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INVITED REVIEW

# Strategies to Reduce Nitrate Leaching into Groundwater in Potato Grown in Sandy Soils: Case Study from North Central USA

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**Abstract** There is increasing public concern to reduce nitrate pollution to groundwater, especially in sandy soils. Strategies to reduce nitrate leaching are developed to increase N use efficiency, reduce groundwater pollution, and increase tuber yield. A growing interest in N management should consider management strategies for N supply, soil moisture for transport, and crop N demand that are economical and compatible with local production systems. We present a review of the literature on conventional and innovative strategies for N, irrigation, and crop management for potato production in reducing N leaching in sandy soils. The amount of fertilizer-N should be decided based on an integrated evaluation of soil organic matter content, soil texture, residual soil N, crop residues, credit to organic N sources, crops to be grown including varieties and crop physiological needs, cropping systems, yield potential, water management, and N concentrations in irrigation water. Research advances have no quick fix for controlling $NO_3$ leaching to groundwater. However, the best combination of proven strategies can reduce leaching potential significantly.

**Resumen** Existe una preocupación pública en aumento para reducir la contaminación de nitrato en el agua del subsuelo, especialmente en suelos arenosos. Se han desarrollado estrategias para reducir la lixiviación de nitratos para aumentar el uso eficiente de N, reducir la contaminación del agua del subsuelo, y para aumentar el rendimiento de tubérculo. Un interés en aumento en manejo de N debería de considerar estrategias de manejo para suministro de N, humedad del suelo para el transporte, y demanda de N del cultivo que sean económicas y compatibles con los sistemas locales de producción. Presentamos una revisión de la literatura en las estrategias convencionales e innovativas para el manejo de N, riego y del cultivo para producción de papa en la reducción de la lixiviación de N en suelos arenosos. La cantidad del fertilizante nitrogenado deberá decidirse con base a una evaluación integrada del contenido de materia orgánica en el suelo, textura, N residual, residuos de cosecha, reconocimiento a las fuentes de N orgánico, cultivos a sembrarse incluyendo variedades y necesidades fisiológicas del cultivo, sistemas de cultivo, potencial de rendimiento, manejo del agua, y concentraciones de N en el agua de riego. Los avances en investigación no tienen un remedio rápido para controlar la lixiviación de NO3 al agua del subsuelo. No obstante, la mejor combinación de estrategias probadas pueden reducir significativamente el potencial de lixiviación.

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## Introduction

Agriculture is a major contributor to elevated nitrate ($NO_3$) concentrations in groundwater, and continues to be of great concern to scientists and to the public (Randall et al. 2008; Hatfield et al. 2009; Bronson et al. 2009). These concerns are especially acute in the Wisconsin sand plain, where cultivation of intensively managed and high value irrigated crops such as potato favors rapid $NO_3$ leaching to groundwater (Kraft and Stites 2003). Most of these regions fall in the high soil nutrient leaching potential category. Current vegetable cropping systems use large amounts of N fertilizer and sprinkler irrigation resulting in $NO_3$ contamination to both surface waters (Mason et al. 1990) and groundwater (Saffigna and Keeney 1977).

Groundwater is the major source of drinking water. Concerns about increasing groundwater concentrations of $NO_3$ from agricultural sources are both human-health and environmentally driven, and have led to calls for new or revised agricultural crop management practices. Maximizing N use efficiency on sandy soil is an important component of limiting groundwater contamination and increasing economic yield. Strategies for reducing $NO_3$ leaching should introduce and implement appropriate counter measures. For example, if leaching is primarily due to low soil water and nutrient holding capacities, the strategies should focus on ways to increase soil organic matter (SOM) in order to increase water and nutrient retention and use efficiencies. However, growers should be careful not to add too much organic matter in a short time period, which might enhance leaching as the OM is mineralized. Delgado and Follett (2002) reported that increasing soil carbon sequestration and the amount of SOM can be a means of reducing $NO_3$ leaching, and that because of its environmental benefits, carbon sequestration should be incorporated into established nutrient management plans. Delgado et al. (2009) reported that removing corn crop residue from Iowa cropping systems resulted in higher levels of $NO_3$ leaching, showing that maintaining adequate crop residue levels and increasing soil organic matter can be used as a strategy to decrease $NO_3$ leaching.

This review complements previous reviews on N management (Dinnes et al. 2002; Meisinger and Delgado 2002; Alva 2004; Davenport et al. 2005; Zebarth and Rosen 2007) by focusing on various soil, water and crop management practices that are designed to reduce N leaching in intensive and irrigated potato production systems in sandy soils. Integrated opportunities are discussed in improving and protecting soil and water quality, especially under conditions similar to those present in North Central USA.

## Field Conditions that Drive Nitrate Leaching to Groundwater

Nitrate leaching requires two major inputs: significant amount of $NO_3$ in the soil profile and enough rainfall or irrigation water to move N beyond the root zone. Nitrate is leached to the groundwater mostly during the fall and winter (time of low evapotranspiration period) when precipitation or ground water recharge exceeds the water holding capacity (WHC) and coincides with high residual soil $NO_3$ levels at the end of the growing season (Table 1). In addition, $NO_3$ leaching can also occur from mineralization of SOM and crop residues in the fall (Meisinger et al. 1991) or after snowmelt, especially if there is a period of rapid snowmelt in early spring. The typical number of irrigation events in north central USA can be 15 per potato crop, about 15 mm per irrigation (Stites and Kraft 2001), increasing percolation and the possibility of solute leaching to the ground water while the crop is growing (Kung 1990). High nitrate leaching potential in potato crop is also due to its shallow root system (Olson et al. 1970; Tanner et al. 1982).

An idealized overlay of typical crop growth, management and climate history from the North Central USA

**Table 1** Nitrogen-fertilizer applied, N-uptake and estimated residual or unaccounted soil N in potato

| N-fertilizer applied | N uptake | Estimated residual N | References |
|---|---|---|---|
| | $Kgha^{-1}$ | | |
| 320 | 170–250 | 70–150 | Saffigna et al. (1976) |
| 224 | 179 | 45 | Mechenich and Kraft (1997) |
| 287 | 124 | 163 | Bundy and Andraski (1998) |
| 270 | 89–151 | 119–181 | Errebhi et al. (1998b) |
| 302–347 | 168 | 134–179 | Bland and Fengming (2000) |
| 258–333 | Not available | Not available | Stites and Kraft (2000, 2001) |
| 224 | 111 | Not available | Nyiraneza and Snapp (2007) |

shows that $NO_3$ leaching potential is lower during the active crop growth period (Fig. 1). However, the potential for leaching before or after the active period, during fall, and spring is high. Growers have little options to manage $NO_3$ leaching when crops are not growing in the winter. Therefore, management strategies should focus on reducing soil $NO_3$ levels before the start of leaching in the fall and spring season.

