Nitrate Leaching and Potato Yield under Varying Plow Timing and Nitrogen Rate

Yefang Jiang,* Judith Nyiraneza, Mohammad Khakbazan, Xiaoyuan Geng, and Brian J. Murray

Core Ideas
• Fall plowing created more post–fall-plow-nitrate leaching than spring plowing.
• Fall or spring plowing did not influence post–potato-harvest nitrate leaching and potato yield.
• Increasing fertilizer N input to potato crops increased post–potato-harvest nitrate leaching.
• Increasing fertilizer N input to potato crops suppressed potato yield.

ABSTRACT
Excessive nitrate leaching from potato (Solanum tuberosum L.) production has been linked to groundwater nitrate contamination and eutrophication in receiving surface water. This study was conducted to assess the effects on nitrate leaching and potato yield of delaying red clover (Trifolium pratense L.) plowing from late fall to spring in a barley (Hordeum vulgare L.)–red clover–potato rotation and varying additions of fertilizer N to potato crops in Prince Edward Island, Canada, between 2014 and 2017. The experiment used a split-plot arrangement in a completely randomized design with three replications. A stainless steel lysimeter was installed in each plot to collect soil water to test nitrate concentrations in leachate. Nitrate leaching occurred primarily between late fall, after the potato harvest, and in spring. Delaying forage plowing from late fall to spring reduced post–fall-plowing nitrate leaching but had no influence on either post–potato-harvest nitrate leaching or potato yield. Increasing fertilizer N input to the potato crops was shown to not only increase the risk of excessive nitrate leaching but also to suppress potato yield. Higher levels of soil N supplies from the mineralization of the plowed-down red clover and soil organic matter to the potato crops in combination with a shorter than ideal growth period for the long-season Russet Burbank potato appear to create overfertilizing situations, resulting in excessive post–potato-harvest nitrate leaching and suppressed yields. Adequately accounting for soil N supplies is critical for enhancing potato productivity while minimizing nitrate leaching.

Abbreviations: AAFC, Agriculture and Agri-Food Canada; ANR, apparent nitrogen recovery; BMP, beneficial management practice; ECCC, Environment and Climate Change Canada; RB, Russet Burbank; SOM, soil organic matter.

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potato (Solanum tuberosum L.), constituting the fourth most important food staple crop after rice (Oryza sativa L.), wheat (Triticum aestivum L.), and maize (Zea mays L.) worldwide, plays a significant role in global food and nutrition security (DeFauw et al., 2012). World potato production is projected to increase by about 30% from 2015 to 2050 as global population and food demands grow (Porter and Faulkner, 2015). Potato producers commonly apply high fertilizer N input rates to potato crops to meet industry tuber yield and quality requirements (Zebarth and Rosen, 2007). Potato plants have a shallow root system with 85% of root length within the upper 0.3-m soil layer (Opena and Porter, 1999), and their apparent N recovery (ANR = whole plant N accumulation – soil N ÷ fertilizer N input) can be as low as 40 to 60% (Zebarth and Rosen, 2007; Vos, 2009). As a result, potato production systems are prone to high nitrate leaching, which has commonly been linked to groundwater nitrate hotspots (Peralta and Stockle, 2001; Wilson et al., 2010; Shrestha et al., 2010; Bero et al., 2014; Zebarth et al., 2015). The nitrate-enriched groundwater discharges to receiving surface waters, contributing to eutrophication (Mitsch et al., 1999; NRC, 2000; Bowen et al., 2007). Optimizing potato N fertilization requires maximizing potato productivity while minimizing negative environmental impacts by balancing N supply and demand for potato plant growth in time and space (Zebarth and Rosen, 2007). Reducing N inputs to potato crops can reduce nitrate leaching but may induce a cost of compromised potato yield and quality if optimal N requirements for potato plant growth are not met (Zebarth et al., 2015).
Soil N supply varies with the quality and quantity of soil organic matter (SOM) including previous crop residues, soil microbial activity, and weather. The uncertainties associated with soil N supply impose a great challenge for potato N management in a humid temperate climate (Zebarth et al., 2012).

In some potato production areas, forage legumes were included in potato rotations to serve as green manure, break pest cycles, and improve physical soil conditions (Neeteson, 1989; Jahanzad et al., 2017; Kelling et al., 2019), which can create additional challenges for potato N management (Neeteson, 1989; Myrbeck, 2014; Kelling et al., 2019). Conventionally, farmers plowed (e.g., moldboard plow) the legumes in the fall as fall plowing provides more time for spring planting, improves soil tilth, reduces soil lumps, produces a favorable seedbed for seedling operations, reduces risk of insect and disease hazards, and better controls weeds and volunteer crops (Neeteson, 1989; Myrbeck, 2014). However, fall plowing increases the risk of erosion in a humid temperate climate (Edwards et al., 1998; Holmstrom et al., 1999) and also increases the risk of nitrate leaching because nitrate can be released from the plowed-down forages via mineralization and leached below the crop root zone during the moist off-season (Francis, 1995; Fraser et al., 2013). Delaying forage plowing from early fall to late fall or spring was reported to reduce nitrate leaching, mainly because the mineralization of the plowed-down forages normally decreases with decreasing soil temperature in late fall–winter seasons and a shortened mineralization period (Francis, 1995; Mitchell et al., 2000). However, in a study conducted in Prince Edward Island, Jiang et al. (2015) observed that the elevated nitrate leaching during the off-season was primarily attributed to the early fall pre-plowing forage termination with glyphosate (a common practice adopted by farmers in Prince Edward Island to improve soil tilth, reduce soil lumps, produce a favorable seedbed for seedling operations, reduces risk of insect and disease hazards, and better control weeds and volunteer crops) instead of the late fall plowing per se, since the termination hastened the mineralization of the forages and exacerbated nitrate leaching. Delaying tillage from fall to spring has resulted in mixed potato yield responses. As examples, DeHaan et al. (1999), Ochuodho et al. (2013), and Jiang et al. (2015) observed that spring tillage increased potato yields in Atlantic Canada, whereas Griffin et al. (2009) found that spring plowing reduced potato yield in Maine, USA; some other studies in Prince Edward Island found potato yield to be similar among tillage treatments (Carter and Sanderson, 2001; Holmstrom et al., 2008). The inconsistent results surrounding the effects of delaying legume tillage from fall to spring on nitrate leaching and potato yield suggest that further experiments are required to better understand the economic and environmental performances of spring plowing before promoting it as a beneficial management practice (BMP) to mitigate nitrate leaching.

