DIRECT AND INDIRECT NITROUS OXIDE EMISSIONS FROM CONTROLLED RELEASE AND CONVENTIONAL FERTILIZERS APPLIED TO POTATOES IN COARSE TEXTURED SOIL

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Charles R. Hyatt

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Dedication

For my girls - the three 'M's.

Abstract

Irrigated potato (*Solanum tuberosum* L.) production requires significant inputs of fertilizer N for optimal tuber yield and quality. However, high N rates carry the risk of high N loss, particularly in coarse-textured, well-drained soils where potatoes are commonly grown. Polymer coated controlled-release ureas (PCU) have shown promise in reducing NO_3^- leaching, a groundwater quality concern, and may potentially also reduce emissions of N_2O, a greenhouse gas with nearly 300 times the warming potential of carbon dioxide. However, comparisons of multiple PCUs are uncommon. Studies were conducted over three years to compare N loss (as NO_3^- and N_2O), yield response, and N use efficiency (NUE) from an unfertilized control, split applied conventional N fertilizer (CSA), and two PCU products (PCU-1 and PCU-2) applied at 270 kg N ha^{-1} yr^{-1}. Tuber yields, NUE, and leaching did not differ among fertilized treatments. Directly measured N_2O emissions were significantly lower with PCU-1 than CSA. Fertilizer induced emissions were relatively low, ranging from 0.10 to 0.49% of applied N. Indirect N_2O emissions, estimated using the IPCC default emission factor of 0.75% of NO_3^- leached, were significantly lower than direct emissions. However, due to uncertainty, indirect emissions could be anywhere from 0.6 to 84.9% of direct. These results show that PCU can potentially reduce N_2O emissions. However, results are product specific and work remains to be done in narrowing the indirect emission factor uncertainty range.

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Introduction

This thesis is comprised of four sections – excluding this brief introduction. The first and last of these are a generalized literature review and conclusion section, respectively. The second and third sections, referred to as Part 1 and Part 2, were authored as standalone manuscripts with the aim of achieving publication, and thus are written in the style and format dictated by the journal to which they were submitted.

Part 1, "Polymer-Coated Urea Maintains Potato Yields and Reduces Nitrous Oxide Emissions in a Minnesota Loamy Sand", was written in collaboration with R.T. Venterea, C.J. Rosen, M. McNearney, M.L. Wilson, and M.S. Dolan and was published in the Soil Science Society of America Journal (Hyatt, C.R., R.T. Venterea, C.J. Rosen, M. McNearney, M.L. Wilson, and M.S. Dolan. 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. Soil Sci. Soc. Am. J. 74:419-428). For this publication, Carl Rosen, Matt McNearney, and Melissa Wilson contributed potato yield and fertilizer prill release data. Rod Venterea provided significant language pertaining to the 2009 (third) season, as well as addressing specific reviewer concerns.

Part 2, "Nitrogen Use Efficiency, Leaching Losses, and Effects on Potential Indirect N_2O Emissions in Three Alternative Best Management Practices for Irrigated Potato Production", was also written in collaboration with R.T. Venterea and C.J. Rosen. Carl Rosen contributed vine and tuber N analysis data, as well as biomass yields. Much of the data presented in this chapter has been submitted for publication to the Journal of Environmental Quality in a substantially modified form with the listed collaborators.

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Literature Review

POTATO HISTORY, BIOLOGY, AND PRODUCTION

Potato as a Food Crop

The common cultivated potato (*Solanum tuberosum*) has long been grown for human consumption. Potatoes are generally accepted to have originated as a food crop in the Andes Mountains (southern Peru into Bolivia) between 7000 and 8000 years before the present (Burton, 1989). However, wild species continue to be collected today as far north as the southwestern United States (Burton, 1989). There are over 150 species of potato known, most of which can be found near the point of origin (Burton, 1989). However, only seven are commonly cultivated (Van den Berg and Jacobs, 2007). The Spanish were the first to transport potatoes to Europe, where after an initial period of being viewed as poisonous, they became widely grown (Burton, 1989). Only later, when the potato was reintroduced as a cultivated crop into North America by European colonists, did it become common in what is now the northern continental United States (Burton, 1989; Salunkhe and Kadam, 1991; Dean, 1994).

A globally important food source, the potato is the world's largest non-cereal food crop, ranking fourth after maize, wheat and rice in kg produced (FAOSTAT, 2010). Containing up to 20% starch and 2.5% protein, potatoes are also a nutrient dense food providing high levels of essential minerals and vitamins, including: potassium, phosphorus, magnesium, vitamin C, niacin, and vitamin B6 (NND, 2009). As of 2008, over 18.8 million Mg of potatoes are produced annually in the United States (NASS, 2009a).

Minnesota Agriculture

The state of Minnesota ranks 7th nationally in potato production (NASS, 2009a). Minnesota is located approximately 45° N latitude and 93° W longitude in the Midwest United States. It is the 12th largest U.S. state with an area of 225,000 km^2, of which 48% is in agricultural production (NASS, 2009b). Average annual temperatures range from -3 to 10 °C with a 170 day growing season in the north to 2 to 13 °C with a 200 day season in the south (MCWG, 2010). Annual precipitation ranges from 860 mm in the southeastern corner to 480 mm in the northwest (MCWG, 2010). In 2008, Minnesota harvested 19,425 ha of potatoes with a 96% harvest rate for all land planted (NASS, 2009a). The largest potato producing region in the state is the central district (Sherburne, Morrison, and Todd counties) with 37% of the statewide total (Bennett and O'Rourke, 2002). Soils in this region (referred to as the Anoka Sand Plain) are typified by coarse textured loamy sands formed from glacial outwash and lacustrine sediments (Meyer et al., 1993).

Physiology of Potato

The potato is a member of the nightshade family of plants and is closely related to tomatoes, peppers, tobacco, and eggplant (Dean, 1994). It is grown as an annual, but considered by some to be a perennial as it is typically propagated through seed tubers and reproduces vegetatively (Dean, 1994). The potato will occasionally produce a seed ball

within a small greenish fruit that resembles a tomato, but individual seeds may be infertile or not breed true to form (Burton, 1989; Dean, 1994). Seed, however, is lower in cost, less susceptible to disease, and easier to transport and store than tubers and is used successfully in a number of countries for propagation, especially when tuber uniformity is not a primary concern (Burton, 1989; Dean, 1994; Gopal and Ortiz, 2006).

In the United States, potatoes are typically propagated via seed tubers. A seed tuber is a tuber from a previous season's planting that is re-planted to initiate the current year's crop. Each seed tuber is covered with a number of buds, or 'eyes', from which new growth develops. The use of seed tubers allows for clonal reproduction and assures conformity and preservation of desirable tuber characteristics (Dean, 1994).

After planting, one or more main stems emerge from each seed tuber and grow to a height of 0.6 to 1.5 m (Dean, 1994). Additional branches may develop from lateral fibrous secondary roots (called stolons) if exposed to light (Dean, 1994). Initially plants tend to remain vertical, but upon flowering the vines spread and become increasingly prone (Dean, 1994). As stolons develop, their tips can enlarge greatly to produce a tuber. Each stolon may produce a tuber, although some do not, and the eventual number is largely dictated by the type and variety of potato (Burton, 1989; Dean, 1994). Plant stress, short days (10-14 hours), and cool nighttime temperatures promote tuber development and growth, while high temperatures can reduce or stop development (Dean 1994).

Potato Production

Potatoes require well-aerated, well-drained soil for optimal tuber development, so field preparation is essential for a successful harvest. A field is typically plowed in the spring to incorporate pre-plant fertilizers, distribute and incorporate organic matter, and break up any compacted areas that would contribute to ponding and anaerobic conditions. Anaerobic conditions can support bacterial pathogens and promote tuber rot. They can also stress the plant, causing it to become susceptible to many other pests and pathogens (Dean, 1994). A coarse-textured well-drained soil can help alleviate these problems as well as encourage higher yields and more uniform tubers (Govindakrishnan and Haverkort, 2006). Potatoes in Minnesota are increasingly grown in these types of soils, typified by the sand plains of the central district (Waddell et al., 1999).

Planting in Minnesota takes place in late April through May after soil temperatures reach about 6.8° C at planting depth. Seed potatoes are planted 0.2-0.4 m apart, 80 mm beneath the soil surface, in rows that are spaced at 0.8-0.9 m (Bennett and O'Rourke, 2002). Current best management practices recommend that N fertilizer be added in at least three split applications: at planting, at emergence, and 15 to 20 days following emergence (Rosen and Bierman, 2008). Additional N fertilizer may be applied based on petiole analysis (Rosen and Bierman, 2008). Fungicide applied at planting is sometimes used to prevent seed potato decay (Bennett and O'Rourke, 2002).

Stem growth is largely dictated by temperature (Burton, 1989; Dean, 1994). Requirements vary, but for many of the cultivars grown in Central Minnesota, 20° C is close to an optimum temperature for emergence (Dean, 1994). When the potato plant

reaches about 50 mm in height, a hilling and cultivation step is performed to control weeds, to promote tuber growth, and to prevent sun and late season frost damage to tubers (Dean, 1994; Scherer et al., 1999). In this procedure, soil is moved using a cultivator or a designated potato hiller from the furrow between planted rows up to cover either side of the plants in the row (Dean, 1994). Small dams may also be formed regularly in the furrow to help capture and hold water to promote infiltration during future irrigation (Dean, 1994). Pesticides are applied in response to current field requirements and may include fumigants to control nematodes and pyrethroids or neonicotinoids for insects such as Colorado potato beetle or green peach aphids – a significant vector of viral pathogens (Burton, 1989; Radcliffe, E.B. 2010).

Much of the potato crop in Minnesota is irrigated, which is used to maintain tuber size and quality in coarse textured soils with little water holding capacity (Bennett and O'Rourke, 2002; Shock et al., 2007). Irrigation timing depends on soil type, current microclimatic conditions, and crop growth stage. It is recommended that water be added to replace that which is lost through evapotranspiration and that soil moisture be kept at about 80% of field capacity until tuber formation (Burton, 1989; Dean, 1994).

Harvest for processing potatoes in Minnesota typically occurs in September when vines are first removed either mechanically (e.g. flail mowing) or via desiccation with a non-translocated herbicide (Dean, 1994). Potatoes can be harvested mature or immature. However, mature tubers tend to be hardier, store better as they resist skinning and bruising, and are easier to process (Kadam et al., 1991). Planting and harvesting times, as well as potato variety, can vary the maturation date, but weather and the market

sometimes dictate an immature harvest (Dean, 1994; Kadam et al., 1991). Harvesting can be done by hand, but is typically mechanized in the U.S. During harvest, tubers are dug, separated from soil, stones, and vine residue, and then moved off the field. Once potatoes are harvested, they are sorted with respect to quality, size, and specific gravity (Dean, 1994; Kadam et al., 1991). Processors require uniformity of size and shape, particularly for potatoes which are used for French fries (Kadam et al., 1991).

NITROGEN IN THE AGRICULTURAL SYSTEM

Nitrogen is an essential nutrient in agricultural systems. It is a primary component in proteins, amino acids, and nucleic acids, and important for many biological functions (such as photosynthesis), but N in a plant available form is relatively scarce in the environment (Bucher and Kossmann, 2007; Voroney and Derry, 2008). Most non-geologic N ($300,000$ Mg ha^{-1}) is found in the atmosphere and is locked in strong, un-reactive, triple-bonded dinitrogen molecules (Voroney and Derry, 2008). Nitrogen can be made available by the photochemical action of lightning (Voroney and Derry, 2008). However, most plant available N in the soil that is not the product of synthetic N fertilizers is produced through either biological fixation (Russell, 2008) or the release of N compounds from organic matter through the process of mineralization (Olk, 2008).

Biological Nitrogen Fixation

A myriad of different species of diazotroph, or nitrogen fixing organism, exist in the soil, but all can be classified as one of two different groups: free-living and those that form symbiotic relationships with plants. Symbiotic bacterial nitrogen fixers such as rhizobia are a predominant contributor of non-fertilizer N in agricultural systems (Russell, 2008). Rhizobia infect the roots of legumes, typically through the root hairs, and trigger the production of nodules. Within these nodules, plants supply Rhizobia with vitamins, sugars, amino acids, and other useful compounds as a carbon and energy source. In turn, the Rhizobia break apart the dinitrogen molecules using nitrogenase enzymes and provide directly usable N compounds such as ammonium (NH_4^+) and amino acids to their host plant (Russell, 2008). Some of these compounds 'leak' and are lost directly to the soil becoming available to other plants (Russell, 2008). It is estimated that by the mid 1990's, about 20% of agricultural use N was supplied by biological N fixation (Smil, 2001).

Nitrogen Mineralization

Biological N can also be introduced into the soil from the incorporation of organic matter. In this case, N is often locked up as a component of an organic molecule and must be made plant available through the process of mineralization. Mineralization occurs when microorganisms break proteins and humic substances down into simple amino compounds which are then hydrolyzed to release the ammonium ion, NH_4^+ (Myrold and Bottomley, 2008). Ammonium can also be reintegrated into organic compounds by soil

bacteria in a process opposite to mineralization called immobilization. Immobilization typically occurs in a carbon rich environment where bacterial population expansion fueled by the excess carbon utilizes N to build biomass (Myrold and Bottomley, 2008).

The Nitrogen Cycle

The process of changing N from one form to another depends on the health and activity of the communities of soil organisms that carry out these processes. Different organisms need specific soil moisture contents, temperatures, pH, soil oxygen levels, and quantities and types of N compounds present in the soil to thrive (Norton, 2008). For example, the ammonium ion described above is directly useable by plants, but it is readily converted in the soil to nitrate (another plant available N compound) through the process of nitrification (Norton, 2008). Nitrification occurs in two steps whereby ammonia is first converted to nitrite by ammonia-oxidizing bacteria such as *Nitrosomonas*. *Nitrobacter* or similar bacteria then complete the conversion by oxidizing nitrite to nitrate.

This process is strongest in aerobic conditions as *Nitrosomonas* and *Nitrobacter* are both highly preferential aerobes (Norton, 2008). In conditions where soil oxygen has been depleted, most commonly through saturation with water, the process of denitrification becomes dominant (Coyne, 2008). In denitrification, soil organisms utilize nitrate as an electron acceptor for metabolism in the absence of oxygen and convert it back into dinitrogen gas which eventually finds its way back to the atmosphere (if it is not first re-converted once again).

Conversion of N from one compound to another is not always direct and often requires a number of steps, as typified by the nitrification process described above. Intermediate compounds with their own properties are often formed such as in denitrification, for example, where a complete reduction to dinitrogen does not always occur (Coyne, 2008). Some of these compounds can volatilize and enter the atmosphere directly (e.g. nitrous oxide). Others may move out of the soil by leaching as rain or irrigation water moves through the profile. In fact, negatively charged nitrate, although not considered an intermediate as described above, travels easily with water past negatively charged micro-sites in the soil to leach well below the root zone of many plants that could use it as an N source. The movement of N through the environment and its conversion from one form to another through these various processes is referred to as the N cycle.

Nitrogen Soil Amendments

The practice of supplementing the available N in a given agricultural soil developed as farmers observed the benefits of adding crop residue, animal manures, and other organic matter to their fields. Initially crops would be grown on a section of land until soil nutrients were depleted. Fields would then be allowed to go fallow to let natural processes again build up nutrients to pre-production levels. Vast land resources allowed farmers to switch to new areas regularly to tap into virgin nutrient pools. However, as populations increased, population pressure forced the reliance on smaller and smaller acreage and farmers needed to revisit depleted fields more often. They soon discovered

that the addition of organic matter to the soil could prevent nutrient, and particularly N, deficiency symptoms in crops allowing them to successfully limit field exchange while still maintaining acceptable yields.

By the mid-1800's, commercial agriculture had reached a level such that traditional, locally supplied, supplemental N sources could not meet growing demand. Producers began to look afield for additional sources of fertilizer N. Guano, deposited by sea birds on the islands off the coast of Peru, was found to be high in nitrate-N and was imported in massive quantities to the U.S. and Europe for use as a N fertilizer (Clark and Foster, 2009). However, within a few decades stocks began to be depleted and by the late 19th century the 'guano era' came to a close (Sheridan, 1979). Guano is still used on a limited basis as an organic fertilizer (Gaskell and Smith, 2007). Large stores of naturally occurring sodium nitrate found in Chilean caliche beds have also been mined and used as a source of agricultural N. Production of Chilean N peaked and dropped off after the introduction of lower cost ammonia synthesis via the Haber-Bosch process early in the 20th century (Clark and Foster, 2009).

Synthetic Nitrogen Fertilizer Development

The conflict of the First World War and the Allied powers' fear that sodium nitrate would be used in the creation of military armaments resulted in a blockade of the South American N that had been supplying German agriculture and explosives production (Erisman et al., 2008). In response, researchers in Germany searched for ways to derive usable N compounds by directly breaking down the dinitrogen molecules from

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the air. A number of processes were mildly successful, but tended to require high energy

inputs while remaining woefully inefficient (Smil, 2001). It was the method first

demonstrated by Fritz Haber in 1909 and scaled up to an industrial level in 1913 by Carl

Bosch that finally proved to be sufficiently productive to supply Germany's wartime

ammonia needs (Erisman et al., 2008). The Haber-Bosch process produces ammonia

from atmospheric N and hydrogen (typically derived from natural gas). The mixture of N

and H gasses is passed over a metallic iron oxide catalyst at 15-25 MPa of pressure and

between 300 and 550° C resulting in NH_3 (Smil, 2001). Altogether, 80% of NH_3

produced is destined for agricultural fertilizer (Erisman et al., 2007).

Cultivated potato systems in the U.S. require significant inputs of fertilizer

nitrogen. In Minnesota, current best management practices recommend that between 260

and 280 kg ha^{-1} N be applied to maintain yields of 56 t ha^{-1} (Rosen and Bierman, 2008).

AGRICULTURAL AND ENVIRONMENTAL CONCERNS OF NITROGEN FERTILIZERS

Deficiencies and excesses of nitrogen are commonly recognizable and repeatedly

cited as problematic. This is the case not only in production agriculture, but in home

gardens and lawns, air and water quality, and even human health.

Nitrogen Deficiencies

Nitrogen deficient plants commonly display symptoms of stunted growth and

yellowing of the leaves (Dean, 1994). Nitrogen is easily translocated within a plant, so

deficiencies first appear in older leaves as the plant attempts to compensate and supply

newer and actively growing areas (Bucher and Kossmann, 2007). Symptoms tend to be

quickly alleviated when additional N is supplied (Bucher and Kossmann, 2007).

