Environmental Impacts of Potato Nutrient Management

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ABSTRACT

Use of soluble chemical fertilizers for crop production, particularly to supply nitrogen, phosphorus, and potassium, has increased potato yields and quality for several decades. Over the past 10 years, however, there has been an increased concern over the environmental impact of agricultural fertilizers, particularly as non-point sources of water pollution. Currently, nitrogen is a target for improved use efficiencies in potato to reduce potential nitrate contamination of groundwater. Phosphorus management is increasingly being examined as a potential non-point source contaminant of surface waters. Potato researchers throughout North America are conducting studies that focus on maintaining or enhancing crop production while reducing the potential of negative environmental impacts. Precision agriculture, cover crops, slow-release fertilizers, and genetic manipulation are key strategies being studied. Concurrently, new challenges are arising, such as concerns over phosphorus leaching and heavy metal contamination in fertilizers. These have the potential to restrict nutrient use in agricultural systems, requiring both potato producers and scientists to seek additional alternatives to improve nutrient-use efficiency.

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RESUMEN

El manejo de nutrientes puede disminuir la severidad de muchas enfermedades importantes de papa y ciertas prácticas, tal como el mantener un pH bajo para el control de la sarna, se ha seguido con este simple objetivo. Con frecuencia, los productores de papa han incorporado modificaciones de la fertilidad con respecto a ciertas enfermedades en particular y condiciones de cultivo. Desgraciadamente, la reducción de la enfermedad puede ser consistente con una fertilización óptima para rendimiento, calidad y rentabilidad. Lo que puede controlar una enfermedad puede no ser bueno para otra enfermedad y los mecanismos involucrados son a menudo complejos e insuficientemente comprendidos. Los productores de papa continuarán experimentando limitaciones conflictivas en la producción. Estas limitaciones incluyen la influencia del precio de los artículos para mejorar el rendimiento y la reducción de los gastos; influencia de las demandas del consumidor para el mejoramiento de la calidad; cambios de variedad debido a las consideraciones anteriores más que a la reducción por enfermedades; incremento en la presión para la justificación; cambios y reducción en el uso de pesticidas; preocupación continua acerca del movimiento del nitrógeno y fósforo en el agua del suelo y su pérdida y un aumento de atención en la rotación de cultivos. En el lado positivo, las estrategias en el manejo de nutrientes para situaciones altamente específicas continúan mejorando y las prácticas referentes a los nutrientes y la variabilidad de las enfermedades dentro del campo se están volviendo más sofisticadas. En este contexto, existen oportunidades para el manejo de practicas culturales que reducen la presión de la enfermedad y la

confianza en el control químico. Para estar efectivamente integrado a tales sistemas especializados de manejo, el mecanismo de estas medidas de control y las condiciones bajo las cuales son practica, necesitarán ser mejor comprendidas. Asimismo, las respuestas de estas tácticas necesitan ser mejor cuantificadas para permitir un adecuado análisis costo-beneficio. Con referencia a los efectos de los pesticidas agrícolas en la seguridad alimentaria, los trabajadores y el medio ambiente, el manejo de los nutrientes disponibles para la planta pueden convertirse en una manera de enfocar la practica para la supresión de enfermedades en el futuro.

OVERVIEW OF FERTILIZER USE IN AGRICULTURE

After World War II, technologies, equipment, and materials to manufacture inexpensive chemically based fertilizers became available. This represents a significant watershed in American agriculture. The adaptation of these materials resulted in large increases in crop yields and qualities. A great deal of research has been conducted to develop strategies to use these materials in major crops which has resulted in increasing fertilizer use until the early 1980s (Harre and White 1985). Since the 1980s, fertilizer use has been at a fairly constant level in the USA (Anonymous 1997).

Commercially available soluble chemical fertilizers are used extensively in potato (*Solanum tuberosum* L.) cropping systems. The three macronutrient elements nitrogen, potassium, and phosphorus are the predominant fertilizers applied. All have been shown to improve yield and quality of potato tubers where native soil supplies are limiting (Westermann 2005).

ENVIRONMENTAL ISSUES AROUND NUTRIENT USE

In recent years agricultural chemicals have become the focus of investigations into their contribution to non-point source pollution of surface and ground waters. In terms of plant mineral nutrients and the fertilizers used to supply them, efforts have focused on phosphorus as a potential contaminant of surface waters (Lemunyon and Daniel 1998) and nitrate as a potential groundwater contaminant (Nolan et al. 1998). To date, the principal focus in potato systems has been on the issue of nitrate in groundwater.