## Strategies to Reduce Nitrate Leaching in Sandy Soils

Strategies to reduce $NO_3$ leaching present a challenge to growers, nutrient managers, soil and environmental scientists who must know and/or develop nutrient, water and crop management plans considering application rate, method and timing of N application, N source, soil moisture and properties, evapotranspiration, and crop and tillage systems for specific sites. Best management practices (BMPs), which reduce N and irrigation inputs without lowering potato yields, can reduce potential risks of groundwater $NO_3$ contamination, improve water quality, and reduce emissions of nitrous oxide, an important greenhouse gas (IPCC 2007). Sometimes the implementation of these BMPs can even bring about increases in potato yields and tuber quality in addition to reducing $NO_3$ leaching, like when cover crops were used with limited irrigation in south central Colorado (Delgado et al. 2007).

### Nitrogen Management

### *Nitrogen Fertilizer Management*

Nitrogen fertilizer management is crucial to minimize loss to the environment and to optimize the yield and quality of potato. Nitrogen application based on crop needs is the primary consideration. However, time, method of placement, and form of N are also important.

*Nitrogen Fertilizer Rate* Application of excessive amount of N is one of the primary causes for N leaching. Nitrate leaching increases rapidly with increasing fertilizer N rate (Zvomuya et al. 2003). Therefore, appropriate N rate is the primary management consideration for sandy soils. There are several factors that a grower should consider in choosing a fertilizer N rate for a specific field including soil type, variety to be grown, previous crop, expected time of harvest, yield goal, crop residue or soil amendments application history, rainfall history, and irrigation. Crop recovery of fertilizer-N decreases with an increase in the rate of N application (Cambouris et al. 2008) and recovery is less in sandy soil (Macdonald et al. 1997). Therefore, sandy soils and especially irrigated systems require split application of N to increase use efficiency and reduce $NO_3$ leaching (Errebhi et al. 1998a). Growing an alternative potato variety, if available, which requires less N or has high fertilizer-N recovery would be a good strategy to reduce potential $NO_3$ leaching in sandy soil. For example, a 3-yr study in sandy soil indicated that Superior and Russet Norkotah require 20% less N than Russet Burbank (Kelling and Speth 2004). Applying recommended rates of N fertilizer without knowing varietal N requirements can increase $NO_3$ leaching in sandy soil. Inclusion of catch crops helps to decrease $NO_3$-N concentration in leachate on sandy soils (Vos and van der Putten 2004), which is discussed in detail in later sections. Inclusion of leguminous crops and cover crops and application of soil amendments should be credited and the fertilizer requirement for potato should be adjusted accordingly. Potato production in sandy soils requires increased frequency of irrigation and more

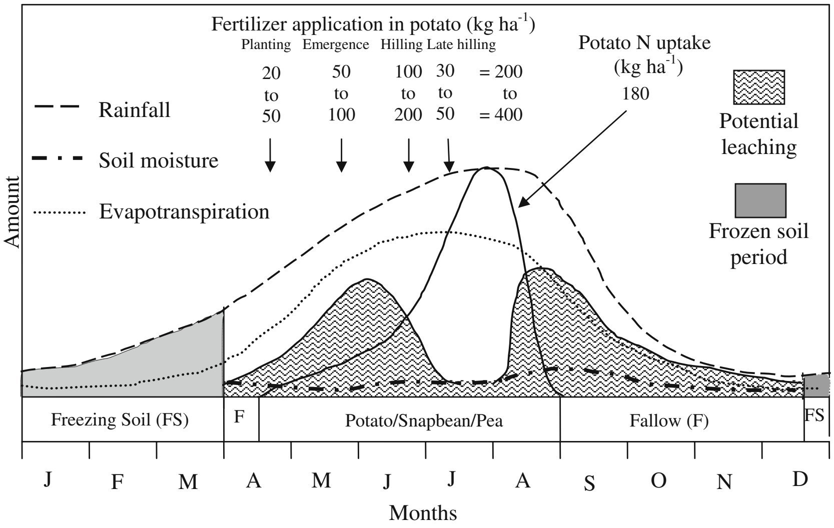

**Fig. 1** Schematic presentation of seasonal rainfall pattern, soil moisture, frozen soil, evapotranspiration, N uptake and their effect on relative leaching potential in north central sand

split application of N-fertilizer. The effects of minimizing N application rates at planting on $NO_3$ leaching are more dramatic when leaching rainfall occurs early in the season (Errebhi et al. 1998a). A study on an irrigated sandy soil of Michigan has shown that acceptable tuber yield can be obtained with lower rates of N than currently applied by the growers with the potential for reduction in $NO_3$ leaching (Joern and Vitosh 1995). For example, reducing N application rates from 260 to 170 kg ha$^{-1}$ for Russet Burbank potato reduced $NO_3$ leaching from 200 to 120 kg ha$^{-1}$ (Saffigna and Keeney 1977).

*Matching N-fertilizer Application Time with Crop Demand* Development of BMPs for N management must consider timing of N supply and crop demand (Zebarth and Rosen 2007). Ideally, supplying N just before a crop's maximum demand when plant growth is active and N uptake is high can reduce $NO_3$ leaching (Sturgul 1994). In sandy soils, N fertilizer applied early can potentially be leached to groundwater. A study conducted in Minnesota indicated that reducing N application at planting, delaying N application to emergence/hilling, and applying N at post hilling based on petiole sap test reduced leaching and increased potato yield (Rosen 1995) (Table 2). Decrease in $NO_3$ leaching and increase in tuber yields were also reported by splitting N (one third at emergence and two third at hilling during normal rain, and five times during very high rainfall) in sandy loam soils (Kelling and Hero 1994; Errebhi et al. 1998a; Waddell et al. 2000). Nitrogen recommendations for Russet Burbank grown on sandy soils are 34 kg N ha$^{-1}$ as starter and 224 kg N ha$^{-1}$ as supplemental (25–30% at emergence, 50–60% at mid-tuberization, and 10–25% at tuberization plus 3 weeks). An additional 34 kg ha$^{-1}$ should be applied if petiole $NO_3$-N levels drop below optimum prior to 70 days after emergence (DAE) (Kelling and Speth 2004).