Adequate supplies of N during critical growth periods have been linked to significantly

increased yields (Burton, 1989).

Nitrogen Excesses

Because synthetic N fertilizers in modern agricultural systems have been

relatively inexpensive, some producers have attempted to supply N in excess to eliminate

any chance of deficiency. However, excess N may cause problems by encouraging

excessive vegetative growth in a plant resulting in structural weakness (lodging) or

increased susceptibility to insect pests (Rosen and Bierman, 2008). Plant available forms

of N can also be quite mobile in the soil. While the positively charged ammonium ion

tends to be attracted to negatively charged soil clay particles, the transformation of NH_4^+

to the negatively charged nitrate ion tends to be fairly rapid (Norton, 2008). Excess

nitrate, which shares the same charge as the soil in temperate regions, can move easily

with water through the soil profile, ultimately ending up in groundwater (Addiscott et al.,

1991).

High levels of nitrate in drinking water can cause health problems for infants and

those with compromised gastrointestinal systems. Methemoglobinemia, or 'Blue baby

syndrome', occurs when nitrate is converted to nitrite by bacteria growing in the weak

acid environment of an infant's stomach (Addiscott et al., 1991). Nitrite then interacts

with hemoglobin in the blood forming methemoglobin, a compound which is extremely poor at transporting essential oxygen to vital organs (Addiscott et al., 1991). In response, the USEPA has set the human health level of nitrite-N in drinking water at 10 mg N L^{-1} (USEPA, 2009). Nearly 6% of drinking water wells in Minnesota were found to exceed this level (Lewandowski et al., 2008). Potato production has been found to be a significant predictor of elevated ground water nitrate (Benson et al., 2006) and water collected from under coarse textured soils where potatoes are regularly grown has been found to contain up to 20 mg N L^{-1} (Kraft and Stites, 2003).

Nitrogen can also move from ground to surface waters and upset the nutrient balance in lakes and streams. Excess N and other agricultural chemicals can result in explosive growth of aquatic plants and organisms usually kept in check by a nutrient limited environment (Addiscott et al., 1991). The ultimate death and decay of these organisms strip oxygen from the water causing hypoxic 'dead zones' devoid of complex life (Scavia et al., 2003). Nitrogen rich water drained from agricultural lands in the Mississippi river basin has been suggested as the cause of recent growth in the Gulf of Mexico hypoxic area (Scavia et al., 2003)

Nitrous Oxide

Excess N can also be lost in a gaseous form. As an intermediate of denitrification, and to a smaller amount nitrification (Firestone and Davidson, 1989; Venterea, 2007), nitrous oxide (N_2O) has recently gained attention as a potentially significant contributor to atmospheric greenhouse gas loading. N_2O has a global warming potential nearly 300

times greater than carbon dioxide (CO_2) and global atmospheric N_2O concentrations are rising at approximately 0.26% per year (Forster et al., 2007). As of 2008, it contributed 4.6% of total annual U.S. greenhouse gas emissions in CO_2 equivalents (USEPA, 2010). Within the US, 68% of anthropogenic N_2O emissions originate from agricultural practices (USEPA, 2010). Overall emissions of N_2O from U.S. agricultural soils have increased 6.1% from 1990 to 2008 (USEPA, 2010).

Nitrous oxide emissions from agricultural sources can enter the environment via direct and indirect pathways. Direct emissions originate in managed agricultural fields, while indirect emissions occur in locations that are geographically removed from the original N application site. Denitrification processes in ground and surface waters are likely to be the ultimate source of most indirect N_2O emissions (Mosier et al., 1998; Nevison, 2000). However, there is still much uncertainty as to how much indirect emissions contribute to the total agricultural N_2O loads (Mosier et al., 1998).

NITROGEN FERTILIZER MANAGEMENT AND TECHNOLOGY

Various technologies and cultural practices have been suggested in an attempt to better match N supply to overall plant demand. The goal has been to provide just enough N to maximize yields in a cost effective manner while minimizing N loss. As profit margins in agriculture have tightened, any loss of an input, in addition to being an environmental liability, comes directly out of the producer's pocketbook.

Fertilizer Management Practices

Agricultural N can be managed in a number of ways. Nitrogen application rate is perhaps the first focus of a producer when faced with modifying current practices in response to budgetary or environmental concerns. Rate is dependent on cultivar, anticipated harvest date, yield goals, and amounts of residual N present in the soil (Rosen and Bierman, 2008). Previous legume crops and N present in irrigation water can supply a portion of required N needs and should be taken into consideration (Rosen and Bierman, 2008). In addition, a late maturing cultivar, such as Russet Burbank, generally requires higher rates of N than earlier maturing varieties (Rosen and Bierman, 2008). By matching supply to specific on-farm conditions, an optimal amount of fertilizer can be applied to maximize yield without exceeding the requirements of the crop. However, as of 1995, central Minnesota potato producers still applied 14-16 kg ha^{-1} more than the University of Minnesota Extension BMP's average recommendations of that time (Bruening, 1996).

A second approach to N management is fertilizer application timing. In potato production, N fertilizer has traditionally been applied either entirely at the beginning of the season (at planting or preplant) or in a 50/50 split application with half either before or at planting, and the remainder as a side or top dressing after tuber initiation (Burton, 1989; Salunkhe et al., 1991). The 50/50 split is an attempt to provide sufficient N to assure timely tuber development and to delay senescence while reducing potential deleterious effects of early over-application, including excessive vegetative growth, plant

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weakness, and leaching (Govindakrishnan and Haverkort, 2006; Rosen and Bierman, 2008).

Recent best management practices in Minnesota recommend not one but multiple split applications with the first at planting, and the remainder during the period of peak plant N demand, which occurs between 20 and 60 days post emergence (Rosen and Bierman, 2008). In addition to the agronomic reasons, split applications attempt to prevent N leaching which can cause groundwater degradation (Rosen and Bierman, 2008). Central Minnesota producers apply over 4 applications of N per season, on average (Bruening, 1996). Applications typically take place at planting, emergence, hilling, and post hilling (Bruening, 1996). Applications of N are frequently made by adding fertilizer to irrigation water, called fertigation, which has shown to increase NUE in potato crops, but may also increase the risk of leaching (Bruening, 1996; Rosen and Bierman, 2008).

Technologies to Manage Nitrogen Availability

An alternative to split application of N is to modify the N fertilizer itself so that N becomes available at a gradual rate paralleling plant demand or remains available for a longer period of time. There are two general methods by which N fertilizers containing urea are modified. The first is to include a compound in the fertilizer that inhibits transformation of N into forms that are not plant available or are easily lost (e.g. N_2 or NO_3^-). Urease inhibitors slow the rate of enzymatic hydrolysis in the soil, limiting the initial formation of NH_4^+ from the amide-N found in urea (Trenkel, 1997). Nitrification

inhibitors prevent the transformation of NH_4^+ to nitrite by suppressing the activity of

Nitrosomonas bacteria (Trenkel, 1997; Norton, 2008). As NH_4^+ is much less mobile in

the soil than the negatively charged nitrite ion or its successor NO_3^-, there is a much

smaller chance of N loss through leaching, yet N is still plant available (Trenkel, 1997;

Norton, 2008). The denitrification process also begins with NO_3^- and nitrite, so

nitrification inhibitors can significantly reduce gaseous N loss as well (Delgado and

Mosier, 1996).

The second way urea is modified is by applying a controlled release semi-

permeable coating that meters out N at a prescribed rate. The first generally available

coated ureas which became available in the 1960's are encapsulated with sulfur and

contain between 30 and 40% N (SCU; Trenkel, 1997). The S coating is slowly broken

down in the soil through microbial, chemical, and physical processes, producing or

enlarging micro-openings from which N is released (Trenkel, 1997). However, up to 1/3

of S coatings in a typical sample of SCU may be damaged producing fast initial N release

('burst') upon contact with water while 1/3 are 'perfect' with no openings which prevents

release until long after peak plant N demand (Shaviv, 2000). Because of this, it is very

difficult to control the precise timing of N release with SCU (Shaviv, 2000).

Recently a number of polymer coated ureas (PCUs) have been designed to

provide more consistent and predictable N release characteristics than SCU to meet the

needs of horticulture and lawn & garden markets (Trenkel, 1997). PCUs allow water to

pass by diffusion through a semipermeable membrane, or through pores in an

impermeable polymer coating, and once inside, dissolve the urea which then can move

back though the coating and into the soil (Trenkel, 1997; Agrium, 2009b). Diffusion

characteristics are determined by temperature, coating composition, and coating

thickness; and damage to the coating or rupture can significantly increase the fertilizer

release rate (Trenkel, 1997; Shaviv, 2000). Polyurethane, polyolefin, and alkyd resins are

all used as coatings by various PCU manufacturers (Trenkel, 1997). The proposed

advantage of PCUs is that their use can deliver the same benefits as split applied

fertilizers without the increased field and equipment time inherent in multiple

applications (Shaviv, 2000). However, until recently, most economic benefits were

outweighed by higher product costs associated with PCU (Trenkel, 1997). New

production methods within the last 10 years have brought the price of PCU down

substantially and growers are once again evaluating the benefits of its use (Wilson et al.,

2009b).

RESEARCH OBJECTIVES

The overall objectives of this research were to:

1.) Quantify and compare direct N_2O emissions under four alternative management systems including a CSA, similar to recommended BMPs, single preplant applications of two different PCU, and an unfertilized control;

2.) Characterize Russet Burbank potato yield and NUE using five different NUE calculations under these same four systems;

3.) Compare the rate of N release in the two PCU products during *in situ* incubation;

4.) Evaluate two ET models for applicability in calculating NO_3^- leaching in Minnesota, including a modified Jensen-Haise and the FAO 56 Penman-Monteith equations;

5.) Compare treatment effect on NO_3^- leaching, and by extension, estimated indirect N_2O emissions;

6.) Compare estimated indirect N_2O emissions to direct for the four management systems using the IPCC default emission factor, as well as the factors lying at the endpoints of the uncertainty range.

REFERENCES

Addiscott, T.M., A.P. Whitmore, and D.S. Powlson. 1991. Farming, fertilizers and the nitrate problem. CAB International, Wallingford, UK.

Agrium, 2009b. ESN Smart Nitrogen: A smarter source of nitrogen, a smarter way to grow. Potato. Available at http://www.smartnitrogen.com/pdf/10915%20ESNPotatoInfoSheet_LR.pdf (verified 14 Apr. 2011). Agrium Inc., Calgary, AB, Canada.

Bennett K. and P. O'Rourke. 2002. Crop profile for potatoes in Minnesota. Available at http://www.ipmcenters.org/cropprofiles/docs/MNpotatoes.pdf (verified 14 Apr. 2011). North Central Pest Management Center, St. Paul.

Benson, V.S., J.A. VanLeeuwen, J. Sanchez, I.R. Dohoo, and G.H. Somers. 2006. Spatial analysis of land use impact on ground water nitrate concentrations. J. Environ. Qual. 35:421-432

Bruening D. 1996. Potato survey: Central Sands 1995. Available at http://www.mda.state.mn.us/en/sitecore/content/Global/MDADocs/protecting/soil protection/fanmappotato.aspx (verified 14 Apr. 2011). Minnesota Department of Agriculture: Farm Nutrient Management Assessment Program, St. Paul.

Bucher, M. and J. Kossmann. 2007. Molecular physiology of the mineral nutrition of the potato. p. 311-329. *In* Vreugdenhil, D. *et al.* (ed.) Potato biology and biotechnology: Advances and perspectives. Elsevier. New York.

Burton, W.G. 1989. The Potato. 3rd Ed. John Wiley & Sons, Inc. New York.

Clark, B. and J.B. Forster. 2009. Ecological Imperialism and the Global Metabolic Rift: Unequal Exchange and the Guano/Nitrates Trade. Int. J. Comp. Sociol. 50:311-334.

Coyne, M.S. 2008. Biological denitrification. p. 201-254. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Dean, B.B. 1994. Managing the potato production system. Food Products Press, imprint of The Haworth Press, Inc. New York.

Delgado, J.A., and A.R. Mosier. 1996, Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. J. Environ. Qual. 25:1105-1111.

Erisman, J.W., A. Bleeker, J. Galloway, and M.S. Sutton. 2007. Reduced nitrogen in ecology and the environment. Environ. Pollut. 150:140-149.

Erisman, J.W., M.S. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter. 2008. How a century of ammonia synthesis changed the world. Nat Geosci. 1:636-639.

FAOSTAT. 2010. Food and Agriculture Organization of the United Nations. FAOSTAT. Available at http://faostat.fao.org/site/339/default.aspx (verified 14 Apr. 2011). Rome.

Firestone, M., and E. Davidson. 1989. Microbiological basis of NO and N_2O production and consumption in soil. p. 7-21. In M. Andreae and D. Schimel (ed.) Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley & Sons, Chichester, UK.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, *et al*. 2007.

Changes in atmospheric constituents and in radiative forcing. P. 131-234. *In* S.

Solomon *et al*. (ed.) Climate Change 2007: The Physical Science Basis.

Cambridge Univ. Press, Cambridge, UK.

Gaskell, M., and R. Smith. 2007. Nitrogen sources for organic vegetable crops.

Horttechnology. 17:431-441.

Gopal, J., and R. Ortiz. 2006. True Potato Seed. p. 557-585. *In* J. Gopal and S.M.P.

Khurana (ed.) Handbook of potato production, improvement, and postharvest

management. Food Products Press, imprint of The Haworth Press, Inc. New York.

Govindakrishnan, P.M. and A.J. Haverkort. 2006. Ecophysiology and agronomic

management. p. 179-229. *In* J. Gopal and S.M.P. Khurana (ed.) Handbook of

potato production, improvement, and postharvest management. Food Products

Press, imprint of The Haworth Press, Inc. New York.

Kadam, S.S., S.S. Dhumal, and N.D. Jambhale. 1991. Structure, nutritional composition,

and quality. p. 9-35. *In* D.K. Salunkhe, S.S. Kadam, and S.J. Jadhav (ed.) Potato:

Production, processing, and products. CRC Press. Boca Raton, Fl.

Kraft, G.J. and W. Stites. 2003. Nitrate impacts on groundwater from irrigated-vegetable

systems in a humid north-central US sand plain. Agr. Ecosyst. Environ. 100:63-

74.

Lewandowski, A.M., B.R. Montgomery, C.J. Rosen, and J.F. Moncrief. 2008.

Groundwater nitrate contamination costs: A survey of private well owners. J. Soil

Water Conserv. 63:153-161.

MCWG. 2010. Minnesota Climatology Working Group. Minnesota location selector. Available at http://climate.umn.edu/hidradius/radius.asp (verified 14 Apr. 2011). Minnesota State Climatology Office, St. Paul.

Meyer, G.N., C.J. Patterson, H.C. Hobbs, and J.D. Lehr. 1993. Surficial geology, plate 1. *In* G.N. Meyer and J. Jalteisek (ed.) Regional hydrogeologic assessment of the Anoka sand plain: Anoka, Chisago, Isanti and Sherburne Counties, Minnesota. Ser. RHA-1. Minnesota Department of Natural Resources, Division of Waters Regional Assessment. St. Paul.

Mosier, A., C Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput. 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycl. Agroecosys. 52:225-248.

Myrold, D.D., and P.J. Bottomley. 2008. Nitrogen mineralization and immobilization. p. 157-172. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

NASS. 2009a. United States Department of Agriculture. National Agricultural Statistics Service. Potatoes: 2008 summary. Available at http://usda.mannlib.cornell.edu/usda/nass/Pota//2000s/2009/Pota-09-24-2009.pdf (verified 14 Apr. 2011). Washington D.C.

NASS. 2009b. United States Department of Agriculture. National Agricultural Statistics Service. 2007 Census of agriculture: United States summary and state data. AC-07-A-51. Available at

http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapte
r_2_US_State_Level/usv1.pdf (verified 14 Apr. 2011). Washington D.C.

Nevison, C. 2000. Review of the IPCC methodology for estimating nitrous oxide
emissions associated with agricultural leaching and runoff. Chemosphere – Global
Change Sci. 2:493-500.

NND. 2009. United States Department of Agriculture, Agriculture Research Service.
National Nutrient Database for Standard Reference, Release 22. Available at
http://www.ars.usda.gov/ba/bhnrc/ndl (verified 14 Apr. 2011). Washington D.C.

Norton, J.M. 2008. Nitrification in agricultural soils. p. 173-200. *In* J.S. Schepers and
W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49.
ASA-CSSA-SSSA. Madison, WI.

Olk, D.C. 2008. Organic forms of soil nitrogen. p. 57-100. *In* J.S. Schepers and W.R.
Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-
CSSA-SSSA. Madison, WI.

Radcliffe, E.B. 2010. Insect control. p. 64-67. *In* Bohl, W.H. and S.B. Johnson. (ed.)
Commercial potato production in North America. The Potato Assn. of America.
Available at
http://potatoassociation.org/documents/A_ProductionHandbook_Final_000.pdf
(verified 14 Apr. 2011). Orono, ME.

Rosen, C.J., and P.M. Bierman. 2008. Best management practices for nitrogen use:
Irrigated potatoes. Publ. 08559. Univ. of Minnesota Ext. Serv., St Paul.

Russelle, M.P. 2008. Biological dinitrogen fixation in agriculture. p. 281-359. *In* J.S.

   Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy

   Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Salunkhe, D.K. and S.S. Kadam. 1991. Introduction. p. 1-7. *In* D.K. Salunkhe, S.S.

   Kadam, and S.J. Jadhav (ed.) Potato: Production, processing, and products. CRC

   Press. Boca Raton, Fl.

Scavia, D., Rabalais, N.N., Turner, R.E., Justić, Dubravko, and Wiseman, W.J., Jr., 2003,

   Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi

   River nitrogen load: Limnology and Oceanography, v. 48, p. 951–956.

Scherer T.F., D. Franzen, J. Lorenzen, A. Lamey, D. Aarke, and D.A. Preston.1999.

   Growing irrigated potatoes. AE-1040. Dakota State Univ. Ext. Serv., North Fargo,

   ND.

Shaviv, A. 2000. Advances in Controlled Release of Fertilizers. Adv. Agron. 71: 1-49.

Sheridan, R.C. 1979. Chemical fertilizers in southern agriculture. Agr. Hist. 53: 308-318.