Nitrogen

A survey by the USGS in the early 1990s found that 24% of wells tested in the USA contained greater than 10 ppm nitrate-nitrogen (Nolan et al. 1998). This survey indicated that areas with the highest concentration of contaminated wells were in areas associated with agricultural production, particularly on coarse, well-drained soils. The 10 ppm critical level was set by the U.S. EPA as the U.S. drinking-water standard and was developed to express human health concerns from high nitrate in drinking water. The human health concern is methemoglobinemia—commonly known as "blue baby" syndrome—and is generally associated with infants. Incidence of blue baby syndrome has been reported sporadically with most cases occurring in households with private wells where the water contained more than 10 ppm nitrate-N. The actual safe limit for nitrate-N in drinking water, however, is in question since many of these wells were also contaminated with bacteria. In 1995, the National Research Council concluded bacterial infections were the leading cause of methemoglobinemia in the USA, with negligible contribution from nitrate in drinking water (Felsot 1998).

In discussing non-point impacts of agricultural practice, recognition must be given to water management in the system. Nutrients are taken up by plant roots only when they are dissolved in the soil water (soil solution). Water in an agricultural system (irrigation or rainfall) that results in movement of nutrients below the root zone or off of a management area as runoff plays a highly significant role in controlling environmental impacts of nutrients.

Non-point groundwater contamination with nitrate is an issue in most agricultural production systems. The nitrate can come from soil organic matter, crop residues or added organic materials, nitrogen fertilizers, or microorganisms that convert N_2 gas into soluble nitrogen (e.g. *Rhizobia* sp. on legumes). Conversion of organic or ammonium nitrogen to nitrate is a microbial process that is well documented and highly effective in all but highly acidic (pH < 5.0) soil conditions (Hanlon et al. 1997; Davenport and DeMoranville, 2004). Estimates of nitrate leaching under potatoes have been reported to range from 70 kg N/ha to more than 200 kg N/ha (Meisinger 1976; Saffinga et al. 1977; Hill 1986; Errebhi et al. 1998a). This leaching has resulted in nitrate concentrations in seepage or drainage effluent in potato systems with mean annual concentration in excess of 10 mg NO_3-N L^{-1} (Milburn et al. 1990). Similar or higher leaching concentrations are characteristic of many annual row crop systems, particularly specialty crops, where N inputs are high, plant populations are relatively low, and the crop is harvested early to mid-season.

Currently, monitoring of the impact of potato production systems on groundwater contamination is directed at monitoring drainage effluent and both shallow and deep wells. Efforts to reduce impacts are underway through a number of research projects throughout North America. Examples of public-private partnership efforts to reduce impact are the Ground Water Management Areas (GWMAs) in Oregon (Feibert et al. 1998) and Washington. These are groups of farmers, local residents, and area conservation districts, who are working together, in cooperation with a government (state or federal) regulatory agency (e.g., EPA), to develop solutions to prevent negative impacts of any rural non-point source of groundwater contamination.

Phosphorus

The impact of phosphorus as a non-point source contaminant has been an issue in agriculture for nearly 30 years (Romkens et al. 1973). There has been a resurgence of attention to this issue due to a number of factors. The driving force has been the development of large confined-animal-feeding operations leading to land application of manures that have resulted in excessive P application and resultant issues related to nutrient runoff and fresh water quality. From a crop production perspective, the resurgence in interest relates to new discoveries in terms of phosphorus soil chemistry ,which have shifted our understanding of phosphorus mobility in soil.

Historically, P has been understood to have very low solubility in soil systems. From a geochemical perspective, there is a very narrow range of soil pH where P is not tied up in low solubility complexes with iron and aluminum (pH < 6.0) or calcium (pH > 6.5) (Stumm and Morgan 1981). Due to this low solubility, a common practice is to add P fertilizers in amounts in excess of plant removal to increase the amount of plant-available P. Potatoes in particular have a high response to P fertilizer. The average removal of P with the potato crop is 25 to 35 kg P/ha, yet P fertilizer application is frequently much higher than this removal rate. Additionally, very recent research has discovered that high P loading is resulting in P movement in the soil profile (Wood 1998), which traditional geochemical information suggests is unlikely to occur. Situations where P movement is most likely to occur are on very sandy soils with low adsorption capacity and when high amounts of organic P in the form of manure or sewage sludge are applied. Accumulation of high soil P has prompted legislation in certain states to limit the amount of P—either from fertilizer or organic wastes—that can be applied based on a soil P test (Sharpley et al. 1996, 2003).

