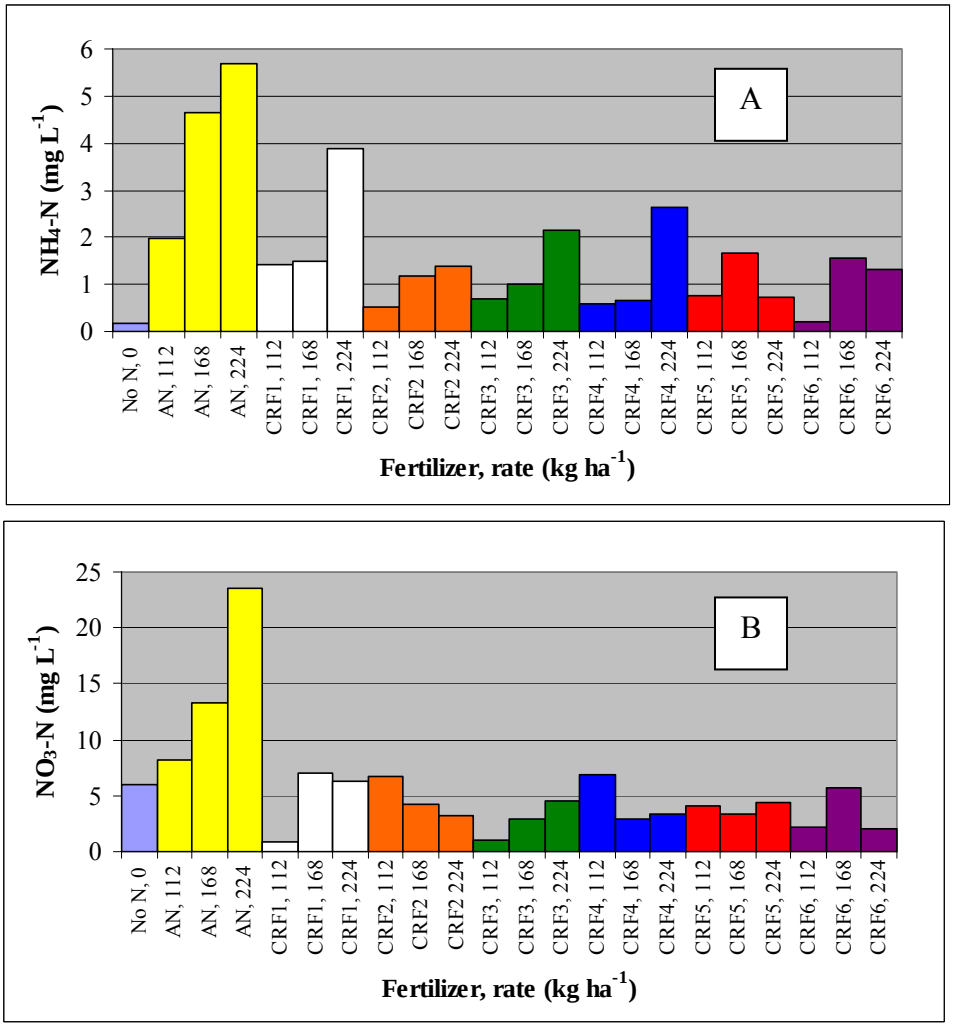


Figure 6-3. Nitrogen in wells by treatment over all sampling dates. A) NH_4-N, B) NO_3-N.

NO_3-N or NH_4-N at any of the sampling dates, with the exception of a significant rate by product interaction for NO_3-N at 29 DAP ($p = 0.0209$). Table 6-13 and Table 6-14 show the fertilizer source main effects across all rates for each sampling date for NH_4-N and NO_3-N (except 29 DAP), with corresponding figures in Figure 6-4 and Figure 6-5, respectively. The simple effects of source by rate for NO_3-N at 29 DAP are shown in Table 6-15.