Shock, C.C., A.B. Pereira, and E.P. Eldredge. 2007. Irrigation Best Management

   Practices for Potato. Am. J. Potato Res. 84:29-37.

Smil V. 2001. Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of

   world food production. MIT Press, Cambridge.

Trenkel, M.E. 1997. Improving fertilizer use efficiency: Controlled-release and stabilized

   fertilizers in agriculture. Int. Fert. Industry Assoc., Paris.

USEPA. 2009. National primary drinking water regulations. Available at

http://www.epa.gov/safewater/consumer/pdf/mcl.pdf (verified 14 Apr. 2011).

USEPA, Washington D.C.

USEPA. 2010. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2008. EPA

430-R-08-006. Available at

http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-

2010_Report.pdf (verified 14 Apr. 2011). USEPA, Washington, DC.

Van den Berg, R.G. and M.M.J. Jacobs. 2007. Molecular taxonomy. p. 55-76. *In* D.

Vreugdenhil (ed.) Potato biology and biotechnology: Advances and perspectives.

Elsevier. New York.

Venterea, R.T. 2007. Nitrate-driven nitrous oxide production under aerobic soil

conditions: Kinetics and biochemical controls. Global Change Biol. 13: 1798-

1809.

Voroney, P. and D. Derry. 2008. Origin and distribution of nitrogen in soil. p. 1-30. *In*

J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy

Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 1999. Irrigation

and nitrogen management effects on potato yield, tuber quality, and nitrogen

uptake. Agron. J. 91:991-997.

Wilson, M.L., C.J. Rosen, and J.F. Moncrief. 2009b. Potato response to a polymer-coated

urea on an irrigated, coarse-textured soil. Agron. J. 101:897-905.

Part 1.

Polymer-Coated Urea Maintains Potato Yields and Reduces Nitrous Oxide Emissions in a Minnesota Loamy Sand.

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[1]Dept. Of Soil, Water, and Climate, University of Minnesota, St. Paul, MN 55108

[2]USDA-ARS, Soil and Water Management Research Unit, St. Paul, MN 55108

* Corresponding author email address: rod.venterea@ars.usda.gov

Polymer Coated Urea Maintains Potato Yields and Reduces Nitrous Oxide Emissions in a Minnesota Loamy Sand

SUMMARY

Irrigated potato (*Solanum tuberosum* L.) production requires large inputs of nitrogen (N), and therefore has high potential for N loss including emissions of nitrous oxide (N_2O). Two strategies for reducing N loss include split applications of conventional fertilizers, and single applications of polymer-coated urea (PCU), both of which aim to better match the timing of N availability with plant demand. The objective of this three year study was to compare N_2O emissions and potato yields following a conventional split application (CSA) employing multiple additions of soluble fertilizers with single pre-plant applications of two different PCUs (PCU-1 and PCU-2) in a loamy sand in Minnesota. Each treatment received 270 kg of fertilizer N ha^{-1} per season. A non-fertilized control treatment was included in two of three years. Tuber yields did not vary among fertilizer treatments, but N_2O emissions were significantly higher with CSA than PCU-1. Over three consecutive years, mean growing season emissions were 1.36, 0.83, and 1.13 kg N_2O-N ha^{-1} with CSA, PCU-1, and PCU-2, respectively, compared with emissions of 0.79 and 0.42 kg N_2O-N ha^{-1} in the control. PCU-1 released N more slowly during *in-situ* incubation than PCU-2, although differences in N_2O emitted by the two PCUs were not generally significant. Fertilizer-induced emissions were relatively low, ranging from 0.10–0.15% of applied N with PCU-1 up to 0.25–0.49% with CSA. These results show that N application strategies utilizing PCUs can maintain yields, reduce costs associated with split applications, and also reduce N_2O emissions. **Abbreviations**: AN, ammonium nitrate; CSA, conventional split application; PCU, polymer-coated urea.

INTRODUCTION

Potato production requires significant inputs of fertilizer N to optimize tuber yield and quality. Due to its shallow main rooting system when irrigated, potatoes are relatively inefficient in capturing applied N. In Minnesota, best management practices (BMPs) for late-season varieties of irrigated potatoes in coarse-textured soils recommend application of up to 260–280 kg ha^{-1} N to optimize yields (Rosen and Bierman, 2008). Using mass balance analysis, Errebhi et al. (1998) found that only 33 to 56% of applied fertilizer N was recovered by a potato crop in an irrigated coarse-textured soil.

Applied fertilizer N can be transformed via nitrification, denitrification, and other processes to nitrous oxide (N_2O) (Firestone and Davidson, 1989). Relative to other soil types, coarse-textured soils may not promote high rates of denitrification-driven N_2O loss. However, the high rates of N application required for potato production and the possibility of nitrification-driven N_2O production (Venterea, 2007), increase the potential for N_2O losses. N_2O is a greenhouse gas of growing concern, with a global warming potential 300 times greater than carbon dioxide (CO_2) (Forster et al., 2007). Global atmospheric N_2O concentrations are rising at approximately 0.26% per year (Forster et al., 2007). Within the US, 72% of anthropogenic N_2O emissions originate from agricultural practices (USEPA, 2008).

One strategy for minimizing N_2O emissions, as well as other N losses, is the use of "split" applications of fertilizer distributed over the course of the growing season. The BMPs for potato production in Minnesota recommend split applications (Rosen and Bierman, 2008). Split applications of conventional N fertilizer have previously shown

promise in reducing N_2O emissions from fields planted to potatoes (Burton et al., 2008). While this practice may conserve fertilizer N and protect environmental quality, it requires time and expense associated with additional field applications. An alternative to split applications is the use of polymer-coated urea (PCU) products, which are designed to release N gradually during the growing season while requiring fewer or only one application. In theory, both techniques better synchronize the timing of N availability with plant demand. In addition to any environmental benefits, the impact of these practices on crop yields must also be considered in evaluating their potential for adoption.

Effects of PCU products on N_2O emissions have been examined for a variety of applications (e.g., Delgado and Mosier, 1996; Cheng et al., 2006; Halvorson et al., 2008; 2010). Previous studies have examined PCU effects on potato yields and N use efficiency with promising results (Shoji et al., 2001; Zvomuya et al., 2003; Hutchinson et al., 2003). A number of studies have examined N_2O emissions in potato as affected by conventional fertilizer management, tillage, and soil properties (Ruser et al., 2006; Vallejo, et al., 2006; Burton et al., 2008; Haile-Mariam, et al., 2008). However, to our knowledge there are no studies examining N_2O emissions with PCUs for potato production. There are also no studies in any cropping system comparing N_2O emissions following multiple (i.e., more than two) split applications of conventional fertilizers versus a single PCU application.

The objective of the current study was to compare N_2O emissions and crop yields under alternative N management systems including a conventional split application (CSA), similar to recommended BMPs, and single pre-plant applications of two different

PCUs for irrigated potato production in Minnesota. Additional measurements were made to compare the rate of N release in the two PCU products during *in-situ* incubation.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted during the 2007, 2008, and 2009 growing seasons (approximately May 1 through September 30) at the University of Minnesota's Sand Plain Research Farm in Becker, MN (45°23′N, 93°53′W). Soils at the site are a uniform Hubbard loamy sand (Sandy, mixed, frigid, Typic Hapludoll) comprised of 82% sand, 10% silt, and 8% clay. Additional soil properties are shown in Table 1-1. The 30-y average annual temperature and precipitation at the site are 6.8° C and 752 mm, respectively; 30-y average temperature and precipitation during May through September are 18.7° C and 479 mm, respectively (MCWG, 2009). A weather station (WatchDog Model 2800 Spectrum Technologies Inc, Plainfield, IL) was positioned onsite to measure air temperature and precipitation at 10-min intervals.

Experiments were conducted in a different section of the farm each year. The fields used for experiments in 2007 and 2009 were planted to non-irrigated, non-fertilized rye (*Secale cereal* L.) during the previous year. The field used in 2008 was planted in the previous year to rye followed by mustard (*Brassica juncea* and *Sinapsis alba* blend) which was fertilized with 34 kg N ha^{-1} as ammonium nitrate (AN). Rye grain was harvested in summer; rye stover and the 2007 mustard crop were disk-incorporated in fall. Each spring, N-fertilizer treatments were established in a randomized complete

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block design with 3 replications of each treatment. Plots were between 3.7 and 4.6 m wide and 6.1 m long. One wk prior to planting in all years, 280 kg ha^{-1} of potassium-magnesium sulfate and 280 kg ha^{-1} of potassium chloride were broadcast and incorporated with a moldboard plow in all plots. On 26 April 2007, 29 April 2008, and 28 April 2009, plots were hand planted with four rows of "Russet Burbank" whole "B" seed potatoes (*Solanum tuberosum* L.) with 0.9-m row spacing and 0.3-m seed spacing. For all but the control plots, a pre-weighed starter fertilizer containing 45 kg N ha^{-1} and 50 kg of P ha^{-1} as diammonium phosphate (DAP), 186 kg K ha^{-1}, 34 kg Mg ha^{-1}, 67 kg S ha^{-1}, 2.25 kg Zn ha^{-1}, and 0.6 kg B ha^{-1} was banded at planting 0.05 m below and 0.08 m to both sides of the row. Control plots received a similar mix that excluded DAP and substituted triple superphosphate.

Nitrogen-fertilizer treatments included a conventional split application (CSA), and two different polymer-coated urea (PCU) treatments employing a single pre-plant application, with all treatments receiving a total of 270 kg N ha^{-1} (including the DAP). In 2008 and 2009, a non-fertilized control treatment was also examined. A summary of the treatments including the form, timing, and rates of N fertilizer application in each treatment is given in Table 1-2. In the CSA treatment, granular urea was surface banded at plant emergence on both sides of the row at 112 kg N ha^{-1}. Within 24 h of urea application, rows were hilled in all treatments (on 15 May 2007, 28 May 2008, and 22 May 2009). Hilling also served to incorporate urea mainly within the hill area. In 2008, equipment malfunction required all plots to be hilled a second time. Post-emergence fertilizer applications in the CSA treatment were broadcast by hand as 50% granular urea

and 50% granular AN evenly over the entire plot (Table 1-2). This blend was then watered-in with overhead irrigation to simulate fertigation with 28% urea-ammonium nitrate, which is a commonly used practice in the area, and consistent with BMP recommendations (Zvomuya et al., 2003; Rosen and Bierman, 2008). Post-emergence fertilizer applications started 2–3 wk after hilling and were repeated at intervals of 9–15 d (actual application dates are reported in the results).

In both PCU treatments, the material was broadcast 1–6 d prior to planting and mechanically incorporated via disking within 24 h of application. One of the PCU treatments (referred to as PCU-1, 42% N by weight), used a product manufactured by Shandong Kingenta Ecological Engineering Co. LTD (Linshu, Shandong Province China). The other PCU treatment (PCU-2, 44% N by weight) used a product (Environmentally Smart Nitrogen) manufactured by Agrium, Inc. (Calgary, AB). The PCU-1 product was obtained directly from the manufacturer. In 2007, PCU-2 was obtained from the manufacturer, while in 2008 and 2009 the product was obtained from a local distributor. Irrigation water was applied through an aluminum pipe solid-set overhead sprinkler system. Irrigations were scheduled through the checkbook method as described in Wright (2002). Potatoes were mechanically harvested from the two inner rows of each plot on 28 Sept 2007, 16 Sept 2008, and 21 Sept 2009. Tubers were graded and the mass of all tubers >113 g were tallied for marketable yield, expressed in metric tons per hectare (t ha^{-1}).

N₂O Fluxes

N_2O flux between soil and atmosphere was measured using cylindrical (0.22 m ID x 0.15 m deep) stainless steel chambers. Chambers were insulated with a surface-applied reflective insulation (Reflectix, Markleville, IN) and equipped with vent tubes, sampling ports with butyl rubber septa, and sharpened bottom edges following Venterea and Rolston (2000). The chambers were inserted directly into the soil prior to sampling. One chamber was positioned on the hill, while its twin was positioned in the furrow within 2 m of the hill location. Chamber locations within each plot were randomly selected on each sampling date.

Chamber insertion depth was kept to 0.02 m, since later in the season tubers can extend to within 0.02 m of the surface. It is known that a shorter chamber insertion depth can underestimate actual emissions; it is also suspected that making measurements immediately after chamber insertion may cause increased fluxes due to soil disturbance (Hutchinson and Livingston, 2002). To address these concerns, in an adjacent field planted to corn, we compared this chamber method to a fixed-anchor chamber method with insertion depth of 0.08 m, and found no significant difference in N_2O flux based on paired t-test analysis of 16 chamber locations.

Gas samples were collected via a 12-ml polypropylene (Monoject) syringe 0, 30, and 60 minutes after chamber insertion as described in Venterea et al. (2005) and transferred to 9-mL glass autosampler vials sealed with butyl rubber septa and aluminum caps (Alltech, Deerfield, IL). Gas flux samples were collected at least weekly from 27 April through 14 September 2007, 1 May through 28 September 2008 (with an additional

sampling on 20 October 2008), and 1 May through 14 September 2009. For nearly the entire 2009 season, and during 15 May to 15 June 2007, and 20 May to 25 August 2008, sampling was performed twice per week. Fluxes were measured a total of 25, 35, and 36 dates in 2007, 2008, and 2009, respectively.

Gas samples were stored at room temperature until analysis, which was done within 3 d of collection. Analysis of N_2O was performed on a gas chromatograph (GC) (Model 5890, Hewlett-Packard/Agilent, Palo Alto, CA) equipped with an electron capture detector. The GC was connected to a headspace auto-sampler (Teledyne Tekmar, Mason, OH). The system was calibrated daily using a set of analytical grade standards (Scott Specialty Gases). After converting N_2O mixing ratios (e.g., parts per million) to concentration units (e.g., $\mu g\ N\ m^{-3}$) using the ideal gas law and the air temperature at the time of sampling, gas fluxes were calculated using quadratic regression of chamber concentration data versus time (Wagner et al., 1997), multiplying the slope at time zero by chamber volume, and dividing by soil surface area.

Soil Sampling and Analysis

Samples for soil moisture content determination were collected within 1 h of gas flux sampling using an 18 mm diameter core sampler to a depth of 0.1 m in three randomly selected locations within the furrow of each plot. Samples were oven dried at 105° C for 24 h. Core samples were also taken to determine bulk density once per season. Soil temperature was measured during gas sampling using temperature probes (Fisher, Hampton, NH) inserted 0.05 m deep in the furrow area within 1 m of each chamber.

N Fertilizer Release

Rates of N release from the two PCU products over the course of the 2007 and 2008 growing seasons were examined in *in-situ* incubation of fertilizer granules using a weight-loss method described by Wilson et al. (2009). Samples of each product (3 ± 0.0002 g) were placed in 0.1-m^2 polypropylene bags (Industrial Netting, Minneapolis, MN) with 1.2 mm^2 mesh size. Bags were heat sealed and buried to a depth of 0.05–0.10 m. Initial bag placement occurred on the same day as fertilizer application (1–6 d prior to planting). Bags were removed during hilling and then re-buried within the hill. Three sets of 10 bags for each of the two PCUs were buried in three plots that had been fertilized with the respective PCU. A single bag was removed from each plot for testing at approximately 2-wk intervals until after harvest. In the laboratory, bags were placed inside paper bags and air dried for at least two weeks. Any attached soil was removed from the granules, which were then weighed to determine the mass of N released (Wilson et al., 2009). Empirical functions describing N release as a function of time were obtained using non-linear regression (Sigma Plot v. 10.0, Systat, Chicago, IL).

Data Analysis and Statistics

To determine total daily N$_2$O flux for each plot, fluxes from the hill and furrow location were averaged, since the hill and furrow sections each represented approximately 50% of plot area. Daily flux was compared to soil moisture and temperature via simple and multiple linear regression using Statgraphics Plus 5.1 (Statistical Graphics Corp., Warrenton, VA). Cumulative flux between successive sampling dates was determined by multiplying the average daily flux of the two sampling dates by the time elapsed between

events (i.e. trapezoidal integration). These values were summed to determine cumulative seasonal emissions. Analysis of variance (ANOVA) in all cases was performed using the general linear model (GLM) procedure in SAS (SAS, 2003). Effects of fertilizer treatment on daily fluxes from the hill and furrow locations, and their daily means, were examined using split-plot ANOVA with fertilizer type as main effect and date as split plot effect. Effects of fertilizer treatment on total cumulative emissions and tuber yields were analyzed using one-way ANOVA separately for each growing season. Effects of fertilizer treatment on total cumulative emissions and tuber yields over the entire study were analyzed using split-plot ANOVA with fertilizer type as main effect and year as the split plot effect. In the text, unless indicated otherwise, significant differences use criteria of $P < 0.05$. Significant differences among treatments are indicated in tables and figures using lower case and upper case letter designations for $P < 0.10$ and $P < 0.05$, respectively. For 2008 and 2009, fertilizer-induced N_2O emissions in each fertilized treatment were determined by subtracting the mean cumulative emissions observed in the control treatment from the mean cumulative emissions in the fertilized treatment, expressed as a percentage of fertilizer N inputs (i.e., 270 kg N ha^{-1}).

RESULTS

Weather

Water inputs during the period May 1 through the date of harvest each season are shown in Figs. 1-1 through 1-3 (plate c). The second year of the study (2008) was relatively normal with respect to growing season rainfall, while 2007 and 2009 were drier

than normal. Precipitation amounts during May through September in 2007, 2008, and 2009 were approximately 85, 95, and 67% of the 30-y average (479 mm), respectively. Total water inputs (including irrigation) were similar each year (745–896 mm). Due to higher precipitation in 2008, a lower proportion of total inputs in 2008 were from irrigation (i.e., 44%) compared with 2007 (55%) and 2009 (57%).

With the exception of an early season spike to nearly 0.35 g H_2O g^{-1} on 18 May 2007, soil moisture remained between 0.08 and 0.16 g H_2O g^{-1} soil (Figs. 1-1 through 1-3, plate c). Based on an average measured soil bulk density of 1.1 g cm^{-3}, this range of water content values corresponds to a range in water-filled pore space (WFPS) of 15 to 30% (66% on 18 May 2007). Average soil and air temperatures during the 2007 growing season were slightly higher compared with 2008 and 2009 (Figs. 1-1 through 1-3, plate d), with no significant differences in water content or temperature between treatments. Mean daily air temperatures during the 2007, 2008, and 2009 growing season were 19.6, 18.4, and 18.1° C, compared with a 30-y average of 18.7° C.