ALTERNATIVE APPROACHES TO NUTRIENT MANAGEMENT FOR ENVIRONMENTAL CONSIDERATIONS

The issues of both nitrate and phosphorus as potential non-point pollutants are related to the movement of these elements to areas where the plant is no longer able to use them. There are a number of alternative crop and fertilizer management strategies that offer approaches to reduce potential non-point pollution. Many of these are currently the focus of potato research programs throughout North America.

To meet crop production needs while reducing potential negative environmental impacts, nitrogen applications timing can be manipulated. Rather than a single bulk pre-plant application, applications can also be made in season to coincide with periods of high plant nutrient demand. In a combination rainfed/irrigated potato production system, split applications have been shown to increase N use efficiency, reduce nitrate leaching, and maintain yield (Errebhi et al. 1998a). The practice was more effective in lower rainfall years since water application could be better controlled. In the arid Pacific Northwest, where in-season water applications are controlled, N fertilizer application has shifted to a combination of pre-plant application and fertigation to "spoon feed" the developing crop. The effectiveness of this technique to increase crop nutrient-use efficacy has been demonstrated and enabled growers to reduce total nitrogen inputs (Roberts et al. 1992).

A new approach for nutrient application strategies is site specific crop management (SSCM)—more commonly referred to as precision agriculture. With this crop production technique, inputs are applied where they are needed in the amount needed and when they are needed. When discussing SSCM for potato nutrient management in irrigated systems, the focus must not be on fertilizer placement alone, but also on water placement. As such, SSCM has the highest potential to reduce non-point movement of plant nutrients in the arid regions where there is little to no rainfall during the production season (Whitley and Davenport, 2003). In growing areas in central North America, irrigation is used to supplement rainfall and in the East, potato production is dominated by rain-fed culture. As the producer's control of water decreases, so decreases the effectiveness of SSCM as a tool for reducing non-point movement of plant nutrients. Systems have been developed to control water, and hence liquid fertilizer, on a site specific basis (Evans et al. 1996; King et al. 1996). Thus, using a site specific approach of pre-plant and in-season N applications provides a system to reduce application rates in areas (either within or between fields) and phenological periods associated with higher environmental risk.

Currently, variable-rate application of preplant fertilizers for meeting P and K requirements are based solely on the soil test values for the nutrient in question, with spacial interpolation across the field to predict values in non-sampled areas. The models used in variable-rate-application equipment can be modified to incorporate more than just the soil test value, which offers the possibility of improving crop response to variable rate fertilizer practices. Preliminary results from research on correlating fertilizer P response with various soil test factors (soil pH, Ca, Fe, and texture) has indicated that soil pH may be a good indicator of potato response to P fertilizer in low soil test P (2-12 ppm) situations (Table 1).

Another potential approach for managing nitrogen movement beyond the root zone is the use of slow-release materials. Slow-release fertilizer technology is not new. However, recent developments with polymer-coated fertilizers offer slow-release materials that are primarily temperature dependent in their release rates and are more predictable than conventional slow release materials such as sulfur-coated urea (Trenkel 1997). By altering the type of polymer coating, nitrogen release rate can be theoretically adjusted to plant demand based on soil temperature. If historical temperatures and nitrogen uptake characteristics of the crop are known, then the correct mixture of materials can be designed and applied for optimum nitrogen release.

Polymer-coated urea fertilizer seems to offer some promise in reducing nitrate losses for potato production. Recent work in Minnesota on coarse-textured irrigated soils has shown improvements in potato yield and quality with polymer-coated urea compared to the same rates applied as conventional urea (Rosen et al. 1997; Rosen and Birong 1998; Zvomuya et al. 2001). In these studies optimum N rate was 30% to 40% lower with coated urea compared to soluble urea. Implicitly, this indicates a higher uptake efficiency of nitrogen with the coated urea and a concomitant decrease in nutrient loss from the root zone. The primary disadvantage of slow-release materials is the cost, which can be four to eight times the cost of urea. In addition, in years where leaching of nitrogen is not significant, response to slow-release fertilizers is often negligible or not observed. Unless some incentives are provided or nitrogen use becomes regulated, adoption of slow-release fertilizers by potato producers will depend on whether the price can be reduced to be competitive with conventional fertilizers. However, despite the price, these materials do offer an appealling alternative to areas where high risk of enivronmental contimination might otherwise prevent production.

