Groundwater Research Report
WR10R004

REDUCING NITRATE IN GROUNDWATER WITH SLOW-RELEASE FERTILIZER

Matthew Ruark
Birl Lowery
Nick Bero

(2012)

Project Number WR10R004

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Matthew Ruark, Ph.D
Department of Soil Science
University of Wisconsin-Madison

Birl Lowery, Ph.D
Department of Soil Science
University of Wisconsin-Madison

Nick Bero
Department of Soil Science
University of Wisconsin-Madison

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Reducing nitrate in groundwater with slow-release fertilizer

Authors:
Dr. Matthew Ruark
Dr. Birl Lowery
Mr. Nick Bero

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Project Summary

Title: Reducing groundwater nitrate with slow-release fertilizer

Project ID: WR10R004

Investigators: Dr. Matthew Ruark, Assistant Professor, Dr. Birl Lowery, Professor, and Mr. Nick Bero, graduate student, Dept. of Soil Science, University of Wisconsin, Madison.

Period contract: July 1, 2010 to June 30, 2012

Objectives: The objective of our study was to investigate fertilizer effect on groundwater NO_3-N concentration, yields, and plant growth parameters in sandy soils under potato production, using the best management practices currently available compared with controlled-release fertilizer technology.

Methods: A 2-yr field experiment was conducted at the Hancock Agricultural Research Station using Russet Burbank potato (*Solanum tuberosum* L.), planted in Plainfield sand. The experimental design was randomized complete block with three replicates which included four nitrogen (N) fertilizer treatments: (1) no nitrogen, (2) 224 kg ha^{-1} as PCU, (3) 280 kg ha^{-1} as PCU, and (4) 280 kg ha^{-1} split applied as ammonium sulfate and ammonium nitrate (AS-AN). The PCU was applied entirely at plant emergence and conventional fertilizer at potato emergence and at tuber initiation. Three groundwater monitoring wells were installed in each plot, were sampled weekly during the growing season, and analyzed for NO_3-N.

Results and Discussion: Controlled-release fertilizer, specifically polymer coated urea (PCU), may reduce the amount of nitrate-nitrogen (NO_3-N) leaching to groundwater; however, few if any field scale studies have been performed in Wisconsin on sandy soils to validate these assertions. Potato growth parameters and yields were maintained between conventional fertilizer and PCU and as a result, N use efficiency was greatly improved at the 224 kg ha^{-1} over both 280 kg ha^{-1} treatments. There were no significant treatment effects between any nitrogen treatments, as plot-to-plot variation was much greater than the differences between mean concentrations.

Conclusions: The use of controlled-release PCU fertilizer is a viable alternative to current management practices of AS-AN applications, but its benefits to water quality are not immediately realized. It is clear that measurements of nitrogen use efficiency are the best way to evaluate the short-term impacts to groundwater quality on sandy soils, while groundwater monitoring should be reserved for evaluating effects over the long-term.

Related publications:

Bero, N.J., M.D. Ruark, and B. Lowery. 2013. Controlled-release fertilizer effect on groundwater nitrogen concentration in sandy soil under potato production. Agronomy Journal (In review).

Bero, N.J., M.D. Ruark, and B. Lowery. 2012. Controlled-release fertilizer effect on groundwater nitrogen concentration in sandy soils under vegetable production. Science-based Policy for Wisconsin's Water Resources – 36th Annual Meeting American Water Resources Association – Wisconsin Section. 1-2 March, Wisconsin Dells, WI.

Bero, N.J., M.D. Ruark, and B. Lowery. 2011. Slow-release fertilizer effect on groundwater nitrogen concentration in sandy soils under potato production. Wisconsin's Role in Great Lake Restoration – 35th Annual Meeting American Water Resources Assoc. – Wisconsin Section, 3-4 March 2011, Appleton, WI.

Bero, N.J., M.D. Ruark, and B. Lowery. 2011. Slow-release fertilizer effect on groundwater nitrogen concentration in sandy soils under potato production. North Central Extension and Industry Soil Fertility Conference Vol. 27, 16-17 Nov., Des Moines, IA.

Key words: groundwater, nitrate, potato, nitrogen, fertilizer

Funding: Wisconsin Groundwater Coordinating Council

Introduction

Many previous studies have focused on NO_3-N flux through the root zone as measured by porous cup samplers, and NO_3-N leaching on the groundwater has only been inferred from these data (Diez et al., 1994; Errebhi et al., 1998; Arriaga et al., 2009; Cooley et al., 2009; Wilson et al., 2010). Several researchers have also studied residual soil N from soil cores that have implicated reduced NO_3-N leaching from PCU or split application (Cameron et al., 1979; Hill, 1986; Zvomuya and Rosen 2001; Zvomuya et al., 2003). In studies where there has been direct sampling of groundwater, there has not been a comparison of different fertilizer sources effect on groundwater NO_3-N concentration (Hubbard et al., 1984; Bergstrom and Brink, 1986; Hill, 1986; Kraft and Stites, 2003). Few, if any, researchers have attempted to directly assess the difference of PCU fertilizer vs. conventional soluble fertilizer effect on groundwater NO_3-N concentrations. The main reason might be that there are difficulties in assessing the groundwater directly. A lag time of a few weeks to months exists between the timing of application of fertilizer N and its arrival in the groundwater (Saffigna and Keeney, 1971; Hubbard et al., 1984; Landon et al., 2000; Burkart, 2002). Additionally, Olsen et al. (1970) found that more NO_3-N leaching occurred between fall and spring samplings than during the growing season. Therefore, research should be conducted to determine the effect of different rates and forms of fertilizer on groundwater NO_3-N concentrations by directly monitoring shallow groundwater. The objective of our study was to investigate fertilizer effect on groundwater NO_3-N concentration, yields, and plant growth parameters in sandy soils under potato production, using the best management practices currently available compared with PCU technology.

Procedures and Methods

This study was conducted at the Hancock Agricultural Research Station on a Plainfield loamy sand (mixed, mesic Typic Udipsamments) in 2010 and 2011. The experimental design was a randomized complete block with three replications. Four N management treatments were evaluated: (i) a recommended rate (280 kg N ha^{-1}) of conventional fertilizer (RCONV), (ii) a recommended rate (280 kg Nha^{-1}) of PCU (RPCU), (iii) a lower than recommended rate (220 kg N ha^{-1}) of PCU (LPCU), and (iv) no fertilizer N inputs (0 N). Plot sizes were 14.6 by 15.2 m, encompassing 16 potato rows. Different field locations were used for each year of the study. The 2010 field was located at 44°07’1”N, 89°32’46” W at the east midpoint and the 2011 field was located at 44°06’52”N, 89°32’37”W at the west midpoint. The full rate of each the LPCU and RPCU treatments was applied at emergence on 17 May 2010 and 20 May 2011. The RCONV treatment included a split application with 93 kg ha^{-1} of N applied as ammonium sulfate at emergence and 187 kg ha^{-1} of N applied as ammonium nitrate at potato tuber initiation on 2 June 2010 and 9 June 2011. All fertilizers were applied by hand to the top of the hill and mechanically incorporated by hilling. The PCU product used in this study was Environmentally Smart Nitrogen® (ESN®) (Agrium, Inc., Calgary, AB).

Russet Burbank potatoes were mechanically planted at 0.9-m row spacing with a seed density of 36,600 seeds ha^{-1} and planted on 29 Apr. 2010 and on 25 Apr. 2011. Potassium chloride and calcium sulfate were applied prior to planting at rates of 430 kg ha^{-1} and 560 kg ha^{-1}, respectively. Starter fertilizer was applied at planting at a rate of 616 kg ha^{-1}, providing 37 kg ha^{-1} of N, 185 kg ha^{-1} of P_2O_5, 135 kg ha^{-1} of K_2O, and 25 kg ha^{-1} of S. The starter fertilizer also contained Thiamethoxam, a systemic insecticide. A surfactant consisting of 10% alkoxylated polyols and 7% glucoethers (Irrigaid, Aquatrols, Paulsboro, NJ) was applied at emergence and tuber initiation fertilization in both years. Irrigation was managed by the Hancock Agricultural Research Station staff and insecticide, fungicide, and herbicide applications were applied by the station staff as needed to reduce pest and disease pressures.

In 2010, groundwater monitoring wells were installed between 10 and 17 May to a depth of 9.8 m from the soil surface with 1.5-m screens. Three wells were placed diagonally across each plot at a distance of 4.9, 7.6, and 9.8 m, respectively, from the south edge of each plot. The average depth to groundwater was 6.7 m at the time of well installation in 2010 and as a result wells were installed approximately 3.1 m below the water table, leaving the top of the screen 1.6 m below the water table, which was to account for the anticipated typical seasonal drawdown of the water table. However, this seasonal drawdown did not occur in 2010, and in response, on 14 Oct. 2010, the center well within each plot was raised so that the screened portion of the well intersected the water table. In 2011, wells were installed between 27 Apr. and 2 May, at a depth of 9.1 m from the soil surface with 2.3-m screens. Depth to groundwater averaged 7.3 m at the time of well installation, and wells screens were within the groundwater surface for all of 2011. Groundwater monitoring wells and screens were constructed from schedule 40 polyvinyl chloride (PVC) pipe with an internal diameter of 3.18 cm. Screens had 0.51-mm slot widths and 3.18 mm between slots. A 7.5-cm long PVC point was attached to the bottom of the screen. Holes for the wells were drilled with a truck-mounted hydraulic probe with drilling capabilities (Giddings Machine Co., Windsor, CO) and 7-cm diam. augers. After well holes were completed, the PVC wells were inserted by hand and the excavated sand from the auger hole was repacked around the well. Sand was replaced to within 30 to 50 cm of the surface, and bentonite clay was used to fill the remaining depth to prevent preferential flow down the side of the wells. Wells were developed by hand bailing to remove as much sediment in the bottom of the well as possible. Wells were cut to 20 cm from the top of the potato hill and then capped with a 3.18 cm schedule 40 cap.