N₂O Emissions

In 2007, maximum N_2O fluxes occurred in the hill chamber positions across all treatments (Fig. 1-1a,b). In the 6-wk period following urea application on 15 May 2007, mean fluxes from hill positions in the CSA treatment peaked to nearly 300 µg N m^{-2} h^{-1} (on 12 June) before decreasing to baseline levels. The PCU-2 treatment also displayed increased emissions from hill positions during the same period, despite no post-plant application. Increased fluxes during this period coincided with a 25–mm rainfall event on 29 May and soil temperatures > 25° C. Following the third post-emergence fertilizer

application (on 2 July), mean N_2O fluxes remained below 30 μg N m^{-2} h^{-1} for the remainder of the season.

In contrast to 2007 and 2009, maximum N_2O fluxes in 2008 occurred in the furrow positions (Fig. 1-2a,b). The CSA treatment displayed several episodes of increased fluxes (>150 μg N m^{-2} h^{-1}) in both hill and furrow positions, some of which may have been responses to post-emergence fertilizer applications and large rain events. A 48-mm rain event on 11 June was followed by large but short-lived increases in fluxes (>300 μg N m^{-2} h^{-1}) from the furrow chamber positions in the CSA and PCU-2 treatments (Fig. 1-2a).

In 2009, mean fluxes remained ≤ 80 μg N m^{-2} h^{-1} for the entire the season in all treatments with the exception of a single sampling date (Fig. 1-3a,b). On August 13, mean fluxes in the furrow position of the CSA and PCU-2 treatment were > 400 μg N m^{-2} h^{-1}, compared with 180 and 80 μg N m^{-2} h^{-1} in PCU-1 and control treatments, respectively. Soil water content in the upper 0-10 cm and temperature at the 5-cm depth were at or near their maximum values of the season on this date. Further analysis of the water input date indicated that cumulative water inputs calculated over the previous 10 d were also close to the maximum value at this time. Thus, it is possible that the observed spike in N_2O flux was due to high soil water content (including depths below 10 cm, due to high cumulative water inputs) coinciding with high soil temperature.

Results of statistical analysis of the daily flux data are shown in Table 1-3. In 2007 and 2008, mean daily fluxes from the hill position were higher in the CSA treatment than the two PCU treatments, while differences in the furrow position fluxes were not

significant. In 2009, daily fluxes in the furrow position in the CSA treatment were higher than PCU-1. After averaging hill and furrow data, fluxes from the CSA treatment were higher (at $P < 0.10$) compared with PCU-1 in 2008 and compared with both PCU treatments in 2007 and 2009. Combined daily fluxes from the control were lower compared with CSA and PCU-2 in 2008 and lower than all fertilized treatments in 2009.

Cumulative N_2O emissions over each growing season ranged from 0.6 to 2.1 kg N ha^{-1} in the fertilized treatments (Fig. 1-4a). Mean emissions from the control treatment were nearly twice as high in 2008 (0.79 kg N ha^{-1}) compared with 2009 (0.42 kg N ha^{-1}), although this difference was not significant ($P > 0.10$). During individual growing seasons, the only significant differences (at $P < 0.10$) were that cumulative emissions from CSA were higher compared with PCU-1 in 2007, and higher compared with the control in 2008 and 2009. However, over the entire study, emissions from CSA were significantly higher than PCU-1, while emissions from PCU-2 did not differ from CSA or PCU-1.

In 2008, fertilizer-induced N_2O emissions were equivalent to 0.49, 0.10, and 0.39% of N inputs in the CSA, PCU-1, and PCU-2 treatments, respectively. In 2009, fertilizer-induced N_2O emissions were equivalent to 0.25, 0.15, and 0.16% of N inputs in the CSA, PCU-1, and PCU-2 treatments, respectively. Across all fertilized treatments, cumulative emissions were significantly higher in 2008 (1.67 kg N ha^{-1}) compared with 2007 (0.73 kg N ha^{-1}) and 2009 (0.92 kg N ha^{-1}). Regression analysis found weak correlations between individual flux measurements and soil moisture or temperature ($r^2 \leq$ 0.2) for the entire data set or when data were segregated by treatment and/or year. There

were no differences in tuber yields among the fertilized treatments (Fig. 1-4b). Yields were suppressed by approximately 28 and 46% in the control plots compared with the fertilized treatments in 2008 and 2009, respectively.

N Release Rates

The cumulative mass of N released from the PCU products during *in-situ* incubation was well-described ($r^2 > 0.96$) by sigmoidal relationships in the form:

$$N_R = N_0 + \frac{a}{[1 + \exp(-\frac{t - t_0}{b})]} \tag{1}$$

where N_R is cumulative N released (mg N g^{-1} product), t is time following bag placement, and N_0, t_0, a, and b are regression coefficients (Fig. 1-5a). Curves obtained using Eq. [1] were used to estimate instantaneous release rates for each product via numerical differentiation (Fig. 1-5b). In both years, PCU-2 released N more quickly than PCU-1. On 21 May 2007, 10 d before the date of the first notable increase in N_2O flux from the PCU-2 treatment (Fig. 1-1b), PCU-2 product in the mesh bags had lost 27% of its total N compared to 18% lost by PCU-1. By 19 June 2007, 4 d after a second increase in N_2O flux, PCU-2 had lost 66% of its total N when PCU-1 had only lost 32% of its total N. In 2008, the difference between the PCUs was just as dramatic with 26 and 65% loss by 2 June for PCU-1 and PCU-2, respectively. Both products released N at faster rates in 2008 than 2007. The maximum release rates, corresponding to the inflection points in Fig. 1-5b, were 2.9 and 3.5 mg N g^{-1} d^{-1} for PCU-1 in 2007 and 2008, respectively, compared to 6.8 and 8.3 mg N g^{-1} d^{-1} for PCU-2.

DISCUSSION

As far as we know, this is the first study to compare N_2O emissions in potatoes fertilized with PCUs versus conventional fertilizers, or to compare single, pre-plant applications of PCUs to multiple (i.e., more than two) split applications of conventional soluble fertilizers in any cropping system. The high N demand of potatoes presents a challenge for minimizing fertilizer N losses, particularly in coarse-textured soils. Growers recognize the need to strategically manage N under these conditions, due to high rates of N loss from leaching that have been observed (Errebhi et al., 1998; Delgado et al., 2001; Zvomuya et al., 2003). The lack of any negative yield impacts of PCUs found here demonstrates that from a purely agronomic perspective, these products may afford potato growers the option to avoid the inconvenience of multiple split applications of urea or other conventional products.

The current results also indicate N_2O emissions may be reduced, or at least maintained, with single application of PCUs for potato production compared with multiple split applications of conventional fertilizers. One of the PCU products (PCU-1) resulted in significantly lower N_2O emissions than CSA over the entire study. Lower N_2O emissions following one-time applications of PCU compared with uncoated urea have been observed in barley, Chinese cabbage, and corn (Delgado and Mosier, 1996; Cheng et al., 2006; Halvorson et al., 2010). PCUs have also shown reduced emissions in corn when compared with two split urea applications (Yan et al., 2001; Hadi et al., 2008; Jumadi et al., 2008).

PCUs are designed to release N gradually over the course of the growing season in response to moisture. Water passes by diffusion through pores in the polymer coating of the PCU granule, dissolving the urea, which then can diffuse back into the soil through the intact coating (Trenkel, 1997; Agrium, 2009a). Rupturing of coatings may also occur, and increased temperature enhances the rate of N release (Shaviv, 2000). While several studies have compared N_2O emissions from PCU products versus urea impregnated with nitrification and/or urease inhibitors (Delgado and Mosier, 1996; Hadi et al., 2008; Jumadi et al., 2008; Dobbie and Smith, 2003), direct comparisons between different types of PCUs are uncommon. In our study, N_2O emissions from the PCU-1 and PCU-2 treatments did not differ significantly over the entire study, but only PCU-1 had lower cumulative emissions than the CSA system. Additional statistical analysis of emissions data from the two seasons where a control treatment was used (2008 and 2009) indicated that emissions from PCU-1 did not vary from the control treatment and were significantly lower than both CSA and PCU-2. These trends may have been due in part to slower release of N from PCU-1 compared with PCU-2, as observed in the *in-situ* incubation experiments. The lower N content of PCU-1 (42%) compared with PCU-2 (44%) indicates that PCU-1 contained a greater mass of polymer per mass of product (8.7%) compared with PCU-2 (4.3%). The higher mass of coating in PCU-1 may have resulted in a slower rate of N release. It is also possible that differences in the chemical composition of coating materials may have contributed to different release rates. Polyurethane, polyolefin, and alkyd resins are all used as coatings by various PCU manufacturers (Trenkel, 1997).

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The bag-incubation method used here, which relied on measurement of granule weight loss over time, compared favorably with bag-incubation that used direct chemical analysis of granule N content over time (Wilson et al. 2009). The weight-loss method is presented primarily as an estimate of relative release rates, i.e., for comparison of different PCUs under the same conditions, or the same PCU under different conditions. However, incubation of granules in bags may not closely mimic the physical contact with soil particles and water experienced by the actual applied product. Wilson et al. (2009) showed that the hole-size of the mesh bags influenced the release rate that was measured. We did use the bag type and hole size found by Wilson et al. (2009) to generate the highest release rates. Nonetheless, the absolute release rates measured in this study were probably less than actual release rates. However, a technique to determine N release which does not include a mesh bag has not been developed.

Averaged across all fertilized treatments, higher N_2O emissions were observed in the 2008 growing season compared with 2007 and 2009. *In-situ* release rates for both PCUs were also higher in 2008 than 2007. These trends may in part have been due to greater and more frequent rainfall in 2008. Rainfall events tended to introduce more water in a shorter time periods than irrigation. In 2008, there were 10 rainfall events delivering more than 20 mm in a 24-h period, compared with 6 such events in 2007, and 4 events in 2009. In 2008, there were two events of ~35 mm prior to emergence, and two additional events of 26 and 48 mm within two wk after emergence. Total rainfall amounts occurring between planting and one wk following the final fertilizer application in the CSA treatment was 285 mm in 2008, compared with only 159 and 172 mm in 2007

and 2009, respectively. Increased frequency of significant rainfall during this period

could have contributed to the multiple spikes in N_2O emissions observed (Fig. 1-2), by

promoting release of N from the PCUs and subsequently promoting N_2O production. The

PCU-2 treatment, and to a lesser extent the PCU-1 and control treatment, displayed

emission peaks that coincided with increased fluxes from the CSA treatment. This

suggests that common factors such as soil moisture and temperature also played a role in

stimulating N_2O production during these periods.

However, the higher emissions in 2008 cannot be definitively or solely attributed

to the wetter conditions that year. The field used in 2008 was planted to rye and mustard

and fertilized (34 kg N ha^{-1}) the previous year, whereas the fields used in 2007 and 2008

were preceded by unfertilized rye. While this did not show up as a large difference in

pre-season inorganic N or organic matter content (Table 1-1), it is possible that greater

mineralization of N occurred during the 2008 growing season due to a larger input of N-

containing plant residues from the previous year. It is also possible that the combined

effect of rainfall and site history was important.

Since soil WFPS was generally < 30%, denitrification was not likely the

predominant source of N_2O. Denitrification-generated N_2O requires nearly completely

anaerobic soil conditions, while nitrifier-generated N_2O can proceed under fully aerobic

conditions, and is enhanced when soil oxygen status is only partly reduced below ambient

conditions (Venterea, 2007). Thus, nitrification was likely responsible for the majority of

N_2O production all three seasons. Similarly, Venterea et al. (2010) concluded that

nitrification was the dominant source of N_2O in corn fertilized with anhydrous ammonia and conventional urea in a well-drained silt loam in southeastern Minnesota.

The temporal patterns in N_2O emissions observed over the course of each growing season differed substantially across the three years of the study, as did trends with respect to emissions from hill versus furrow chamber positions (Figs. 1-1 through 1-3). In 2007, emissions were dominated by a large and prolonged response in the hill chamber position following the initial urea application. This pattern is similar to that found by Haile-Mariam et al. (2008) who also saw higher flux from hills compared with furrows under center pivot irrigation-applied urea ammonium nitrate; and to that observed by Burton et al. (2008) with band-applied AN. In 2008, there were multiple apparent responses to water inputs and fertilizer additions over the course of June through September, primarily in the furrow and to a lesser extent in the hill. The spikes in emissions did not appear to correspond to application dates, in contrast to Haile-Mariam et al. (2008), who observed a direct, almost one-to-one response, between fertilizer application dates and N_2O emission spikes. Higher flux in the furrow position has been reported by others (Ruser et al., 1998; Smith et al, 1998) but these studies were conducted in finer-textured soils where inter-row compaction or higher water filled pore space in the furrows may have contributed to higher N_2O emissions. In the current study, soil moisture samples were collected exclusively from the furrow position and differences in bulk density between hill and furrow locations were not measured, so we are unable to assess whether differences between hill and furrow were attributable to these factors. In 2009, fluxes were dominated primarily by one large spike in mid August, mainly in the furrow. These

results confirm the need for frequent flux sampling and also accounting for fluxes originating in different sub-sections of the inter-row area in order to more accurately assess field-scale emissions.

We found no significant difference in marketable tuber yields with respect to fertilizer treatments. Zvomuya et al. (2003) observed occasional increases in potato yields in a loamy sand in Minnesota using a PCU compared with conventional fertilizers, particularly under conditions of high N leaching. The authors surmised that leaching reduced N availability in fields amended with conventional fertilizers, resulting in increased N use efficiency and yields with PCU. Worthington et al. (2007) found significantly higher potato yields in northeast Florida in a fine sandy soil with a coated urea compared with AN under a variety of leaching conditions. Pack et al. (2006) found in another northeastern Florida fine sand that potato yields following PCU applied at 146 kg N ha^{-1} were not significantly different compared with AN applied at 225 kg N ha^{-1}. These studies suggest that PCUs can reduce N leaching losses while maintaining, if not increasing, potato yields.

CONCLUSIONS

Over three consecutive years, mean cumulative growing season N_2O emissions were 1.36, 0.83, and 1.13 kg N ha^{-1} with conventional split application (CSA), and two different PCU products (PCU-1, and PCU-2), respectively. As expected in a very coarse-textured soil, these emissions represented only 0.1 to 0.5% of applied fertilizer N after accounting for emissions from non-fertilized control treatments. However, on an absolute scale, these emissions are comparable to rates measured in other cropping systems that

require smaller N inputs. For example, in corn fertilized with single applications of 146 kg N ha^{-1} y^{-1} with conventional urea in a silt loam in Minnesota, N$_2$O emissions ranged from 0.6 to 1.4 kg N ha^{-1} over three consecutive growing seasons (Venterea et al., 2010). Thus, the N$_2$O contribution from a high N input crop such as potatoes, even though it may be grown in a sandy soil, can be very comparable to that from other crops grown in finer textured soils.

These results show that N application strategies utilizing PCUs can maintain potato yields, reduce costs associated with split applications, and also reduce N$_2$O emissions. A PCU-based treatment can reduce equipment field time and personnel costs, but these must ultimately be weighed against the increased cost of the PCU products. An economic analysis is needed to determine what, if any, financial benefit PCU products provide. What is clear is that the environmental benefits combined with potential economic benefits make coated urea fertilizers worth continued study, especially in high value crops such as potato.

REFERENCES

Agrium, 2009a. A new generation in smart nitrogen: ESN Controlled-release fertilizer.
Potato. Available at
http://www.agriumat.com/agtech/includes/esn_potato_fact_sheet.pdf (verified 14
Apr. 2011). Agrium Inc., Calgary, AB, Canada.

Brown, J.R. (ed.). 1998 Recommended chemical soil test procedures for the North
Central Region. Doc. SB 1001. Missouri Agric. Exp. Stn., Columbia.

Burton, D.L., B.J. Zebarth, K.M. Gillam, and J.A. MacLeod. 2008. Effect of split
application of fertilizer nitrogen on N_2O emissions from potatoes. Can. J. Soil Sci.
88: 229-239.

Cheng, W., S. Sudo, H. Tsuruta, K. Yagi, and A. Hartley. 2006. Temporal and spatial
variations in N_2O emission from a Chinese cabbage field as a function of type of
fertilizer and application. Nutr. Cycling Agroecosyst. 74: 147-155.

Delgado, J.A., and A.R. Mosier. 1996, Mitigation alternatives to decrease nitrous oxides
emissions and urea-nitrogen loss and their effect on methane flux. J. Environ.
Qual. 25:1105-1111.

Delgado, J.A., R.R. Riggenbach, R.T. Sparks, M.A. Dillon, L.M. Kawanabe, and R.J.
Ristau. 2001. Evaluation of nitrate-nitrogen transport in a potato-barley rotation.
Soil Sci. Soc. Am. J. 65: 878-883.

Dobbie, K.E., and K.A. Smith. 2003. Impact of different forms of N fertilizer on N_2O emissions from intensive grassland. Nutr. Cycling Agroecosyst. 67: 37–46.

Errebhi, M., C.J. Rosen, S.C. Gupta, and D.E. Birong. 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. Agron. J. 90: 10–15.

Firestone, M., and E. Davidson. 1989. Microbiological basis of NO and N_2O production and consumption in soil. p. 7–21. *In* M. Andreae and D. Schimel (ed.) Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley & Sons, Chichester, UK.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, et al. 2007. Changes in atmospheric constituents and in radiative forcing. P. 131-234. *In* S. Solomon et al. (ed.) Climate change 2007: The physical science basis. Cambridge Univ. Press, Cambridge, UK.

Hadi, A., O. Jumadi, K. Inubushi, and K Yagi. 2008. Mitigation options for N_2O emission from a corn field in Kalimantan, Indonesia. Soil Sci. Plant Nutr. 54: 644-649.

Haile-Mariam, S., H.P. Collins, and S.S. Higgins. 2008. Greenhouse gas fluxes from an irrigated sweet corn (*Zea mays* L.) – potato (*Solanum tuberosum* L.) rotation. J. Environ. Qual. 37: 759-771.

Halvorson, A.D., S.J. Del Grosso, and F. Alluvione. 2010. Tillage and nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Sci. Soc. Am. J. 74: 435-445.

Halvorson, A.D., S.J. Del Grosso, and C.A. Reule. 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. J. Environ. Qual. 37: 1337-1344.