Use of other plants in potato-cropping systems offers a few avenues for managing non-point impacts of nutrients. Potatoes are most commonly grown in rotation with other crop plants for pest control (particularly disease) considerations. The choice of the preceding and following crop can influence nutritional management consideration. Growing potato after a legume crop would result in residual soil N and thus could reduce the amount of N applied early in the growing season and would offer a "time-release" material. However, timing of crop residue incorporation influences efficacy. Sanderson and MacLeod (1993) found that early fall-incorporated legume was less effective as a nitrogen source than when it was incorporated in the late fall. Additionally, following the potato with a deep-rooted plant or a highly efficient "scavenging" crop—for example, sugar beet (*Beta vulgaris* L.)—could

TABLE 1—*Relationship of potato yield and quality to soil pH and P fertilizer rate. Data from Davenport et al. (1998).*

Soil pH Level	P Fertilizer Rate (kg ha^{-1})	Yield* (Mg ha^{-1})	U.S. #1* (%)
Low (6.1-6.5)	29	57.45 a	95.21 a
	120	47.98 b	93.75 b
	169	50.65 b	93.42 b
High (8.0-8.1)	29	52.98 b	94.14 b
	120	51.77 b	95.78 a
	169	54.68 a	95.85 a

*Significant between the 0.05 and 0.01 level. Mean separation LSD 0.05 level.

result in mining any residual N or P from the system. This approach is especially important for potatoes, where rates of P applied are often in excess of removal (Bertilsson and Forsberg 1997).

A slightly different approach would be the use of cover crops following potato, rather than leaving the soil "fallow" for the winter season. Recent research has shown that planting grass or cruciferous plants following the potato offers an opportunity to recycle post harvest N into plant biomass. Recent research has shown increased N available for plant uptake in the surface 45 cm of soil when winter cover crops were grown vs when fields were left fallow for the winter or planted to crops that did not survive the winter (Pan et al. 1997; Weinert et al. 2002). In eastern Canada, mean annual nitrate concentration in tile drainage effluent from a potato field was reduced up to 30% compared to the control when winter wheat was seeded immediately following harvest of an early potato crop (cv Superior). Similar results were obtained when immobilization of residual soil N was enhanced through spreading and incorporating cereal straw immediately following potato harvest (Milburn et al. 1997). Collectively, these management strategies have promise for most growing areas regardless of the precipitation pattern. However, areas with extreme winters may not be able to locate suitable plants that can provide the desired winter cover. Conversely, areas where summer temperatures do not allow for complete breakdown of the added or grown plant material may limit the adaptation of this practice.

Several investigators have shown that there is considerable variation in nitrogen uptake efficiency within available potato germplasm and existing potato cultivars (Kleinkopf et al. 1981; Sattelmacher et al. 1990; Errehbi et al. 1998b; Zebarth et al. 2004). This suggests that the commercial potato cultivars of the future could be designed for more efficient nitrogen extraction, through either traditional plant breeding approaches (Errehbi et al. 1999) or using genetic engineering. Plant-breeding programs typically have focused on increasing crop yield and quality with the assumption that nutrients are not a limiting factor. The focus of these programs could be broadened to also select for plants that have higher nutrient-uptake efficiencies (Gilles Saindon, pers comm). Developments in these areas could provide major additions to the current fertilizer, soil, and crop management tools used to reduce nitrate leaching potential.

HEAVY METAL CONTAMINATION IN FERTILIZERS

In the spring of 1997, the Seattle Times printed an article that discussed heavy metal contamination of fertilizers as an environmentally hazardous issue. The article was triggered by reports of some unresolved crop production (including potato) problems in the Columbia Basin of Washington State. Of particular concern was using fertilizer materials in agricultural production that are derived from waste products (either relabeled materials or used as raw materials to produce fertilizers) that contain "tag-along" heavy metals. The newspaper article was featured on the World Wide Web to increase interest and distribution. Virtually overnight, the relatively small local issue of trying to determine if there is a soil contamination problem from repeated use of registered agricultural fertilizer supplements became a national focus (Wilson 2001).

Depending on the material, there are some inherent impurities in conventional fertilizer materials. The base material for making phosphorus and potassium fertilizers are naturally formed mineral materials, which typically are mined from either below ground or surface deposits. Of these two macronutrients, concerns with tag-along heavy metals are generally associated with phosphorus. Other plant nutrient or soil-conditioning additions are derived from mined mineral deposits also—with agricultural lime being a familiar example. Additionally, several of the essential mineral elements often provided as either granular or liquid fertilizers are considered heavy metals—e.g., copper, zinc, and iron. Historically the issue that has received the most attention is cadmium in phosphorus fertilizers (PPI 1998). A recent study from Australia reports a wide variability in cadmium content of potato tubers grown on commercial farms; however, tuber cadmium could not be related to soil cadmium content (McLaughlin et al. 1997).

