Chapter 10
Nitrogen Fertilization Strategies in Relation to Potato Tuber Yield, Quality, and Crop N Recovery

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Abstract In this chapter, we discuss the challenges to optimizing nitrogen (N) management in rain-fed potato production in eastern Canada, and evaluate a series of N fertilization strategies for their effects on tuber yield, size distribution and quality and on apparent recovery of fertilizer N by the potato crop. Selection of the optimal fertilizer N rate remains one of the most important decisions for growers. Optimal fertilizer N management is necessary to achieve economic goals associated with tuber yield and size, whereas over-fertilization greatly increases the risk of environmental losses of N and of reduced tuber quality. However, large variations in crop N demand and soil N supply among fields and among years, and also within fields, make selection of an optimal fertilizer N rate problematic. Improved predictions of crop demand and soil supply both in time and in space will be required to address this. Fertilizer N management can also be improved through appropriate timing of fertilizer application, fertilizer placement, and fertilizer formulation. Efficiency of N management can be improved through development of N management systems on a whole-field basis, or on a within-field basis using Site Specific Nutrient Management (SSNM), where soil-based tests are used to determine at-planting N management and plant-based or soil-based tests are used for in-season N management. In addition, use of controlled release fertilizer products can be beneficial in soils where the risks of leaching losses are high. In order to manage N efficiently and sustainably, it is important to consider N management as one component of an integrated cropping system.

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10.1 Introduction

Potatoes are an economically important crop in eastern Canada (defined here as Quebec and Atlantic Canada). In 2009, approximately 145,000 ha of potatoes were harvested in Canada, of which about 50% was in eastern Canada (Statistics Canada 2010). A large proportion of this potato production is grown for processing (primarily French fry) and a smaller proportion for seed as well as for the table market.

Good nitrogen (N) management is a critical component of successful potato production (Zebarth and Rosen 2007). A sufficient N supply is important in achieving economically viable potato yields, and in meeting tuber size and quality targets in processing potato contracts. However, N is also easily lost from potato fields to water through nitrate leaching, and to the atmosphere as nitrous oxide, a greenhouse gas. Good N management is therefore required to meet both economic and environmental objectives in potato production.

In this chapter, we discuss the challenges to optimizing N management in rain-fed potato production in eastern Canada, and evaluate a series of N fertilization strategies for their effects on tuber yield, size distribution and quality and on apparent recovery of fertilizer N by the potato crop. Subsequent chapters address the use of soil- and plant-based test systems to improve fertilizer N recommendations (Chapter 11); N management in organic potato production systems (Chapter 12); and N losses to water (Chapter 13) and to the atmosphere (Chapter 14) in potato production systems in eastern Canada.

10.2 Challenges to Optimizing Fertilizer N Management

10.2.1 Climate, Soils and Cropping Systems

Potato production in eastern Canada occurs primarily in the provinces of Prince Edward Island (PEI), New Brunswick, and Quebec. The region has a cool temperate climate with a mean annual temperature ranging from 4 to 7°C, and humid soil moisture regimes with a mean annual precipitation ranging from 1050 to 1300 mm (Environment Canada 2011). The growing season is relatively short (approximately 120 days). Potential total tuber yield in New Brunswick is about 50 $t\,ha^{-1}$ (Bélanger et al. 2000).

Soils on which potatoes are grown range from sandy to clayey soil texture, with loam and sandy loam soils most common. Potato fields range from flat to steeply sloping where the latter are commonly terraced to reduce soil erosion. Substantial within-field variation in soil texture, soil organic matter, soil drainage or topography occurs in many fields.

Cropping systems vary with potato (*Solanum tuberosum* L.)-barley (*Hordeum vulgare* L.)-red clover (*Trifolium pratense* L.) the most common crop rotation in PEI, potato-barley the most common rotation in New Brunswick, and potatoes commonly grown in rotation with corn (*Zea mays* L.) or cereal crops in Quebec. There has been greater diversity in crop rotations in recent years with increasing use of Italian ryegrass (*Lolium multiflorum* Lam.) and corn in potato rotations to address pest and disease issues, however this has not influenced the frequency of potatoes grown in the rotations.

Potato production in this region is primarily rain-fed. Use of irrigation is limited by lack of suitable water supplies, sloping fields, and heterogeneous soils. In addition, although tuber yield is frequently increased by irrigation, there is not an economic benefit from irrigation in all growing seasons (Bélanger et al. 2000a). There is, however, a trend towards increased irrigation due to significant crop losses when drought occurs in some years.

10.2.2 Challenges in Fertilizer N Management

Currently, general fertilizer N recommendations for potatoes in this region range from 125 to 200 kg N ha^{-1} (NBDAFA 2001; CRAAQ 2010). Fertilizer N is commonly banded all at planting in PEI and New Brunswick, where split application may limit tuber yield in some years (Porter and Sisson 1993; Zebarth et al. 2004a). In contrast, due to generally sandier soils used for potato production, fertilizer N is commonly applied as a split application in Quebec, with granular fertilizer N commonly applied at planting and 30 days after planting at first or final hilling. In comparison, rapid plant N uptake occurs during tuber initiation and set (from about 50 to 70 days after planting) and is reduced during tuber bulking (from about 70–90 days after planting) (Zebarth and Rosen 2007).

Optimizing N fertilization requires matching the supply of N to the crop N demand in space and time. Practical problems arise in making fertilizer N recommendations due to uncertainty in crop N demand and in soil N supply among and within fields and among years (Zebarth et al. 2009a).

Crop growth is regulated by the relative internal supplies of carbon and N (Lemaire and Millard 1999). Crop N demand and uptake under non-limiting N supply are primarily determined by crop growth (Gastal and Lemaire 2002) and there is commonly a close relationship between plant N uptake and plant dry matter accumulation (Vos 1997). Thus, crop N demand varies with factors that influence crop growth.