Table 6-13. Well NH_4-N fertilizer source main effects at each sampling date.

	NH_4-N (mg L^{-1})				
Fertilizer	29 DAP[1]	41 DAP	64 DAP	78 DAP	92 DAP
AN	16.06 a[2]	4.10	0.14	0.18	0.02
CRF1	8.71 b	2.10	0.17	0.26	0.03
CRF2	3.62 bc	1.18	0.04	0.22	0.04
CRF3	5.16 bc	1.00	0.01	0.22	0.10
CRF4	5.14 bc	0.93	0.09	0.28	0.05
CRF5	3.39 bc	1.36	0.13	0.25	0.14
CRF6	2.69 c	2.14	0.03	0.27	0.05
ANOVA p-value	< 0.0001	0.0639	0.2341	0.8321	0.2293
Tukey LSD	5.91	ns	ns	ns	ns

[1] – DAP = Days after planting.
[2] - Means in columns followed by same letters not significantly different.

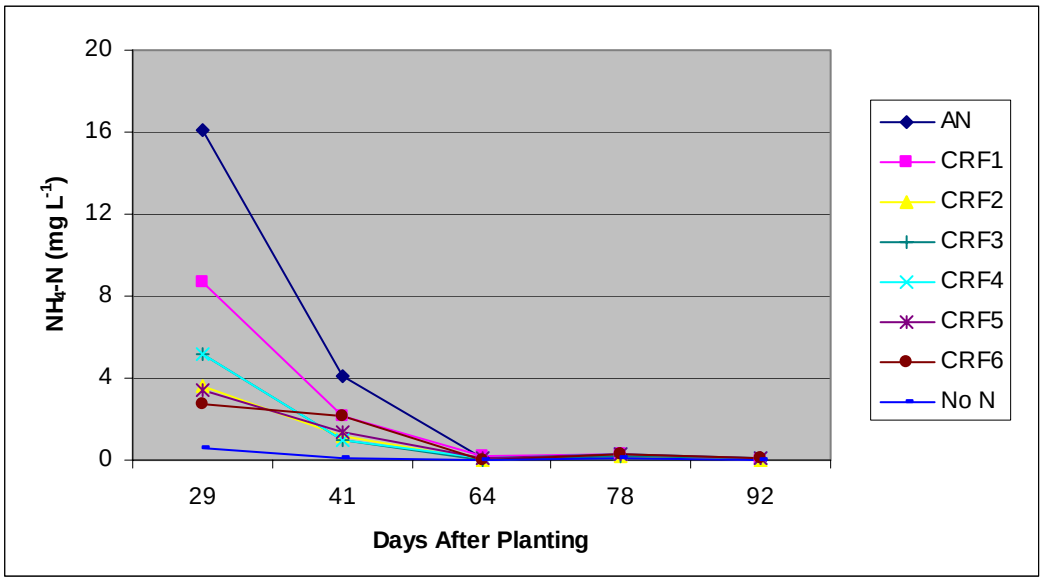


Figure 6-4. Well NH_4-N concentrations from each fertilizer product for each sampling date over the growing season.

For NH_4-N, highest well concentrations were found below AN fertilized plots early in the season (29 DAP). Subsequent samplings showed no significant difference between AN treatments and CRF treatments for well NH_4-N. Lowest well NH_4-N at 29 DAP was found in CRF6 fertilized treatments. NO_3-N in wells from AN fertilized plots was significantly greater than in any of the CRF fertilized plots, which were themselves statistically similar to each other. Late in the season no difference was observed between

Table 6-14. Well NO_3-N fertilizer source main effects at each sampling date.