Hutchinson, C., E. Simonne, P. Solano, J. Meldrum, and P. Livingston-Way. 2003. Testing of controlled release fertilizer programs for seep irrigated Irish potato production. J. Plant Nutr. 26: 1709-1723.

Hutchinson, G.L. and G.P. Livingston. 2002. Soil-atmosphere gas exchange. p. 1159–1182. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Jumadi O., Y. Hala, A. Muis, A. Ali, M. Palennari, K. Yagi, and K. Inubushi. 2008. Influences of chemical fertilizers and a nitrification inhibitor on greenhouse gas fluxes in a corn (*Zea mays* L.) field in Indonesia. Microbes Environ. 23: 29-34.

MCWG. 2009. Minnesota Climatology Working Group. Minnesota location selector. Available at http://climate.umn.edu/hidradius/radius.asp (verified 14 Apr. 2011). Minnesota State Climatology Office, St. Paul.

Pack, J.E., C.M. Hutchinson, and E.H. Simonne. 2006. Evaluation of controlled-release fertilizers for northeast Florida chip potato production. J. Plant Nutr. 29: 1301-1313.

Rosen, C.J., and P.M. Bierman. 2008. Best management practices for nitrogen use: Irrigated potatoes. Publ. 08559. Univ. of Minnesota Ext. Serv., St Paul.

Ruser, R, H. Flessa, R. Russow, G. Schmidt, F. Buegger, and J.C. Munch. 2006. Emission of N_2O, N_2 and CO_2 from soil fertilized with nitrate: effect of compaction, soil moisture and rewetting. Soil Biol. Biochem. 38: 263-274.

Ruser, R. H. Flessa, R. Schilling, H. Steindl, and F. Beese. 1998. Soil compaction and fertilization effects on nitrous oxide and methane fluxes in potato fields. Soil Sci. Soc. Am. J. 62: 1587-1595.

SAS Institute. 2003. SAS System for Windows, Release 9.1, SAS Inst., Cary, NC.

Shaviv, A. 2000. Advances in Controlled Release of Fertilizers. Adv. Agron. 71: 1-49.

Shoji, S., J. Delgado, A. Mosier, and Y. Miura. 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. Commun. Soil Sci. Plant Anal. 32: 1051-1070.

Smith, K.A., I.P. McTaggart, K.E. Dobbie, and F. Conen. 1998. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. Nutr. Cycling Agroecosyst. 52: 123-130.

Trenkel, M.E. 1997. Improving fertilizer use efficiency: Controlled-release and stabilized

    fertilizers in agriculture. Int. Fert. Industry Assoc., Paris.

USEPA. 2008. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2006. EPA

    430-R-08-005. Available at

    http://www.epa.gov/climatechange/emissions/downloads/08_CR.pdf (verified 14

    Apr. 2011). USEPA, Washington, DC.

Vallejo, A, U.M. Skiba, L. García-Torres, A. Arce, S. López-Fernández, and L. Sánchez-

    Martín. 2006. Nitrogen oxides emission from soils bearing a potato crop as

    influenced by fertilization with treated pig slurries and composts. Soil Biol.

    Biochem. 38: 2782-2793.

Venterea, R.T. 2007. Nitrate-driven nitrous oxide production under aerobic soil

    conditions: Kinetics and biochemical controls. Global Change Biol. 13: 1798-

    1809.

Venterea, R.T., M. Burger, and K.A. Spokas. 2005. Nitrogen oxide and methane

    emissions under varying tillage and fertilizer management. J. Environ. Qual. 34:

    1467-1477.

Venterea, R.T., M. S. Dolan, and T.E. Ochsner. 2010. Urea fertilizer decreases N_2O

    emissions compared to anhydrous ammonia in continuous corn and corn/soybean

    cropping systems in Minnesota. Soil Sci. Soc. Am. J. 74: 407-418.

Venterea, R.T. and D.E. Rolston. 2000. Nitric and nitrous oxide emissions following

    fertilizer application to agricultural soil: Biotic and abiotic mechanisms and

    kinetics. J. Geophys. Res. D: Atmos. 105:15117-15129.

Wagner, S.W., D.C. Reicosky, and R.S. Alessi. 1997. Regression models for calculating

    gas fluxes measured with a closed chamber. Agron. J. 89: 279-284.

Wilson, M.L., C.J. Rosen, and J.F. Moncrief 2009a. A comparison of techniques for

    determining nitrogen release from polymer-coated urea in the field. HortScience,

    44:492–494.

Worthington, C.M., K.M. Portier, J.M. White, R.S. Mylavarapu, T.A. Obreza, W.M.

    Stall, and C.M Hutchinson. 2007. Potato (*Solanum tuberosum* L.) yield and

    internal heat necrosis incidence under controlled-release and soluble nitrogen

    sources and leaching irrigation events. Am. J. Potato Res. 84: 403-413.

Wright, J. 2002. Irrigation scheduling: Checkbook method. FO-01322. Univ. of

    Minnesota Ext. Serv., St. Paul.

Yan, X., Y Hosen, and K. Yagi. 2001. Nitrous oxide and nitric oxide emissions from

    maize field plots as affected by N fertilizer type and application method. Biol.

    Fertil. Soils. 34: 297-303.

Zvomuya F, C.J. Rosen, M.P. Russelle, and S.C. Gupta. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. J. Environ. Qual. 32: 480-489.

Table 1-1. Selected chemical properties of site soils. Samples were collected before establishing treatments (in April of each year) from the upper 0.15 m, except for inorganic nitrogen samples, which were collected from upper 0.6 m. Methods of analysis from Brown (1998). Means with standard errors in parentheses are shown ($n = 2$–5).

	2007	2008	2009
		--	
pH	6.7 (0.04)	6.2 (0.13)	4.9 (0.03)
		% by weight	
organic matter	1.5 (0.07)	2.0 (0.03)	2.4 (0.03)
		$\mu g\ g^{-1}$	
Bray-P	32 (2.3)	32 (1.9)	23 (1.9)
K	88 (7.0)	110 (2.0)	66 (2.6)
SO_4	not done	2.0 (0)[†]	5.0 (1.0)
B	0.20 (0)[†]	0.21 (0.01)	0.28 (0.01)
Ca	720 (49)	810 (6.0)	335 (65)
Mg	140 (9.0)	140 (2.0)	40 (5.5)
Zn	0.67 (0.03)	0.70 (0)[†]	1.35 (0.05)
Fe	19 (0.70)	29 (0.20)	114 (9.90)
Cu	0.30 (0.04)	0.41 (0.01)	0.50 (0)[†]
Mn	4.9 (0.17)	7.2 (0.05)	37.6 (4.25)
NH_4^+-N	1.8 (0.10)	2.5 (0.39)	1.6 (0.13)
NO_3^--N	1.3 (0.11)	2.2 (0.14)	1.4 (0.09)

[†]All replicates had same result.

Table 1-2. Timing and rate of fertilizer applications used with conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2) and control treatments.

Treatment	Pre-planting	Planting[†]	Emergence[‡]	Post-emergence[§]	Total[¥]
kg N ha^{-1}					
2007					
CSA	0	45	112	5 x 22.5	270
PCU-1	225	45	0	0	270
PCU-2	225	45	0	0	270
2008 and 2009					
CSA	0	45	112	4 x 28	270
PCU-1	225	45	0	0	270
PCU-2	225	45	0	0	270
Control	0	0	0	0	0

[†]All fertilized treatments received 45 kg N ha^{-1} starter as diammonium phosphate.
[‡]Emergence applications consisted of 100% urea.
[§]Post-emergence applications consisted of 50% urea and 50% NH_4NO_3.
[¥]All treatments received additional inputs equivalent to 34, 33, and 24 kg N ha^{-1} in 2007, 2008, and 2009, respectively, from NO_3^- contained in irrigation water.

Table 1-3. Daily soil N_2O fluxes (mean and standard error in parentheses) in plots fertilized using conventional split application urea (CSA), polymer-coated urea (PCU) products, and unfertilized control. Within each column and year, values with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, and lowercase letters indicate $P < 0.10$.

| | Daily N_2O flux | | |
	Hill Position	Furrow Position	Combined[†]
	$\mu g\ N\ m^{-2}\ h^{-1}$		
2007			
CSA	51.3 (11) B	16.6 (2.1)	33.9 (5.9) c
PCU-1	23.2 (2.1) A	16.2 (2.2)	19.7 (1.6) a
PCU-2	30.6 (5.0) A	21.8 (3.1)	26.3 (2.9) ab
2008			
CSA	57.7 (7.3) C	69.7 (12)	63.7 (7.1) b
PCU-1	35.0 (3.9) B	28.8 (3.9)	31.9 (2.8) a
PCU-2	41.5 (3.9) B	67.6 (16)	54.6 (8.3) b
Control	22.0 (2.7) A	19.8 (2.7)	20.9 (1.9) a
2009			
CSA	29.7	39.1 C	34.4 c
PCU-1	27.3	24.9 B	26.1 b
PCU-2	23.0	30.2 BC	26.6 b
Control	15.7	9.41 A	12.5 a

[†] Combined data were obtained by averaging hill and furrow data for each sampling date.
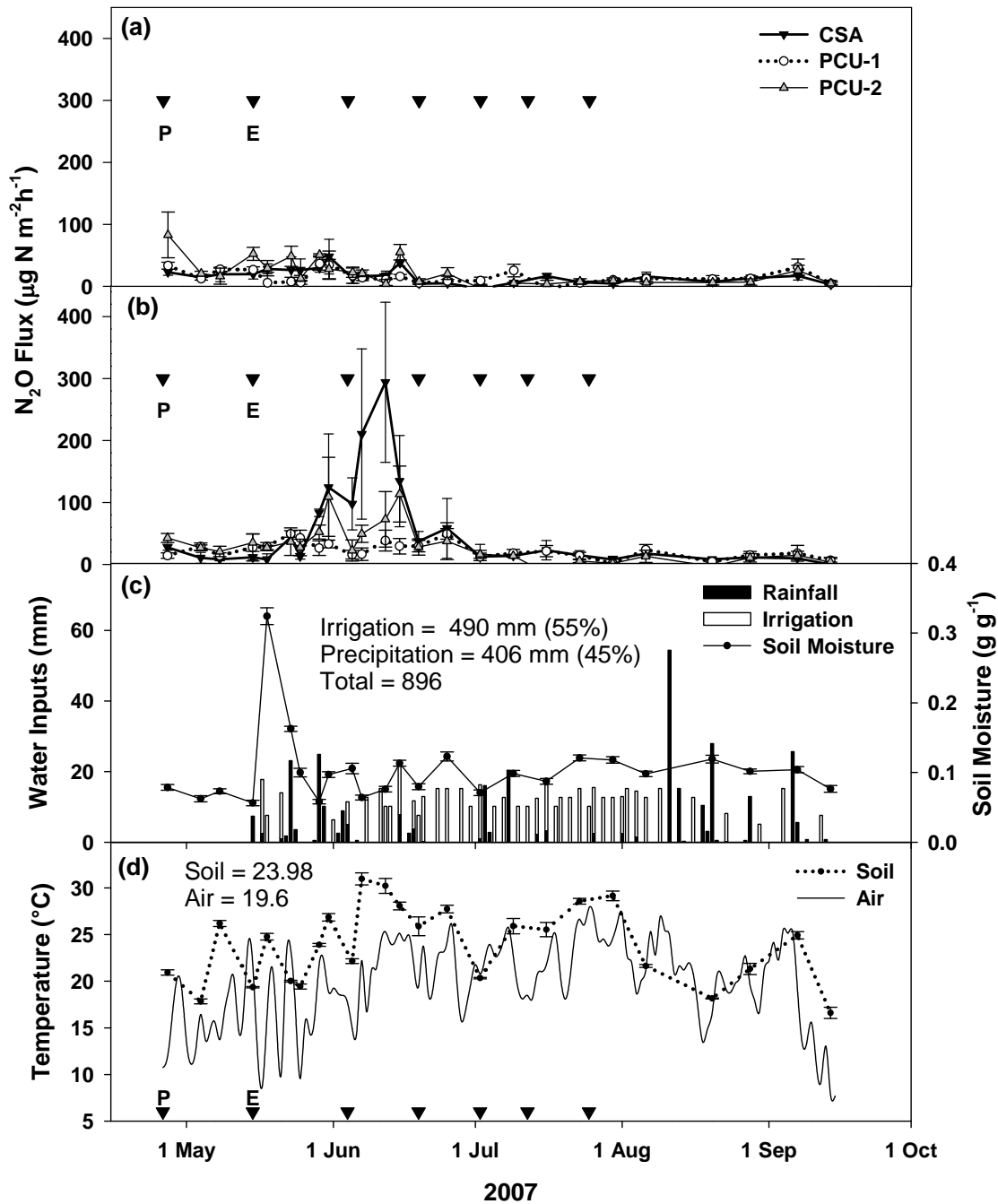
Figure 1-1. Soil N_2O fluxes from the hill (a) and furrow (b) positions of potato fertilized using a conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2); (c) water inputs and soil moisture; and (d) soil and air temperatures during 2007. Arrows indicate timing of fertilizer applications with CSA, which occurred at planting (P), emergence (E), and five times after emergence. The PCUs were added in a single preplant application. Total seasonal precipitation and irrigation inputs are given in (c) as a percentage of total inputs, and seasonal mean soil and air temperatures are given in (d).
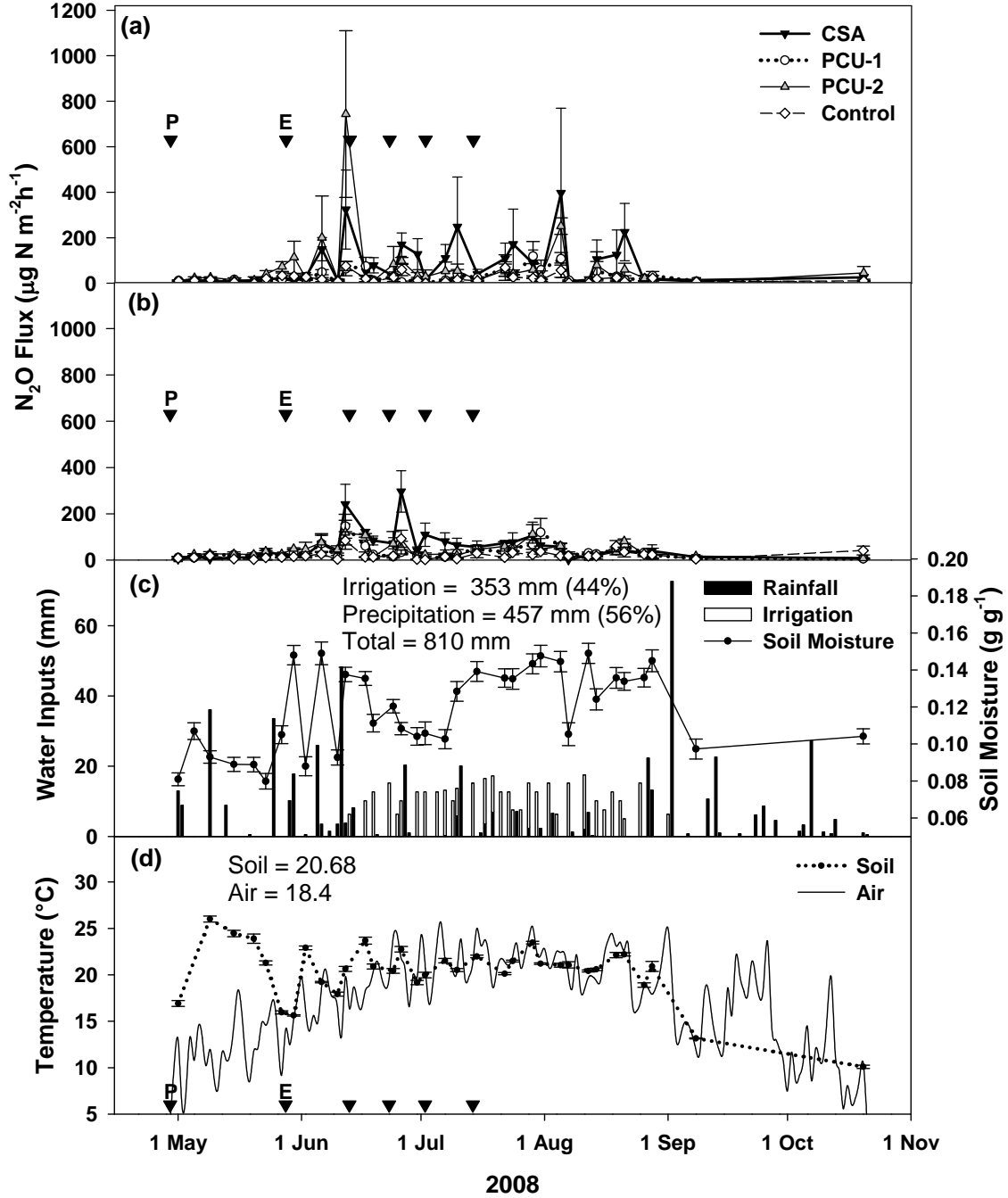
Figure 1-2. Soil N$_2$O fluxes from the hill (a) and furrow (b) positions of potato fertilized using a conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2); (c) water inputs and soil moisture; and (d) soil and air temperatures during 2008. Arrows indicate timing of fertilizer applications with CSA, which occurred at planting (P), emergence (E), and four times after emergence. The PCUs were added in a single preplant application. Total seasonal precipitation and irrigation inputs are given in (c) as a percentage of total inputs, and seasonal mean soil and air temperatures are given in (d).