Two observation wells were installed at the north-south midpoint of both fields in both years, outside of the field boundary, to continuously record of depth to water table with an Instrumentation Northwest PS-9805 submersible pressure/temperature transducer (Instrumentation Northwest, Kirkland, WA) placed inside the well at a depth of 1.22 m under the water table. The pressure transducer, along with an Onset RG3 tipping bucket rain gauge (Onset Computer Corp., Bourne, MA) was then connected to a Campbell Scientific 10X data logger (Campbell Scientific, Logan, UT). The rain gauge and pressure transducers were calibrated in the laboratory prior to installation. Measurements were logged with a Campbell Scientific SM192 storage module (Campbell Scientific, Logan, UT) every 15 min. Maximum and minimum daily air temperatures were recorded by a weather station managed by the Hancock Agricultural Research Station. A third observation well that only monitored depth to water table was installed approximately 1000 m south of the observation well from the field in 2010 and 500 m west of the observation well from the field used in 2011 at 44°06’49”N, 89°32’43.15”W. This well was installed 25 Aug. 2011 and with the other two observation wells, provided a large triangle grid for determining groundwater flow direction.Well elevations and positions were determined with a Leica GPS 1200 (Leica Geosystems, Norcross, GA, 30092). A fixed control point, DH5653 managed by the State of Wisconsin cartographer’s office, was used to calibrate the surveyed points and determine absolute orthometric height of each well above mean sea level.

Potato yields were obtained by mechanical harvesting of 3.1-m sections of four rows in each plot on 30 Aug. 2010 and 12 Sept. 2011. Harvest rows were determined by observation of rows least disturbed by well drilling. Potatoes were mechanically graded into sizes of B grade (< 85 g), 85 to 113, 114 to 170, 171 to 283, 284 to 368, 369 to 454, and > 454 g. Culled potatoes (knobby, green, or rotted) were removed manually. Yields are reported as total and marketable, which excludes B grade and culled potatoes. Ten potatoes from the size class of 170 to 283 g were subsampled and analyzed for specific gravity and disease. Plant N status was assessed by sampling petioles, tubers, and above-ground biomass. Potatoes emerged on 17 May 2010 and 20 May 2011, and petioles were sampled at 32, 44, 58, and 73 days after emergence (DAE) in 2010 and 27, 40, 54, and 67 DAE in 2011. Twenty petioles were collected from the center two rows from each plot. The fourth petiole from the plant crown was removed by hand, stripped of leaves, and dried and ground. Above-ground biomass (AGB) and tubers were collected at mid-season (DAE 44 in 2010 and DAE 47 in 2011) and at the end of season (AGB – DAE 92 in 2010 and DAE 97 in 2011; tubers – DAE 105 in 2010 and DAE 115 in 2011). Mid-season AGB and tuber samples were taken from five plants per plot. End-of-season AGB samples were from five plants pre-vine kill and tuber samplers were from six potatoes collected from the 170 to 283 g size class at harvest. Petiole NO_3-N, and AGB and tuber total N and total C were assessed at the UW-Madison Soil and Plant Analysis Laboratory using total Kjeldahl N (Ruzicka, 1983; Leco Corp., 1995), EPA nitrate 353.2, and the Leco Corp. procedure for C by dry combustion on a Leco CNS-2000 analyzer (Leco Corp., 2002, 2003), respectively. Total N uptake in AGB was converted to dry matter N uptake per unit area by multiplying dry matter N concentration by the seeding density and total N uptake in tubers was converted to dry matter N uptake per unit area by multiplying dry matter N concentration by total yield.

Groundwater was sampled weekly between planting and 1 month after harvest (19 May to 14 Oct. 2010 and 6 May to 31 Oct. 2011). Groundwater was sampled monthly while the field was out of production (14 Oct. 2010 through 23 May 2011 and 31 Oct. 2011 through 26 Apr. 2012). Water samples were collected from each well with a 375-mL stainless steel bailer. The first sample extraction was discarded, and subsequent water extractions were placed into 500-mL plastic Nalgene bottles. Upon collection, samples were transported back to the laboratory, filtered within 24 h after collection, and stored at 4°C until analysis could be performed.

Groundwater samples were analyzed for nitrate, ammonium, and total N. Nitrate concentration was determined using the single vanadium chloride reagent method (Doane and Horwath, 2003) and was reported as NO_3-N. Since this method reduces nitrate to nitrite, selected well samples were assessed for only nitrite with the same method, by not adding vanadium chloride to the reagent. All samples analyzed for nitrite (NO_2-N) concentration were below the detection limit and thus all N determined using this method was assumed to be NO_3-N.

Analysis of variance was conducted to determine treatment differences in yield, size grade, petiole NO_3-N, AGB and tuber total N content, AGB and tuber total N uptake using Proc GLM in SAS (SAS Institute Inc., Cary, NC). Tukey's studentized range was used for means comparison at the α=0.1 significance level. Analysis of variance was conducted to determine treatment differences in groundwater NO_3-N concentrations across all weeks using Proc Mixed with repeated measures on plot, with an auto regression correlation structure in SAS at the α=0.1 level of significance. The adjusted Tukey-Kramer adjusted P-value was used to determine the differences in treatment means. Nitrate, NH_4-N and organic N concentrations were averaged across three wells to provide one concentration value per plot per sample time. Variation in the NO_3-N concentration was then determined by the three replicate blocks, and blocks were considered a random effect in the model. The model used the correlation structure and repeated measures on the plot to relate the adjacent week's NO_3-N concentration to the current week's NO_3-N concentration. The model then is able to account for the actual NO_3-N concentration and change in NO_3-N concentration between weeks among treatments.

Results and Discussion

The 2010 growing season was quite different with respect to rainfall amount and temperature patterns, with 2010 having greater rainfall and greater average temperature than 2011. There was 540 mm of rainfall and 213 mm of irrigation during the 2010 growing season and 217 mm of rainfall and 283 mm if irrigation during the 2011 growing season (Fig. 1). Average air temperature was 19.2°C for the 2010 growing season and 18.2°C for the 2011 growing season. The average growing season rainfall and temperature over the past 30 yr (1982 to 2012) has been 435 mm and 17.5°C, respectively.

Yield and N Uptake

Both growing seasons produced statistically equivalent yields in all plots between all treatments with supplemental fertilizer, which were all significantly greater than the 0 N. The RPCU fertilizer plots had the greatest overall average in both marketable and total yield in 2010 (Table 1), but was not significantly greater than the RCONV or LPCU. The 2010 potato growing season had overall average marketable yields near 40 Mg ha^{-1} for all plots receiving supplemental fertilizer. The average marketable yields from all fertilized treatments in 2011 were 50 Mg ha^{-1}, which was 10 Mg ha^{-1} greater than 2010 (Table 1). Total yields in 2010 were 8.8 Mg ha^{-1} greater than marketable yields, whereas in 2011 total yields were 5.6 Mg ha^{-1} greater than marketable yields, making the difference between total yield and marketable yield smaller in 2011 compared with 2010. In both years, potato size grades showed similar trends. Higher yields were in the smaller size grades in lower rates of fertilizer contrasted with greater yields in the larger size grades in the higher fertilizer rates.

The AGB N uptake from in 2010 was similar across fertilizer treatments and sample dates (Table 2). The AGB N uptake at mid-season in 2011 was only significantly greater in the RPCU over the RCONV. However, by harvest in 2011, all fertilizer treatments had statistically similar AGB N uptake. Tuber N uptake was similar across all treatments receiving fertilizer at the end of the season for both years (Table 2). Total N uptake (AGB + tuber) was similar across treatments receiving fertilizer at both sample dates in 2010. Total N uptake in 2011 was greater in the RPCU than the RCONV at mid-season sampling, but by the end of season all fertilizer treatments had equivalent total N uptake. The proportion of total N uptake at mid-season vs. the harvest averaged 91% for the RCONV treatment, 97% for RPCU, 89% for the LPCU, and 108% for the 0 N. In, 2011, N uptake at the middle of the season as a percentage of final N uptake was 67% for RCONV treatment, 84% for the RPCU, 79% for the LPCU, and 70% for the 0 N. Harvest total N uptake from an N budget standpoint (total N uptake ÷ N applied) was less in 2010 than that in 2011. In 2010, total N uptake as a percentage of fertilizer applied averaged 58% in the RCONV, 51% in the RPCU, and 67% in the LPCU. In 2011, total N uptake as a percentage of fertilizer applied averaged 100% in the RCONV, 98% in the RPCU, and 121% in the LPCU.