Crop growth and the resulting tuber yield vary with environmental conditions. This can be reflected in differences in the relationships between plant N accumulation and tuber yield (Fig. 10.1). Potato cultivars also vary in the relationship between growth and crop N uptake (Zebarth et al. 2004c), however, cultivar differences in tuber yield response to fertilizer N rate between Shepody and Russet Burbank, the two main potato cultivars used in the region, are often limited (Bélanger et al. 2000a). Tuber yield is sensitive to seasonal variation in temperature in this region which has a relatively short growing season. Cool, wet spring conditions can delay planting in some years, and thereby reduce yield (Fig. 10.1). Yield can also be

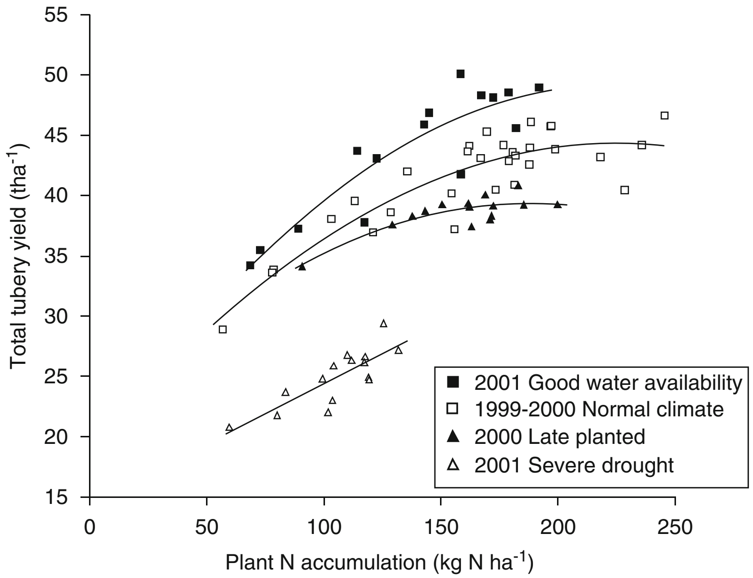

Fig. 10.1 The relationship between total tuber yield and N accumulation in the plant (tubers plus vines) prior to vine desiccation varies among years and environmental conditions (Adapted from Zebarth et al. 2004b, 2005b)

reduced in some years when drought occurs (Bélanger et al. 2000a), typically during tuber bulking, or because of disease or insect stress. As a result, the quantity of N which is required to obtain maximum tuber yield, and the amount of yield for a given quantity of N taken up, varies among sites and years (Fig. 10.1).

A study conducted at 12 site-years in New Brunswick illustrates the range in crop demand among fields and years. Maximum total tuber yield ranged from 24 to 51 $t\,ha^{-1}$ in rain-fed production (Bélanger et al. 2000a). Where supplemental irrigation was applied to overcome drought stress, maximum total tuber yield at these sites still ranged from 32 to 50 $t\,ha^{-1}$ (Bélanger et al. 2000a). This variation in yield among sites results in variable crop N demand among fields and years.

Soil N supply is also variable among and within fields and among years. High precipitation over the fall and winter period results in loss of most residual soil nitrate from the root zone, primarily as nitrate leaching (Zebarth et al. 2003a, 2009a). Soil N supply for a given growing season is therefore controlled primarily by soil N mineralization. Although soil mineral N measured in spring is often well correlated with growing season soil N supply (Sharifi et al. 2007), soil mineral N used alone is not an effective predictor of optimum fertilizer N rate for potatoes in this region (Bélanger et al. 2001a).

Soil N supply is controlled by the quantity and quality of soil mineralizable N in combination with environmental conditions during the growing season. Soil mineralizable N is influenced by history of organic amendment use (Sharifi et al. 2008a), crop rotation (particularly inclusion of legume and non-legume forage crops)

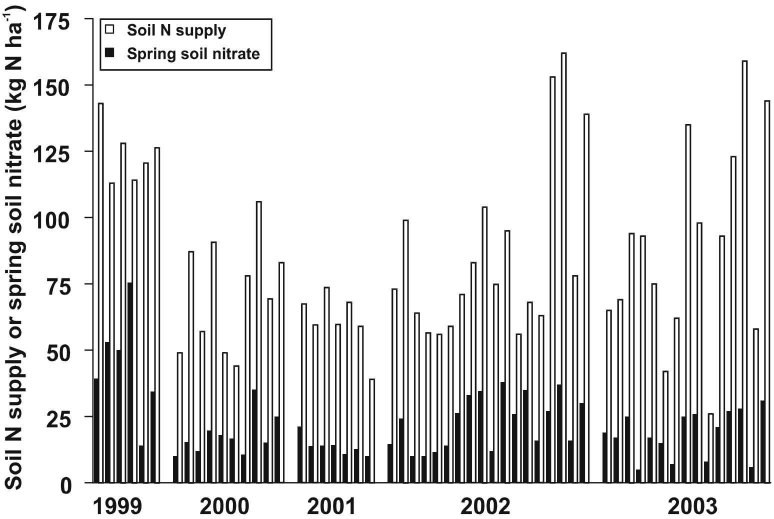

Fig. 10.2 Soil N supply (plant N accumulation in tubers plus vines at vine desiccation with no fertilizer N applied) varies among fields and years, and is commonly much higher than spring soil nitrate to 30 cm depth, indicating that most soil N supply is derived from soil N mineralization (Adapted from Zebarth et al. 2005a)

(Sharifi et al. 2009a), tillage (Sharifi et al. 2008b), soil properties and climatic zone (Dessureault-Rompré et al. 2010). In some cases, soil mineralizable N is influenced by management of the rotation crop (Sanderson et al. 1999; Zebarth et al. 2009b). Estimates of soil N supply in Atlantic Canada, based on plant N uptake in zero N fertilizer plots (Zebarth et al. 2005a), varied widely ranging from 26 to 162 kg N ha^{-1} (average 85 kg N ha^{-1}) (Fig. 10.2). In comparison, spring soil nitrate concentration to 30 cm depth ranged from 2 to 124 kg N ha^{-1} (average 22 kg N ha^{-1}) indicating that most of the soil N supply could be attributed to soil N mineralization in most years. The among field variation in soil N supply is also reflected in tuber yield response. For example, total tuber yield with no N applied under rain-fed production at 12 site-years in New Brunswick ranged from 19 to 47 t ha^{-1}, representing 61–93% of maximum yield (Bélanger et al. 2000a). It is important to note, however, that the environmental conditions which provide a higher crop growth typically also enhance soil N supply.