This study was conducted to assess the effects of forage plowing practices and potato N management on nitrate leaching and potato productivity of the local industry standard potato rotation (i.e., grain–forage legumes–potatoes) in Prince Edward Island, Canada. Specific objectives were to (i) assess the effects of fall vs. spring plowing of red clover (Trifolium pratense L.) in a barley (Hordeum vulgare L.)–red clover–potato rotation on nitrate leaching and potato yield; and (ii) assess the effects of varying fertilizer N inputs into potato crops on nitrate leaching and potato yield. It is hypothesized that postponing plowing red clover from fall to spring will limit the mineralization of the red clover and reduce nitrate leaching during the off-season while retaining more N in the soil for subsequent potato crops. The overall objective is to provide improved knowledge to inform whether spring plowing can replace fall plowing as a BMP within the potato rotation to mitigate nitrate leaching in a humid temperate climate.

MATERIALS AND METHODS

Field Experiment

The experiment was conducted at the Agriculture and Agri-Food Canada (AAFC) Harrington Research Farm (46°20′31.045″ N, 63°10′19.8″ W, elevation of 57 m above sea level) in Charlottetown, PE, Canada between 2014 and 2017. The field (1.5% slope) has sandy loam soil, which was derived from local glacial till. Based on the Canadian soil classification system, this soil is an Orthic Hurno-Ferric Podzol (MacDougall et al., 1988). Soil analyses performed at the beginning of the trial showed that the soil (0–0.3 m) consisted of 53% sand, 38% silt, and 9% clay based on tests using the hydrometer method proposed by Gee and Bauder (1979). The soil had 3.1% (30.1 g kg⁻¹) organic matter; soil organic C was measured by dry combustion using an Elementar analyzer (Vario Max, Element Analyzer, Hanau, Germany), and percentage soil organic matter was estimated as the product of organic C and a conversion factor of 1.72. The soil had an average pH value of 6.5 based on measurements using 10 g soil/10 mL water. Potato production in Prince Edward Island typically takes place on this type of soil. The climate is characterized by mean annual precipitation of 1174 mm (25%) as snow, based on 1988 to 2017 data from the nearby Environment and Climate Change Canada (ECCC, http://climate.weather.gc.ca/ climate_data/daily_data_e.html?StationID=50621, accessed 30 July 2017) weather station at the Charlottetown Airport (46°17′21″ N, 63°5′9″ W). The frost-free period varies between 100 and 160 d.

The main experimental factor was the timing of plowing (i.e., fall vs. spring) and the second factor was increasing N rates (0, 60, 120, 180, and 240 kg N ha⁻¹) banded to potato crops (Russet Burbank variety) as ammonium nitrate (34–0–0) at planting. The N rate factor was intended to help determine optimal N input rates for potato production under spring vs. fall plowing. The provincial recommended N rate for the Russet Burbank (RB) variety was 185 kg N ha⁻¹ (Prince Edward Island Government, 2014), which was subject to adjustment depending on SOM and previous crops (personal communication, 2018). The experiment used a split-plot arrangement in a completely randomized design with three replications. The fall vs. spring plowing treatments were randomly assigned to six experimental blocks with the five N rates being randomly assigned to the five plots within each block. Each experimental plot (totaling 30) with a dimension of 6 m wide by 8 m long contained six rows of potato with row spacing of 0.91 m and plant spacing of 0.38 m. Inter-plot area was 2 m. Besides the fertilizer N, 200 kg P₂O₅ ha⁻¹ as superphosphate (0–46–0) and 200 kg K₂O ha⁻¹ as muriate of potash (0–0–60) were banded in potato crops during planting. Weed, pest, and disease control was based on standard cultural practices (Bernard et al., 1993). Crop sequence and other experimental details are summarized in Table 1.

Sampling and Monitoring

Soil Sampling

In all cases, soil samples were collected in 0.15-m increments to a depth of 0.45 m using a handheld Dutch auger (0.05-m diameter). Before planting barley in spring 2014, soil cores were randomly collected at three locations in each block (totaling six) and bulked to
Crop Tissue Sampling

On 15 July, and again on 2 Sept. 2015, a day before red clover clipping by flailing (a common practice to prevent red clover from flowering and producing seeds in commercial fields in Prince Edward Island), a 0.5 × 0.5 m red clover sample was collected from each plot (totaling 30) to characterize the biomass and N accumulation in red clover before clipping. A total of 30 samples (replicates) were collected during each sampling event, which was considered to be sufficient for the characterization, although each individual sample size was relatively small. The samples were weighed and a subsample (1–2 kg) was taken from each plot. The subsamples were weighed and dried at 60 °C for 48 h. The dry samples were weighed to determine sample moisture levels. A portion of the dried samples was ground to pass through a 1-mm sieve and analyzed for total N and C concentrations. The N and C concentrations were determined by the dry combustion method using an elemental analyzer (Vario Max, Elementar Analyzer, Hanau, Germany). These samples were used to determine aboveground red clover biomass and N and C content before red clover clipping.