Groundwater elevation and nitrate concentrations

The water table in the 2010 field rose from about 6.7 m below the soil surface to 5.6 m below the soil surface during the course of the growing season (Fig. 3). Then during the winter of 2010-2011, the water table declined consistently, with a subsequent rise during the spring thaw. The potato field in 2010 was within the cone of depression of the irrigation pumping well, and its effect can be seen in the sharp changes in the water table when pumping occurred (Fig. 3). The 2011 growing season had a continuous and consistent drop of the water table throughout the growing season from 7.3 to 7.9 m below the soil surface, and showed no indication of the effects of pumping (Fig. 3).

Groundwater flow direction was to the southwest at approximately 230° SW. When irrigation wells were pumping, the observation well from the first year of the study in 2010 was within the cone of depression, and apparent groundwater flow direction shifted to the northwest toward the pumping well. However, the observation well from the second year of the study and the third observation well did not show a pumping affect and groundwater flow may have still been to the southwest in this field.

Average NO_3-N concentrations in the 2010 potato field had no significant differences between treatments, including the 0 N (Fig. 4). Average NO_3-N concentrations for the entire growing season ranged from 15.8 to 22.6 mg NO_3-N L^{-1}. Individual well ranges for the growing season were 11.4 to 28.3 mg NO_3-N L^{-1}. After the raising of the center well, overall plot averages expanded to between 14.9 and 26.1 mg NO_3-N L^{-1} with individual wells range expanding to between 6.9 and 43.5 mg NO_3-N L^{-1}. Separating the NO_3-N concentrations by treatment into plot average was inspected and all treatments and the 0 N had similar ranges of averages from 13.2 to 29.9 mg NO_3-N L^{-1} (Fig. 5).

With well screens that intersected the water table for the entire growing season, average NO_3-N concentrations in the second year of the study, in a new field, also had no statistical differences between treatments including the 0 N (Fig. 6). The plot averages of NO_3-N concentrations ranged between 7.4 and 19.2 mg NO_3-N L^{-1}. These average concentrations were less than what was measured in the first growing season dropping from the 2010 average range of 15.8 to 22.6 mg NO_3-N L^{-1}. Variability persisted both between and amongst treatments as individual well NO_3-N concentrations ranged from 0.4 to 40.1 mg NO_3-N L^{-1}. Although no statistically significant differences were observed in the second year of the study, the average of the RCONV treatment was greater than both PCU treatments for the entire growing season. No correlation between precipitation or irrigation events was observed. Nitrate concentrations separated by treatments into each plot average had similar ranges of averages between

2.0 and 37.3 mg NO_3-N L^{-1} across blocks for the three treatments and the 0 N as well (Fig. 7). An increase in NO_3-N concentration was seen in all treatments over the winter of 2012.

There was little to no NH_4-N or organic-N in the groundwater for the duration of the study. The greatest NH_4-N concentrations were seen early in the season in both years; however, NH_4-N contributed very little to groundwater N concentration. In 2010, the plot average NH_4-N concentrations were between the minimum detection of 0.05 to 0.35 mg NH_4-N L^{-1}. The average concentration was 0.08 mg NH_4-N L^{-1}, and the median was 0.06 NH_4-N L^{-1}. There was no statistical difference between treatments. In 2011, the range of plot averages was between 0.05 and 0.20 mg NH_4-N L^{-1}. The average concentration was 0.07 mg NH_4-N L^{-1}, and the median was 0.06 NH_4-N L^{-1}. There was no statistical significance between treatments in either year of the study. Plot average organic N concentrations ranged between 0 and 1.2 mg organic N L^{-1} in 2010. Treatment averages were 0.58 mg organic N L^{-1} with the median at 0.46 mg organic N L^{-1}. Plot average organic N concentration in 2011 was between 0 and 0.69 mg organic N L^{-1}. Treatment averages were 0.13 mg organic N L^{-1} with the median at 0.08 mg organic N L^{-1}. No dates for either 2010 or 2011 had a statistically significant difference in organic N concentration.

Discussion

Both the use of PCU and a reduction in N rate with use of PCU maintains yield while increasing N use efficiency. Both PCU treatments maintained average total and marketable yields as the split applied RCONV treatment. The fact that the LPCU treatment maintained yields of the RPCU and RCONV which had greater rates of N applied is similar to findings of Hopkins et al. (2008), who found that all potato size categories with PCU had greater yields at lesser rates of application, than that of urea at greater rates of application. Thus, it follows that an optimum economic rate of PCU N may be below the recommended conventional rates thereby increasing uptake efficiency. Results from other studies have also demonstrated that potato grown in sandy soils using PCU fertilizers are able to maintain or even increase yield (Liegel and Walsh, 1976; Zvomuya et al., 2003; Pack et al., 2006; Worthington et al., 2007; Hyatt et al., 2010). Data from these studies have shown that PCU fertilizers produce equivalent yields to AN or urea fertilizers even under a variety of leaching environments. It is also interesting to note that several researchers have reported a delay in tuber growth when high amounts of soil N are available early in the season (Cox and Addiscott, 1976; Kleinkopf et al., 1981; Westermann and Kleinkopf, 1985; Errebhi et al., 1998). However, applying all of the PCU fertilizer at emergence did not seem to delay tuber growth or final tuber yield in this study. The PCU application also did not affect final petiole NO_3-N concentrations in potato, although the RCONV treatment had greater petiole NO_3-N concentrations than both PCU treatments in 2010 and the LPCU in 2011 early in the season. These results are similar to the findings presented by Liegel and Walsh (1976). According to Haverkort and van de Waart (1994), high leaf NO_3-N concentrations early in the season were not associated with high yields at the end of the season. The lack of correlation between yield and early and midseason N concentration held true for this study.

The nitrogen budget data reinforces Hopkins et al. (2008) assertion that optimum economic rates of PCU fertilizers can be lesser than RCONV fertilizer. The increase in use efficiency between years can be explained by available system N. Nitrogen is present in the irrigation water, and Bundy and Andraski (2005) found that irrigation could provide 3.9 to 5.2 kg N ha^{-1} per 25 mm of irrigation applied (Arriaga et al., 2009). This means that in 2010, irrigation supplied between 33 and 44 kg N ha^{-1} and between 44 and 59 kg N ha^{-1} in 2011. This N applied by irrigation in 2010 would have been leached by frequent heavy rainfall events; however, in 2011, with few rainfall events, and no large single rain storms, N from irrigation water would have been more available to be utilized by potato plants.

Rainfall and temperature patterns exert tremendous control on yield and N use efficiency. The growing season in 2010 was warmer, had a greater amount of precipitation, and had more intense rainfall events than 2011. As a result, the 2011 potato yields were greater than the 2010 yields (most likely the result of differences in soil N availability). In 2010, it is possible that the PCU fertilizer had exhausted its supply of N because of increased dissolution of urea from the fertilizer prior to the end of potato uptake, leading to reduced yields. The PCU fertilizer used has a thermoplastic shell, and the porosity of the shell increases with increasing temperature, and with 2010 being wet and warm, N release may have been more rapid than 2011. The drier weather in 2011 not only limited the release of N from the PCU treatments but also limited the leaching from the RCONV treatment which reduced the advantage of PCU, which acts as to buffer against intense rainfall events.

The variation in NO_3-N concentration, both within and among treatments led to an inability to determine a significant difference or treatment effect on groundwater NO_3-N concentration. Similar large variation has been found in several other studies as well (Saffigna et al., 1977; Hubbard et al., 1984; Hill, 1986; Hubbard et al., 1986). Variation provided large standard errors (2.1 in 2010 and 6.9 in 2011), and with average NO_3-N at similar concentrations amongst treatments throughout the year, there was not a significant difference among treatments. This variation may be due in part to whether or not the monitoring wells in a given plot intercepted a preferential flow path. These flow paths can lead to solutes entering the water table in a much smaller cross section than what would be applied to the plot (Kung, 1990a,b). The short time scale of this study was not sufficient to overcome the variation in NO_3-N concentrations in order to determine treatment differences. This is not uncommon as other studies have shown that groundwater quality responses to new agricultural practices can take decades (e.g. Tomer and Burkart, 2003). From an N budget standpoint, the amount of N available for leaching from the application of fertilizer was calculated, i.e., the N removed by plant uptake compared with N applied (CREC). This indicated that there was less N available for leaching in the LPCU ($P \geq 0.007$ in 2010 and $P \geq 0.055$ in 2011). The calculated remaining nitrogen in the field after harvest ((1- CREC) × N applied) in the RCONV, RPCU and LPCU averaged 181, 199, and 137 kg N ha^{-1}, respectively in 2010, and 154, 162, and 107 kg N ha^{-1}, respectively in 2011. This further indicated that variation in the background groundwater NO_3-N concentration masked what would have been expected lower concentrations from less leached N in the LPCU.