These uncertainties in crop N demand and soil N supply make fertilizer N management challenging. Under rain-fed production, foliar application of urea is the only practical option for fertilizer N application after hilling. Foliar applied urea is a relatively efficient way of applying N to the crop (Millard and Robinson 1990), but the quantity of N which can be applied is limited due to the potential for leaf damage. Consequently, most decisions with respect to fertilizer N management must be made early in the crop growing season when the options for use of plant-based measures of N status are limited (Zebarth et al. 2009a).

Soil tests based on residual nitrate, which are commonly used in many production areas (Greenwood 1986; Hergert 1987); are generally not effective in making fertilizer N recommendations in this region (Bélanger et al. 2001a) due to the loss of soil nitrate over the fall and winter period (Zebarth et al. 2009a). Soil tests based on mineralizable N show some promise (Sharifi et al. 2007; Sharifi et al. 2009b), but to date none have been adopted by commercial growers.

Here we discuss some of the options for improving fertilizer N management within the rain-fed potato production in eastern Canada. These include the potato crop response to rate, placement, formulation and timing of N fertilization, as well as options for site-specific N management. Options for use of soil- and plant-based tests to improve fertilizer N recommendations are explored in detail in Chapter 11.

10.3 Strategies to Improve Fertilizer N Management

10.3.1 Rate of N Fertilization

The rate of N fertilization is perhaps one of the most important decisions with respect to fertilizer N management, and will therefore be a focus of this chapter. General fertilizer N recommendations based on average response curves have been the main source of information for potato growers. In this section, the high variability in the response to N fertilization will be discussed along with its cause and consequences. It highlights the need for developing site-specific recommendations.

10.3.1.1 Tuber Yield and Size Response to N Rate

Potato tuber yield depends on the amount of intercepted radiation, the efficiency with which this intercepted radiation is used in the production of crop biomass (radiation use efficiency), and the harvest index (i.e. the proportion of the biomass partitioned to tubers). The amount of intercepted radiation depends on the leaf area index which is a function of the leaf area development and duration. Potato growth prior to emergence is controlled primarily by soil temperature (Yuan and Bland 2005) and the physiological maturity of the seed piece (Allen and Scott 1992); it is therefore not affected by N. Increased fertilizer N application increases leaf area index through increased size and number of leaves (Vos 1995). Increased fertilizer N application can also increase leaf longevity (Vos and Biemond 1992), thereby increasing leaf area duration. An adequate supply of N is required to achieve a canopy capable of intercepting most radiation, whereas excessive N can delay crop maturity, result in excessive vine growth, and increase the risk of foliar diseases (Allen and Scott 1992).

Nitrogen fertilization is known to affect the radiation use efficiency of several crop species but studies in potatoes have shown no effect of N deficiencies on radiation use efficiency (Vos and van der Putten 1998). The harvest index commonly decreases with increasing rates of N fertilization. For example, the harvest index averaged over six site-years in New Brunswick decreased from 80% with no N applied to 76% with 100 kg N ha^{-1} applied (Bélanger et al. 2001b).

Tuber yield is responsive to fertilizer N addition in almost all cases (Zebarth et al. 2009a). Fertilizer N application increases yield primarily though an increase in tuber mass (De la Morena et al. 1994). Tuber number per plant has been shown to increase, decrease or to be unaffected by N fertilization (Bélanger et al. 2002; De la Morena et al. 1994). Average fresh tuber weight increased with increasing N application rates with both Shepody and Russet Burbank in a 12 site-year study conducted in New Brunswick (Bélanger et al. 2002). Bulking rates, however, are not always affected by fertilizer N application. Fertilizer N application significantly increased bulking rates at two of six site-years in New Brunswick (Bélanger et al. 2001b) but in one case, a high N rate caused a decrease in tuber bulking rates. Although this has not often been quantified, over-fertilization can result in decreased tuber yield. In comparison, stem density is controlled primarily by cultivar and physiological age of the seed (Allen and Scott 1992).

The rate of fertilizer application required to achieve optimum yield varies with site, growing conditions, crop management, and incidence of disease and insects (Zebarth and Rosen 2007). Even for the same potato cultivar grown in the same year, yield response to N fertilization can vary widely among fields (Fig. 10.3a). This complex response reflects the fact that variation in soil N supply can often be as important as crop N demand in determining the optimal fertilizer N rate (Scharf et al. 2005; Lobell 2007). For example in Fig. 10.3a, sites S1 and S2 had different maximum marketable tuber yields but similar optimal fertilizer N rates whereas sites S1 and S3 had similar maximum marketable tuber yields but had much larger differences in optimal fertilizer N rates.

10.3.1.2 Tuber Quality Response to N Rate

Fertilizer N rate also has important effects on tuber quality. Tuber specific gravity, an important quality parameter for potato processing, is often unaffected by fertilizer N rate, or decreases with increasing fertilizer N rate, particularly when fertilizer N rate exceeds crop N requirement (Laboski and Kelling 2007). In eastern Canada, tuber specific gravity commonly decreases with increasing N rate across all rates applied (Bélanger et al. 2002; Zebarth et al. 2004a), although increasing from zero to a low fertilizer N rate may result in a small increase in tuber specific gravity in some cases (Zebarth et al. 2004a). This decrease in specific gravity with increasing N rates was shown to be greater for Shepody than for Russet Burbank (Bélanger et al. 2002).