*Placement of N-fertilizers* Whether N is applied using band placement, broadcast, fertigation, or incorporation by hilling, can significantly affect nutrient recovery and loss to the environment. The highest N recovery or lowest leaching losses are obtained if N is placed in the active water uptake zone. Fertilizer placement, especially for potato, is important as more than 90% of the roots are in the upper 25 cm of the soil profile (Lesczynski and Tanner 1976; Saffigna et al. 1976). A three-year experiment conducted in a loamy sand soil showed higher N use efficiency, potato yield and quality when N was applied by band placement in the hill and away from the furrow, where most of the water infiltrates, compared to broadcast or irrigation water (Saffigna et al. 1976; Kelling et al. 1998).

Reduction in leaching potential by increasing water use efficiency can be obtained with fertigation using overhead sprinklers if water and nutrient are applied together based on crop requirements at a specific time (Hagin and Lowengart 1996). However, fertigation for the sole purpose of N application may promote leaching. Fertigation results in a significant amount of water and N being shed into the furrow, potentially bypassing the roots. The importance of fertigation in improving water and N use efficiency and reducing $NO_3$ leaching has been reported in maize (Schepers et al. 1995). Fertigation reduces $NO_3$ leaching and greatly enhances the farmers' opportunity to meet in-season N needs especially in high leaching years (Kelling et al. 1998).

*Forms of N-fertilizer*

Ammonium vs nitrate fertilizer:

Leaching often does occur in the spring. Therefore, fertilizer sources containing $NO_3$ (i.e. ammonium nitrate) should be avoided at planting. Ammonium sulfate or urea is the preferred N source for starter fertilizer. An advantage of urea over ammonium nitrate is delayed potential for leaching. However, ammonia volatilization loss is greater with urea or ammonium sulfate compared to that from ammonium nitrate or potassium nitrate (Liu et al. 2007). Therefore, urea or ammonium sulfate must be incorporated after application to avoid volatilization losses, and its slow conversion to $NO_3$ especially in cool climates/seasons may reduce yield. Anhydrous ammonia may be of advantage in this situation; however, it may not be good for side dress

**Table 2** Effect of N application timing on nitrate leaching, N recovery and total tuber yield of potato on sandy soil of Minnesota (Errebhi et al. 1998b)

| Total N | N treatment | N recovery by tubers and vines | | $NO_3$ leaching | | Total tuber yield | |
|---|---|---|---|---|---|---|---|
| | | 1991 | 1992 | 1991 | 1992 | 1991 | 1992 |
| | Kgha$^{-1}$ | (%) | | Kgha$^{-1}$ | | Mgha$^{-1}$ | |
| 0 | 0 | – | – | 23 | 18 | 38 | 34 |
| 270 | 0+135+135[a] | 40 | 55 | 100 | 71 | 53 | 68 |
| 270 | 45+112+112 | 37 | 53 | 184 | 72 | 55 | 64 |
| 270 | 90+90+90 | 31 | 61 | 211 | 89 | 54 | 67 |
| 270 | 135+67+67 | 25 | 56 | 257 | 96 | 55 | 63 |
| N response | | b | NS | b | b | b | b |

*NS* not significant, b = significant at the 0.01 probability levels

[a] at planting, emergence and hilling

applications. An increase in N recovery and decrease in risk of $NO_3$ leaching was reported with ammonium sulfate compared to ammonium nitrate or calcium nitrate in a five-year study conducted on irrigated sandy soil (Bundy et al. 1986). Petiole $NO_3$ concentrations were also higher with ammonium sulfate than calcium nitrate at all sampling dates.

Slow release fertilizer

The environmental and agronomic benefits of using slow release fertilizers have been reviewed and show potential for reducing $NO_3$ leaching, but their performance depends on soil type and climate (Shaviv and Mikkelsen 1993). The slow release fertilizers coated with polymers such as polyolefin coated urea could be a better choice for increasing N uptake efficiency because N release from polyolefin coated urea is controlled by soil temperature, which also determines plant and soil microbial activities (Gandeza et al. 1991). Total and grade A potato yields obtained with the application of polyolefin coated urea, in a 2-yr study conducted in MN, were similar to those with split applications of soluble N, even though weather conditions were hotter and drier than average (Wilson et al. 2009). Polyolefin coated urea application in potato may reduce or eliminate the need for split application of N especially on coarse-textured soils and reduce $NO_3$ leaching and associated management costs (Wilson et al. 2009). The polyolefin coated urea applied during planting in irrigated Russet Burbank potato grown in loamy sand soil reduced soil $NO_{3,}$ compared to prilled urea applied at emergence and hilling, without affecting yield (Zvomuya and Rosen 2001). Application of 280 kg N $ha^{-1}$ as polyolefin coated urea on loamy sand soil of MN reduced $NO_3$ leaching by 34–49%, improved total and marketable tuber yield by 12–19%, and improved N recovery by 7% compared to three split applications of urea (Zvomuya et al. 2003). A recent study conducted by Wilson et al. (2010) in a loamy sand soil of MN reported a significant reduction in $NO_3$ leaching and improvement in apparent N recovery with the application of Environmentally Smart Nitrogen (ESN), a new polymer-coated urea, in potato over two split applications of soluble N at equivalent rates. This may be because of a better synchrony between N availability and demand.

In another Minnesota study conducted on a loamy sand soil, sulfur-coated urea resulted in less water-soluble soil $NO_3$ compared to ammonium nitrate (Rosen et al. 1993). Shoji et al. (2001) found that 134 kg N $ha^{-1}$ with controlled release fertilizer was able to generate the same potato yield as commercial farmers' traditional operations that applied 269 kg N $ha^{-1}$. This study, which was conducted under commercial farm operations in a sandy soil of south central Colorado, showed that the slow release fertilizer decreased N loss to the environment compared to traditional farmers' practices. Liegel and Walsh (1976) reported that sulfur-coated urea resulted in high N recovery and potato yields because of its slow dissolution and reduced leaching loss of N. However, Jackson et al. (1987) did not find sulfur-coated urea economical due to high cost and poor synchronization between fertilizer N release and crop N uptake.