Soil Water Sampling

A stainless steel lysimeter (SW-071-260) from Soil Measurement Systems (SMS) (Tucson, AZ) was installed in each plot (totaling 30) to sample soil water for measuring nitrate and ammonium concentrations in leachate. The lysimeter was located at 2.5 m in the plot measuring horizontally from the middle point of the length-side plot edge and was installed at depth with the sampling porous membrane intake situated at 0.7 to 0.8 m below the ground surface (Fig. 1). Before installation, each lysimeter was connected with TB-072 (4–5 m) tubing (SMS) to its two sampling ports (one for water return and the other for applying suction/pressure) and the tubing was covered using a 4-m-long flexible PVC pipe (0.025-m diam.) to protect it from kinking or being damaged. The tubing assembly...
was buried using the excavated soil, leaving the last (about 0.5–0.7 m) section sticking up vertically at the plot edge to collect soil water samples. Although this new installation design positions the lysimeter under potato rows to optimize the representativeness of lysimeter sampling, it also allows the lysimeter to remain in situ throughout the project without being removed to accommodate routine farm operations and disturbed or damaged by plowing operations.

The lysimeter allows soil water seep through its porous membrane to produce a water sample (referred to as “freely drained water”) in the collection cup without applying any suction if and when the soil water potential is high enough to overcome the resistance in the stainless steel porous membrane (normally under a saturated soil condition). Otherwise (under an unsaturated soil condition), suction has to be applied through the tubing to collect a soil water sample while keeping the water return tubing closed. In this study, when the soil became saturated during the fall–winter–spring leaching seasons, the lysimeters were pumped weekly for freely drained water from the sampling tubing using an air bicycle pump. During each sampling run, if freely drained water was not available, and the soil was relatively wet (16–20% volumetric moisture) and/or the soil was not frozen, suction (0.002–0.034 MPa or 5 to 8 PSI) was continuously applied on the tubing for about 5 to 10 min using a peristaltic pump (Geotech, Denver, CO) while keeping the sampling tubing closed to collect a vacuum-driven sample; the sample directly bypassed the collection cup and then discharged through the pump tubing into a collection bottle. In addition, leaching sampling checks were performed after heavy rainfall events (including the summer seasons). Upon sample collection, the leftover water was completely pumped out from the collection cup to create an empty chamber for storing upcoming water. The samples were stored at <4°C until analysis. The leachate samples were first tested for nitrate concentration using a Submersible Ultraviolet Nitrate Analyzer (SUNA) (Sea-Bird Electronics, Bellevue, WA) within 1 wk of collection. The leftover samples were stored at <4°C. For quality control purposes, most of the leftover soil water samples were reanalyzed within a month of collection on a Lachat QuikChem 8500 flow injection analysis system (Lachat Instruments, Loveland, CO) using a colorimetric technique for nitrate and ammonium with a detection limit of 0.025 mg N L⁻¹.

**Soil Moisture and Temperature Monitoring**

A small soil temperature and moisture station (H21-002 Micro Station with S-SMA-M005 sensors, HOBO) was installed in a spring plowing plot (180N spring plowing) and another in a fall plowing plot (180N fall plowing), to measure hourly soil moisture and temperatures at depths of 0.15 and 0.3 m, respectively. The monitoring data were used to calculate daily averages of temperature and moisture, which were in turn used to calibrate and verify the LEACHN (Hutson, 2003) model for estimating soil drainage.

**Nitrate Leaching Estimation**

Nitrate concentrations in leachate per se cannot accurately indicate the nitrate leaching magnitude (e.g., the concurrence of a high nitrate concentration and a low drainage level can result in a relatively low nitrate leaching scale but can be interpreted as a high level by mistake). In this study, the sum of daily nitrate leaching, which was calculated as the product of daily nitrate concentration in leachate and associated soil drainage volume during a specific period, was used to indicate the effects of the experimental factors on nitrate leaching. Specifically, the nitrate leaching occurring from 1 d after the fall plowing (7 Nov. 2015) to 1 d before the spring plowing (29 Mar. 2016) was used to indicate the effects of the experimental factors on post-fall-plowing nitrate leaching; the nitrate leaching occurring from 1 d after the potato harvest (26 Oct. 2016) to 1 d before planting barley (22 May 2017) was used to assess the effects of the experimental factors on post-potato-harvest nitrate leaching. The nitrate leaching occurring from when fall leaching started (29 Oct. 2014) to the day when red clover regrew in 2015 (31 Mar. 2015) was also calculated to indicate post-barley-harvest nitrate leaching. The daily nitrate concentrations in leachate from 11 June 2014 to 31 May 2017 in each plot were interpolated from the lysimeter sampling data using...
the one-way spline method (SRS1 Software). The interpolated time series of daily nitrate leaching concentrations were utilized to estimate daily nitrate leaching from the soil profile. Daily soil drainage was estimated from coupled LEACHN and MODFLOW modeling, which is detailed in Appendix 1.

### Statistical Analysis

All data were tested for normality using the SAS Univariate procedure (SAS version 9.4, SAS Institute, 2012). The SAS MIXED procedure was used to perform statistical analyses considering a split-plot design and by treating block and block × forage plowing time as random effects and N rates and forage plowing time as fixed effects. Multiple comparisons among fixed factors were performed using the DIFF option of SAS.