Fertilizer N rate has inconsistent effects on chip or fry color. Chip color has been reported to be unaffected by fertilizer N rate (Silva et al. 1991; Long et al. 2004; McPharlin and Lancaster 2010), to improve when increasing N rate from zero to the optimal fertilizer N rate (Zebarth et al. 2004a) and to result in darker fry color with excessive N fertilization (Feibert et al. 1998). Increasing N rate from zero to the optimal fertilizer N rate was also reported to reduce after-cooking darkening (Wang-Pruski et al. 2007).

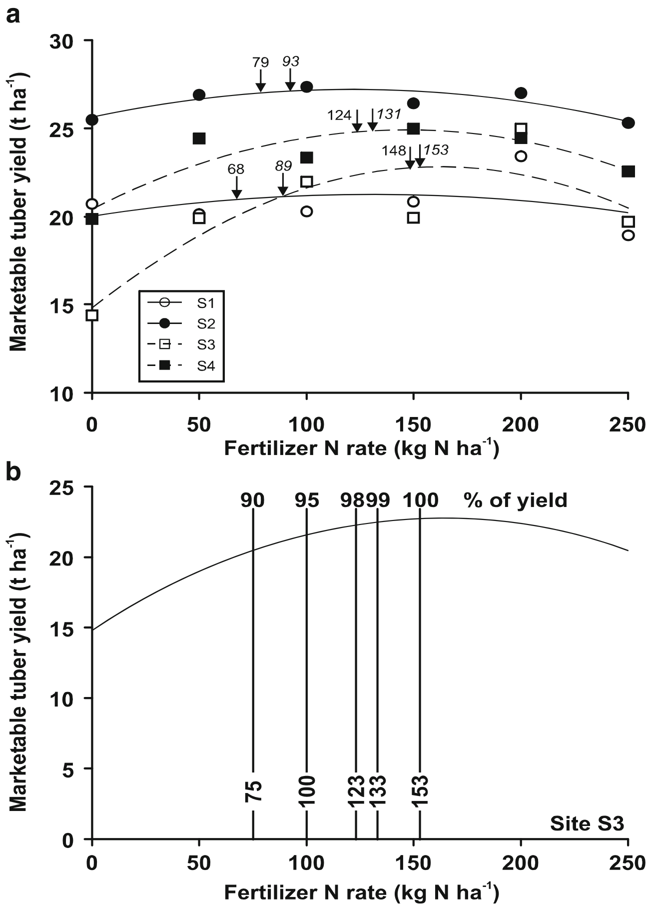

Fig. 10.3 (**a**) Tuber yield response varies among four sites planted to Shepody potatoes in 1995. For each site, the optimal fertilizer N rate at a cost:price ratio of 0.006 (italics) or 0.009 (normal) is indicated by arrows. (**b**) Using site S3 as an example, much of the fertilizer N applied results in a relatively small increase in tuber yield (Adapted from Bélanger et al. 2000a)

Increasing fertilizer N rate can also increase the incidence of internal tuber disorders such as hollow heart and internal brown spot, but these responses are inconsistent across sites (McPharlin and Lancaster 2010). Both insufficient and excess N fertility have been reported to increase the risk of sugar end disorder (Thompson et al. 2008).

Fertilizer N rate can also influence the human nutritional properties of tubers. Tuber nitrate concentration generally increases with increasing fertilizer N rate, with the highest tuber nitrate concentrations occurring when relative yield is at or close to 1.0 (Bélanger et al. 2002). In some cases, drought may be more important than N rate in contributing to high tuber nitrate concentrations (Zebarth et al. 2004a).

Most importantly, increasing fertilizer N rate has been reported to increase tuber concentrations of asparagine and reducing sugars, which are precursors to the production of acrylamide during frying (Gerendás et al. 2007; Lea et al. 2007).

10.3.1.3 Environmental Considerations of N Fertilization

Not all of the plant available N is utilized by the potato crop. Both the rate of fertilizer N application, and the relative efficiency of the potato crop in taking up the applied fertilizer, influence the potential for loss of N to the environment. Apparent recovery of fertilizer N in the potato plant is commonly 50–60% or less at commercial rates of fertilization (Vos 2009). Estimates of recovery of ^{15}N-labelled fertilizer and of apparent recovery in the whole plant range from 29–77% (as reviewed by Zebarth et al. 2009a). Apparent fertilizer N recovery typically decreases with increasing N rate, especially for above-optimal N rates (Vos 2009). Apparent recovery can also be reduced by factors that limit crop growth or N uptake such as delayed planting, drought, or incidence of diseases. Estimates of apparent N recovery in the whole potato plant in eastern Canada range from 29–70% on loamy soils in Quebec (Li et al. 2003) and 30 to 77% on loamy soils in New Brunswick (Zebarth and Milburn 2003; Zebarth et al. 2004b) and apparent N recovery in potato tubers from 21–62% on sandy soils in Quebec (Cambouris et al. 2008).

It is common for 70–85% of the N in the plant to be present in the tubers (Li et al. 2003; Zebarth et al. 2004b), with lower values occurring at high fertilizer N rates or in immature crops (Zebarth et al. 2009a). Nitrogen is mineralized rapidly from vegetable crop residues (Akkal-Corfini et al. 2010). Therefore, it is common for half or more of the applied N to remain in the field after tuber harvest, and for most of this N to be at risk of loss to the environment (Vos 2009).