### *Nitrification Inhibitors*

Chemical inhibition of nitrification can improve N use efficiency (NUE) and reduce $NO_3$ leaching (Zerulla et al. 2001). Nitrification inhibitors (e.g., nitrapyrin) slow down the conversion of $NH_3$ to $NO_3$ and should be used with $NH_4$-forms of fertilizer if application is made pre-plant in sandy soil (Sturgul 1994). A study conducted in a sandy soil showed reduction in marketable and total tuber yield with nitrapyrin treated fertilizer (Hendrickson et al. 1978). Another study also reported a decrease in potato yield in 15 and an increase in 8 out of 38 site-years with application of nitrification inhibitors in loamy sand soil (Kelling 1998). This may have been due to potato preference for the $NO_3$-N over the ammonium.

### *Petiole $NO_3$ Test*

In-season measurement of crop N sufficiency such as petiole $NO_3$ concentration can be used as the basis for optimizing N management in potato. Petiole sampling for $NO_3$ test is a simple and reliable diagnostic tool for monitoring N status and need for supplemental fertilizer to reduce N leaching (Belanger et al. 2003; Wu et al. 2007). Portable $NO_3$ electrodes, Cardy or Hach meters are useful for rapid quantitative on-site determination of $NO_3$-N in petiole sap, and the Wescan meter is useful for a fixed laboratory determination (Errebhi et al. 1998b). A four-year field experiment conducted on a loamy sand soil of Minnesota showed a significant linear relationship of dry petiole $NO_3$-N with petiole sap $NO_3$-N with $r^2$ of 0.91, 0.92 and 0.93 for the Cardy, Hach, and Wescan methods, respectively (Errebhi et al. 1998b). The fully expanded youngest leaves on the main stem, typically fourth or fifth from the top, should be used for petiole $NO_3$ test. Research has shown that it is best to perform the test at 7–14 days intervals from late June through July (30–65 DAE) at mid morning (around 10 AM) (Kelling 2000). The test is not useful after July as potatoes take up relatively little N after about 70 days of emergence (Kelling et al. 1998).

### *Nitrogen Credits*

Nitrogen credits are adjustments made to fertilizer recommendations to account for soil and crop management practices known to have influence on N supply such as from a preceding legume crop, application of manure or soil amendments, and SOM. Only 3.7% of the potato growers in Wisconsin who use organic sources consider N credits in deciding fertilizer rate (WPVGA 1995). To reduce leaching in sandy soil, it is important to adjust fertilizer N recommendation for other N sources such as manure applications, cover crop, crop residue, green manure, and amount of organic wastes or compost applied in the field (Sturgul 1994). This can be done by estimating N inputs from these organic sources and subtracting at least 50% of N input from organic sources (assuming 50% N mineralization) from the N required for potato crop. Kelling et al. (1993) reported 56 to 112 kg ha$^{-1}$ of supplemental N adequate for Russet Burbank following perennial alfalfa and 84 to 140 kg N ha$^{-1}$ following red clover cover crop. Wolkowski et al. (1996) also reported N credit for alfalfa in sandy soil of 157 kg ha$^{-1}$ for good stand (>43 plants/sq. meter), 123 kg ha$^{-1}$ for fair stand (43 to 16 plants/sq meter) and 90 kg ha$^{-1}$ for poor stand (16 plants/sq. meter). In Wisconsin, no credit is given for soybean and vegetable legumes (Boerboom et al. 2009) due to their low N-fixing capacity and high potential of legume N loss before it can be utilized by crops. Honeycutt et al. (1996) in Maine reported N-fertilizer replacement values of 65, 43, 26, and 11 kg N ha$^{-1}$ for annual *Medicago sativa* cv. Nitro, *Vicia villosa*, *Lupinus albus* cv. Ultra and oats cv. Astro, respectively.

### *Site-Specific Nitrogen Management (SSNM) and Precision Agriculture*

Significant spatial variation in soil N status, soil processes, and crop N status can exist within a field. The spatial variation in response to N fertilization and irrigation has led to an interest in precision farming, which considers site-specific soil variability, provides data on the amounts of N needed for specific field, and reduces potential $NO_3$ leaching. Therefore, it is critical to manage N using site specific nutrient management (SSNM) system, which accounts for spatial soil variability within the fields and makes precise recommendation of N need that increases efficiency of applied N (Khosla et al. 2002; Cambouris et al. 2008). Site-specific N management has reduced $NO_3$ leaching on areas with high leaching potential on loamy fine sandy soil of Washington, indicating SSNM's potential to improve N management in potato cropping system (Whitley et al. 2001). This can be done either by dividing fields into management zones which differ in term of soil properties, landscape position, and yield potential or using optical methods to assess spatial variation in crop and soil N status. Delgado et al. (2005a) reported that site-specific management zones decreased $NO_3$ leaching by 25% compared to traditional farming practices. Therefore, site-specific management zones could potentially be used to reduce $NO_3$ leaching in North America (Delgado et al. 2005b). Remote sensing was also used for irrigated corn grown in commercial operations in Colorado (Delgado and Bausch 2005). They reported that remote sensing could be used to increase synchronization of N application with N needs while decreasing $NO_3$ leaching by 47%. These new technologies are useful to assess spatial variability across the landscape and increase site-specific efficiency of conservation practices (Berry et al. 2003, 2005). Delgado and Berry (2008) listed a series of precision conservation practices that can be used to improve nutrient management and reduce $NO_3$ leaching and off-site transport of N via surface and underground flows. These precision conservation practices could integrate variable flows and adjust the conservation practice by using site-specific information to apply buffers, sedimentation traps, denitrification traps, and management of drainage ditches to minimize N transport in the environment (Dosskey et al. 2005).

A simple hand chlorophyll meter, Minolta SPAD-502, was used successfully to determine supplemental N requirements for potato (Vos and Bom 1993; Shaaban and El-Bendary 1999; Olivier et al. 2006) and showed a strong correlation of yield and quality with the amount of chlorophyll in the leaf and N content in the plant (Minotti et al. 1994). The early season SPAD values gave maximum marketable tuber yields, ranging from 49 to 56 depending on year, variety, and location (Minotti et al. 1994). SPAD is useful to identify areas with N deficiency, where petiole $NO_3$ testing is not possible. This will help to correct N deficiency only in deficient areas thereby protecting potential $NO_3$ leaching, where the automated N-sensor is not available.