### RESULTS AND DISCUSSION

#### Weather

Growing season (May–Sept. 2016/potato phase) precipitation (409 mm) was 90% of the long-term (1988–2017) average (459 mm) (Fig. 2). Monthly precipitation during May, June, July, and September in the potato year (2016) was 28, 30, 16, and 22.2 less than the long-term average, respectively, but the precipitation in August was 27% higher than the average (Fig. 2). Air temperatures during the 2016 growing season were very similar to the long-term averages (Fig. 3).

#### Soil Nitrate Content

At the beginning of the experiment (spring 2014), soil nitrate and ammonium content (including standard deviations) based on soil sampling in the six blocks were 6.2 ± 0.8 (0–0.15 m), 6.5 ± 0.5 (0.15–0.3 m), and 4.5 ± 0.7 kg N ha⁻¹, and 0.4 (0–0.15 m), 0.9 ± 1.0 (0.15–0.3 m), and 0.9 ± 0.5 kg N ha⁻¹ (0.3–0.45 m), respectively (Fig. 4). These data indicate that the experimental field started off with low nitrate and ammonium content and uniform fertility. Before 6 Nov. 2015 when fall plowing was conducted in the three fall plowing blocks, soil nitrate content in all plots followed similar trends, with soil nitrate content increasing from about 17 kg N ha⁻¹ on 13 May 2014 and then to 37 to 53 kg N ha⁻¹ on 19 May 2015 (all ammonium content <3 kg N ha⁻¹, which is considered negligible and has been omitted from the discussion). The fact that similar management practices had been followed field-wide since 2009 may explain the similar trends. The elevated nitrate content detected in the soil profile in May 2015 was in part attributed to nitrate release from the decay of SOM and limited drainage due to deep snow cover during winter 2014 to spring 2015. Soil nitrate content in all plots dropped to low levels (~7 kg N ha⁻¹) by 19 Apr. 2016, regardless of whether the plots were plowed in fall 2015 or were not plowed yet. The soil nitrate content immediately before potato topkill was significantly influenced by fertilizer N rate to potato crops and not by tillage timing (Fig. 4; Table 2). The soil nitrate content a month after topkill dropped to about 50% of the pre-topkill levels for the high N rate cases, but remained relatively high. Nitrate leaching likely contributed to the decline of the soil nitrate contents between the two sampling events because potential nitrate losses via other sinks, such as plant uptake and denitrification, were expected to be limited; potato plant growth and associated N uptake are limited after topkill (Ivany and Sanderson, 2001) and denitrification was considered to be limited in this kind of soil and climate (Dandie et al., 2008; Snowdon et al., 2013). These data suggest that the accumulation of high nitrate content in the soil profile at the end of the potato plant growth stage in coexistence with the excessive soil moisture during the off-season created a high risk of nitrate leaching in this humid temperate region.

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**Fig. 2.** Monthly precipitations at the Environment and Climate Change Canada weather station at Charlottetown Airport (46°17′21″ N, 63°7′9″W).

**Fig. 3.** Observed daily soil temperature in the study field and air temperature at the Environment and Climate Change Canada weather station at Charlottetown Airport (46°17′21″ N, 63°7′9″W).
Red Clover and Potato Plant Nitrogen

Nitrogen accumulation (including standard deviation) in aboveground red clover biomass was $132 \pm 35 \text{ kg N ha}^{-1}$ (C/N = 23) (30 samples collected on 15 July 2015 before the first cut of red clover). The regrowth of red clover accumulated $62 \pm 26 \text{ kg N ha}^{-1}$ (C/N = 17; based on 30 samples) in aboveground biomass by 2 Sept. 2015 (before the second cut of red clover). By 18 May 2016, the regrowth accumulated $27 \pm 7 \text{ kg N ha}^{-1}$ (C/N = 13; based on 15 samples from the spring plowing plots) in aboveground biomass before spring plowing. Root N of red clover was reported to account for about 20 to 30% of whole-plant N in Atlantic Canada (aboveground/belowground N ratio was about 2.3–4) (Bolinder et al., 2002). Bowren et al. (1969) showed that the ratio of aboveground/belowground N accumulations in fall-harvested red clover biomass was 2.6. Assuming that the aboveground/belowground N accumulation ratio was 3 (similar to the values in the literature) and the root did not grow significantly after the first cut, the whole-plant N accumulations in red clover by 15 July 2015, 2 Sept. 2015, and 18 May 2016 were calculated.