The vertical placement of wells is critical when attempting to measure the amount of NO_3-N reaching the surface of the water table from a specific fertilizer treatment. Nitrate concentrations are generally greatest at the top of a shallow water table and decrease with depth because of dilution and mixing (Hill, 1982; Hubbard et al., 1986; Mueller and Helsel, 1996). The large amount of rainfall in 2010 led to a rise in the water table and after installing the well screens 1.6 m below the water table to account for the anticipated seasonal decline, the rise seen in 2010 put the screens, on average 3.0 m below the water table. As changes in NO_3-N typically decrease with depth in the water table as noted by Hubbard et al. (1986), Power and Schepers (1989), Spalding and Exner (1993), and Mueller and Helsel (1996), the water samples from the wells that were 3.0 m below the water table measured the bulk, mixed water rather than from nitrates that reached the surface of the water table that were leached from the N applied plot. Our results are consistent, as when the center well was raised after the growing season, higher average groundwater NO_3-N concentration were measured than when the well were deeper. This also impacted statistical comparisons as with one well intersecting the water table, the average range, and therefore variation, of NO_3-N concentrations increased. Had the 2010 wells intersected the water table during the wet growing season, they may have shown more leaching, as leaching of N occurs mainly during periods of high precipitation (Bergstrom and Brink, 1986). The sharp increase in the NO_3-N concentrations in the raised wells reinforces this conclusion, and the raised wells would give a better indication of the nitrates leached from a specific plot and fertilizer treatment, whereas the deeper well NO_3-N measurements could be that of water carried from off plot by groundwater flow, which has also been pointed out as a difficulty by Hubbard et al. (1984).

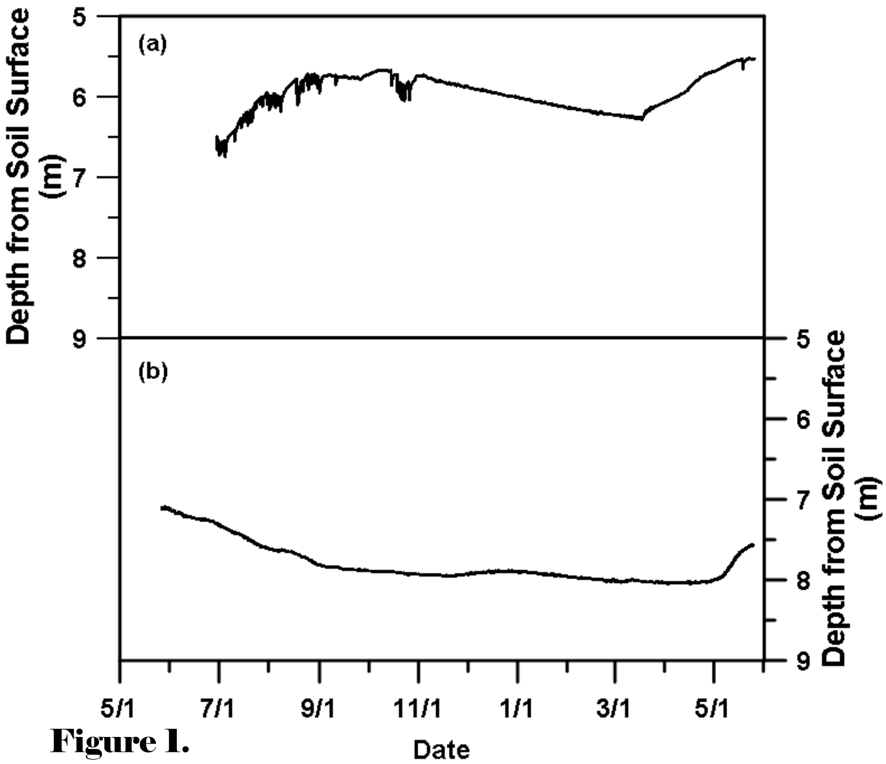

Figure 1.

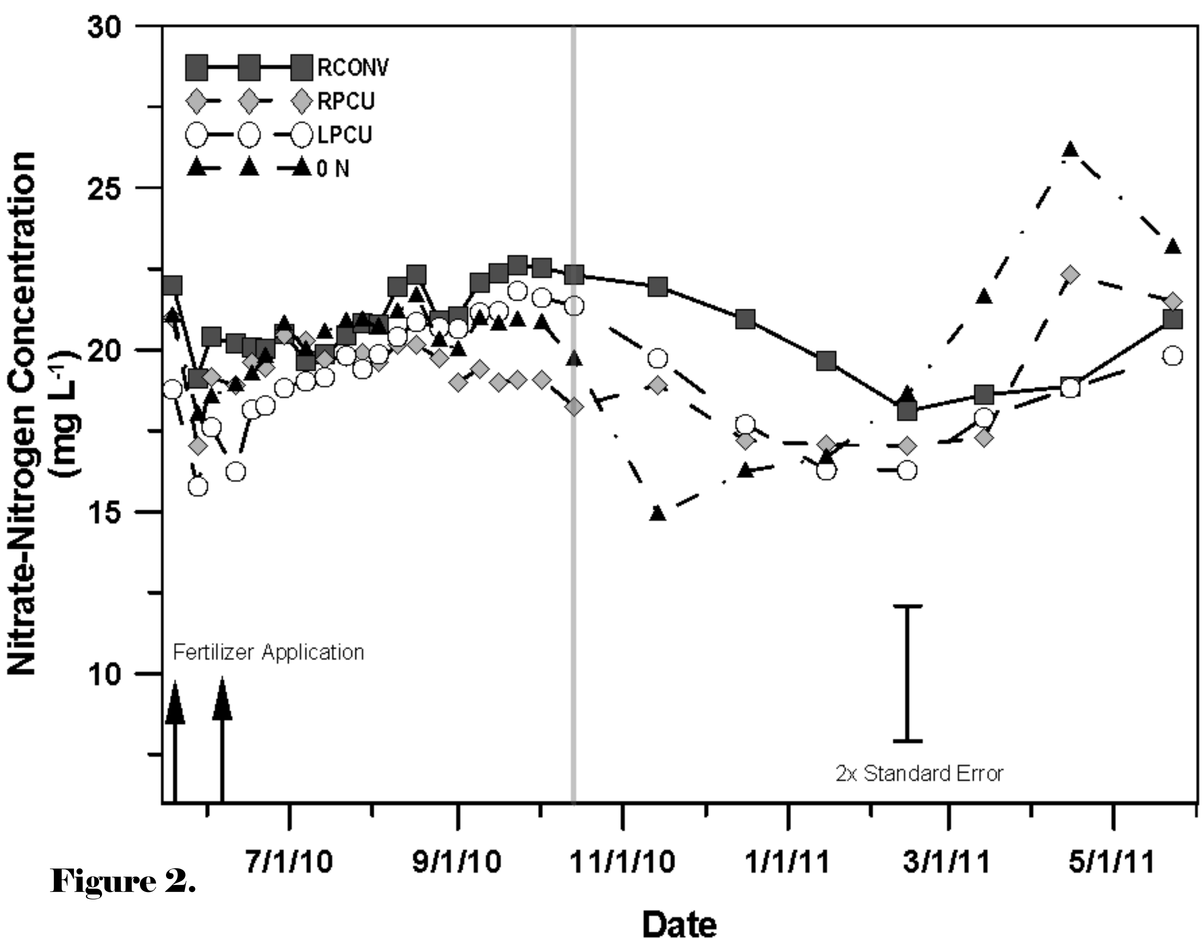

Figure 2.