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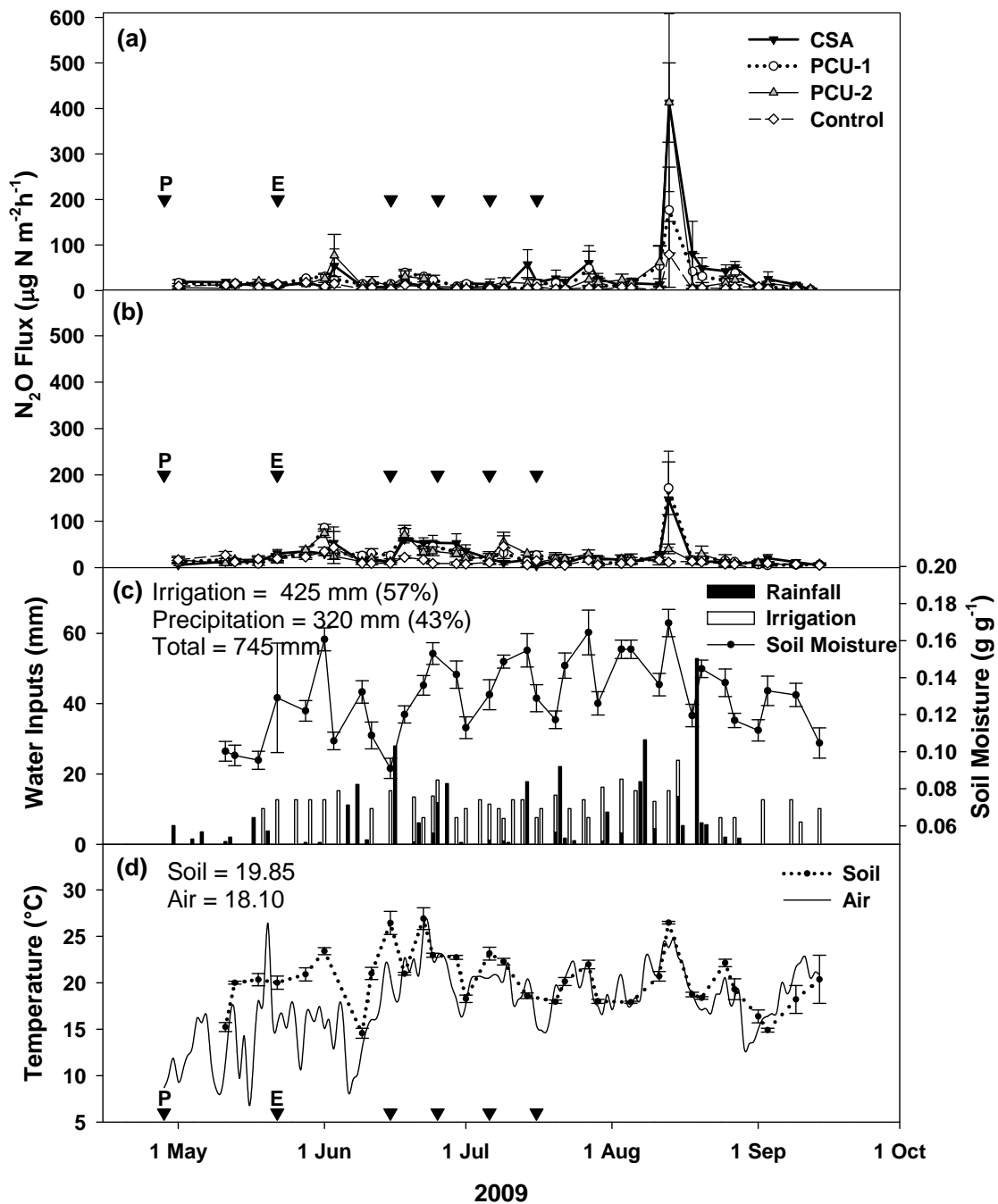
Figure 1-3. Soil N$_2$O fluxes from the hill (a) and furrow (b) positions of potato fertilized using a conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2); (c) water inputs and soil moisture; and (d) soil and air temperatures during 2009. Arrows indicate timing of fertilizer applications with CSA, which occurred at planting (P), emergence (E), and four times after emergence. The PCUs were added in a single preplant application. Total seasonal precipitation and irrigation inputs are given in (c) as a percentage of total inputs, and seasonal mean soil and air temperatures are given in (d).

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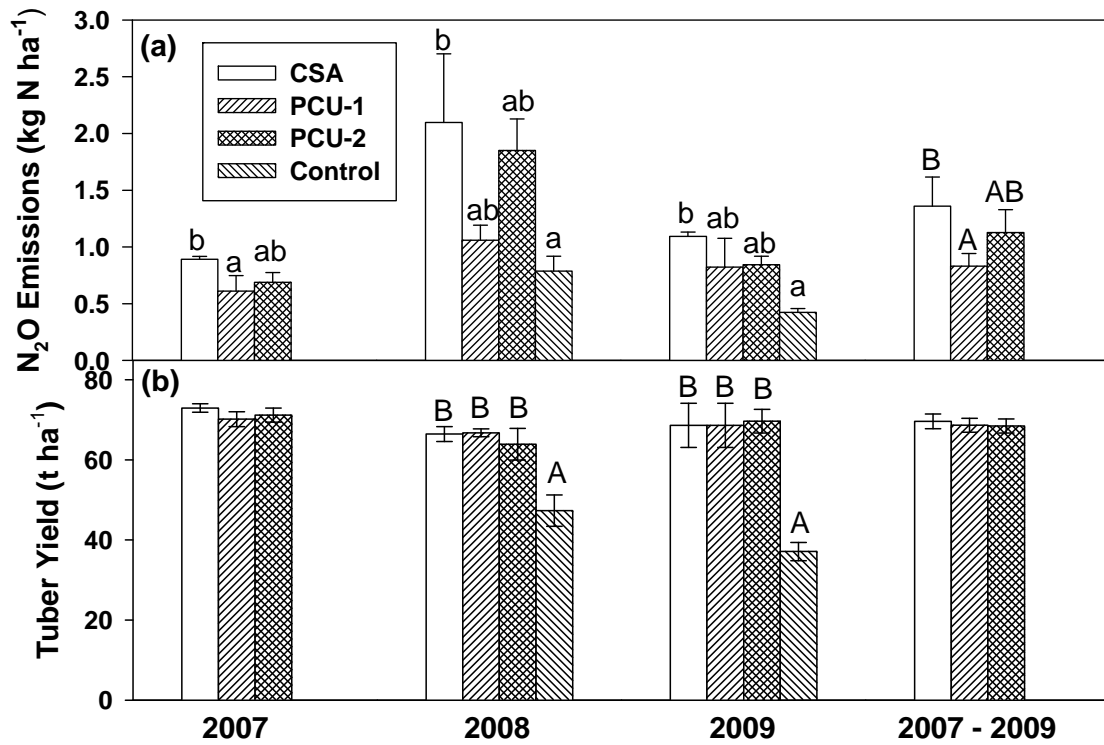
Figure 1-4. (a) Total seasonal cumulative N_2O emissions and (b) marketable tuber yield in plots fertilized using a conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and unfertilized control. Mean values with standard error bars are shown ($n = 3$). Values during the study period (2007–2009) are shown only for the fertilized treatments. Within each time period, bars with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, lowercase letters indicate $P < 0.10$.
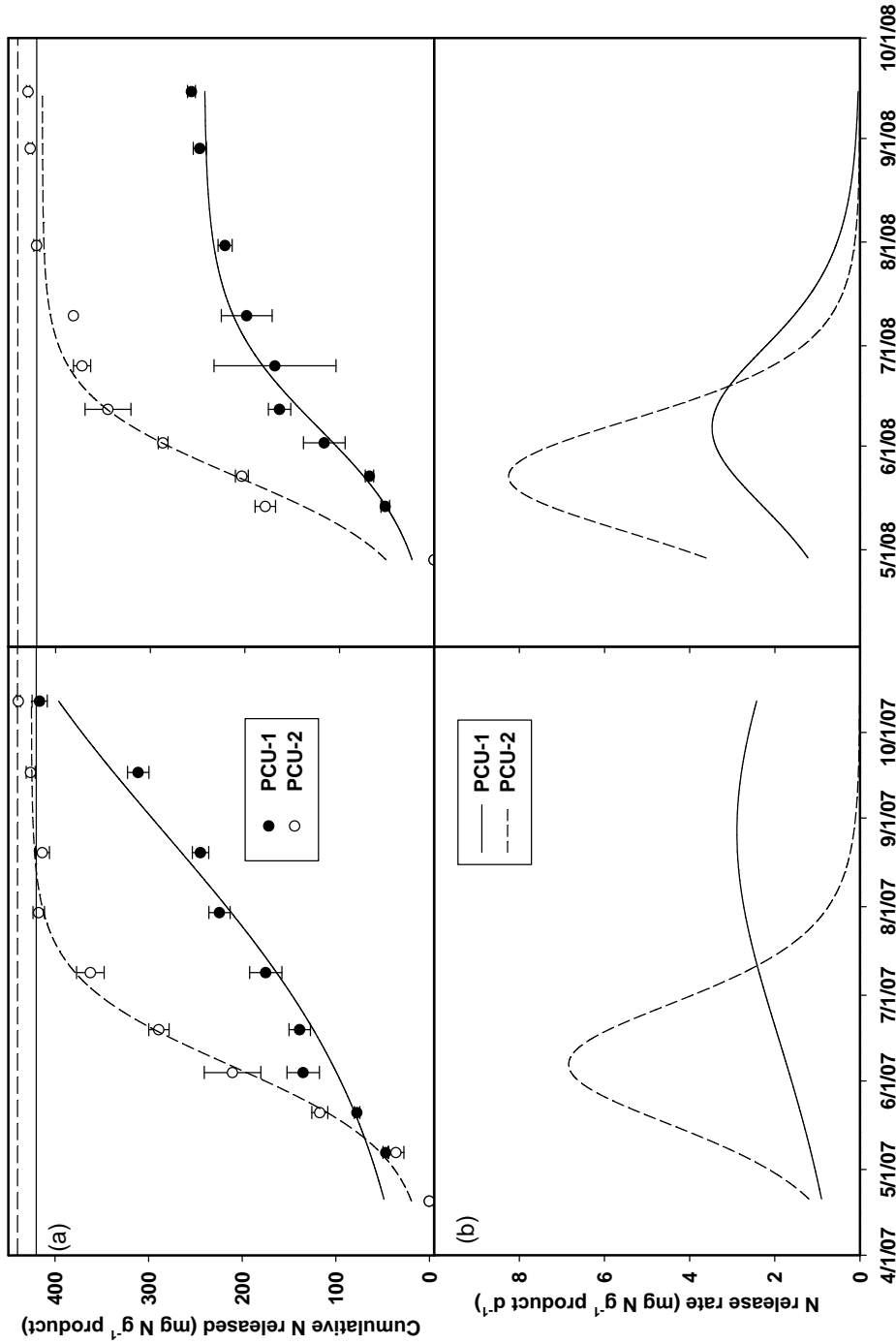
Figure 1-5. (a) Cumulative mass of N released from polymer-coated urea products (PCU-1 and PCU-2) during *in situ* incubation and (b) corresponding N release rates during 2007 (left) and 2008 (right). Symbols are mean with standard error bars (n = 3). Curves in (a) were obtained by nonlinear regression using Eq. [1], and curves in (b) were obtained by numerical differentiation of the curves in (a). Incubation bags were installed 20 Apr. 2007 and 28 Apr. 2008. Horizontal lines in (a) represent maximum potential loss based on N content of PCU-1 (solid line) and PCU-2 (dashed line), i.e., 420 and 440 g N kg^{-1}, respectively.

Part 2.

Nitrogen Use Efficiency, Leaching Losses, and Potential Effects on Indirect N_2O Emissions in Three Alternative Best Management Practices for Irrigated Potato Production

Much of the data and a number of the results and conclusions found in the following

chapter have been submitted for publication in a modified form with the listed

collaborators.

Nitrogen Use Efficiency, Leaching Losses, and Effects on Potential Indirect N$_2$O Emissions in Three Alternative Best Management Practices for Irrigated Potato Production.

Charles R. Hyatt[1], *Rodney T. Venterea[1,2], and Carl J. Rosen[1].

[1] Dept. Of Soil, Water, and Climate, 1991 Upper Buford Circle, Univ. of Minnesota, St. Paul, MN 55108

[2] USDA-ARS, Soil & Water Management Research Unit, 1991 Upper Buford Circle, St. Paul, MN 55108.

* Corresponding author email address: rod.venterea@ars.usda.gov

Nitrogen Use Efficiency, Leaching Losses, and Effects on Potential Indirect N_2O Emissions in Three Alternative Best Management Practices for Irrigated Potato Production.

SUMMARY

Irrigated potato (*Solanum tuberosum* L.) with its high Nitrogen (N) demand, shallow root system, and potentially high NO_3^- leaching losses, could be a significant contributor of indirect N_2O emissions. The current IPCC default indirect emission factor is 0.75% of NO_3^- leached. However, there is a large uncertainty range. The study of individual polymer-coated urea (PCU) products has shown a reduction in NO_3^- leaching when compared with conventional split application (CSA) systems using multiple additions of soluble fertilizers. PCUs have also been shown to reduce direct N_2O emissions compared to CSA. This 3-yr study compared NO_3^- leaching, potential indirect, and total N_2O emissions following CSA, single preplant applications of two different PCUs (PCU-1 and PCU-2), and an unfertilized control in a loamy sand. Fertilizers were applied at 270 kg N ha^{-1} yr^{-1}. Two evapotranspiration (ET) models (modified Jensen-Haise, JH, and FAO 56 Penman-Monteith, PM) were also compared, with PM selected as the preferred method. N use efficiencies were not found to be significantly different (P<0.05) among treatments. Leaching was also not significantly different among treatments. Indirect N_2O emissions were significantly lower than direct under the default emission factor. However, it was found that indirect emissions could potentially range from 0.6 to 84.9% of direct emissions, due to uncertainty. This study found that the use of PCU could maintain NUE and leaching levels and may reduce total N_2O emissions when compared with a more field intensive CSA system. However, more work remains to be done to narrow the indirect emission factor uncertainty range. **Abbreviations**: CSA, conventional split application; ET, Evapotranspiration; JH, Jensen-Haise; PCU, polymer-coated urea; PM, Penman-Monteith.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is a nitrogen (N) intensive crop requiring significant inputs of fertilizer N. In Minnesota, current best management practices recommend application of between 260 and 280 kg ha^{-1} N (after rye) to maintain yields of 56 t ha^{-1} (Rosen and Bierman, 2008). Potato is commonly grown on coarse textured soils with low water holding capacity. Under these conditions, regular irrigation is required to maintain tuber size and quality (Shock et al., 2007). Irrigated potato plants tend to concentrate 60-85% of their root mass within the top 30 cm of soil (Stalham and Allen, 2001; Lesczynski and Tanner, 1976). Due to this shallow main root system, potatoes are relatively inefficient in capturing fertilizer N. Using a mass balance approach, Errebhi *et al*. (1998) found that an irrigated potato crop grown on coarse textured soil recovered, on average, only between 33-56% of the N that was applied. There are two major pathways for N loss, via leaching below the root zone and into the ground water, or movement into the atmosphere as a volatile compound.

The form of N that is most susceptible to loss via leaching is the negatively charged nitrate ion (NO_3^-). Nitrate is the end product of the nitrification process, and because it shares the same charge as the clays of a typical soil, it tends to move quickly with water through the soil profile. This is particularly the case in the types of coarse textured soil where potatoes are commonly grown. In the Canadian province of Prince Edward Island, the percentage of land in potato production was a found to be a significant predictor of elevated levels of groundwater NO_3^- (Benson et al., 2006). In the U.S., groundwater NO_3^- concentrations have increased significantly over the last decade

(Rupert, 2008). A survey of private drinking water wells in Minnesota found that 6% of wells sampled had NO_3^- concentrations above the USEPA maximum contaminant level of 10 mg L^{-1} and another 5% of wells had between 5 and 10 mg L^{-1} (Lewandowski et al., 2008). Nitrate concentrations up to 20 mg L^{-1} were found in shallow groundwater in a central Wisconsin sand plain used for potato and corn production (Kraft and Stites, 2003). At our experimental site where potatoes are commonly grown, groundwater from 17-m deep wells contained between 6 and 10 mg NO_3^--N L^{-1} resulting in 24 to 34 kg N ha^{-1} added to treatments with irrigation water (Hyatt et al., 2010).

In addition to loss via leaching, N can also move off the agricultural landscape via volatilization into the atmosphere. Nitrous oxide (N_2O) is a greenhouse gas with a global warming potential approximately 300 times greater than CO_2 (Forster et al., 2007). As of 2008, it contributed 4.6% of total annual U.S. greenhouse gas emissions in CO_2 equivalents (USEPA, 2010). Global atmospheric N_2O is rising in concentration at approximately 0.26% per year (Forster et al., 2007). Nearly 68% of anthropogenic N_2O emissions in the U.S. are the result of agricultural soil management with overall emissions of N_2O from U.S. agricultural soils increasing 6.1% from 1990 to 2008 (USEPA, 2010). Fertilizer, or other sources of soil N, can be transformed to N_2O via nitrification, denitrification, or other processes (Firestone and Davidson, 1989).

Agricultural N_2O emissions can be divided into two categories, (i) direct and (ii) indirect. Direct emissions originate in managed agricultural fields, while indirect emissions occur in locations that are geographically removed from the original N application site. Much direct agricultural N_2O production occurs under denitrification-

promoting conditions (Firestone and Davidson, 1989). Despite this, there is also evidence

of significant nitrification-driven N_2O production from coarse-textured soils, such as

those in potato production (Venterea, 2007; Hyatt et al. 2010). Direct N_2O emissions in

potato have been examined in a number of recent studies with respect to fertilizer

management, tillage, and soil properties (Ruser et al., 2006; Vallejo et al., 2006; Burton

et al., 2008; Haile-Mariam et al., 2008; Hyatt et al., 2010).

Indirect N_2O emissions, originating from agricultural N that has been displaced

from the original application site can also significantly contribute to total N_2O emission

rates. As described above, N can move readily through the environment, and does so

primarily by volatilization which is followed by atmospheric deposition or with water via

leaching or runoff (Mosier et al., 1998). Denitrification processes in ground and surface

waters working on this displaced N are likely to be the ultimate source of most indirect

N_2O emissions (Mosier et al., 1998; Nevison, 2000). However, indirect emissions can be

difficult to measure directly due to the scale of the water/movement system and

uncertainty inherent in both N movement pathways. In fact, indirect emissions account

for nearly two thirds of the uncertainty in total global agricultural soil N_2O emission

estimations (Mosier et al., 1998). The Intergovernmental Panel on Climate Change

(IPCC) suggests that a value of 0.75% be used as a default emission factor when

calculating the percentage of leached NO_3^- that is converted to N_2O (Eggleston et al.,

2006), but their methodology includes an uncertainty range of 0.05-2.5% (95%

confidence interval).