Table 2. Effects of forage plow timing and N rate on fall soil nitrate in potato year, potato yields, tuber- and total N uptake, and nitrate leaching after fall plowing and potato harvest.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Fall soil nitrate in potato year</th>
<th>Total yield</th>
<th>Marketable yield</th>
<th>Tuber N uptake</th>
<th>Total N uptake</th>
<th>Post–fall- plowing nitrate leaching</th>
<th>Post–potato- harvest nitrate leaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plow timing kg N ha$^{-1}$</td>
<td>mg ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
<td>kg N ha$^{-1}$</td>
</tr>
<tr>
<td>Spring plowing</td>
<td>43.3a</td>
<td>32.8a</td>
<td>31.4a</td>
<td>72.1a</td>
<td>139.8a</td>
<td>2.8b</td>
<td>149.4a</td>
</tr>
<tr>
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<td>35.8a</td>
<td>34.7a</td>
<td>79.1a</td>
<td>157.3a</td>
<td>10.6a</td>
<td>166.2a</td>
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<tr>
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<td>1.8</td>
<td>1.8</td>
<td>3.5</td>
<td>6.5</td>
<td>0.9</td>
<td>21.3</td>
</tr>
<tr>
<td>N rates</td>
<td>0N</td>
<td>11.2d</td>
<td>40.5a</td>
<td>39.5a</td>
<td>64.9c</td>
<td>111.0b</td>
<td>5.8a</td>
</tr>
<tr>
<td></td>
<td>60N</td>
<td>13.2d</td>
<td>32.9ab</td>
<td>32.0abc</td>
<td>75.7abc</td>
<td>141.9a</td>
<td>7.1a</td>
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<tr>
<td></td>
<td>120N</td>
<td>32.1c</td>
<td>38.7a</td>
<td>37.2ab</td>
<td>87.7a</td>
<td>175.4a</td>
<td>7.2a</td>
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<td></td>
<td>180N</td>
<td>55.3b</td>
<td>29.2b</td>
<td>27.8c</td>
<td>79.4ab</td>
<td>160.2a</td>
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<td></td>
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<td>29.9a</td>
<td>28.7bc</td>
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<tr>
<td>Standard error of mean</td>
<td>5.5</td>
<td>2.8</td>
<td>2.9</td>
<td>5.0</td>
<td>14.6</td>
<td>1.5</td>
<td>1.5c</td>
</tr>
<tr>
<td>Analysis of variance</td>
<td>Plow timing (PT)</td>
<td>NS†</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td></td>
<td>N rate (N)</td>
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<td>NS</td>
<td>NS</td>
<td>NS</td>
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</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NS, nonsignificant.
and 18 May 2016 (spring-plowed plots only) were estimated to be about 176 (aboveground/belowground = 132/44), 62 (aboveground only), and 28 (aboveground only) kg N ha⁻¹, respectively. The red clover residues clipped in September 2015 and May 2016 likely included some of the N released from the decay of the red clover clipped in July and September 2015, respectively. Some of the N released from the decomposition of the red clover tissues clipped and left in the field in July and September 2015 may have contributed to nitrate leaching, but this leaching was expected to be small due to the lack of drainage in the summer. Thus, the N accumulations in red clover biomass under fall and spring plowing were estimated to range from 176 (excluding N in the regrowth biomass) to 252 kg N ha⁻¹ (including N in the regrowth biomass until 2 Sept. 2015 plus 50% of N in the regrowth biomass until 18 May 2016), and from 176 to 266 kg N ha⁻¹ (including N in all regrowth biomass), respectively. These data agree with the upper bound values as reported in Neeteson (1989) and Kelling et al. (2019). Although these current data cannot be used to accurately determine the recycling N, leaching N and denitrified N levels associated with the clipped red clover tissues, the vast majority of the N accumulations were expected to be either incorporated into the soil in fall after fall plowing or in spring after spring plowing. As a result, the potential soil N supply from the plowed-down red clover alone to the succeeding potato crops would be high compared with the potato plant N uptake (110–180 kg N ha⁻¹) as discussed later.

Fertilizer N rate significantly influenced tuber N and whole-potato plant N (Table 2). When soil N supply to potato plants was defined as plant N at harvest with no fertilizer N applied (Zebarth et al., 2004b), soil N supply was 113 and 109 kg N ha⁻¹ under fall and spring plowing, respectively. These levels of soil N supply were very likely sourced from in-season mineralization of SOM, and the plowed-down red clover biomass as soil nitrate contents on 19 Apr. 2016 before potato planting were as low as ~7 kg N ha⁻¹ (Fig. 4), which would not match these levels of soil N supply. The timing of plowing did not have a significant effect on tuber N or plant N (Table 2).

**Potato Yield Responses**

Typically, potato plants increase N accumulation with an increasing N rate up to relatively high N rates, whether a tuber yield response is observed or not; tuber yield commonly increases with the initial increments of fertilizer N applied, becomes relatively insensitive to N rate over a fairly wide range of further increments of N addition, then at very high levels yield decreases (e.g., White and Sanderson, 1983; Zebarth et al., 2004a, 2012). Surprisingly, potato yields in this study decreased with increasing fertilizer N inputs (Table 2; Fig. 5), with the highest yields obtained at zero fertilizer N input and the lowest yields at the highest fertilizer N inputs under both fall and spring plowing treatments; increasing fertilizer N input from 0 to 120 kg N ha⁻¹ increased potato plant N uptake and reduced potato yields, and further increasing fertilizer N inputs reduced both plant N uptake and potato yields (Table 2). These responses did not fully follow the typical patterns in the literature.

Inconsistent potato yield and plant N responses to varying fertilizer N input have been reported in the literature (e.g., Waterer, 2002). The rate of fertilizer N application required to achieve optimum yield varies with site, growing conditions, crop management, and incidence of disease and insects (Zebarth and Rosen, 2007). A lack of N response in terms of tissue N levels and yields could be expected if N uptake was limited by adverse growing conditions.
or poor crop vigor (Waterer, 2002). The lower than normal precipitation in May to July 2016 may have restricted potato plant growth to some extent in this study. However, Zebarth et al. (2004a) reported that RB yields increased with increasing fertilizer N inputs in Fredericton, NB, Canada in both 1999 and 2001, despite drier weather conditions in both years, which were similar to those observed in 2016 in the present study. Their findings implied that the relatively dry weather in the 2016 growing season does not fully explain the decreasing potato yield trend observed in this study. The suppressed yields were unlikely associated with any diseases or pests as none were observed during the experiment.