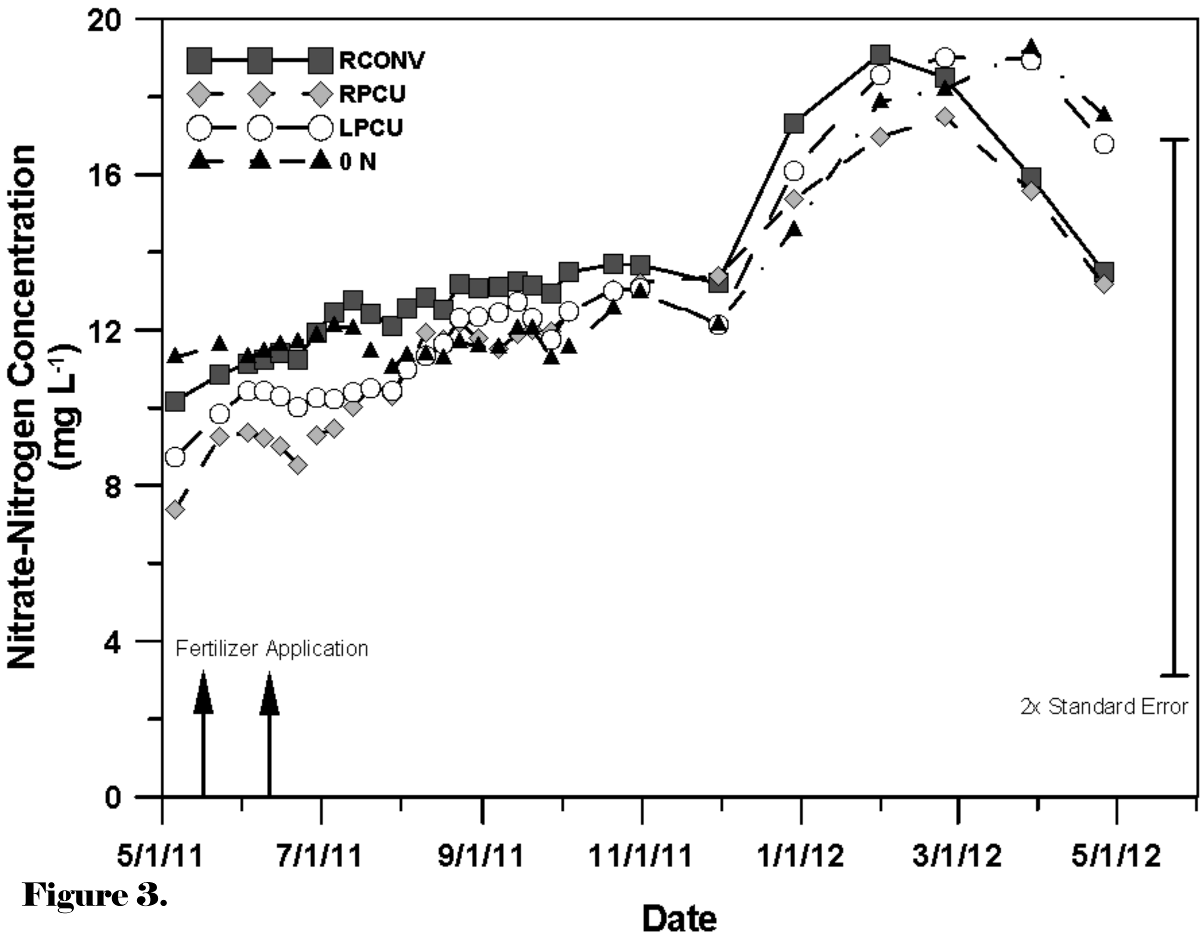

Figure 3.

Table 1. Marketable and total potato yields for 2010 and 2011.

Treatment †	2010 Marketable	2010 Total	2011 Marketable	2011 Total
	-- Mg ha^{-1}	--		
RCONV	39.9 a ‡	48.8 a	50.0 a	54.7
RPCU	41.8 a	50.2 a	50.9 a	56.5
LPCU	39.3 a	47.8 a	52.1 a	56.5
0 N	21.6 b	30.9 b	41.1 b	48.7
P>F	<0.001	<0.001	0.025	0.138

† The conventional fertilizer, RCONV, 280 kg N ha^{-1} as 93 kg ha^{-1} ammonium sulfate applied at emergence and 187 kg N ha^{-1} as ammonium nitrate; recommended controlled-release fertilizer, RPCU, 280 kg N ha^{-1} as PCU applied at emergence; low rate controlled-release fertilizer, LPCU – 224 kg N ha^{-1} as PCU applied at emergence.

‡ Mean values followed by letters indicate statistically significant difference at the α=0.10 level.Table 2. Potato N uptake.

Table 2. Potato nitrogen uptake.

Year	Treatment †	AGB ‡		Tubers		Total uptake	
		MS	Harvest	MS	Harvest	MS	Harvest
		---------------------- kg ha^{-1} ----------------------					
2010	RCONV	128 a §	49 a	18	113 a	147 a	162 a
	RPCU	117 a	29 ab	22	115 a	139 a	144 a
	LPCU	110 a	39 a	24	110 a	134 a	150 a
	0 N	44 b	10 b	23	53 b	68 b	63 b
	P>F	<0.001	0.030	0.714	<0.001	0.004	<0.001
2011	RCONV	170 b	92 a	17 b	189 a	187 b	281 a
	RPCU	203 a	74 a	25 b	199 a	228 a	273 a
	LPCU	192 ab	66 a	23 b	206 a	215 ab	272 a
	0 N	72 c	20 b	37 a	135 b	109 c	155 b
	P>F	<0.001	0.007	0.015	<0.001	<0.001	<0.001

† Above-ground biomass (AGB) and tubers at mid-season (MS) samples taken day after emergence (DAE) 44 in 2010 and DAE 47 in 2011. Harvest AGB samples were taken at DAE 92 in 2010 and DAE 97 in 2011 and harvest tubers were taken at DAE 105 in 2010 and DAE 115 in 2011.
‡ The conventional fertilizer, RCONV, 280 kg N ha^{-1} as 93 kg ha^{-1} ammonium sulfate applied at emergence and 187 kg N ha^{-1} as ammonium nitrate; recommended controlled-release fertilizer, RPCU, 280 kg N ha^{-1} as PCU applied at emergence; low rate controlled-release fertilizer, LPCU – 224 kg N ha^{-1} as PCU applied at emergence.
§ Mean values followed by letters indicate statistically significant difference at the α=0.10 level.

Conclusions and Recommendations

The controlled release PCU maintained plant growth response to applied N compared conventional split applied management practices. When applied at less than recommended rates, PCU led to measured improvements in the PFP and PNB NUE components. The magnitude of increase in these NUE components is still dependent on growing season conditions, but use of PCU should be considered as an alternative fertilizer source for potato. An added benefit of PCU is the one-time application, which would save fuel costs and time in the field possibly preventing crop damage.

Although large plots, 15 by 15 m, were sufficient in size to reduce the impact of plot to plot contamination, variability in NO_3-N concentrations at the surface of the groundwater made it difficult to determine a fertilizer treatment effect on water quality. While a statistical difference was not found between treatments, trends suggest that future research into fertilizer effect on groundwater NO_3-N using PCU treatments might be warranted as conventional split-applied fertilizer management had greater NO_3-N concentrations than the PCU treatments through most of the sample period. In the short term, data collection should continue using the near surface measurements from porous cup samplers and soil tests, which have shown decreases in NO_3-N flux in the root zone using PCU fertilizers. Using N use efficiencies or root zone fluxes may be better at determining the impact of fertilizer on groundwater quality in the short term until more efficient strategies of directly monitoring groundwater can be developed. Future use of wells that directly monitor groundwater could overcome variability in NO_3-N concentrations and groundwater flow with field size plots dedicated to a single treatment, monitored over a very long time, which could allow cumulative fertilizer effects to supersede the difficulties present in direct groundwater monitoring. These large, long-term studies, while costly, may produce statistical differences and allow better conclusions to be made comparing conventional split applied fertilizer to PCU treatments.

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Appendix A

Bero, N.J., M.D. Ruark, and B. Lowery. 2013. Controlled-release fertilizer effect on groundwater nitrogen concentration in sandy soil under potato production. Agronomy Journal (In review).
Bero, N.J., M.D. Ruark, and B. Lowery. 2011. Slow-release fertilizer effect on groundwater nitrogen concentration in sandy soils under potato production. North Central Extension and Industry Soil Fertility Conference Vol. 27, 16-17 Nov., Des Moines, IA.
Award : Nick Bero, 2012 Grad Student Award, 2011 North Central Soil Fertility Industry and Extension Conference.

Appendix B

Other available data (e.g. petiole nitrate, potato specific gravity and internal defects) are reported in Nick Bero's MS Thesis (Dept. of Soil Science, University of Wisconsin, 2012). Available as pdf upon request.

Tracer study

Materials and Methods

A Br^- tracer field experiment was conducted at the Hancock Agricultural Research Station in a Plainfield loamy sand soil. Two fields were divided into twelve 14.6 m × 15.24 m plots, arranged two plots wide by six plots long. Three wells were placed diagonally across each plot, at a distance of 4.9 m (A well), 7.6 m (B well), and 9.8 m (C well) respectively from the south edge of each plot (Figures 1 and 2). Wells were completed on 17 May 2010 in the first field and on 2 May 2011 in the second field. The average depth to groundwater was 6.7 m at the time of well installation in 2010. Wells were installed approximately 3.1 m below the water table, leaving the top of the screen 1.6 m below the water table. On 14 October 2010, the center well, labeled as the B well, was raised to 7.3 m depth, which was 1.3 m below the water table to allow for sampling at the surface of the water table and assessment of the vertical placement of well screens. On 23 May 2011, all wells in the first field were raised so that the well screens intersected the water table. Wells in the second field in 2011, which were used in the 2012 Br^- application, were installed at a depth of 9.1 m with 2.3 m screens at 1.8 m of depth into the water table. Wells in 2012 intersected the water table at all times during the study period. Bromide was applied to plots 202 and 302 at a rate of 112 kg ha^{-1} (2.72 kg $plot^{-1}$), and Cl^- to plots 103 and 203 at a rate of 224 kg ha^{-1} (5.44 kg $plot^{-1}$), on 14 October 2010 (Figure 1). Bromide was applied on 9 March 2012 to the second field in plots 103 and 302 (Figure 2). Chloride was not applied to the second field in the spring of 2012. A CO_2 powered backpack sprayer with a four nozzle spray boom was used to uniformly apply the tracers to the plot. Each plot required two tanks of dissolved tracer, and application was done North-South using the first tank and East-West on the second tank to assure uniform coverage of tracer to plots. Yearly well sampling was such that wells were sampled twice weekly following tracer application from 14 October 2010 until 16 December 2010, monthly until 27 May 2011, then again weekly until 14 October 2011, then monthly until 26 April 2012, where the data set ended. The second replicate in the second field was sampled weekly from 15 March 2012 to **3 August 2012** and analyzed for concentration mg L^{-1} of Br^- tracer.