There are few studies examining indirect emissions of N_2O in potato, and as far as we are aware, none that estimate emissions by applying the IPCC emission factor to directly measured groundwater NO_3^- concentrations in that crop. Koga *et al*. (2006) did address indirect N_2O emissions in potato. However, they estimated potential emissions in potato by multiplying the quantity of fertilizer-N applied by IPCC's default N leaching fraction value of 0.30 (Eggleston et al., 2006), and then multiplying this value by an indirect N_2O emission factor of 1.24%, derived from a combination of IPCC (1997) emission guidelines and the recommendations of Sawamoto *et al*. (2005).

There are a number of strategies employed to reduce the amount of N lost from agricultural fields through both leaching and volatilization which could also ultimately minimize indirect N_2O emissions. Polymer coated urea (PCU) is designed to release N slowly over the course of the season to parallel crop demand, leaving less excess N available to be lost. PCUs have been seen to reduce both NO_3^- leaching (Wilson et al., 2010) and direct N_2O emissions (Hyatt et al., 2010) in potatoes when compared with a conventional soluble fertilizer split application strategy (CSA). Their use has also been shown to maintain potato yields (Hyatt et al., 2010) while reducing the equipment field time and personnel costs associated with CSA. Wilson *et al*. (2009b) found that net economic returns using single applications of PCU and CSA were comparable, even considering the higher initial cost of PCU. However, studies examining PCU with respect to N_2O emissions in potatoes are uncommon (Hyatt et al., 2010) and as far as we are aware, there have been no studies that have compared NO_3^- leaching from multiple PCUs

to a CSA type system and none with the aim of applying these data to estimate indirect N_2O emissions.

In studies examining PCU's ability to meter out N to match plant requirements, PCUs have been found to compare favorably to CSA with respect to total plant N uptake. Nitrogen Use Efficiency (NUE) refers to a given crop's ability to uptake and utilize fertilizer N at the applied rate. A higher NUE results in less residual fertilizer N in the soil and a reduction in the potential for N leaching loss. There are a number of different indices that can be used to evaluate how N is being used by the crop in a particular cropping system. These indices take into account factors such as yield, biomass production, and/or biomass N content (Zvomuya et al., 2002). In potatoes, studies have shown that NUE can be influenced by the rate and timing of fertilizer application, the type of cultivar grown, soil type, and the use of slow release fertilizers (Zvomuya et al., 2003; Zebarth et al., 2004; Zebarth et al., 2008). Wilson *et al*. (2010) reported that the use of PCU resulted in improved potato N uptake when compared with CSA split applied in two applications, but comparable to CSA applied in 6 applications. Hutchinson et al. (2003) found that PCUs achieved a higher NUE than soluble fertilizers when three different PCUs were compared to urea and ammonium nitrate. However, in that study, NUE was only calculated in a singular fashion as a ratio of yield to fertilizer application. As far as we are aware, there are no studies that compare multiple PCUs to CSA with respect to NUE in potatoes using multiple NUE metrics.

In order to address some of the gaps in the literature outlined above, the objectives of this current study were to:

1. Determine the effects of alternative N management systems on nitrate leaching rates in a Minnesota potato production system due to N management systems that included CSA, similar to recommended BMPs, and single preplant applications of two different PCUs.

2. Evaluate potential differences in nitrogen use efficiency between treatments using five different NUE calculations.

3. Estimate total N_2O emissions using previously measured direct emissions and potential indirect emission values calculated by applying the IPCC recommended indirect emission factor to measured nitrate leaching data.

MATERIALS AND METHODS

Site Description and Experimental Design

This study was carried out in three consecutive growing seasons (2007-2009) at the University of Minnesota Sand Plain Research Farm in Becker, MN (45°23′N, 93°53′W). Soils at the site are a coarse textured uniform Hubbard loamy sand (Sandy, Mixed, frigid, Typic Hapludoll) comprised of 82% sand, 10% silt, and 8% clay. Additional soil properties are shown in Table 2-1. The site has a 30-yr average annual temperature and precipitation of 6.0° C and 745 mm, respectfully, and sampling season (May-Nov) average temperature and precipitation of 13.7° C and 582, respectively (MRCC, 2010). A weather station (CR1000, Campbell Scientific, Inc, Logan, UT) was positioned onsite to measure air temperature, wind speed, relative humidity, and net solar radiation at 10-min intervals. To address gaps in the dataset due to power interruptions,

weather data measured hourly at the National Interagency Fire Center Remote Automated

Weather Station (RAWS: CSCM5) located only 20 km northeast of the field site

(45°32′N, 93°45′W) in Sherburne, MN were also used (20 Apr through 9 Jul and 19 Sep

through 30 Nov, 2007 and 5 Sep through 30 Nov, 2008;

http://mesowest.utah.edu/index.html).

A different section of the farm was utilized for experimentation each year. The

fields used for the 2007 and 2009 experiments were planted to non-irrigated, non-

fertilized rye (*Secale cereal* L.) during the previous year. The field used for the 2008

experiment was planted the previous year to rye followed by 'Caliente' mustard

(*Brassica juncea* and *Sinapsis alba* blend) and was fertilized with 34 kg N ha^{-1} as

ammonium nitrate (AN). Rye grain was harvested in summer; rye stover and the 2007

mustard crop were disk-incorporated in fall. Each spring, N-fertilizer treatments were

established in a randomized complete block design with 3 replications of each treatment.

Plots were 6.1 m long and between 3.7 m (with four planting rows) and 4.6 m (with five

planting rows) wide. One wk prior to planting in all years, 280 kg ha^{-1}of potassium-

magnesium sulfate and 280 kg ha^{-1} of potassium chloride were broadcast and

incorporated with a moldboard plow in all plots. On 26 April 2007, 29 April 2008, and 28

April 2009, plots were hand planted with "Russet Burbank" whole "B" seed potatoes

(*Solanum tuberosum* L.) and fertilized with a pre-weighed starter fertilizer applied as a

band 0.05 m below and 0.08 m to the side on both sides of the row. For all but the control

plots, the starter contained 45 kg N ha^{-1} and 50 kg of P ha^{-1} as diammonium phosphate

(DAP), 186 kg K ha^{-1}, 34 kg Mg ha^{-1}, 67 kg S ha^{-1}, 2.25 kg Zn ha^{-1}, and 0.6 kg B ha^{-1}

Control plots received a similar mix that excluded DAP and substituted triple superphosphate.

Nitrogen-fertilizer treatments included a conventional split application (CSA), consisting of an initial application of granular urea surface banded on both sides of the row at plant emergence followed by 4 (2008 & 2009) or 5 (2007) split applications of urea ammonium nitrate (UAN) as 50% granular urea and 50% granular AN. The UAN was broadcast uniformly over the entire plot and watered in to simulate fertigation with 28% urea-AN, consistent with recommended BMPs for the system (Zvomuya et al., 2003; Rosen and Bierman, 2008). Post-emergence CSA fertilizer applications started 2–3 wk after hilling and were repeated at intervals of 9–15 d (indicated in Figs. 2-2, 2-3, and 2-4, for 2007, 2008, and 2009, respectively). In addition, two polymer coated urea treatments (PCU-1 and PCU-2), each employed a single application which was broadcast 1 to 6d before planting and incorporated by disking within 24h of application. A non-fertilized control was also included in each year. All treatments except the control received a total of 270 kg N ha^{-1} (Table 2-2).

The PCU-1 treatment used a product containing 42% N by weight which was manufactured by Shandong Kingenta Ecological Engineering Co. LTD (Linshu, Shandong Province China). The PCU-2 treatment used a product (Environmentally Smart Nitrogen) containing 44% N by weight which was manufactured by Agrium, Inc. (Calgary, AB). The PCU-1 product was obtained directly from the manufacturer. In 2007, PCU-2 was obtained from the manufacturer, while in 2008 and 2009, product was obtained from a local distributor.

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Within 24-h of the initial CSA urea application (on 15 May 2007, 28 May 2008, and 22 May 2009), rows in all treatments were hilled. In 2008 equipment malfunction required all plots to be hilled a second time. Irrigation water was applied through an aluminum pipe solid-set overhead sprinkler system. Irrigations were scheduled by the checkbook method as described in Wright (2002) and contributed the equivalent of an additional 34, 33, and 24 kg N ha^{-1} in 2007, 2008, and 2009, respectively, due to nitrate present in the well water used for irrigation.

Potato vine kill was achieved via flail mowing on 19 Sept 2007, 15 Sept 2008, and 17 Sept 2009. Samples of vines were collected immediately prior to mowing by hand cutting 3 m of vines from two inner rows pre-identified as "harvest rows" in each plot. Vine samples were then weighed. Potato tubers were mechanically dug from the center 5.5-m of the harvest rows of each plot on 28 Sept. 2007, 16 Sept. 2008, and 21 Sept. 2009 and weighed. Total yield for vines and tubers were determined on a kg dry matter ha^{-1} basis. Subsamples of vines and tubers were taken from each plot, weighed, dried at 60° C to a constant weight (for at least 72 h) and again weighed to determine percent dry matter. The dry samples were ground with a Wiley mill to pass a 2-mm screen and analyzed for percent total N with a combustion analyzer (vario EL, Elementar Americas Inc., Mt. Laurel, NJ) following the methods of Horneck and Miller (1998). Nitrogen content was determined by multiplying total dry matter yield (percent dry matter × total yield) by percent total N. This calculation was done for vines and tubers individually.

Nitrogen Use Efficiency

In potato systems, Errebhi *et al.* (1999) defined NUE as total plant dry weight per unit of available N in the soil. Zvomuya *et al.* (2002) used a similar equation, referred to as 'agronomic use efficiency', or a measure of biomass produced per unit of applied N, and defined three additional NUE equations including; 'N uptake efficiency', the ability of the plant to recover available N; 'physiological use efficiency', how recovered N is utilized in the plant for biomass production; and 'N harvest index', how N is used by the plant to supply the harvest portion, i.e. tubers, as compared to the total biomass. In our study, we examined these four indices with the following equations (adapted from Zvomuya et al., 2002):

$$\text{N uptake efficiency} \quad = \quad \frac{B_f - B_0}{F} \qquad\qquad [1]$$

$$\text{Agronomic use efficiency} \quad = \quad \frac{D_f - D_0}{F} \qquad\qquad [2]$$

$$\text{Physiological use efficiency} \quad = \quad \frac{D_f - D_0}{B_f - B_0} \qquad\qquad [3]$$

$$\text{N harvest index} \quad = \quad \frac{T_f - T_0}{B_f - B_0} \qquad\qquad [4]$$

where F is fertilizer N applied, B is total N uptake by tubers plus vines (biomass), T is total N uptake by tubers alone, and D is total biomass dry matter; with all terms expressed in kg ha^{-1}. The subscripts f and 0 refer to values for a given fertilized treatment and the control plot, respectively.

In addition to the agronomic indices presented above, an economic index, the partial factor productivity (PFP) of applied N on yield, was examined to determine total economic outputs relative to fertilizer inputs. This was shown by (adapted from Cassman et al., 1996):

$$PFP \quad = \frac{Y}{F}$$ [5]

where Y represents total fresh tuber yield (kg ha^{-1}). With this calculation, PFP is found to be equivalent to yield achieved per unit of fertilizer applied (kg yield kg^{-1} N). By multiplying PFP by the ratio of crop price by fertilizer cost, general economic benefit comparisons can be made. However we have not evaluated treatments in regards to specific economic criteria for this study.

Soil Water NO$_3^-$ Concentrations

Water samples from below the rooting zone were collected at a depth of 1.2 m with suction cup lysimeters (represented in Fig. 2-1). Each lysimeter consisted of a round-bottom, neck-top, 1-bar high flow porous ceramic cup (60-mm length, 48-mm O.D., 44-mm neck diameter, Soilmoisture Equipment Corp, Santa Barbara, CA) affixed with epoxy to one end of a 1.3-m length of 48-mm I.D. SDR-26 polyvinylchloride (PVC) pipe (1.5 in nominal size). The other end of the pipe was fitted with a #10 black rubber stopper that was held in place with vinyl tape wrapped around the junction. Two sections of 6.35-mm O.D. polyethylene (PE) tubing passed through fitted holes in the stopper to the inside of the PVC pipe with one section (the vent tube) terminating approximately 0.1

m below the stopper and the other section (the sample tube) extending to approximately 2 mm above the inside surface of the ceramic cup. Both sections of PE tubing extend approximately 0.5 m above the top of the stopper on the outside of the lysimeter and were connected to 0.1 m sections of clear R-3603 tygon tubing (4.76-mm I.D.) which were equipped with ratcheting tubing clamps (12-position medium polypropylene clamp, Halkey-Roberts Corp, Saint Petersburg, FL).

Lysimeters were installed in the hill zone of the first non-harvest row adjacent to the harvest row. Lysimeter installation was completed by 15 May 2007, 20 May 2008, and 5 May 2009. Prior to installation, lysimeters were prepared by submerging in water, clamping the vent tubes, and applying 40 kPa of suction via the sample tube with a hand pump sampler (model 2006G2, Soilmoisture Equipment Corp, Santa Barbara, CA). Sample tubes were clamped for >30 min to allow water to be drawn into the ceramic cups. A 1.3-m deep hole was bored in each plot using an 83-mm manual "regular" soil auger. Approximately 0.5 L of slurry consisting of 1 part silica flour and 3 parts water by volume was poured into the borehole. Lysimeters were then placed vertically, seating the cup into the silica slurry with the center of the cup positioned at a depth of approximately 1.2 m. Soil removed from the borehole was then replaced and gently tamped, filling the gap between the lysimeter and the edge of the hole. Soil was replaced in reverse order of removal paying attention to horizonation. At a depth of 0.15 m, a 10-mm thick powdered bentonite clay cap was evenly applied to the hole around the lysimeter to prevent preferential water flow down the sides of the PVC tube. The remainder of the removed soil was then replaced over the bentonite until the hole was refilled to a level consistent

with the surrounding soil. After approximately 24 hr, water was drawn out of the

lysimeters with the hand pump sampler by opening both vent and sample tubes and

applying suction to the sample tube. Suction was maintained until water could no longer

be drawn from the sample tube. This water was then discarded. In preparation for the first

sampling, the vent tube was clamped and a vacuum of 40 kPa was re-applied to the

lysimeters through the sample tube, which was then also clamped.

Sample water was collected from the lysimeters approximately once per wk

during all growing seasons except 18 Jun through 12 Jul 2008 and 1 Jul through 16 Jul

2009. Water samples were collected in 50 mL capped polypropylene vials via hand pump

as described above by opening the vent and sample tubes and then applying vacuum to

the sample tube until all water was drawn out. Excess water (>50 mL) was discarded.

Samples were collected a total of 30 times in 2007 between 7 May and 25 Nov 2007, 19

times in 2008 between 30 May and 12 Nov 2008, and 28 times in 2009 between 18 May

2009 and 25 Nov 2009. An additional 6, 3, and 4 samples were collected in the fields the

spring (23 Mar – 2 Jun) following the 2007, 2008, and 2009 seasons, respectively.

Water samples were stored at -5° C until analysis. Prior to analysis, samples were

thawed at room temperature or in a water bath (~38° C). Samples from the 2007 season

were analyzed for NO_3^- and NH_4^+ on a flow-through colorimetric analyzer connected to

an auto-sampler (ISIS Autosampler, Teledyne Isco, Inc, Lincoln NE) utilizing the

diffusion-conductivity method (Carlson et al., 1990). Analysis in 2008 and 2009 was

performed via flow injection analysis (QuickChem 8500 with ASX 520 series auto-

sampler, Lachat Instruments, Milwaukee, WI) according to Wendt (2003). In this

analysis, NO_3^- in the water samples was reduced to nitrite by passage through copperized cadmium. Total $NO_2^- + NO_3^-$ was then reported as the sum of the reduced NO_3^- and any residual nitrite present in the sample prior to NO_3^- reduction. Samples for 2008 and 2009 were typically analyzed at a 1:4 dilution in ultrapure water (Synergy, Millipore, Billerica, MA), however occasionally a sample would be rerun at 1:8 to move its area count within range of the standard curve.

Water Balance and NO_3^- Leaching Estimation

Leaching can be described using the general water budget equation (adapted from Errebhi et al., 1998); Inputs – Outputs = Change in Storage, or:

$$(P + I) - (ET + D) = \Delta S \qquad \textbf{[6]}$$

where P is precipitation, I is irrigation water applied, ET is evapotranspiration, D is drainage, and ΔS is change in the soil water storage; with all terms expressed in mm day^{-1}.

Eq. [6] was applied to estimate the volume of water leaching below the root zone in the following manner: (i) the initial amount of water stored in the profile after ground thaw on 13 Apr 2007 and 2008, and 20 Apr 2009, was assumed to be equivalent to the available water capacity (AWC), where AWC is defined as the quantity of water between field capacity and the permanent wilting point. For the soils at this site, AWC was assumed to be 85.09 mm (NRCS, 2002); (ii) for each 24-h time interval under consideration, P was determined by on-site measurement using a National Weather Service catch can and gage stick, I was estimated based on irrigation flow rate and

duration of application, and *ET* was estimated using semi-empirical models (described below); (iii) potential water storage (mm) at the end of the interval (PS_n) was then calculated by the equation:

$$PS_n = S_{n-1} + P + I - ET \qquad \text{[7]}$$

(adapted from Waddell et al., 2000) where S_{n-1} is the water storage (mm) at the start of the interval; (iv) actual water storage at the end of the interval (S_n) and drainage during the interval (D_n) were then determined as follows:

$$IF\ PS_n > AWC, \qquad D_n = PS_n - AWC \qquad \textbf{and}$$

$$S_n = AWC$$

$$ELSE \qquad D_n = 0 \qquad \textbf{and}$$

$$S_n = PS_n \qquad \text{[8]}$$

where D_n is the current day's drainage and S_0 is the initial condition AWC of 85.09 mm. It is assumed by this method that there is no variation in water percolation across plots or replicates.

Evapotranspiration (ET) was determined using two different estimation methods. The first method applied the Jensen-Haise (JH) equation (Jensen and Haise, 1963) to estimate ET for an alfalfa reference crop. This equation, as modified by Killen (1984) to take into account regional environmental factors, is commonly used in Minnesota for irrigation scheduling. The other method is the FAO 56 Penman-Monteith (PM) equation which uses a grass reference crop and has recently been recommended as the international standard for calculating ET for agricultural applications (Allen et al., 1998).