Most nitrate is leached from the root zone over the autumn and winter period, therefore residual soil nitrate after potato production is commonly used as a measure of the risk of nitrate leaching loss (Zebarth et al. 2003a). On loamy soils in New Brunswick, Bélanger et al. (2003) found average residual soil nitrate to 90 cm depth for 12 site-years to range from 33 kg N ha^{-1} for non-fertilized plots to 160 kg N ha^{-1} in plots receiving 250 kg N ha^{-1}. Residual soil nitrate ranged from 46 to 99 kg N ha^{-1} at the optimal fertilizer N rate, and increased rapidly with increasing N application above the optimal rate (Fig. 10.4). In comparison, Zebarth et al. (2003a) measured residual soil nitrate to 30 cm depth of 3–250 kg N ha^{-1} in a survey of commercial potato fields. Residual soil nitrate generally increased with increasing fertilizer N rate and varied with potato cultivar with average values of 117, 56 and 43 kg N ha^{-1} to 30 cm depth for Russet Norkotah, Russet Burbank and Shepody, respectively. In a sandy soil in Quebec, Cambouris et al. (2008) reported residual soil nitrate to 70 cm depth to range from 53–114 kg N ha^{-1} for non-fertilized plots to a maximum value of 212 kg N ha^{-1} for a fertilizer N rate of 240 kg N ha^{-1}.

For N not recovered in tubers, there are two pathways of N loss to the environment which are of greatest concern: nitrate leaching to groundwater and emissions of nitrous oxide (N_2O), a greenhouse gas (Zebarth et al. 2009a). Nitrate leaching is

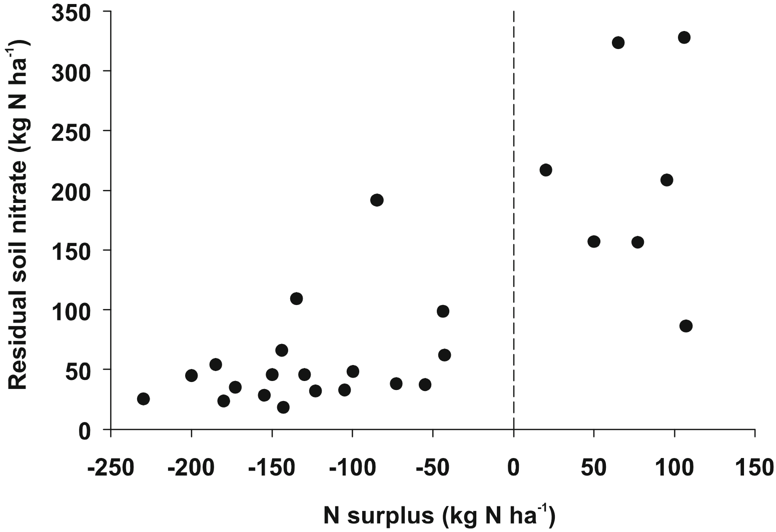

Fig. 10.4 Relationship between residual soil nitrate content to 30 cm depth and N surplus for seven site-years in New Brunswick. The N surplus is the fertilizer N rate minus the optimal fertilizer N rate (Adapted from Bélanger et al. 2003)

commonly the greatest pathway of loss in eastern Canada, with estimates of nitrate leaching losses from potato production ranging from 5–33 kg N ha^{-1} in loamy soils in New Brunswick (Milburn et al. 1990) and from 78–171 kg N ha^{-1} in sandy soils in Quebec (Gasser et al. 2002). Nitrate concentrations in leachate from potato fields commonly exceed the 10 mg NO_3-N L^{-1} drinking water guideline for nitrate (Milburn et al. 1990; Gasser et al. 2002; Vos and van der Putten 2004). In comparison, there are few estimates of denitrification or nitrous oxide emissions from potato production systems in eastern Canada. Burton et al. (2008) measured cumulative growing season emissions of N_2O ranging from 0.2–2.2 kg N ha^{-1} for potatoes grown in a loamy soil in New Brunswick, indicating that while this loss pathway can be of significant environmental importance, it has minimal impact from an agronomic standpoint.

10.3.1.4 Economic Considerations of N Fertilization

Fertilizer represents a significant cost to potato growers. For example, fertilizer was estimated to represent approximately 40% of direct input costs for potato production in PEI in 2007 (BDO Canada 2009). Thus, selection of the correct fertilizer N rate is of significant economic importance to growers. The economic risk associated with insufficient N fertilization, due to loss of tuber yield or size, is of far greater concern than the economic risk associated with excessive N fertilization, primarily due to low specific gravity. It is therefore common for growers to apply a sufficiently high fertilizer N to ensure that the crop N demand is met under most growing conditions.

The optimal fertilizer N rate for potatoes varies widely among experimental trials. For example, Neeteson and Wadman (1987) reported the optimal fertilizer N rate from 86 trials in The Netherlands to range from <50 kg N ha^{-1} to >350 kg N ha^{-1}. This optimal fertilizer N rate reflects the crop biological response, but is also influenced by economic considerations. The calculated optimal fertilizer N rate can also vary with the mathematical model used (Neeteson and Wadman 1987). Bélanger et al. (2000b) demonstrated that a quadratic model was suitable for potato experiments in New Brunswick.

This high variation in optimal N rate occurs even for the same potato cultivar grown in the same year. For example, the optimal fertilizer N rate for four field trials in New Brunswick where Shepody was grown ranged from 89–153 kg N ha^{-1} for a cost:price ratio of 0.006 and from 68–148 kg N ha^{-1} for a cost:price ratio of 0.009 (Fig. 10.3A).

The tuber yield response curves to fertilizer N rate in eastern Canada are commonly quite flat, and consequently there is a high degree of uncertainty associated with prediction of the optimal fertilizer N rate (Neeteson and Wadman 1987). In addition, the relatively flat yield response curve results in a limited increase in yield for a significant proportion of the fertilizer N applied. For example, Neeteson (1989) found that for trials in The Netherlands, a 25% reduction in recommended fertilizer rate resulted in a non-significant reduction in tuber yield. In Quebec, depending on the growing season, a yield reduction of 1.5% allowed a reduction in N rate ranging from 15–24% and from 15–22% for the total and the marketable tuber yield, respectively (Cambouris et al. 2007). Using the most responsive trial from Fig. 10.3A, fertilizer N rates of 75, 100, 123, 133 and 153 kg N ha^{-1} were predicted to result in 90%, 95%, 98%, 99% and 100% of the yield at the optimum fertilizer N rate (Fig. 10.3B).