The optical method measures reflectance. The reflectance related to canopy chlorophyll content is linked to GIS information that provides a map of up-to-date N status. These measures of "real-time" crop N status can be linked directly to variable rate fertilizer N applicators, which can immediately translate the measurements into fertilizer rates, and tailor N management to the precise need of the crop for a specific field at real time. Variable fertilizer N application method can reduce N loss (Whitley and Davenport 2003). This practice is common in Europe for cereal crops (Zillmann et al. 2006; Jorgensen and Jorgensen 2007), but has not been fully developed for potatoes. In practice, the optical system is integrated with the tractor and connected with a fertilizer spreader or sprinkler irrigation equipment collecting N measurements while the tractor moves in the field. The spreader is calibrated to release the appropriate rate as the device detects the N needs. This option is interesting but has a few limitations including misrepresentation of chlorophyll content and compaction caused by tractors. The optical method measures reflectance related to canopy chlorophyll content. However, canopy chlorophyll content can be affected by disease, insect or other nutritional deficiencies. Therefore, growers should make sure that chlorophyll content is truly reflection of soil N content of potato, and not misrepresented by other factors. Development of aerial measurement method to record variability and adjust fertilizer using variable rate fertigation should be explored to overcome compaction problem.

### *Newly Developed N-management Tools*

A recently developed web-based N-index tool (NIT), formatted as a spread-sheet, is an effective tool for the assessment of agricultural management practices on $NO_3$ leaching loss (Delgado et al. 2008a). NTT provides a reliable and easy-to-use method of calculating N credits for water quality improvement and enhances management-induced reduction in N losses at the farm level (Delgado et al. 2008b; Gross et al. 2008). The NTT couples the N Loss and Environmental Assessment Package (NLEAP) with a user-friendly web-based interface to allow producers to calculate N savings from different agricultural practices (Gross et al. 2008). These credits may then be bought or sold in water quality markets across the country.

## Water Management

Nitrogen management alone cannot effectively reduce $NO_3$ leaching in sandy soils. It is a challenge to supply water to the crops on a sandy soil, which has low water holding capacity, while trying to minimize leaching.

### *Irrigation Strategies*

Good irrigation strategies (the right amount at the right time) are important as irrigation amount and timing are strongly related to leaching, especially in sandy soils (Cates and Madison 1994). Irrigation scheduling, a primary water management tool, should integrate soil moisture at the time of irrigation, WHC of soil, crop water use, infiltration, soil texture, and weather. Improved management of N and irrigation (frequent but smaller application) can reduce N and irrigation requirement and decrease $NO_3$ leaching and concentration of leachate (Saffigna et al. 1977). Waddell et al. (2000) reported that 40% reduction in irrigation amount could help to reduce the risk of $NO_3$ leaching from potato without affecting yield.

A recent study reported that water content within the center of the potato hill, where the greatest densities of roots occur, were greater under drip irrigation than those of sprinkler irrigation (Cooley et al. 2007). Therefore, management strategies targeted at wetting the hill center would likely improve water use efficiency (Starr et al. 2005). Similarly, another study showed that allowing soil to become drier between irrigation events or the use of surface drip irrigation rather than sprinkler, furrow, or buried drip irrigation would be beneficial in reducing N leaching (Waddell et al. 1999, 2000). Significant reduction in $NO_3$ leaching from subsurface irrigation system is due to its lowest water use requirement since it delivers water directly to the hill locations where uptake is greatest, thereby reducing irrigation amount required (Starr et al. 2008).

Irrigation is a critical issue for potato production because of low soil WHC. Frequent and high amount of irrigation can contribute to $NO_3$ leaching in sandy soils (WPVGA 1995). Irrigation scheduling in Wisconsin is done by estimating soil moisture by hand (89%), estimating evapotranspiration and using the “checkbook” (24%), determining crop need (17%), using modeling program (8%), and scheduling irrigation regularly on a calendar basis (4%) (WPVGA 1995). Several methods such as the Wisconsin Irrigation Scheduling Program (WISP) (Curwen and Massie 1984; Bland and Wayne 2003) or soil tensiometers (Shae et al. 1999) can be used to schedule irrigation. Soil tensiometers are also excellent tools for sandy soils.

### *Improving Water and Nutrient Retention*

Non-ionic surfactants (Preference®) are useful to increase water infiltration into unsaturated hydrophobic soils, redistribute water and N, and improve use efficiency in the potato hills (DeBano 1971; Arriaga et al. 2009). Studies conducted in sandy soils have reported an increase in water and N use efficiency and a decrease in $NO_3$ concentrations at the time of peak $NO_3$ leaching with application of surfactant at the rate of 9 L $ha^{-1}$ to the center of the potato row (Nehls et al. 2002; Lowery et al. 2005). A recent study conducted in a sandy soil to determine the effects of surfactant application at 9.35 L $ha^{-1}$ in the seed furrow (20-cm depth) at planting also showed significant increase in water infiltration and decreased $NO_3$ leaching (Cooley et al. 2007, 2009). However, more research is needed to refine its use as surfactant effects are variable (Arriaga et al. 2009).

### *Groundwater Vulnerability Assessment Using GPS and GIS*

Global positioning systems (GPS) is a useful tool to record precise sampling location and geographic information system (GIS) can store and manipulate different large data sets affecting $NO_3$ leaching such as soil texture, amount of fertilizer applied, irrigation, etc. Real-time monitoring techniques (e.g., N reflectance index) can be combined with GPS and GIS which can identify site-specific N budgets and losses from the field to develop crop N status maps. De Paz and Ramos (2002) in Spain linked the

GLEAMS (Groundwater Loading Effects of Agricultural Management Systems, Version 2.10) model with GIS to evaluate the risk of $NO_3$ pollution in an area of 230 km$^2$ and a pollution risk map was developed. This is helpful for managing N in $NO_3$ pollution risk areas located in the map, thereby reducing potential $NO_3$ leaching.

### *Strategies of Building Soil Organic Matter that Increases Water Holding Capacity*

Although research on irrigated sandy soils has focused on N, irrigation, and cover crop management in reducing potential for $NO_3$ loss, reducing $NO_3$ leaching is still a challenge because of unforeseen rainfall events. Therefore, efficient alternative approaches are urgently needed. Typically, soils used for potato production are either inherently low in SOM or decline in SOM from intensive crop management practices (Saini and Grant 1980). The role of SOM in these soils is extremely important (Stevenson 1982; Paustian et al. 1997). Al-Sheikh et al. (2005) showed that when a cover crop residue is incorporated or cover crop with deep root system is grown and incorporated in irrigated potato systems in sandy soils, SOM, C and N sequestration can increase. Practices that increase SOM in sandy soils can have a dramatic effect on soil physical quality improvement and water retention. Increase in water retention capacity of a soil can reduce $NO_3$ leaching. This is explained by a positive relationship of SOM with water and nutrient holding capacity (Zibilske and Bradford 2007), indicating increase in SOM increases water and nutrient holding capacity (Schulte and Walsh 1993) thereby decreasing $NO_3$ leaching potential. Maintaining optimum level of SOM in sandy soil can ultimately improve the sustainability of crop production. However, a high level of SOM can cause leaching from mineralization, especially in sandy soils. The amount and quality of SOM depends on the quantity and type of organic materials (such as cover crop, crop residue, compost, manure, and organic waste) added to soil, as well as how and when they are applied.