	NO_3-N (mg L^{-1})			
Fertilizer	41 DAP[1]	64 DAP	78 DAP	92 DAP
AN	25.06 a[2]	3.58	4.93	1.42
CRF1	6.77 b	5.20	4.63	3.84
CRF2	6.92 b	6.42	3.73	3.41
CRF3	4.57 b	3.73	2.33	1.27
CRF4	6.79 b	3.72	5.67	1.73
CRF5	4.85 b	6.23	3.81	2.12
CRF6	3.67 b	3.98	5.77	1.51
ANOVA p-value	< 0.0001	0.8253	0.7825	0.559
Tukey LSD	13.29	ns	ns	ns

[1] – DAP = Days after planting.
[2] - Means in columns followed by same letters not significantly different.

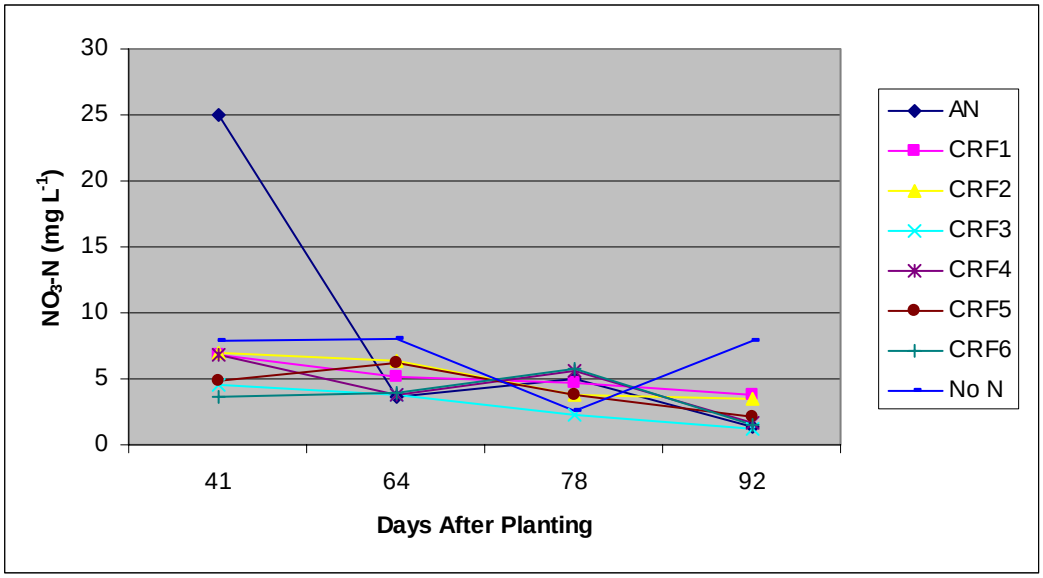


Figure 6-5. Well NO_3-N concentrations from each fertilizer product for each sampling date over the growing season.

AN and CRF treatment well concentrations. At 29 DAP, NO_3-N in wells was highest in AN treatments at 224 kg ha^{-1}. Only AN treatments at 168 kg ha^{-1} N were statistically comparable. AN at the low rate resulted in well NO_3-N concentrations not different than any of the CRF products at any rate. No CRF product at any rate was significantly different from any other CRF by rate combination.

Table 6-15. NO_3-N concentrations in wells for each sampling date.

Fertilizer	N rate kg ha^{-1}	NO_3-N (mg L^{-1}) 29 DAP[1]	
AN	112	21.05	bc[2,3]
AN	168	38.51	ab
AN	224	60.55	a
CRF1	112	1.53	c
CRF1	168	3.84	c
CRF1	224	4.00	c
CRF2	112	2.79	c
CRF2	168	5.01	c
CRF2	224	1.85	c
CRF3	112	1.05	c
CRF3	168	2.17	c
CRF3	224	3.91	c
CRF4	112	5.98	c
CRF4	168	3.46	c
CRF4	224	2.72	c
CRF5	112	1.50	c
CRF5	168	0.22	c
CRF5	224	6.48	c
CRF6	112	0.81	c
CRF6	168	3.46	c
CRF6	224	0.58	c
ANOVA *p*-value		< 0.0001	
Tukey LSD		26.49	

[1] - DAP = Days after planting.
[2] - Means in columns followed by same letters not significantly different.
[3] - NO_3-N from wells in the control plot averaged 3.64 mg L^{-1}.