For potatoes, the fertilizer N rate required to optimize net economic return is similar to, or in some cases even above, that required to achieve maximum biological tuber yield (Bélanger et al. 2000a; Bélanger et al. 2000b). For example, using sites S1–S4 from Fig. 10.3A under rain-fed production, the calculated economic optimum fertilizer N rate averaged 148 kg N ha^{-1} whereas the N rate predicted to achieve maximum biological tuber yield averaged 155 kg N ha^{-1}. This occurs because of the relatively low cost of N fertilizer compared with the value of potato tubers, and because tuber size increases in response to increasing fertilizer N over a wide range of fertilizer N rates (Zebarth and Rosen 2007). The optimal fertilizer N rate will also vary with changes in fertilizer N cost and tuber value, however this variation is commonly less than the among-field variation in optimal fertilizer N rate (Fig. 10.3A).

The choice of the optimal fertilizer N rate also has environmental implications. For most crops, residual soil nitrate or leaching potential begins to increase rapidly as the fertilizer N rate approaches that required to achieve maximum biological yield (Steenvoorden et al. 1986). Application of N above the optimal fertilizer N rate to potatoes can result in substantial increases in residual soil nitrate (Bélanger et al. 2003; Fig. 10.4) and consequently increase the potential for N losses to air and water.

10.3.2 Placement of Fertilizer N

Relatively few studies have examined the effects of fertilizer N placement in potato production. In Idaho under furrow irrigation, banded application of fertilizer N increased crop growth, tuber yield and plant N uptake compared with broadcast fertilizer N application (Westermann and Sojka 1996). Under rain-fed potato production in Germany, Maidl et al. (2002) found greater recovery of ^{15}N-labelled ammonium nitrate placed in the hill than applied as a broadcast. The benefit of fertilizer placement in this study was attributed primarily to a wet period between planting and emergence. When fertilizer was applied as a split application, there was little benefit of fertilizer N placement. On a fine-textured soil in Manitoba, banded application at planting increased petiole nitrate concentration, but not crop N uptake, compared with a pre-plant broadcast application (Zebarth et al. unpublished). Fertilizer placement may also change the shape of the yield response curve, because a small amount of fertilizer can be utilized more efficiently when placed than when broadcast (Harris 1992). Improperly placed fertilizer can damage germinating plants thereby reducing growth and tuber yield.

Most mineral fertilizer applied to potatoes in eastern Canada is banded at planting or surface broadcast just prior to hilling (commonly from emergence to about 50 days after planting) and incorporated by the hilling process. Pre-plant broadcast application of mineral fertilizer is avoided. Banding of fertilizer can increase efficiency of crop N uptake in several ways. First, banding places fertilizer N closer to the crop root system, which can enhance crop uptake, particularly early in the growing season. There is greater water infiltration in the furrow compared with the hill (Saffigna et al. 1976) and consequently banding fertilizer in the hill would also be expected to reduce the risk of nitrate leaching. Banding of fertilizer in the potato hill also delays nitrification due to very high concentrations of salts in the vicinity of the fertilizer band (Zebarth and Milburn 2003), maintaining more mineral N in ammonium form which is less susceptible to loss by leaching.

10.3.3 Timing of N Fertilization

Split fertilizer N application is a commonly used approach to improve crop fertilizer N utilization by improving the synchrony between N supply in soil and crop N demand (Zebarth and Rosen 2007). Several studies have reported split N application to increase recovery of fertilizer N in the potato crop compared with all fertilizer N applied at planting (Westermann et al. 1988; Vos 1999; Maidl et al 2002). Split N application is very effective in reducing nitrate leaching losses and increasing tuber yield and N uptake in irrigated production on sandy soils (Errebhi et al. 1998a). However in many studies, split application resulted in no effect or a modest increase in tuber yield and crop N uptake (Joern and Vitosh 1995; Vos 1999). This can be attributed to there being little or no benefit to split N application in situations where the risk of nitrate leaching is small (Harris 1992). In contrast, split N application

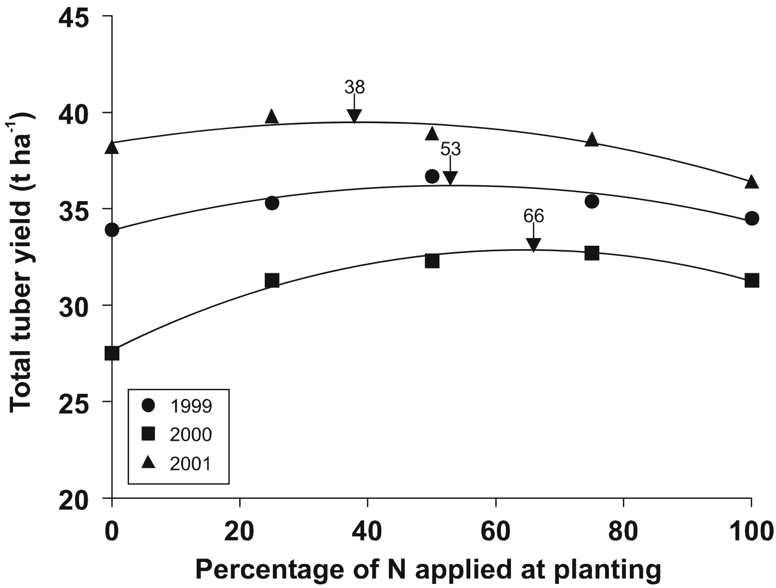

Fig. 10.5 Effect of proportion of N applied at planting on total tuber yield in 3 years on sandy soils in Quebec. The optimal timing ranged from 38% to 66% at planting with the remainder at final hilling (Adapted from Cambouris et al. 2007)

was reported to decrease crop N uptake and reduce tuber yield compared with all N applied at planting when dry soil conditions occur during the growing season (Porter and Sisson 1993; Zebarth et al. 2004a, b).