Infiltration and downward movement of the tracer was driven by irrigation and rainfall in 2010 (Figure 3). If rainfall did not occur within 2 days, approximately 18 to 35 mm of water was applied during the period of 14 October to 28 October 2010 by irrigation. Irrigation was then discontinued after October because of freezing temperatures. In 2012, rainfall and scheduled crop irrigation was the driver for leaching Br^- from the soil profile (Figure 4). Contrary to the 2010 application of tracer, the second field in 2012 did not have the irrigation turned on for the growing season as of application date, and could not be used to provide water for immediate leaching.

The Br^- microplate analysis used in this study was a modified colorimetric method from Lepore and Barak (2009). Their method capitalizes on the transformation of phenol red to bromine blue in the presence of Br^-. A Biotek PowerWave XS (BioTek Instruments Inc. Winooski, VT 05404) microplate reader was used to measure absorbances, and concentration of Br^- each week's set of samples was based on a standard curve prepared with four replicates of standards from 0-12.5 mg Br^- L^{-1}. The Cl^- analysis for this study utilized the reaction between mercury thiocyanate, ferric nitrate, and Cl^-, and absorbances were again read by the Biotek microplate reader. Unknown sample concentrations were calculated from standards that ranged from 0-100 mg Cl- L^{-1} (Adriano and Donnor, 1982). Secondary Cl^- analysis was performed on the two shallow middle B wells of the Cl^- applied plots to verify the numbers calculated from the Cl^- microplate analysis with the Dionex Ion Chromatograph (Thermo Scientific Sunnyvale, CA 94088). The groundwater BTCs were then constructed from the resulting water concentrations of Br^- and Cl^-.

Results-Bromide

The total amount of water applied during the initial downward leaching of Br in 2012 was 25.7 cm as of 18 July 2012. The cumulative amount of water that was applied during the initial downward leaching of the tracers from 14 October to 15 December was 17.14 cm in 2010. The plots for which Br^- were applied showed breakthrough at the shallow well, but there was no breakthrough in wells that were screened deeper into the water table. The Br^- BTCs were characteristic bell shaped for plots 202 and 302 between days 2 November and 10 December 2010 and each plot showed two peaks (Figure 5 and 6). Breakthroughs for wells 202B and 302B occurred on November 2nd, and peak concentration was observed the next sample day of November 5th. The second breakthrough occurred again in wells 202B and 302B approximately three weeks later spanning November 23rd through December 10th. The Br^- concentration in plot 302 was greater than that of plot 202 by approximately 6 mg Br^- L^{-1}. The peak concentration in plot 302 was about 8 mg Br^- L^{-1} where plot 202 peak reached 1.5 mg Br^- L^{-1}. During the initial infiltration of Br^- wells in the surrounding plots show no indication of Br^- breakthrough during the initial downward leaching (Figures 7 and 8). On the 14 February 2011 sample date, Br^- was detected in the raised center well in plots 103 and 203. These plots are to the southwest of the plots to which Br^- was applied and concentrations above background persisted for several months (Figures 7 and 8). Bromide reappeared in the wells of plots to which it was applied in concentrations that were greater than the initial breakthrough concentrations and persisted throughout the summer of 2011 and winter of 2012. Concentrations of Br^- above background were also detected in the wells in plot 204 during the summer of 2011. At the end of sampling in the field used in 2010, there was Br^- in the system in plots 103 and 203. As of the 25 July 2012 sample date, Br^- had not been detected in any well in the second field (Figures 9 and 10).

Results - Chloride

Chloride was found in plots 303, 304, 301, 104, and 102. Changes in Cl^- concentrations were seen in several non-Cl^- applied plots, but the data do not provide a pattern that is useful for solute leaching analysis (Figures 11 and 12). The results from the Dionex Ion Chromatograph show that although the concentrations from the two methods are different, the shape of the Cl^- concentration curves for each of the wells are similar to one another (Figure 13).

Figures listed here and below refer to Figure numbers in Bero's MS Thesis.

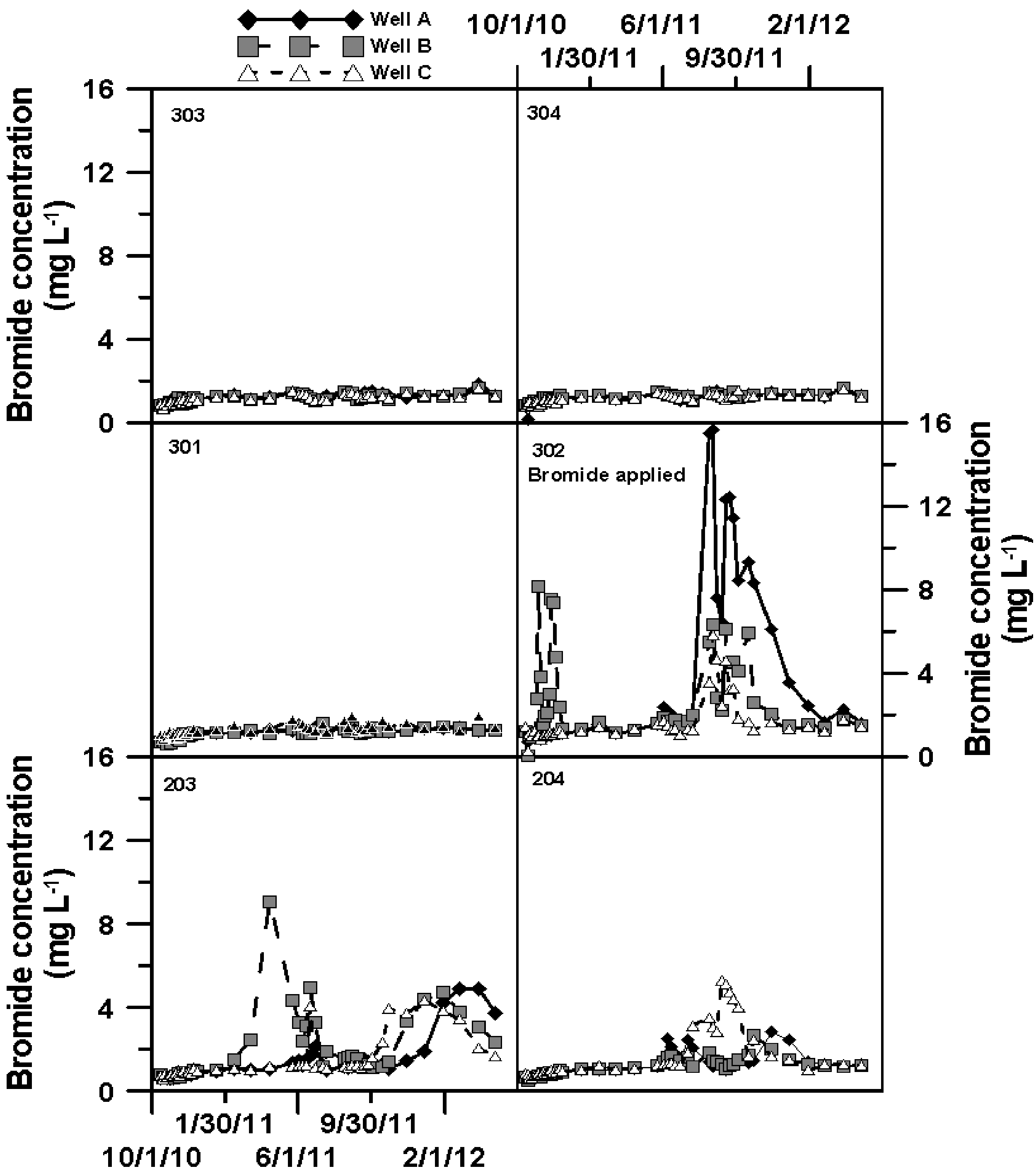

Figure 1. Bromide concentrations in the north six plots of the first field where bromide was applied on 14 October 2010. The first sample date represents the day on which bromide was applied.