Analysis of rate main effects across all fertilizer sources at each sampling date provides additional information. Table 6-16 and Table 6-17 show the results for NH_4-N and NO_3-N, respectively. As might be expected, higher N rates resulted in higher N in wells, particularly early in the season. At no time during the season did wells from plots fertilized at the 168 kg ha^{-1} rate have significantly higher NH_4-N than wells in plots

fertilized with 112 kg ha^{-1} N. By 64 DAP, well N concentrations were not significantly different between the various fertilizer rates.

Table 6-16. Well NH_4-N rate main effect at each sampling date.

Rate	NH_4-N (mg L^{-1})				
kg ha^{-1} N	29 DAP[1]	41 DAP	64 DAP	78 DAP	92 DAP
112	3.43 b[2]	0.62 b	0.06	0.25	0.07
168	6.17 b	2.17 ab	0.11	0.24	0.31
224	9.59 a	2.70 a	0.10	0.23	0.07
ANOVA p-value	< 0.0001	0.0135	0.5921	0.8854	0.7673
Tukey LSD	3.43	1.7	ns	ns	ns

[1] – DAP = days after planting.
[2] - Means in columns followed by same letters not significantly different.

Table 6.17. Well NO_3-N rate main effect at each sampling date.

Rate	NO_3-N (mg L^{-1})			
kg ha^{-1} N	41 DAP[1]	64 DAP	78 DAP	92 DAP
112	5.92	4.23	4.22	2.07
168	7.23	4.98	5.43	2.48
224	11.99	4.87	3.59	2.00
ANOVA p-value	0.0872	0.8903	0.4896	0.8846
Tukey LSD	ns	ns	ns	ns

[1] – DAP = days after planting.

Lysimeter Nitrogen

Water sample collection through lysimeters was sporadic in 2003 to the extent that no meaningful statistical analysis could be performed. This was caused by poor seals on the caps of lysimeters which had been cut to accommodate the desired 30 cm burial depth for water collection. This lack of seal prevented the maintenance of a vacuum necessary to collect samples. On two sampling dates (20 Mar and 8 May), no solution was obtained from any of the lysimeters. After the 20 Mar sampling, the lysimeters were re-buried to ensure that there was proper soil-lysimeter contact, but this did not solve the problem.

Though no statistical analyses were run, some trends were noted in the data collected. Highest NO_3-N and NH_4-N concentrations from any treatment at any sampling date over the season were found in all three AN treatments (112, 168, and 224 kg ha^{-1} N)

at 41 DAP, and was as high as 42 mg L^{-1} for NH_4-N and 146 mg L^{-1} for NO_3-N. No comparably high values were found for any CRF treatment at any other time over the season (a high of 11 mg L^{-1} for NH_4-N at 41 DAP, and a high of 17 mg L^{-1} for NO_3-N at 41 DAP). Samples taken at 64 DAP showed no apparent N difference with the AN fertilized plots compared to the CRF fertilized plots.

Nutrient Movement Discussion

The presence of nitrogen in the soil and wells over the growing season appeared to correlate with observed environmental conditions. Early in the season, heavy rains translated into nutrient movement into the perched water table. Work by Zvomuya *et al*. (2003) corroborated these results when they reported that nitrogen fertilizer additions generally increased NO_3-N leaching compared with a no fertilizer control. The high concentrations of nitrogen found in wells and lysimeters from the AN treatments early in the season illustrate the relatively high movement of nitrogen from the water soluble sources.