Some studies have identified a crop physiological response to N timing. High fertilizer N application early in the growing season can delay tuber initiation and bulking in indeterminate potato cultivars (Kleinkopf et al. 1981). However, other studies concluded that the timing of fertilizer N application does not have an effect on the time between tuber initiation and establishment of a high tuber bulking rate (Harris 1992). In some cases, late fertilizer N application may also reduce tuber specific gravity (Laboski and Kelling 2007) or increase second growth on tubers (Roberts et al. 1982). Split N application provides an additional practical advantage to growers with respect to flexibility; by applying a lower fertilizer rate at planting, a wider range of options are available with respect to in-season N management.

In eastern Canada under rain-fed production, timing of fertilizer N application on a medium-textured soil had little effect on crop N uptake or on tuber yield or quality parameters under normal rainfall conditions whereas split N application decreased tuber yield and crop N uptake under dry soil conditions (Zebarth and Milburn 2003; Zebarth et al. 2004a,b). In contrast, split N application under rain-fed production on sandy soils in Quebec increased tuber yield and N recovery in tubers compared with all fertilizer N applied at planting (Cambouris et al. 2007, 2008). For example, the proportion of N applied at planting to reach the maximum yield varied from 38% to 66% depending on the climatic conditions of the growing season (Fig. 10.5).

These results are in contrast to previous work in Quebec which found little benefit to split N application on seven soils ranging from sandy to sandy loam (Giroux 1982) and on a silty loam soil (Li et al. 1999).

10.3.4 Fertilizer N Formulations

A variety of mineral fertilizer products have been evaluated for their use in potato production. In general, availability and cost are the most important factors to consider in choosing a fertilizer formulation (Giroux 1982; MacLean 1983). In some cases, fertilizer products which produce an initial alkaline reaction in soil (e.g. urea) may result in yield loss, but this is less likely to occur on acidic soils (Meisinger et al. 1978; Giroux 1982).

Controlled release fertilizer products are fertilizer formulations that offer an alternative means to synchronize N supply with crop N demand without the need for multiple fertilizer applications. Currently, most controlled release fertilizer products are comprised of urea granules with sulphur or polymer coatings. These products are most effective on sandy, irrigated soils where the risk of nitrate leaching is high (Zebarth and Rosen 2007). Generally positive results are obtained with use of controlled release fertilizer products on potatoes in sandy soils (Zvomuya and Rosen 2001; Hutchinson et al. 2003), however negative responses can be obtained if the rate of fertilizer release is too slow to meet crop demand (Waddell et al. 1999). On sandy soils, the benefit may occur as increased tuber yield (Zvomuya and Rosen 2001; Ziadi et al. 2011), or as similar tuber yield with reduced N losses through nitrate leaching (Zvomuya et al. 2003; Wilson et al. 2009). These products also reduce or eliminate the additional cost associated with multiple fertilizer applications on sandy soils (Wilson et al. 2009). The primary limitation to use of controlled release fertilizer products has been increased cost relative to conventional mineral fertilizer N products (Simonne and Hutchinson 2005). Recently, new polymer-coated urea products have become available with better N release properties and at lower cost. This has resulted in increased use of these products in potato production.

In a recent study on sandy soils in Quebec, Ziadi et al. (2011) compared a controlled release fertilizer product (Environmentally Smart Nitrogen or ESN produced by Agrium Advanced Technologies, Calgary, AB; 44-0-0) with calcium ammonium nitrate in 3 years. The ESN increased marketable tuber yield by 12% compared with calcium ammonium nitrate (Table 10.1). The ESN also resulted in increased nitrate availability in soil during the growing season as measured using anion exchange membranes.

10.3.5 Site-Specific N Management

Crop N response can vary widely within fields (Shillito et al. 2009). Despite the recognition of significant spatial and temporal variation in soil N availability for crops within fields, the most common practice is still uniform applications of N.

Table 10.1 Effect of a controlled release N fertilizer (ESN) on marketable yield and yields of three potato size classes in a 3 year study in Québec

Treatment	Marketable tuber yield	Tuber size class[a]		
		Jumbo	Medium	Small
	Mg ha^{-1}			
Unfertilized control	17.2	3.0	7.5	6.8
150 kg N ha^{-1} as Calcium ammonium nitrate (CAN)	26.0	7.4	10.9	7.3
150 kg N ha^{-1} as Environmentally Smart Nitrogen (ESN)	29.3	8.6	14.6	6.8
Contrasts (probability level)				
Control vs. others	<0.01	<0.001	<0.001	0.54
CAN vs. ESN	0.03	0.29	<0.01	0.34

Adapted from Ziadi et al. (2011)
[a]Jumbo > 227 g; medium < 277 g and > 5.1 cm long; small between 2.54 and 5.1 cm long

In some cases, this practice can result in under-fertilization and resulting yield loss in some parts of the field, and over-fertilization with implications for environmental N losses in others (Fiez et al. 1994; Kitchen et al. 1995; Vetsch et al. 1995). The goal of Site-Specific N management (SSNM) is to match N supply to crop N demand in space and time, and SSNM requires an understanding of the controls on within-field variation in crop N demand and soil N supply (Pan et al. 1997). Until recently, characterization of the spatial distribution of crop N demand and soil N supply was time consuming and costly which discouraged adoption by growers. Other limitations to adoption of SSNM include the absence of site-specific recommendations and lack of qualified services (Robert 2002).