Cover crops are more suited for use in humid regions (Unger and Vigil 1998) than arid or semi-arid, because they may use water from the soil profile, which could reduce yields from the next crop in dry regions. However, even under semiarid conditions there may be conditions where cover crops can have a positive impact, especially if they reduce wind erosion (Balkom et al. 2007). Linear relationships have been observed between the amount of residue applied, and changes in soil carbon (C) (Larson et al. 1972). Cover crops have the potential to increase or restore SOM, reduce evaporation, enhance biological activity, increase soil permeability, improve soil aggregate stability and WHC, and reduce bulk density and noncapillary porosity (Reicosky and Forcella 1998).

The importance of SOM in soil is well documented and has been appreciated for decades, but often not well understood for $NO_3$ leaching. Recovery of SOM pools in sandy soil is possible by adding compost or organic material as reported by Newman (2002) in a 4 year study. Newman (2002) demonstrated that moderate to high amounts of either fresh or composted paper mill residuals (PMR) increased SOM content of sandy soils. Newman (2002) applied PMR raw (fresh), composted alone or with a bulking agent (bark) at low rates of 22, 33 and 33 Mg ha$^{-1}$, and high rates of 39, 78 and 78, respectively in a 3-yr rotation of potato-snap bean-cucumber. Newman observed a slight decrease in total C over the first year. However, all amended soils maintained significantly higher total soil C than without amendment. Paper mill residue composted with bark was the best in increasing total C, followed by composted alone and fresh. The extent of increase of total C was also rate related (the greater increase with higher application rate). The increase of total C following the second amendment application suggests that PMR, especially composted with bark, can build stable total C pools in soils with inherently low total C (9–10 g kg$^{-1}$ soil) and course-textured sandy soils.

The amendment application in potato increased soil porosity, and plant available water by 5 to 45% compared to the control (Fig. 2). In a field plot study, Foley and Cooperband (2002) reported that increase in total soil C due to amendment application was inversely proportional to irrigation amount and frequency (Fig. 3). The application of soil amendments reduced the amount of irrigation water required for potato production by 4 to 30%, and the number of irrigation by 10 to 90%. Thus, increasing SOM content helps reduce $NO_3$ leaching due to improvement in soil physical properties (Gaines and Gaines 1994).

Similarly in a sandy loam soil of Connecticut, spent mushroom compost and chicken manure compost were incorporated in vegetables at the rate of 56 and 112 Mg ha$^{-1}$, respectively, into the soil by rototilling in the spring prior to planting (Maynard 1993). Nitrate concentrations in ground water beneath compost-amended plots were less than 5 ppm. In contrast, plots receiving only chemical fertilizer had

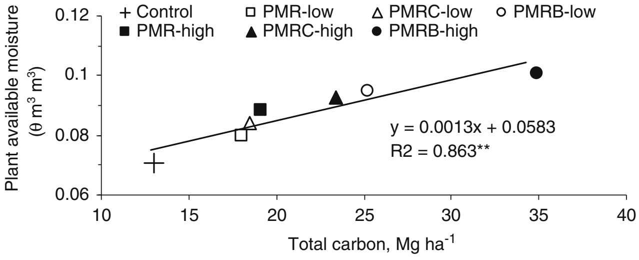

**Fig. 2** Relationship between total C and plant available water (1998 to 2002) ARS, Hancock, WI, USA (Drawn using summarized data from Newman 2002)

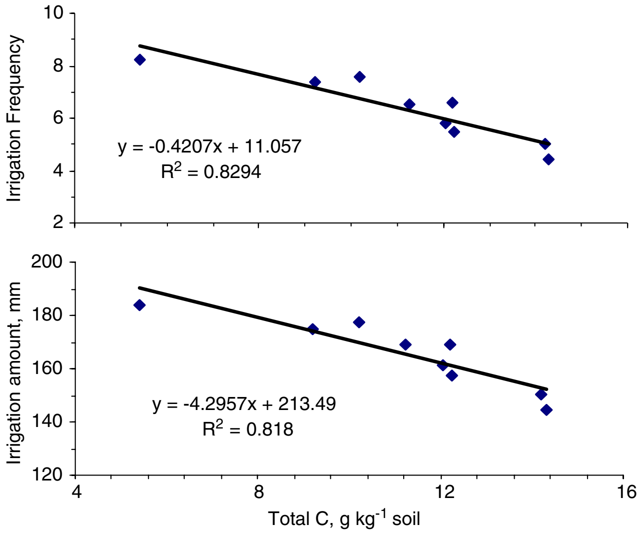

**Fig. 3** Effect of carbon on irrigation frequency and amount. Data used from Foley and Cooperband (2002)

groundwater $NO_3$ concentrations close to 15 ppm, higher than compost application. The beneficial effects of compost in reducing $NO_3$ leaching in sandy soil are related to increases in SOM (Maynard 1993). The effect of these amendments in reducing $NO_3$ leaching can be maximized, if the light fraction C is allowed to stabilize by minimizing soil disturbance and enhancing soil aggregation (Six et al. 1999).

## Cropping System

### *Introducing Cover Crops*

The strategies to reduce $NO_3$ leaching should focus on either minimizing N losses during the entire crop growing season by balancing demand and supply or capturing or recovering residual N by growing cover crops after crop harvest. In recent years, the use of cover crops to reduce $NO_3$ leaching has received much interest in USA (Delgado 1998; Dabney et al. 2001; Logsdon et al. 2002) in addition to protecting soil from wind and water erosion (Reicosky and Forcella 1998; Kaspar et al. 2001). Two major attributes of an ideal winter cover crop would be the ability to significantly capture soil $NO_3$ and recycle N to the next crop (Reicosky and Forcella 1998; Shrestha and Ladha 2002). Cover crops can have significant input on soil quality by returning C input, recycling N input, and improving water quality (Reicosky and Forcella 1998).