The unusual responses appear to be associated with the combination of a shorter growth period for the long-season RB potato and higher levels of N supplies to the potato crops. The potato plants were planted on 31 May 2016 and vine desiccated on 15 to 16 Sept. 2016, corresponding to a growth period of 108 d, which was shorter than the ideal growing period (120–140 d) required for the RB variety (note that topkill in mid-September is required in Atlantic Canada so the potato crop can be harvested before the tubers freeze in the ground). This shorter than an ideal growing period likely limited potato plant growth and N uptake as observed by White and Sanderson (1983) in Prince Edward Island. The facts that the addition of fertilizer N promoted plant N uptake within the lower range of N inputs, but compromised potato yields in all cases implies that potato crops received excessive N supplies, given the shorter growth period. This is supported by the fact that the soil nitrate content immediately before potato topkill was higher in the fertilized plots (Fig. 4). The release of N from the mineralization of SOM and the preceding plowed-down red clover crop over the growing season appeared to be sufficient for potato plant growth in the prevailing weather and growth period conditions. Under these conditions, the addition of any amount of fertilizer N may exceed plant growth needs, resulting in reduced tuber yields. Sattelmacher and Marschner (1979) reported that high N applications might contribute to a delay in tuberization, thus reducing potato yield and/or maturity. Nectenson (1989) noted that a previous legume crop could provide high soil N supply to potato, and therefore that the failure to accurately account for soil N supply from rotational legume crops can lead to a significantly increased risk of high nitrate leaching and reduced tuber yield. Potato yield was not found to be responsive to the timing of red clover plowing (Table 2).

Nitrate Leaching

Nitrate leaching occurred primarily during late fall, winter, and early spring when crop uptake diminished and elevated soil nitrate contents coexisted with soil–water movement from the root zone (Fig. 6). Soil–water movement occurred between March and May in response to drainage induced by snowmelt, and between October and February when evapotranspiration diminished and snowmelt and/or rainfall induced drainage. Soil–water movement was limited between June and October when evapotranspiration exceeded precipitation and drainage was limited. The timing of leaching generally agreed with local data reported by Jiang et al. (2011, 2012, 2017). Nitrate concentration trends were similar in all plots before 6 Nov. 2015 when fall plowing was performed, as cultural practices had been kept the same across the field. Nitrate concentrations in leachate during the barley and red clover phases rarely exceeded 7 mg N L⁻¹, which was consistent with the tile-drain nitrate concentrations during barley and forage phases as observed by Jiang et al. (2017) in a commercial field. Nitrate concentration trends remained similar in all plots until the potato crop was planted on 31 May 2016, regardless of whether they underwent fall or spring plowing.

Post–barley-harvest nitrate concentrations in leachate were significantly elevated above the values observed during the barley–forage phases in all plots including zero N input plots, with the highest values occurring in the highest fertilizer N input plots (Fig. 6). Recall that a significant amount of nitrate was accumulated in the soil profile immediately before potato topkill, all the soil nitrate contents decreased to about 50% of the pre-topkill levels immediately after potato harvest, and decreased further to 4 to 9 kg N ha⁻¹ by 4 May 2017 (Fig. 4). The concurrence of decreasing soil nitrate content and increasing nitrate concentration in leachate suggests that the elevated nitrate leaching originated in part from the accumulated soil nitrate, which was sourced from the mineralization of SOM including the red clover biomass in 2015 in the zero N input plots and from the combination of mineralization of SOM plus the red clover biomass in 2015 and fertilizer N residue in the fertilized plots. Interestingly, some post–potato-harvest nitrate concentrations in leachate in zero fertilizer N input plots were elevated above the Canadian drinking water guideline (10 mg N L⁻¹), implying that the nitrate leaching derived from mineralization of SOM plus from the red clover biomass without including any fertilizer residue can be significant. Relatively high variations of nitrate concentration in leachate (indicated by the large standard deviations) existed among plots under the same treatment (Fig. 6). The high spatial variations could be controlled by soil heterogeneity and spatial non-uniformity of the experimental treatment.

Post–barley-harvest (29 Oct. 2014–3 Mar. 2015) nitrate leaching based on estimations in the fall vs. spring plowing blocks was 4.4 and 3.8 kg N ha⁻¹, respectively. Post–fall-plowing (7 Nov. 2015–29 Mar. 2016) nitrate leaching (10.6 kg N ha⁻¹) under fall plowing was significantly higher than that (2.8 kg N ha⁻¹) under spring plowing (Table 2). However, the timing of forage plowing did not significantly influence post–potato-harvest nitrate leaching (Table 2). Increasing fertilizer N input to potato crops resulted in a significant increase in post–potato-harvest nitrate leaching as indicated by the replicate-based nitrate leaching averages (Fig. 5; Table 2). The high positive correlation between fertilizer N input and nitrate leaching indicates low N use efficiency (or high nitrate leaching risk) in the rotation system.

Post–potato-harvest nitrate leaching was much higher than the potential nitrate leaching as indicated by soil sampling (Table 2). This discrepancy can be attributed to the following factors. First, nitrate released from the mineralization of SOM occurring after the soil sampling added to the post–potato-harvest nitrate leaching but was not reflected by the soil sampling. It would take some time for the soil nitrate detected by the soil sampling to travel and be measured by the soil samples. The nitrate leaching risk) in the rotation system.
post–potato-harvest nitrate concentrations in leachate under the same treatment varied substantially in time and space, especially under high N input treatments, which created largely different interpolated time series curves (Fig. 6) and associated nitrate leaching levels (i.e., high standard deviations in Fig. 5). More lysimeters and higher sampling frequency under the same treatment may be required to characterize the uncertainties.

Implications for Nitrogen Management for Potato in Rotation with Legumes

The above data (Table 2) show that fall plowing produced higher post–fall-plowing nitrate leaching than spring plowing (10.6 vs. 2.8 kg N ha\(^{-1}\)). Therefore, it is beneficial to adopt spring plowing to mitigate nitrate leaching from the rotation. However, the post–potato-harvest nitrate leaching (166 vs. 149 kg N ha\(^{-1}\)) was one to two orders higher than the post–fall-plowing nitrate leaching and the post–barley-harvest nitrate

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Fig. 6. Observed nitrate concentrations in leachate (replicate-based averages and standard deviations; F120N represents fall plowing and 120 kg N ha\(^{-1}\) fertilizer input to potato crops; each dashed-box spans a crop phase).
leaching (<5 kg N ha\(^{-1}\)). Therefore, from a nitrate leaching mitigation perspective, it is more imperative and effective to target the potato phase than the two rotational crop phases.