Many strategies exist to characterize the spatial variability of soils and crops but the use of proximal or remote sensors is commonly most efficient. Yield monitors, soil apparent electrical conductivity instruments, instruments to map light reflectance from crop canopies, and airborne or satellite imagery can rapidly provide detailed information about soil and crop variability.

There are two main approaches to application of SSNM: (1) Variable Rate Application (VRA) and (2) use of Management Zones (MZ). The MZ approach, in which uniform management is applied to smaller more homogenous units, is generally more successful with soil-based than for the plant-based parameters because of the high heterogeneity over small distances of N variability in soil (Zebarth et al. 2009a). The VRA approach is generally more effective for plant-based parameters and can be applied using commercially available proximal sensors such as the Hydro N Sensor and the Greenseeker which measure crop N status using canopy light reflectance.

Few studies have been done on SSNM of potatoes in eastern Canada. In New Brunswick, Zebarth et al. (2003b) used the Hydro N Sensor to map N status in a potato field during two consecutive years. The Hydro N Sensor was generally effective in mapping spatial variability in crop N status, however application of a VRA approach was limited by uncertainty in what fertilizer application to assign to a given level of crop N status. In addition, an area with low apparent crop N status

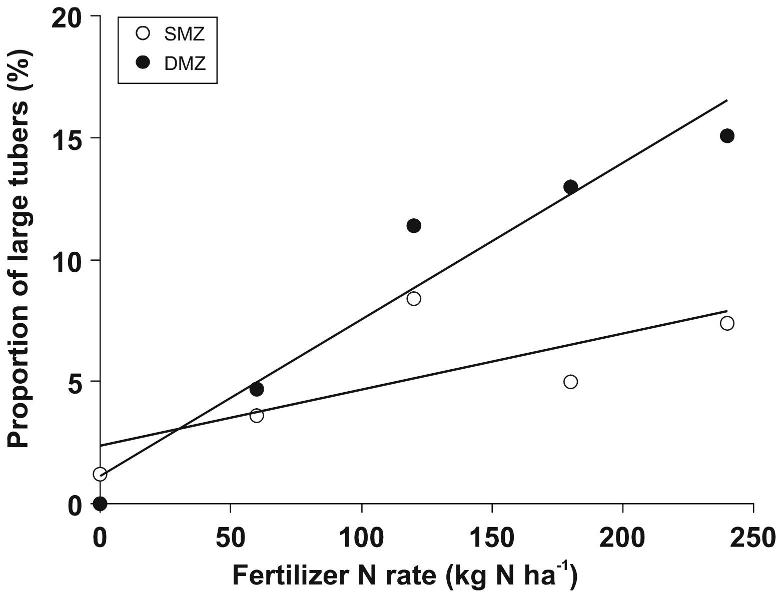

Fig. 10.6 Effect of fertilizer N rate on the proportion of large (88 mm ≤ diameter ≤ 112 mm) tubers from experimental trials in two management zones (SMZ vs DMZ) differing in soil water availability in Quebec (Adapted from Cambouris et al. 2007)

did not necessarily require higher fertilizer N application, rather it could reflect the presence of some other limitation to crop growth such as low stem density or excessive water.

The MZ approach was tested in Quebec using the Geonics EM38 sensor to map the spatial variability of soil in a 13-ha commercial potato field (Cambouris et al. 2006). Two management zones named SMZ and DMZ (to reflect shallow and deep soil depth over a clayey substratum, respectively) were delineated based on soil electromagnetic conductivity. The two MZ differed in tuber yield and quality due to differences in soil water holding capacity (Cambouris et al. 2006). In addition, response of tuber yield, size distribution and specific gravity to rate and time of N fertilization often differed between experiments located in the SMZ and DMZ zones (Cambouris et al. 2007). In some cases, these differences may be sufficiently large to justify different potato management practices (e.g., nutrient management, seedpiece spacing) to optimize potato production for the chip processing market. For example, the production of large tubers was more responsive to fertilizer N addition at the DMZ site compared with the SMZ site (Fig. 10.6).

To date, no study in eastern Canada has attempted to combine the two SSNM approaches. Use of MZ to optimize at-planting N management in combination with VRA during the growing season based on a measure of crop N status may be the best way to apply SSNM in potato production.

10.4 Conclusions

Fertilizer N management is an important but challenging aspect of rain-fed potato production in eastern Canada. Selection of the optimal fertilizer N rate remains one of the most important decisions for growers. Optimal fertilizer N management is necessary to achieve economic goals associated with tuber yield and size, whereas over-fertilization greatly increases the risk of environmental losses of N and of reduced tuber quality. However, large variations in crop N demand and soil N supply among fields and among years, and also within fields, make selection of an optimal fertilizer N rate problematic. Improving this will require improved predictions of crop N demand and soil N supply, both in time and in space.

Fertilizer N management can also be improved through appropriate timing of fertilizer application, fertilizer placement, and fertilizer formulation. Efficiency of N management can be improved through development of N management systems on a whole-field basis, or on a within-field basis using SSNM, where soil-based tests are used to determine at-planting N management and plant-based or soil-based tests are used for in-season N management. In addition, use of controlled release fertilizer products can be beneficial in soils where the risks of leaching losses are high.

In order to manage N efficiently and sustainably, it is important to consider N management as one component of an integrated cropping system. Sustainability of potato cropping systems can be enhanced by use of longer potato rotations, inclusion of legumes in potato rotations, use of organic amendments (Stark and Porter 2005) and reduced tillage (Carter et al. 2009). Such cropping systems can also influence soil health and populations of nematodes and soil-borne pathogens (Carter et al. 2003). Fertilizer N management can also have interactive effects with crop insect and disease management (Miller and Rosen 2005). There may also be the potential to improve efficiency of N utilization in potato production through genetic improvement of the potato crop (Errebhi et al. 1998b; Zebarth et al. 2004c).

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