Early in the season, both air and soil temperatures were relatively cool and CRF release may have been correspondingly slow, so it is not unexpected that the relative amounts of nitrogen from the CRF treatments were low early in the season. Nitrate and ammonium concentrations in the soil were lower early in the season (15 DAP) than later in the season, the reverse of what would be expected under normal release conditions. However, as the season progressed and rainfall declined, soil nitrogen levels increased as CRF release continued without being leached out of the root zone. At the end of the season, all N levels were reduced reflecting nitrogen depletion of the bed either by uptake, denitrification, or leaching.

Early in the season (29 DAP), NH_4-N in the perched water table below the root zone was 3.4 times as high in the AN treatments as in the CRF while subsequent sampling dates were not significantly different between CRF and AN fertilized plants. Because of a significant rate by product interaction, NO_3-N was evaluated at each rate. With 224 kg ha^{-1} N, NO_3-N was 18.9 times as high in the AN versus CRF treatments, with 168 kg ha^{-1} N, it was 12.6 times as high, and with 112 kg ha^{-1} N, it was 9.3 times asa high. At 41 DAP, NO_3-N from wells with AN treatments was 4.5 times as great as with CRF treatments. This reduced leaching trend is consistent with that reported by Zvomuya *et al*. (2003) who reported a 40% reduced nitrate leaching for PCU products compared to urea at a rate of 280 kg ha^{-1} N. Errebhi *et al*. (1997) reported that 33% N recovery during a wet year (1991) and 56% recovery during 1992 which had fewer leaching events.

Returning to the hypothesis that CRF products could reduce the amount of fertilizer leached below the root zones and into water bodies during the cropped period. This study showed that CRF products could significantly reduce the amount of nitrogen moved from the root zone into the perched water table compared to AN. Early in the season this difference was especially marked. CRF products can significantly reduce the amount of leaching of nitrogen into the watershed and from there into the St. Johns River.

CHAPTER 7
CONCLUSIONS

It is useful to reiterate the three-fold goal of this research project. The first of the three research objectives was to evaluate the release characteristics of controlled-release fertilizers (CRF) under both laboratory and field conditions. This was accomplished with the incubator experiment in cooled incubators and with the meshbag experiment at the research farm. The second objective was to determine the effects of different CRF products on potato production. Potato production data evaluated tuber total and marketable yields, specific gravity, internal and external tuber quality, plant nutritional status, plant biomass, and nutrient recovery efficiency. Both the CRF production experiment and the replacement experiment evaluated this objective. The third objective was to determine the effects of different CRF products on soil nitrogen movement below the plant root system and into watersheds. This was accomplished within the CRF production experiment using lysimeters and wells for aqueous samples together with soil samples.

The data from the three individual research objectives outlined in Chapter 4 through Chapter 6 can be combined to draw general conclusions regarding both the characteristics of the CRF products evaluated and their influence on potato production and nitrogen leaching as well as provide direction for future study and research. Each will be briefly summarized here.

Incubator and Meshbag Experiments

Incubator Experiment

The incubator experiment, which consisted of seven CRF products, urea, ammonium nitrate (AN), and a no-fertilizer control (No N), was evaluated over 13 consecutive weeks of leaching, revealing several important trends. All CRF products, with the exception of CRF6, had a high peak of release at the first sampling date. Though this would be expected from the water-soluble AN and urea, the CRF products were not expected to copy this behavior. In particular, CRF1, CRF2a, and CRF3 N release curves were shaped like those of water-soluble products. Contrastingly, N release curves from CRF2b, CRF5, CRF6, and to a lesser degree CRF4, exhibited prolonged periods of nutrient release.

Temperature-based release of the CRF products varied greatly as well. CRF5 had the highest Q_{10} of all products across all temperature comparisons, averaging 2.2 at 7 days and 2.4 at 14 days. CRF1, CRF2a, and CRF3, showed no indication of temperature-based release with Q_{10} values of approximately 1.