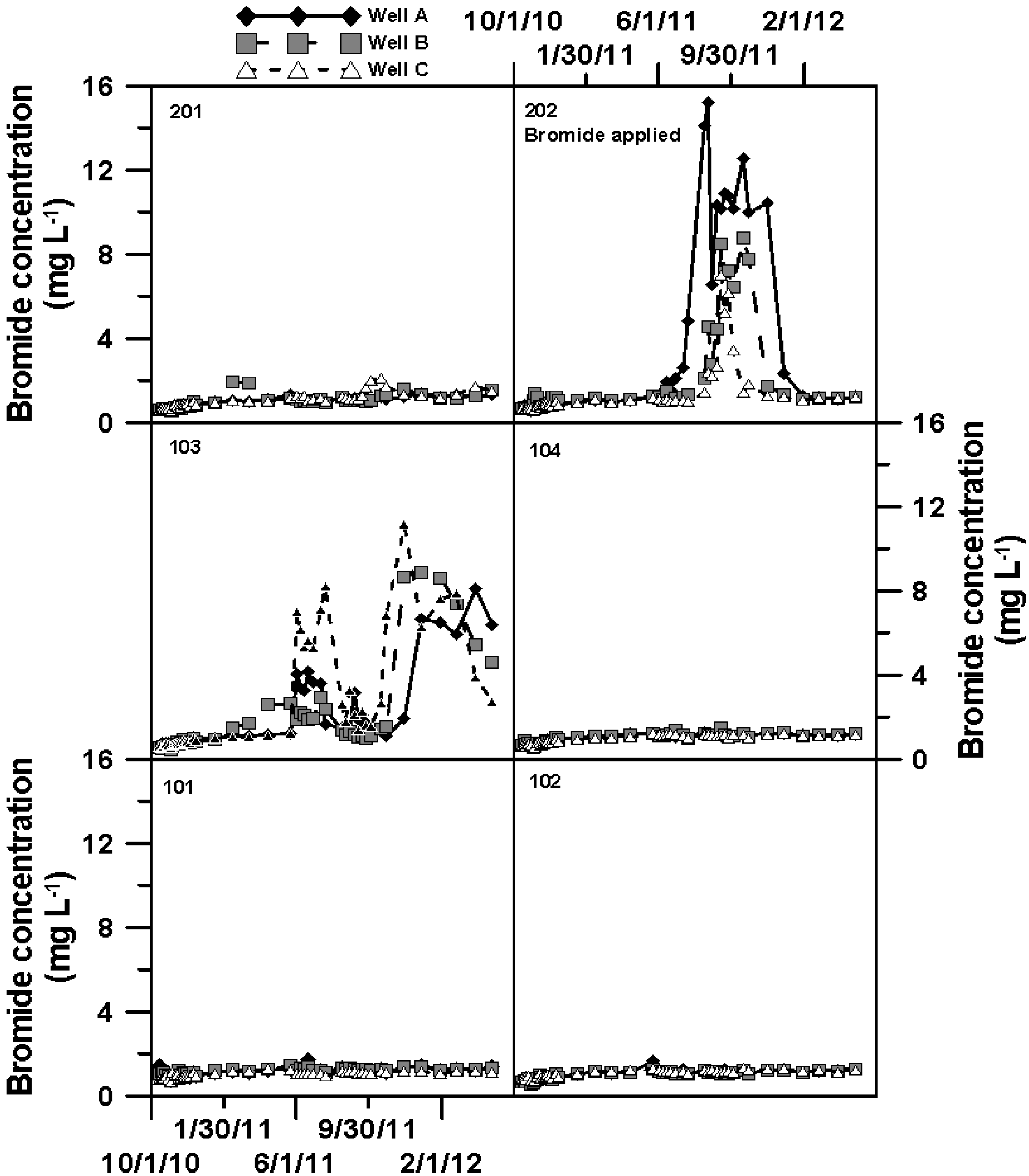

Figure 2. Bromide concentrations in the south six plots of the first field where bromide was applied on 14 October 2010. The first sample date represents the day on which bromide was applied.

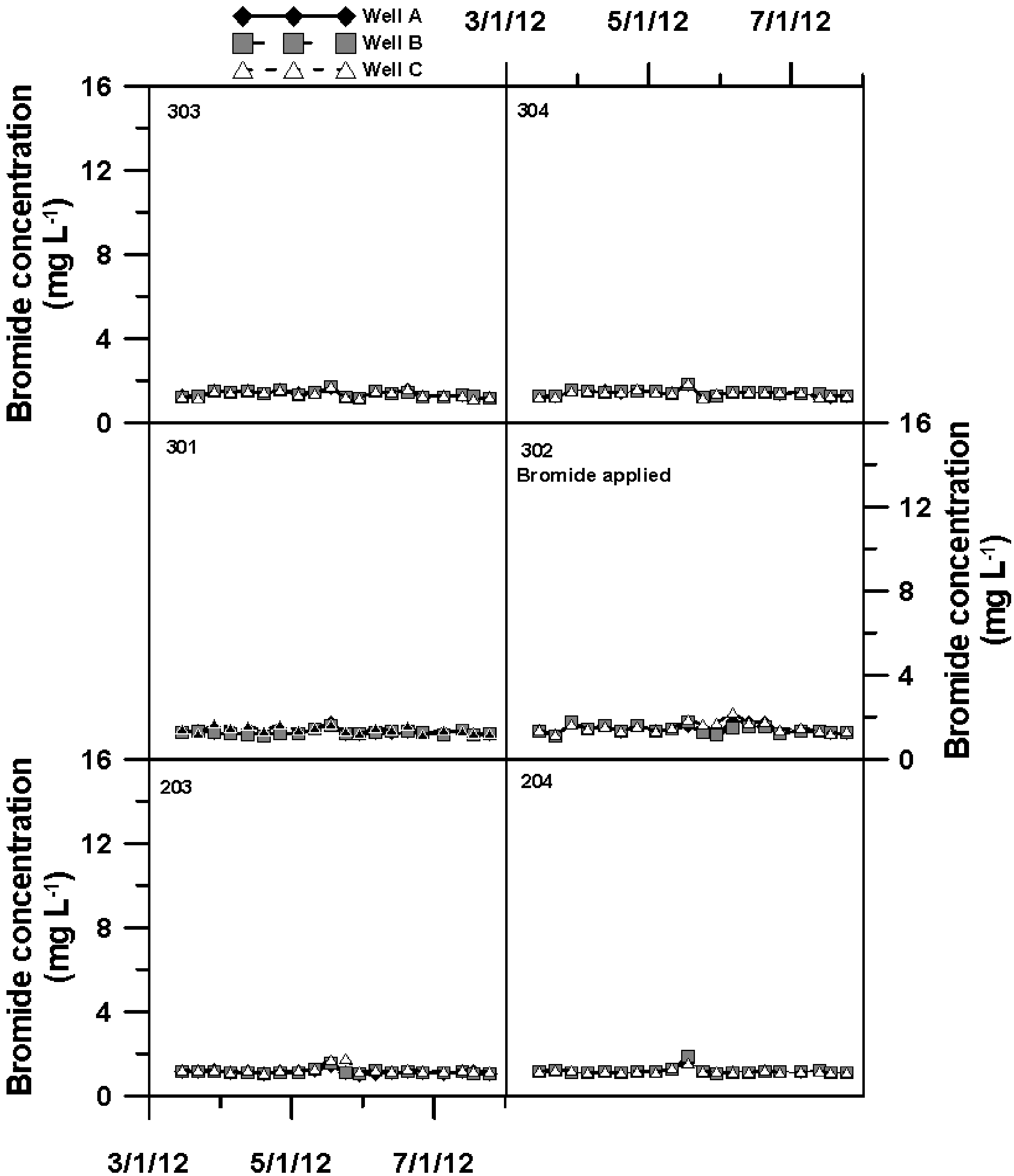

Figure 3. Bromide concentrations in the north six plots of the second field where bromide was applied on 9 March 2012. The first sample date represents the day on which bromide was applied.

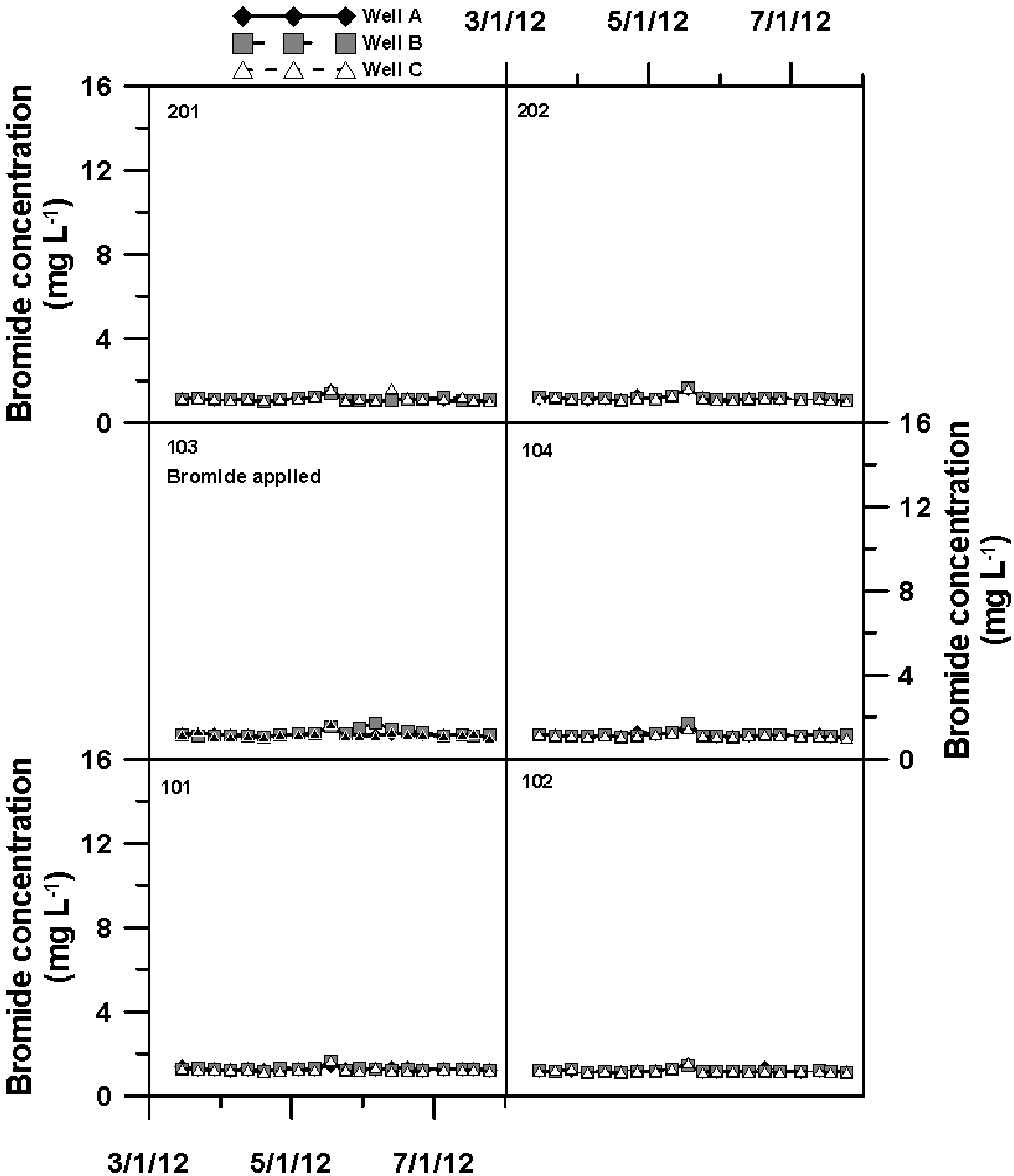

Figure 4. Bromide concentrations in the south six plots of the second field where bromide was applied on 9 March 2012. The first sample date represents the day on which bromide was applied.