The entire issue is extremely complex. In an era where waste disposal is an increasingly problematic issue, looking to land application to take materials that can supply plant nutrients is a very attractive approach. Land application of wastes is far from a new concept. Prior to the availability of low-cost soluble commercial fertilizers, animal waste products (especially manures) were regularly applied to soils. With the resurgence of interest in "organic" and "sustainable" production systems, there is renewed interest in using "recycled products." For example, byproducts from fish processing are often turned into fertilizers for sale on the commercial market. These recycled products, plus manures and other organic materials also contain impurities that can equal or exceed that in conventional soluble fertilizer materials.

Soils, and the rocks they are formed in, are highly variable in their native content of metals (Table 2). To address the issue of cadmium loading, nine countries have either mandatory or voluntary restrictions on the cadmium content allowed in phosphorus fertilizers. Canada has long had regulations on the amount of impurity loading allowed with fertilizers use (Table 3). Developing these limits involves determining the amount of a heavy metal contaminant naturally occurring in soil and then restricting the amount that can be added as impurities to focus on preventing a build up over time.

To date, Washington State has developed standards for the amount of heavy metals loading from conventional fertilizers (Table 3). Like many other states, there already are restrictions on the amount of loading allowable with biosolid materials. The advent of this entire issue suggests that national standards may be forthcoming.

TABLE 2—*Mean concentrations of selected heavy metals in bedrock (soil forming) and soil materials. Data from PPI (1998).*

Source		Cadmium	Copper	Lead	Nickel	Zinc
		mg kg^{-1}				
Basalt		0.13	90	3	150	100
Granite		0.09	13	24	0.5	52
Limestone		0.03	5.5	5.7	7	20
Soils From:	No. of Samples					
U.S.	2771	0.155	15.5	10.4	17.1	41.1
Idaho	54	0.338	20.9	10.4	24.4	64.3
Maine	27	0.165	64.8	12.6	41.2	71.8
Minnesota	89	0.280	21.8	12.0	29.5	68.0
Washington	122	0.184	26.7	8.5	26.4	66.0
Wisconsin	94	0.207	17.1	10.1	17.5	53.5

TABLE 3—*Canadian and proposed Washington standards for maximum acceptable cumulative metal additions to soil.*

Metal	Canadian standards for maximum acceptable cumulative additions to soil (kg ha^{-1}) over a 45 year period[y]	Proposed Washington State standards for maximum allowable soil loading (kg ha^{-1} yr^{-1})[z]
Arsenic	15.0	0.333
Cadmium	4.0	0.088
Cobalt	29.9	0.665
Lead	99.8	2.219
Mercury	1.0	0.021
Molybdenum	4.0	0.088
Nickel	35.9	0.713
Selenium	2.8	0.062
Zinc	369.3	8.208

[y]Data from PPI 1998.
[z]Data from Washington Agricultural Code (WAC) 16-200-7064.

NUTRIENT MANAGEMENT IN THE FUTURE

Improved yield and quality in potato production through additions of conventional soluble fertilizers is well documented. Also well documented is that use above an optimal amount can actually decrease both yield and quality. With today's infrastructure, agricultural products can be grown in very specialized areas and transported to a large market either directly or as processed goods. The land ideal for agricultural production, however, often is ideal for other uses—for example, buildings or roads. This often results in a loss of prime farm land, moving agricultural production to less optimal areas, and increasing the need to supplement production with water, nutrients, and other management needs.

Maintaining and improving potato production over time while maintaining environmental quality encompasses several issues. Certainly efforts to prevent movement of prime land out of agriculture are key. This paper also highlighted several research approaches to develop alternative nutrient-management strategies for potato production. Balancing both environmental and crop production needs in the future, land management will likely become more complex, using a combination of approaches to manage production units specifically based on soil and topographic characteristics to optimize production.

SUMMARY

Fertilizer forms, application technologies, and crop rotations all play roles in nutrient management. However, increasing scrutiny of nutrient management as a source of environmental contimation will continue to affect potato production practices. Research to develop practices that enable the producer to sort through the host of new technologies and chose those that are both environmentally and economically advantageous must be continued in light of emergring issues like fertilizer purity and phosphorus mobility in soils.

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