Residual fertilizer from each of the CRF products varied considerably. CRF1 and to a lesser degree CRF3 resulted in very little residual fertilizer at the end of the study, independent of temperature. CRF2a, while temperature-independent, had nearly 63% of its product and unavailable for release after 13 weeks. CRF2b, CRF4, CRF5, and CRF6 all had decreasing amounts of residual fertilizer as temperature increased and of the four products, only CRF6 had greater than 20% residual fertilizer at either the 25°C or 30°C temperature settings.

Meshbag Experiment

The meshbag experiment consisted of the same seven CRF products as the beaker experiment, but was performed in the field and subjected to 2003 moisture and temperature conditions. As with the CRF release experiment, the CRF products all had relatively high release by the first sampling date, with CRF6 again having the lowest release. Also, as with the beaker experiment, CRF2 had the highest percentage of permanently unavailable N, at 28%, while all other CRF products approached 90% or greater release. Though the initial release was greater in the meshbag experiment compared to the CRF release experiment, sustained release from the CRF products thereafter was similar between experiments, with the exception of CRF2b.

CRF Production and Replacement Experiments

CRF Production Experiment

Six CRF products were evaluated for production parameters in comparison to AN in the CRF production experiment. CRF2 was a blend of CRF2a and CRF2b, thus utilizing the seven products evaluated in the meshbag and incubator experiments. All products were also evaluated at three rates—224 kg ha^{-1} N (the BMP rate), 168 kg ha^{-1} N, and 112 kg ha^{-1} N.

Of all plants, those fertilized with CRF2 (224 kg ha^{-1} N) and CRF4 (224 kg ha^{-1} N) had highest total yields, marketable yields, and specific gravity (SG). Plants with treatments at the 168 kg ha^{-1} N fertilizer rate produced statistically similar yields and SG to those grown with the 224 kg ha^{-1} N rate. Nutrient recovery efficiency was not different between AN and CRF treatments.

Replacement Experiment

CRF4 and CRF6 were blended with AN at differing ratios in the replacement experiment. 'Atlantic' and 'Red LaSoda' potatoes were evaluated for total and marketable yields and SG. No significant difference was observed between plants with any of the AN:CRF fertilizer ratios for either CRF product for total yields, marketable yields, or SG. The only exception to this was with plants fertilized with CRF6 which had statistically higher marketable yields than AN on 'Atlantic' potatoes at the AN:CRF6 25:75 ratio.

Leaching Experiment

The leaching experiment was performed within the CRF production experiment and had the same product and fertilizer rate conditions. Soil, suction lysimeter, and well samples were taken periodically over the growing season.

Soil NO_3-N concentrations were statistically highest over the season with CRF1 (224 kg ha^{-1} N) and CRF3 (224 kg ha^{-1} N). Well NH_4-N and NO_3-N concentrations were statistically higher with AN treatments than with CRF treatments at 29 (NH_4-N and NO_3-N) and 41 DAP (NO_3-N). At 29 DAP, well samples from under CRF plots had 70% less NH_4-N than samples under AN plots. At 224 kg ha^{-1} N, NO_3-N from under CRF plots was 95% less than samples under AN plots, while at 168 kg ha^{-1} N, it was 92% less, and at 112 kg ha^{-1} N, it was 89% less. At 41 DAP, well samples from under CRF plots were 78% less than samples from under AN plots for NO_3-N while NH_4-N was not significantly different between CRF and AN plots. Due to sporadic data collection, lysimeter samples were not analyzed statistically, though NO_3-N and NH_4-N concentrations observed in samples from AN fertilized plots were much higher than in

CRF fertilized plots. AN plots reached a high of 146 mg L^{-1} NO_3-N and 41 mg L^{-1} for NH_4-N, while CRF plots reached a high of 17 mg L^{-1} NO_3-N and 11 mg L^{-1} for NH_4-N.

Lessons for Future Work

Through the series of experiments conducted, valuable lessons have been learned which provide a basis for future research, both in direction and in quality. By improving this protocol, data from future experiments will be more useful in interpretation and application to the grower.