Two possible factors can explain why post–fall-plowing nitrate leaching was very low, but N accumulation in the incorporated red clover biomass was very high. First, the fall plowing in this study was performed on 6 Nov. 2015, which was relatively late in the fall. From the fall plowing date on in this temperate climate zone, soil temperature at a depth of 30 cm declined from 6.5°C to the freezing mark by late Dec. 2015, and remained at, around, or below the freezing mark by late Mar. 2016 (Fig. 3). The low temperatures limited the mineralization of the fall plowed-down red forages. As a result, most of the N in the plowed-down red clover was retained in the soil, but only a small fraction of the N was released as nitrate during the post–fall-plowing period, contributing to the relatively low post–fall-plowing nitrate leaching. These data are consistent with Francis (1995), Mitchell et al. (2000), and Myrbeck (2014). Second, the forages were not terminated using herbicide before fall plowing in this study, which prevented the forages from being rapidly mineralized and creating relatively low post–fall-plowing nitrate leaching. The data did not contradict the previous local data (Jiang et al., 2015) either.

The excessive post–potato-harvest nitrate leaching was highly correlated with fertilizer N applications and soil N supply to the potato crops. When soil N supply was defined as plant N accumulation plus soil inorganic N content at harvest with zero fertilizer N (Zebarth et al., 2004a), soil N supplies to the potato crops under fall and spring plowing were 123.5 and 118.4 kg N ha\(^{-1}\) (Fig. 4 and Table 2), respectively. These values do not include nitrate leaching during the potato phase. Assuming that the soil inorganic N content (10.5 and 9.4 kg N ha\(^{-1}\) under fall vs. spring plowing) at harvest with zero fertilizer N was subject to leaching, when potato phase nitrate leaching was defined as the sum of nitrate leaching occurring in the zero fertilizer N plots between 26 Oct. 2016 (when major drainage events occurred after potato harvest) and 15 Jan. 2017 (when the soil started to freeze), the potato phase nitrate leaching losses derived from SOM and from the plowed-down red clover under fall and spring plowing were calculated to be 67.3 and 34.7 kg N ha\(^{-1}\), respectively. Thus, potential soil N supplies (soil N supply plus nitrate leaching) during the potato phase under fall and spring plowing were estimated to be 190.8 and 153.1 kg N ha\(^{-1}\), respectively (nitrate leaching corresponding to 35 and 23% of the potential soil N supplies, respectively). As shown before, the high levels of N accumulation in the red clover biomass can match these levels of potential soil N supplies, but what fraction of the potential soil N supplies was exclusively derived from the decay of the plowed-down red clover remains unknown. Neeteson (1989) reported that the decay of the plowed-down red clover occurred mainly within a year in the heavy loam soil in the Netherlands. His data imply that the contribution of plowed-down red clover to the potential soil N supplies in this current study may not be a smaller fraction. The yield data, red clover tissue N data, potato plant N data, soil nitrate content data, and nitrate leaching data consistently suggest that the mineralization of SOM and the plowed-down red clover provided sufficient N to meet the long-season RB potato plant growth needs within the shorter growth period, and that the addition of fertilizer N not only raised the risk of nitrate leaching but also suppressed potato yields.

Prince Edward Island is the smallest province (5750 km\(^2\)) but the largest producer of potato in Canada, accounting for 25% of Canadian potato crops (Statistics Canada, 2016). Potato production plays a critical role in local economy. However, excessive nitrate leaching from potato production has been linked to drinking water contamination and reoccurring anoxic events in many receiving estuaries (Jiang and Somers, 2009; Zebarth et al., 2015). Developing sustainable potato N management strategies has been a local environmental and economic priority. Potato yields have been stagnant for years in Prince Edward Island, which stands in contrast to increasing yields in other Canadian provinces (Statistics Canada, 2016), and this is an economic concern for the local industry. This situation has been attributed to soil degradation, declining SOM (Nyraneza et al., 2017), soil moisture deficiency, and crop disease in some cases. This current study shows that increasing fertilizer N input to potato crops decreased potato tuber yield with zero fertilizer N input producing the highest tuber yields in this field/year, which were as high as 39 and 42 Mg ha\(^{-1}\) under fall and spring plowing, respectively, and were 30 to 40% higher than the provincial average (28–30 Mg ha\(^{-1}\) in Statistics Canada, 2016). As noted above, these yield responses may not be typical, but the data clearly imply that fertilizing inadequately accounting for soil N supplies from the decay of SOM plus preceding plowed-down legume crop under a shorter growth period could suppress yields for the long-season RB variety. For example, if a grower follows the current provincial fertility recommendation for RB potato (i.e., applying 185 kg N ha\(^{-1}\) minus a 17 kg N ha\(^{-1}\) credit if SOM levels are above 3.5% and minus another 17 kg N ha\(^{-1}\) credit if the preceding crop is a red clover forage) (personal communication, 2018) in a field that has not been planted with potato for years, the grower would create an over fertilizing situation and likely obtain a suppressed potato yield, as observed in this study. Further studies are required to assess soil N supplies under the barley–red clover–potato rotation to make more realistic N recommendations for sustainable potato production in Prince Edward Island.