The choice of cover crop species depends on the cropping system, amount of time between harvest of the primary crop and the end of the growing season, climate, and soil type (Naderman 1991; Meisinger et al. 1991; Jackson et al. 1993). Non-legume cover crops like oats (*Avena sativa* L.) (Mitchel and Teel 1977), barley (*Hordeum vulgare* L.) (Ditsch and Alley 1991), sorghum (*Sorghum bicolor* L.), sudan grass (*Sorghum sudanensis* L.), rye grass (*Lolium multiflorum* L.) (Martinez and Guiraud 1990), wheat (*Triticum* spp.), cereal rye (*Secale cereale* L.) (Rayns et al. 2000), *Brassica* such as mustard (*Brassica* spp.), rape (*Brassica rapa* spp. olifera), and radish (*Raphanus sativus* L.) (Bertilsson 1988; Martinez and Guiraud 1990) can be used as cover crops for northern humid climates of USA.

*Cover Crops that are the Best N Scavengers* Cover crops can capture $NO_3$ and reduce amount and concentration of leachate by 20 to 80% (Meisinger et al. 1991; Staver and Brainsfield 1998; Dabney et al. 2001). Cover crops can grow deep in the soil profile and act as scavengers that recover $NO_3$ that has been already leached from the shallower root zone of the previous vegetable crop (Shrestha and Ladha 1998), and even reduce the amount of $NO_3$ leaching that occurs in the next crop (Delgado 1998; 2001a). Efficiency of fall planted cover crops in capturing residual soil N depends upon ability to establish early with adequate growth before leaching starts and can capture large amount of N (Shepherd and Lord 1996).

Grasses are winter hardy and better at scavenging and sequestering excess soil nitrates (Meisinger et al. 1991; Dabney et al. 2001). Brassicas are not as winter hardy as grasses but are known for their rapid establishment, cool season growth, large biomass, and N uptake (Fielder and Peel 1992). Cover crops that are not winter hardy, such as yellow mustard, should not be planted in sandy soil due to possible leaching of $NO_3$. The ability of cover crops to deplete soil $NO_3$ depends on enough biomass to be an efficient N sink, and to develop deep rooting system to scavenge and exploit soil $NO_3$. Thorup-Kristensen (2001) found that the concentration of subsoil $NO_3$ at 0.5 to 1.0 meter negatively correlated with root intensity indicating cover crop with deep rooting system (e.g., alfalfa, italian ryegrass, and fodder radish) could capture more $NO_3$.

*Cover Crops Best Suited to Planting after a Late Season Main Crop* Planting winter cover crops (e.g., rye) immediately after potato can recover residual and mineralized soil N besides controlling wind erosion (Delgado et al. 1999). Management practices such as the timing and methods of planting and seeding rates are important for good fall growth and N uptake (Ditsch and Alley 1991). Evanylo (1991) reported that over-wintering rye (*Secale cereale*) cover crop on sandy loam soil in Virginia improved recycling of residual and fall-applied N. Delaying incorporation (October 1) of lupin (*Lupinus albus*) cover crop increased N recycling (26–34 kg $ha^{-1}$) in Russet Burbank potato compared to early incorporation (September 1) (5–13 kg $ha^{-1}$) in Canada (Sanderson and MacLeod 1994). Delgado et al. (2004) conducted $^{15}N$ crop residue exchange studies using a large plot design and found that deeper rooted crops such as wheat and barley recycled about 6 to 13%, respectively, of the crop residue N to the subsequent irrigated potato crop. Using the Delgado et al. (2004) crop residue exchange methodology, Collins et al. (2007) conducted $^{15}$N crop residue exchange studies in potato systems of the Pacific Northwest and found that cover crops with lower C/N ratios recycled about 34% of their N content to the following potato crop. Assuming a fertilizer N use efficiency of about 50%, the cover crops' N cycling was equivalent to about 90 kg N ha$^{-1}$. Delgado et al. (2009, DOI 10.1007/s10705-009-9300-9) reported that the crop residue N cycling efficiencies are much higher than those from inorganic N fertilizer and that they have lower $NO_3$ leaching losses and lower emissions of $N_2O$ when compared to inorganic N fertilizer, especially if they have high C/N ratios.

Rye, winter barley, spring barley, winter wheat, and triticale planted after potato in sandy soils of the Columbia Basin, Oregon for two consecutive years reduced soil $NO_3$ by 87, 73, 73, 73, and 66%, respectively (Fernando 1996). He also observed higher inorganic soil N in fields planted with spring barley, winter barley, and triticale compared to fallow at 0–60 cm depth indicating recycling of residue N. However, studies conducted in irrigated sandy soils of Midwest reported that winter rye cover crops, commonly grown in the region and planted in two consecutive years after potato or sweet corn, did not utilize residue N or soil N and was lost by leaching (Bundy and Andraski 2005). This may be due to growth of cover crops in winter under western conditions, while in the Midwest growth is negligible from November to April.

*Cover Crops Best Suited to Planting after a Short Season Main Crop* Planting cover crops immediately after harvest or relay with main crop is important as it reduces fallow period and allows enough crop growth to accumulate soil N before winter $NO_3$ leaching (Fielder and Peel 1992). For example, a rye cover crop planted on 1, 14 and 30 October in Maryland showed an increase in N accumulation and a decrease in soil $NO_3$-N with early planting (Staver and Brainsfield 1998). In a loamy sand soil, over-winter cover crops (e.g., wheat, *Triticum aestivum*) planted after early potato (Milburn et al. 1997); and wheat, rye, rapeseed (*B. napus*) seeded after sweet corn and incorporated in spring appeared to be most effective in recycling N to potato crop (Weinert et al. 2002). However, sudan grass (*Sorghum vulgare*) or white mustard (*Brassica hirta*) were not found to be beneficial and are not recommend to be planted in the fall (Weinert et al. 2002).

A strategy of over seeding cover crops (e.g., oat) after 80 DAE of potato when N uptake is negligible can capture residual fertilizer N or soil N from late season mineralization. Relayed oat crop can capture unutilized N from potato, and rye can capture mineralized N from oat and residual N from potato, if there is any (Bundy and Andraski 2005). Cover crops can be incorporated in winter just before soil freezes, which can recycle nutrients for succeeding crops. Mixing different cover crop species can provide assurance and increase benefits, but there is little information on the ability of mixtures in improving groundwater quality (Mitchel and Teel 1977).