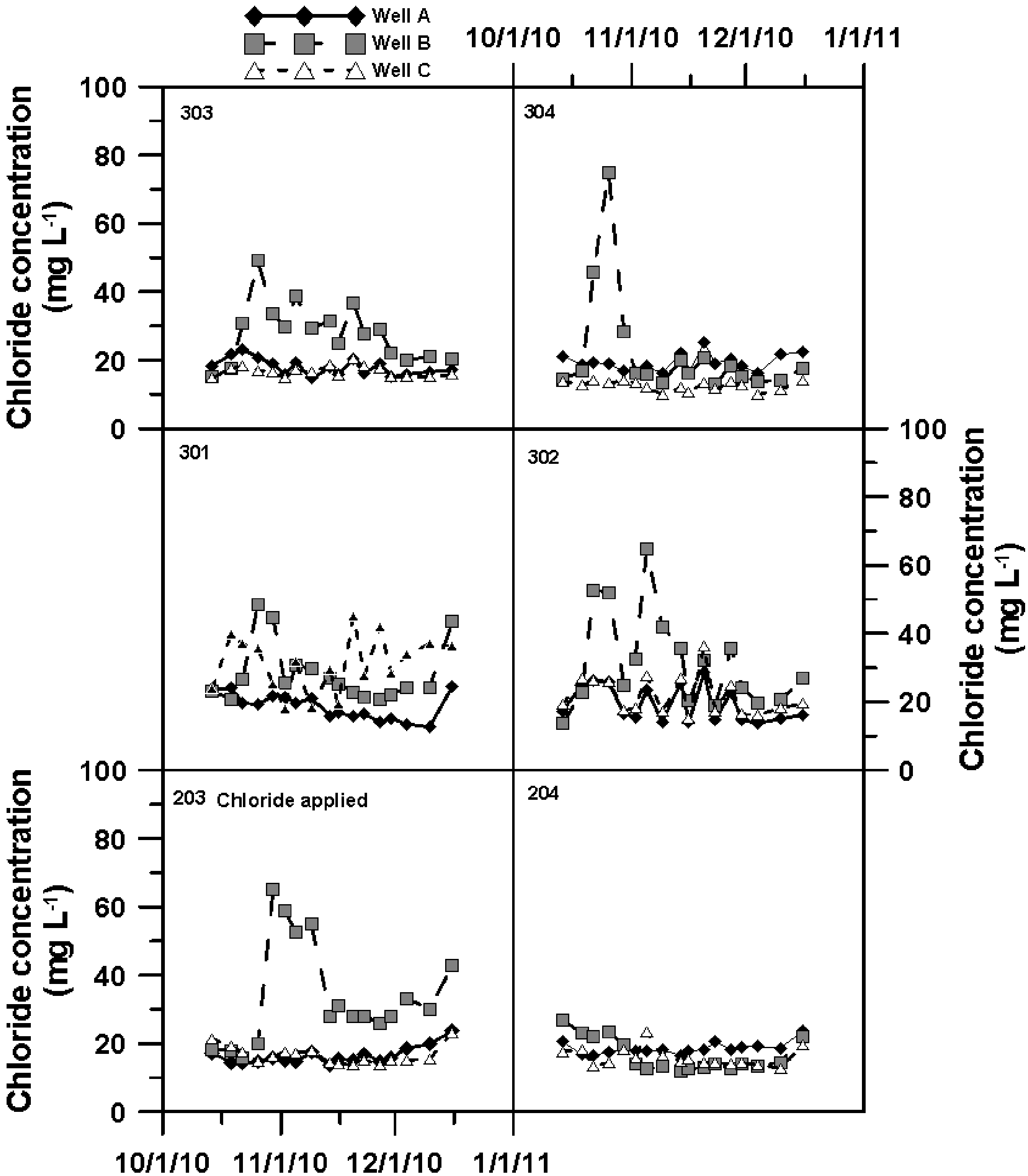

Figure 5. Chloride concentrations in the north six plots of the first field where chloride was applied on 14 October 2010. The first sample date represents the day on which chloride was applied.

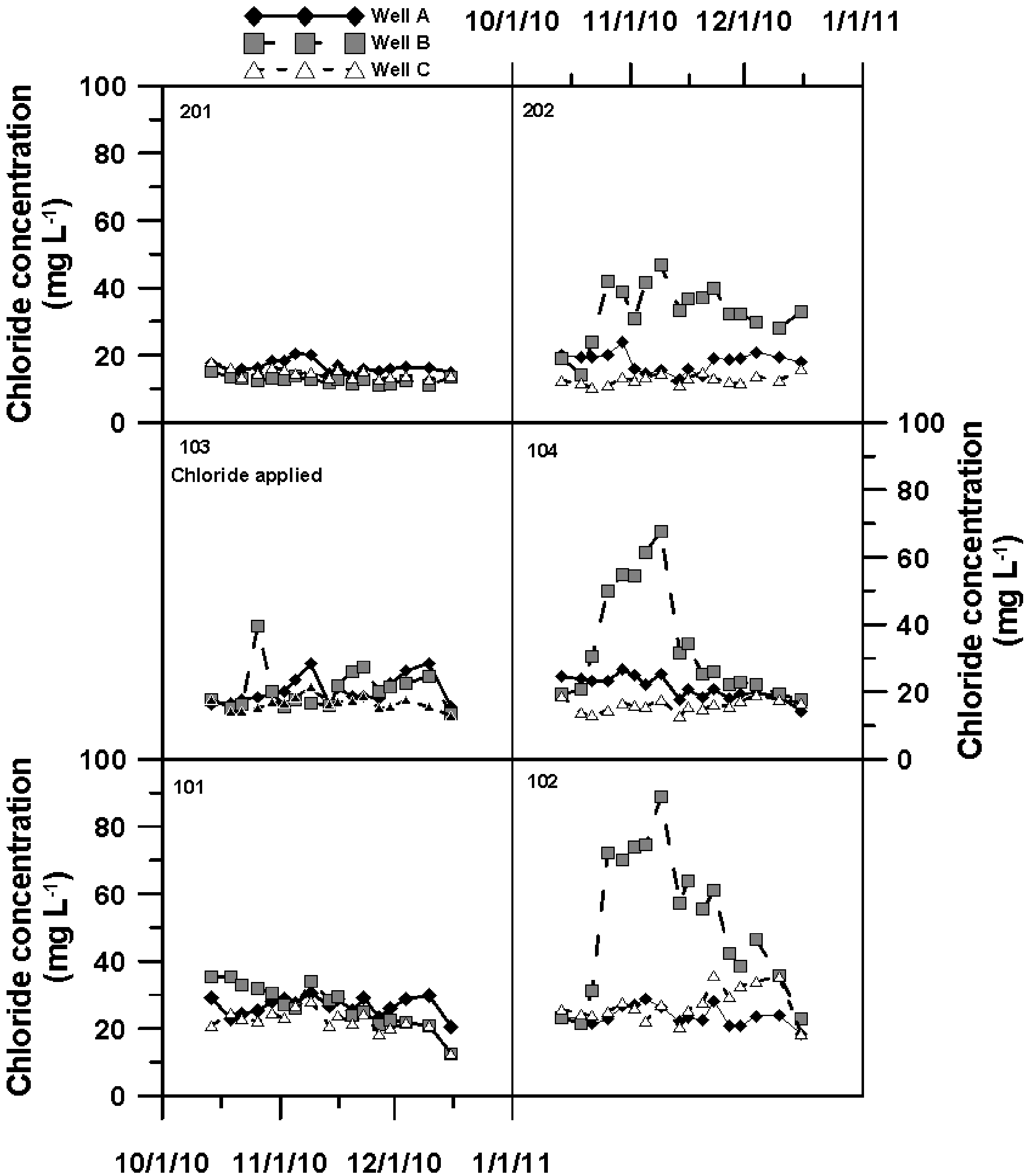

Figure 6. Chloride concentrations in the south six plots of the first field where chloride was applied on 14 October 2010. The first sample date represents the day on which chloride was applied.