In the CRF release experiment, weekly samples were analyzed for TKN. Though little was converted to nitrate, the TKN method does not analyze for nitrate. The Dumas method (combustion method) would provide an improved N analysis method, in that all N, independent of chemical form, is analyzed. Also, the Dumas method is less sensitive to high N concentrations than the Kjeldahl method, making high dilutions and digestion problems unnecessary (Dumas, 1831; Watson and Galliher, 2001).

In the meshbag experiment, the cheesecloth meshbags utilized degraded quickly in the field. This made bi-weekly samplings difficult. Alternative bags or containers would save time both in preparation and sampling.

In the well and lysimeter experiment, water samplings began later in the season than desirable. This was evidenced by only seeing the "tail" of the release profiles—the early part of the season, where the most rainfall and the highest amounts of nutrient release occurred, passed without sampling. Though these data would not influence potato plant uptake (growing plants utilize stored nutrients from the seed tuber early in the season), samplings earlier in the season of both the soil solution and the perched water table could provide valuable fertilizer initial-release data under growing conditions, which relates to nutrient leaching.

Summary

Considering the results of the various studies together provides useful information. From the field production experiments, greatest total and marketable tuber yields were obtained from CRF2, CRF4, CRF5, and CRF6 while highest SG were obtained from CRF1, CRF2, CRF3, and CRF4. Total and marketable yields and SG were not significantly different between the 168 and 224 kg ha^{-1} N rates. From the CRF release and meshbag experiments, CRF2b, CRF4, CRF5, and CRF6 exhibited the greatest degree of temperature-based nutrient release, had prolonged release periods, and had little residual fertilizer "lockout". All of the CRF fertilized plots had significantly less NO_3-N and NH_4-N in wells early in the season than did AN fertilized plots.

From this combined data, CRF2 (particularly CRF2b), CRF4, CRF5, and CRF6 are good candidates for future research. CRF2b and CRF4 produced high yields of quality potatoes with high SG, significantly reduced N leaching into water bodies, and had nutrient release based on temperature. CRF5 and CRF6 exhibited similar characteristics to CRF2b and CRF4, though SG was somewhat lower in tubers from those treatments. Based on the results it is concluded that this may have been due to too-prolonged nutrient release of these products. Also, a reduced fertilizer rate would be useful for future evaluation. Reduced application rates reduce input costs and quantities of nutrient available for leaching, and if tuber yields and quality are not compromised, then there is no disadvantage to a reduced rate.

The long-term goal of this research project is to help potato growers to grow high yields of quality potatoes using environmentally responsible practices. With that goal in mind, controlled-release fertilizers provide a viable fertilizer alternative to ammonium nitrate. Yields and tuber quality remain high while nitrogen leaching into the

environment is reduced, making CRF products good candidates for a BMP program for growers in northeast Florida.

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BIOGRAPHICAL SKETCH

Jeffery Earl Pack was born in Salt Lake City, Utah, on November 17, 1974, to Allen E. and Valeen Pack, the oldest of five children. He graduated from West Jordan High School in 1993, from Salt Lake Community College with an Associate of Science degree in 1998, and from the University of Utah with a Bachelor of Science degree in biochemistry in 1999. After graduating from the University of Utah, he worked two years before enrolling at the University of Florida to work on a Master of Science degree in horticultural sciences, which was completed in August 2004.

Jeffery was married to Jerami Baker in the LDS Salt Lake Temple in Salt Lake City, Utah, on September 4, 1999. They currently have three children, Sarah, Rachel, and Elisabeth.

Jeffery expects to pursue the Doctor of Plant Medicine degree offered at the University of Florida after which he expects to enter industry as a plant doctor consultant. He is a member of the Church of Jesus Christ of Latter-day Saints and served a two year proselyting mission to Córdoba, Argentina. He currently resides in Gainesville, Florida, with his family.