### *Mixing Crops with Different Rooting Habit*

Better use of soil resources (nutrients and moisture) can also be done by including crops or varieties with different rooting depths (deep and shallow) in a crop rotation (Shrestha and Ladha 1998). Delgado 2001b) positively correlated rooting depths with N use efficiencies and the capability of crops to mine $NO_3$ from ground irrigation waters. Crop root depths were negatively correlated with $NO_3$ leaching. Commercial operations that used cover crops and crops that were rooted more deeply were able to increase the N use efficiency of their farm operations while minimizing the amount of residual soil $NO_3$ in the profile and $NO_3$ leaching to groundwater (Delgado et al. 2000, 2006). The deeper rooted crops acted as a biological filter that recovered $NO_3$ from irrigated groundwater, helping to mine the $NO_3$ (Delgado et al. 2007). Rotations of potato with barley, winter wheat and cover crops help to increase N use efficiency in the system while minimizing $NO_3$ leaching (Delgado 1998). Including alfalfa in a rotation especially in moderate sandy soil is also an effective approach in reducing leaching because of its deep rooting and high water usage (Owens 1987).

The amount of crop residue N varies with the crop species, varieties, management practices, climate, and soil. Recovery of fertilizer N in potato is about 50% with current management practices. Distribution of fertilizer N recovery in potato averaged 24% in tubers, 9% in residue, 14% in soil, and 53% leached (Bundy and Andraski 2005). This suggests that 23% of residues and soil N could be returned to the soil, if properly managed. A study conducted in Canada with cauliflower, red cabbage and spinach residues incorporated in autumn and spring and mulched in autumn showed greater risk of $NO_3$ leaching with autumn residue handling compared to spring handling (Guerette et al. 2002). Autumn handling of cauliflower residues and both incorporation treatments (spring and autumn) for red cabbage residues contributed significant amounts of N to the following wheat crop (equivalent to 27 to 77 kg N ha$^{-1}$). Incorporation of crop residue with high carbon to nitrogen ratio should be encouraged to immobilize residual $NO_3$ left in the root zone (Brinsfield and Staver 1991).

In summary, although some of the studies have emphasized the importance of BMPs, they do not provide a complete solution. The effects of these BMPs on reducing $NO_3$ leaching are variable, ranging from no effect (Osborne and Curwen 1990) to 30% reduction (Mechenich and Kraft 1997). This indicates that BMPs should be carefully evaluated for specific conditions.

### Use of Simulation Modeling

Simulation models (e.g., NLEAP) are a powerful tool to understand soil-crop-atmosphere hydrology cycle, simulate water budgets, schedule irrigation, evaluate and select best management practices, predict leaching potential, crop growth, N and water dynamics during a growing season, and provide a guide in N management strategies to reduce potential for $NO_3$ leaching (Delgado 2001a; Minshew et al. 2002). For example, a crop growth and N budget model for potato predicts crop growth and potato N uptake for differing environments and climatic conditions (Yuan and Bland 2004).

A cropping system model, CropSyst, is useful to simulate interaction of crops, soil, weather, irrigation, and fertilization (Peralta and Stockle 2001). Peralta and Stockle (2001) simulated scenarios with fertilization above recommended rate, and found that potato had the highest $NO_3$ leaching, but when fertilization approached the recommend rate, leaching amount was low. Leaching was found to be higher during fall and winter fallow periods.

A growth model, SIMPOTATO, can simulate daily water and N requirements for potato based on initial soil status and daily weather conditions for sandy soil (Hodges 1998). Simulated water and N requirements were close to the actual amount applied to the experimental field in Washington but were considerably less than applied to the commercial fields (Hodges 1998). Danish N Simulation System, DAISY, which considers N balance in soil-plant-atmosphere system, compost type, application rate, management and cropping practice, is useful to predict long-term effects of compost application on $NO_3$ leaching (Gerke et al. 1999).

## Summary and Recommendations

There is no quick fix for controlling $NO_3$ leaching to ground water. However, integrated use of efficient and tested strategies can reduce leaching potential significantly.

*Nitrogen Management* Reducing over fertilization, applying the right source of N at the right time and place, and matching N application rate with crop need increases N use efficiency and reduces $NO_3$ leaching. Band application of fertilizer should be encouraged at emergence and hilling. After hilling, fertilization should be decided based on petiole $NO_3$ test using portable $NO_3$ electrodes such as Cardy or Hach meters.

*Irrigation Management* Careful management of irrigation amount and schedule considering water-holding capacity of soil, evaporation, rainfall, and crop growth stage help to reduce $NO_3$ leaching. On sandy soil, it is always better to irrigate amount equal to or little less than the estimated consumptive use for specific stage and ground cover. For this purpose, irrigation scheduling programs or soil tensiometers are useful tools.

*Cover Crops and Residue Management* It is important to select efficient N scavenging fall cover crop and plant as early as possible. The ability of cover crops to scavenge and deplete soil $NO_3$ depends on large biomass growth (e.g., *Brassicas* and grasses) to be an efficient N sink, and deep rooting system (e.g., alfalfa, Italian ryegrass and fodder radish) to capture $NO_3$ from deeper depth. Winter hardy cover crop with high biomass such as winter wheat, rye (*Secale cereale*), ryegrass (*Lolium multiflorum*) and *Triticale* can be planted in fall immediately after harvesting potato, and incorporated in spring before planting succeeding crop. This can recycle nutrients for the succeeding main crop potato.

Crop residues with high fiber content such as corn can be left on the soil and incorporated next spring before planting potato. Claiming N credit from crop residues, compost, and previous legume crops is vital for economical crop production and water quality protection.

*Soil Amendments* Growers, especially in North Central USA, should be encouraged to apply enough soil amendments just to meet the N requirement of potato and reduce potential $NO_3$ leaching. Soil amendments should not be applied to frozen soil when temperature is <10°C and to soil with slope >6%. Otherwise, nitrification inhibitor should be used and available N rate should be limited to 130 kg $ha^{-1}$.

*Site-Specific N management* Variability in soil fertility can be high within a field due to variation in soil profile, topography, and hydrology. Therefore, efforts should be made to manage fields according to spatial soil variability, which can reduce potential for over fertilization and $NO_3$ leaching. Site-specific N management can be done using chlorophyll meter for small scale. Implementations of site specific N management tools, such as use of automated N-sensors, are needed for precise N management to manage soil variability and produce a good crop without risking groundwater pollution. A tool should also be developed which can integrate different factors affecting fertilizer rate determination for a specific field such as indigenous soil N, soil texture, nutrient holding capacity of soil, yield goal, residue N, crop demand, and weather; and validate for local condition.

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