Although reducing fertilizer N input by giving more N credits from the plowed-down red clover to the succeeding potato crops can be explored as a beneficial practice, replacing the red clover with a non-leguminous grass crop in the rotation may be explored as another beneficial alternative as the post–potato-harvest nitrate leaching would have been less if the red clover had not been in the rotation. Neeteson (1989) reported that the optimum rate of fertilizer N to potato in rotation with red clover resulted in lower tuber yields and probably heavier nitrate leaching compared with potato in rotation with the reference crop (i.e., oat, Avena sativa L.), and thus, recommended replacing red clover with a non-leguminous grass crop in the rotation. Studies should be performed to examine if replacing red clover with a non-leguminous grass crop in potato rotation is economically viable and environmentally beneficial in Prince Edward Island.

**CONCLUSIONS**

This study was conducted to examine the effects on nitrate leaching and RB potato yield of delaying red clover plowing from late fall to spring in a barley–red clover–potato rotation and varying additions of fertilizer N to the potato crops in Prince Edward Island, Canada between 2014 and 2017. Nitrate leaching primarily occurs during the fall–winter–spring seasons. The data from this one rotation cycle show that delaying forage plowing from late fall to spring reduced post–fall-plowing nitrate leaching but did not influence post–potato-harvest nitrate leaching; the post–potato-harvest nitrate leaching was one to two orders larger than the
post–barley-harvest and post–fall-plowing nitrate leaching. The study also shows that delaying forage plowing from late fall to spring did not influence potato yield; increasing fertilizer N input to the potato crops not only increased the risk of excessive nitrate leaching but also compromised potato yield. Higher levels of soil N supplies from the mineralization of the plowed-down red clover and soil organic matter to the potato crops in combination with a shorter than ideal growth period for the long-season RB variety appear to create overfertilizing situations, resulting in excessive post–potato-harvest nitrate leaching and suppressed yields. This study implies that adequately accounting for soil N supply from the mineralization of plowed-down red clover and SOM to the subsequent potato crops is required to enhance potato productivity while minimizing nitrate leaching from the rotation in this temperate climate region.

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APPENDIX 1

Soil Drainage Modeling

Owing to the difficulties of accurately measuring daily soil drainage, coupled LEACHN and MODFLOW modeling was performed to estimate daily soil drainage for calculating daily nitrate leaching. Specifically, a LEACHN model was developed by following the modeling approach proposed by Jiang et al. (2011) to predict daily soil drainage leaving a 0.9-m soil column, which approximately corresponds to the depth of the porous membrane on the lysimeter. A uniform spatial step of 0.1 m was adopted for the model. The simulation covered the period of 1 June 2014 to 31 May 2017 with a uniform time step of 0.1 d. Soil retention properties were estimated using soil texture and soil organic matter (SOM) data following Rawls and Brakensiek (1985). The soil texture and SOM data reported in the text were used to define initial model input for the soil layers at depths of 0 to 0.45 m and the soil texture and SOM for the depths of 0.45 to 0.9 m were assumed to be similar to the data at 0.35 to 0.45 m in the absence of measurement. The crop data based on field records and measurements or estimated by field observations were used to define crop information for the LEACHN model. Meteorological input values, including daily precipitation, maximum/minimum temperature, and snow depth on the ground, were obtained from the onsite weather station operated by Environment and Climate Change Canada (46°52′37.02″ N, 63°10′11.05″ W). The LEACHN simulated soil moisture values were compared with the observed soil moisture data for model calibration and verification purposes. The initial texture input data were adjusted within observed ranges at the Harrington Farm to improve model fit for model calibration from 1 June 2014 to 31 Mar. 2016. The model was then rerun from 1 Apr. 2016 to 31 May 2017 for model verification. The calibrated and verified model was used to predict daily soil drain-
et al. (2012). The average annual precipitation for 2014 to 2017 (1216 mm) being higher than that of 2000 to 2008 (1075 mm) can partly explain the higher drainage values.

Sorensen et al. (2014) noted that the value of soil moisture data as the sole diagnostic for groundwater recharge modeling studies is questionable because they found that four different unsaturated flow models honored the same moisture data well, but produced largely different recharge values as two different sets of evapotranspiration, runoff, and drainage can create similar soil moisture content. They implied that using soil moisture data alone to constrain soil drainage modeling can produce non-unique drainage estimation. In this current study, soil drainage estimation was constrained simultaneously using soil moisture, groundwater level, and base flow data instead of soil moisture alone via coupled LEACHN and MODFLOW modeling, which was expected to minimize the probability of non-uniqueness in drainage estimation. Many of the coupled LEACHN and MODFLOW modeling details were omitted. The readers are referred to Jiang and Somers (2009) and Jiang et al. (2011) for details about boundary conditions, spatial discretion, steady state simulations, model parameters, sensitivity analysis, and water budget analysis of groundwater flow modeling, and to Jiang et al. (2011, 2012) for more details about LEACHN modeling. The key difference between the soil drainage simulations in this current study and in Jiang et al. (2011, 2012) is that the simulated drainage values in this current study were constrained simultaneously by soil moisture, groundwater level, and base flow data but the values in Jiang et al. (2011,
Agrosystems, Geosciences & Environment 13 of 14

2012) were constrained by water level data alone. As the coupled LEACHN and MODFLOW modeling respected the soil moisture, groundwater level, and separated stream base flow data well in terms of timing and magnitude, the LEACHN-simulated soil drainage values were accepted to calculate daily nitrate leaching.

REFERENCES FOR APPENDIX


Fig. A3. Comparison of separated and simulated base flows at Suffolk.

Fig. A4. Simulated soil drainage at the bottom of the 0.9-m soil column, observed water levels at Sleepy Hollow and observed precipitation at the Environment and Climate Change Canada Charlottetown Airport weather station; the simulated timing of soil drainage occurrence and the observed timing of water level rising were well correlated.

REFERENCES