The Killen modified JH equation (Killen 1984) is defined as follows:

$$ET_{0(in)} = (0.0105 \times T_F - 0.22) \times R_{s(in)} \qquad \text{[9]}$$

where $ET_{o(in)}$ is evapotranspiration for a reference alfalfa crop in inches day^{-1}, T_F is average daily temperature (in Fahrenheit), $R_{s(in)}$ is solar radiation inches day^{-1} equivalent water evaporated (measurement described below), and 0.0105 and 0.22 are constants based on saturated vapor pressures for maximum and minimum temperatures in the warmest month and elevation calculated for St. Cloud, MN, approximately 30 km northwest of the field site (Killen, 1984). By converting to SI units with ET in mm day^{-1}, T in °C, and R_s in mm day^{-1} equivalent ($R_{s(mm)}$), Eq. [9] becomes:

$$ET_0 = (0.0189 \times T + 0.116) \times R_{s(mm)} \qquad \text{[10]}$$

The PM equation is defined as (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad \text{[11]}$$

where R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the air temperature (°C) and u_2 is the wind speed (m s^{-1}) each at 2 m above the surface, e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the curve of saturation vapor pressure as a function of temperature (kPa °C^{-1}), and γ is the psychrometric constant (0.065 kPa °C^{-1}, Allen et al., 1998). For this equation R_n was determined as described below, G was assumed to be zero for daily calculations (Allen et al., 1998), and T and u_2 were measured with an on-site weather station at 10 min intervals from which the maximum and minimum temperature were determined and the average wind speed was calculated for a given 24-h time period.

Relative humidity was also measured with the weather station at 10 min intervals and from this and T, e_s and e_a were estimated using the following equations (Allen et al., 1998):

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \tag{12}$$

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^0(T_{min}) + e^0(T_{max})}{2}\right] \tag{13}$$

$$e^0(T) = 0.6108\exp\left[\frac{17.27T}{T + 237.3}\right] \tag{14}$$

where T_{min} and T_{max} are the minimum and maximum T for the given time interval, respectively, $e^0(T_{min})$ and $e^0(T_{max})$ are the saturation vapor pressure at the maximum and minimum air temperatures for a given 10 min period (kPa), RH_{mean} is the mean relative humidity for a given 10 min period, and exp[..] is the base of the natural logarithm (2.7183) raised to the power [..]. The slope of the saturation vapor pressure curve (Δ) was determined via (Allen et al., 1998):

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \tag{15}$$

Solar radiation data for use in both ET calculations was collected for the majority of the season by net radiometer which was attached to a field weather station. Periodic power failures in 2007 and 2008 necessitated using solar (shortwave) radiation collected via pyranometer at the Sherburne, MN RAWS station. These data were converted to net radiation (R_n) using the equations (Allen et al., 1998):

$$R_n = R_{ns} - R_{nl} \qquad [16]$$

$$R_{ns} = (1 - \alpha)R_s \qquad [17]$$

where R_{ns} is net solar radiation, R_{nl} is net longwave radiation, and R_s is measured solar radiation; all in MJ m^{-2} day^{-1}, and α is albedo - in this case a default dimensionless value of 0.23 (Allen et al., 1998). Net outgoing longwave radiation was calculated via (Allen et al., 1998):

$$R_{nl} = \sigma \left[\frac{T_{max,K}^4 + T_{min,K}^4}{2} \right] \left(0.34 - 0.14\sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \qquad [18]$$

where σ is the Stefan-Boltzmann constant (4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}), $T_{max,K}$ and $T_{min,K}$ are maximum and minimum absolute temperature (°C + 273.16) during the 24-hour period, respectively, e_a is the actual vapor pressure (kPa), R_s/R_{so} is relative shortwave radiation (limited to ≤ 1.0) with R_{so}, or clear-sky radiation calculated by (Allen et al., 1998):

$$R_{so} = (0.75 + 2 \times 10^{-5} z)R_a \qquad [19]$$

where z is altitude of the site (296 m) and R_a is extraterrestrial radiation assumed to be a mid-season (slightly higher than seasonal average) value of 35.4 MJ m^{-2} day^{-1}.

Eq. [18] was additionally modified by exchanging $\left[\dfrac{T_{max,K}^4 + T_{min,K}^4}{2} \right]$ with

$T_{avg(10),K}^4$ resulting in:

$$R_{nl} = \sigma \left[T_{avg(10),K}^4 \right] \left(0.34 - 0.14\sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \qquad [20]$$

where $T_{avg(10),K}$ is the absolute temperature measured at 10 min intervals. Finally, R_{nl} was limited to values > 0. Missing individual solar radiation and wind speed data points were estimated using the mean of the immediately preceding and following measured data points.

As the ET results for both the JH and PM equations reflect estimated ET of a given reference crop (alfalfa for JH and grass for PM), ET_0 values for both equations were multiplied by a crop coefficient based on stage of growth in a potato crop to give daily ET predictions for potato with the equation:

$$ET = ET_o \times K_c \hspace{4cm} [21]$$

where ET_o is evapotranspiration for a reference alfalfa or grass crop in mm day^{-1} and K_c is a dimensionless crop coefficient determined experimentally at North Dakota State University (Stegman et al., 1977). The daily crop coefficient values for potato presented by Stegman *et al.* (1977) were developed for an ET equation, such as JH, that specifically uses alfalfa as a reference crop. To adapt these values to a grass reference crop equation, alfalfa crop coefficients were multiplied by a conversion ratio of 1.24 as demonstrated by the equations below (Allen et al., 1998):

$$K_{ratio} = 1.2 + \left[0.04(2.2-2) - 0.004(30-45)\right]\left(\frac{0.5}{3}\right)^{0.3} = 1.24 \hspace{1cm} [22]$$

$$K_g = K_{ratio} \times K_a \hspace{4cm} [23]$$

where K_{ratio} is a ratio between the grass and alfalfa reference crop coefficients and K_a and K_g are crop coefficients for alfalfa and grass reference crops, respectively.

Once daily drainage was determined, NO_3^- leaching was estimated by multiplying soil water sample NO_3^- concentrations by the drainage. As soil water NO_3^- concentrations were measured weekly, daily concentrations were estimated via linear interpolation between measured weekly values.

Data Analysis and Statistics

Cumulative seasonal NO_3^--N leaching was determined by summing daily NO_3^--N leaching values. Cumulative direct N_2O flux was compared by treatment and year to cumulative NO_3^- concentrations via simple and multiple linear regression. Effects of fertilizer treatment on daily NO_3^- concentrations were examined using split-plot ANOVA with fertilizer type as main effect and date as split plot effect. Effects of fertilizer treatment on biomass N concentration, uptake, and N use efficiency was examined using one-way ANOVA for each growing season and split-plot ANOVA for the three season combined time period with fertilizer type as main effect and date as split plot effect. Effects of fertilizer treatment on total cumulative NO_3^- leaching were analyzed using one-way ANOVA for each growing season. Effect of fertilizer treatment on total cumulative leaching over the entire study was analyzed using split-plot ANOVA with year as main effect and fertilizer type as the split plot effect.

For all seasons, fertilizer-induced leaching values were determined in each fertilized treatment by subtracting the mean cumulative NO_3^- leaching observed in the control treatment from the mean cumulative NO_3^- leaching in the fertilized treatment, expressed as a percentage of fertilizer N inputs (i.e., 270 kg N ha^{-1}). Negative results (i.e.

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higher leaching from control than fertilized treatment) were counted as a fertilizer-induced leaching factor of zero.

All direct N_2O emissions values are from Hyatt *et al*. (2010). Indirect N_2O emissions were calculated using a modified Tier 1 approach from the 2006 IPCC Guidelines for Greenhouse Gas Inventories (Eggleston et al., 2006). This was achieved by multiplying daily NO_3^--N leaching values by the default emission value (EF_5) of 0.0075. In comparison, minimum and maximum potential indirect emissions were calculated by multiplying daily NO_3^-- N values by emission factors of 0.005 and 0.0250, respectively. In this study, leaching is taken to be the primary source of N for indirect emissions. Due to coarse textured soils and flat topography at the study site, surface N runoff is assumed to be negligible and not a significant contributor to indirect N_2O emissions. Indirect and direct N_2O fluxes were combined for total N_2O emissions. The effect of fertilizer treatment on these emissions was analyzed using one-way ANOVA for each growing season and split-plot ANOVA to examine the entire study period with year as main effect and fertilizer type as the split plot effect.

Seasonal differences in total flux within a single treatment were analyzed using one-way ANOVA. Direct flux was compared with indirect flux using a paired *t* test. The results from applying the minimum, default, and maximum indirect N_2O emission factors were also compared using a paired *t* test. In the text, unless indicated otherwise, significant differences use criteria of *P*<0.05 and are presented in tables and figures using upper case letter designations.

One way analysis of variance (ANOVA) and paired t tests in all cases and split-plot ANOVA for daily NO_3^- concentrations, biomass N concentration and uptake, and N use efficiency were performed using the Statistix 9 statistical analysis software package (Analytical Software, Tallahassee, FL). Split-plot ANOVA for leaching and indirect emissions, as well as contrast analysis, were performed using the general linear model (GLM) procedure in SAS (SAS, 2003). Simple and multiple linear regressions were computed using Statgraphics Plus 5.1 (Statistical Graphics Corp., Warrenton, VA).

RESULTS

Weather

Water inputs (rainfall + irrigation) for the sampling season of May 1 through Nov 30 were higher in 2007 (1015 mm, Fig. 2-2a) when compared with 2008 (908 mm, Fig. 2-3a) and 2009 (938 mm, Fig. 2-4a). Precipitation equaled 90, 95, and 88% of the 30-yr May through Nov average of 582 mm for 2007, 2008, and 2009, respectively.

Air temperature and solar radiation are shown in Figs. 2-2 through 2-4 (plate b). Mean daily air temperature for the 2008 and 2009 May through Nov sampling seasons were within 1 degree of the 30-yr average of 13.7 °C, while the mean temperature in 2007 for the period was 2 degrees higher than average (15.7 °C). This was primarily due to higher temperatures early (May-Jun) and late (Oct-Nov) in the 2007 season. Average daily solar radiation was 12.5, 11.9, and 10.2 MJ m^{-2} day^{-1} in 2007, 2008, and 2009, respectively.

Evapotranspiration and Drainage

Of the two methods that were evaluated for ET estimation, PM produced consistently higher ET rates, with cumulative evaporative water losses more than twice those estimated by the JH method (Figs. 2-2 through 2-4; plate c). A lower ET from JH resulted in a total seasonal water drainage that was 45 to 89% higher than the PM estimate (Figs. 2-2 through 2-4; plate e). The PM method was chosen as the preferred method of ET estimation, and results using that method are presented below. Further review of ET equation differences will be presented in the discussion section.

In all three seasons, daily ET estimates peaked in the first half of Jul and were reduced to < 1 mm water lost day^{-1} by the mid Sep vine kill. Cumulative seasonal estimated ET loss (via PM) fell by 119 mm from 2007 to 2008 and by 76 mm from 2008 to 2009. Peak drainage events corresponded to high rainfall in all three seasons (Figs. 2-2 through 2-4; plate d) due to the use of water budgeting to estimate soil drainage (Eqs. [6], [7], and [8]). Cumulative drainage in 2007 and 2008 was nearly equal (383 and 389 mm, respectively) as reduced water inputs in 2008 were balanced by reduced ET. In 2009, an increase in water inputs of 30 mm over 2008 and further reduced ET resulted in a total drainage 100 mm higher than the two previous seasons (496 mm total).

Soil Water Nitrate Concentrations

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NH_4^+ was not found to be a significant contributor to total N concentrations in water samples (data not presented). Daily soil water NO_3^- concentrations were not significantly different among N fertilized treatments during the 2007, 2008, or 2009 growing seasons (Table 2-3). However, fertilized treatments tended to result in higher soil water nitrate concentrations than the zero N control, although not always by a significant amount (Table 2-3). All treatments displayed a characteristic rise and fall pattern mid-season (Fig. 2-5). However, the timing of this rise, the date of peak N concentration, and the return to background concentrations varied among seasons. Peak concentrations in 2007 and 2009 were measured at 20 and 21 mg N L^{-1} in CSA, respectively, and in 2008 at 40 mg N L^{-1} for both PCU treatments. Concentrations returned to background levels after approximately 14 Aug, 12 Sep, and 26 Aug in 2007, 2008, and 2009, respectively, but then began to increase again mid-Oct in 2007 and 2009. In the CSA plots there was no correlation between split fertilizer application timing (dates indicated in figures by unlabeled arrows) and concentration levels.

In water samples collected the following spring, only those samples from in 2008 displayed any significant differences in daily N concentration. In this instance, PCU-1 was significantly higher than any other treatment, with a mean concentration nearly double that of PCU-2, the next highest treatment (19.9 vs. 10.4 mg N L^{-1} water, respectively).

Nitrate Leaching

Nitrate leaching events occurred on dates with elevated water inputs. The largest events corresponded to leaching dates with the highest rainfall. However, high water

inputs did not consistently result in high leaching. In 2007, rain events > 20 mm in a 24-h period occurred on 10 dates. However, on only one of these dates (11 Aug, Fig. 2-2a) was the average amount of N leached from a plot ≥ 1 kg N ha^{-1} (Fig. 2-6b). The 2008 and 2009 seasons experienced 11 and 8 rain events > 20 mm in 24 h, respectively, but leaching of 1 kg N ha^{-1} day^{-1} or greater occurred on only four dates in both years (Figs. 2-3a and 2-4a.). Leaching events also varied by year. Leaching > 1 kg ha^{-1} day^{-1} triggered by rainfall occurred prior to 15 Jul in 2008, but the singular event in 2007 occurred nearly 1 month later on 11 Aug. In 2009, most events occurred mid-season (21 Jul – 19 Aug), except one event which took place on 1 Oct.

Cumulative NO$_3^-$ leaching during each growing season ranged from 7.61 to 35.07 kg N ha^{-1} in the fertilized treatments. Within growing seasons and across the combined three season period (2007-2009), none of the fertilizer treatments or the control was significantly different from one another on an individual basis (Table 2-3). Contrast analysis of fertilized treatments vs. the control did, however, show a significant difference between the two categories of treatments ($P<0.05$) over the entire study. Mean leaching from the control treatments was significantly higher in 2008 (26.4 kg N ha^{-1}, $P<0.05$) than in other years at nearly 4 times the leaching of 2007 (6.0 kg N ha^{-1}) or 2009 (7.2 kg N ha^{-1}, Table 2-3). There was no significant difference among years with respect to cumulative fertilizer induced leaching (Table 2-3). Spring NO$_3^-$ leaching was not examined for this study due to the nature of the leaching calculations and the lack of winter/spring-melt water input data.

N Uptake and Nitrogen Use Efficiency

Results of biomass N analysis and NUE calculations are presented in Table 2-4 (Fig. 2-9) and Table 2-5 (Fig. 2-10), respectively. There were no significant differences in the percent N concentrations in vines among treatments in 2007, 2009, or when the three seasons (2007-2009) were combined (Fig. 2-9). However, in 2008, vines from the CSA treatment showed significantly lower N that PCU-1 and PCU-2, although N concentration of the vines from the control was not significantly different from those of any of the other treatments. With respect to the percent N concentrations in tubers, there were no significant differences among fertilized treatments in 2008, 2009, or within the combined study period. In 2007, however, tuber %N from PCU-2 was significantly lower than found in tubers from PCU-1 and CSA at $P<0.10$. The control produced tubers with significantly lower %N than those of the CSA and PCU-1 treatments in 2007, PCU-2 in 2008, and any of the fertilized treatments in 2009 and for the combined period.

Total nitrogen uptake was significantly higher in the fertilized treatments when compared with the control in all three seasons and the combined three season period (Fig 2-9). Additionally, total N uptake from the PCU-2 treatment was significantly lower than CSA in both 2007 and 2009. When separated into vine and tuber accumulation categories, there were no significant differences among fertilized treatments except with tuber N uptake in 2007, where tubers from PCU-2 took up significantly less N than tubers from PCU-1, and vine N uptake in 2009, where vines from PCU-1 took up significantly less N than vines in the CSA treatment. Tuber N accumulation in the control was significantly different from levels found in the other treatments in all cases. In 2008, there

were also no significant differences among any of the treatments with respect to vine N uptake. Uptake of N by the vines in 2009 was not significantly different between the control treatment and PCU-1.

With respect to NUE, the only statistical differences were seen when each growing season was analyzed individually. In 2008 significant differences were only evident with the PUE index, which resulted in a higher value for the CSA treatment than the PCU-2 treatment ($P<0.10$).

N_2O Emissions

Methods of sampling and a detailed analysis of direct N_2O emissions are covered in Hyatt *et al.* (2010). Cumulative direct N_2O emissions during each growing season ranged from 0.6 to 2.1 kg N ha^{-1} in the fertilized treatments (Fig. 2-11). Direct emissions from CSA were significantly ($P<0.10$) higher than the control in 2008 and 2009 and higher than PCU-1 in 2007. Over the three season period (2007-2009), emissions from CSA were significantly higher than PCU-1, while emissions from PCU-2 did not differ from CSA or PCU-1. Averaged across all fertilized treatments, higher N_2O emissions were observed in the 2008 growing season compared with 2007 and 2009 (Hyatt et al., 2010).

When indirect emissions were estimated from nitrate leaching via the direct arithmetic conversion of the IPCC method, seasonal and three season combined comparisons showed direct emissions to be significantly higher than estimated indirect emissions ($P<0.001$). Regression analysis found little correlation between cumulative potential indirect and cumulative direct N_2O emissions ($r^2 \leq 0.2$) for the entire dataset or

when the data were segregated by year (Table 2-6). When segregated by treatment, only the control (examined in 2008 and 2009 only) displayed strong correlation ($r^2 > 0.8$) between cumulative direct and estimated indirect. The fertilized treatments displayed positive but somewhat weaker correlations ($r^2 \leq 0.3$), possibly due to the higher direct N_2O emissions in 2008 when NO_3^- leaching was not significantly different from other years.

When the estimated indirect emissions were combined with direct emissions for a total N_2O emission value, cumulative N_2O emissions during each growing season ranged from 0.5 to 3.3 kg N ha^{-1} in the fertilized treatments (Fig. 2-11). In 2007 there were no significant differences among treatments. In 2008, CSA (2.33 kg N ha^{-1}) was higher than control (0.98 kg N ha^{-1}, $P<0.10$, Fig. 2-11). In 2009, the CSA (1.28 kg N ha^{-1}) and PCU-2 (1.06 kg N ha^{-1}) treatments were found to be significantly higher than the control (0.48 kg N ha^{-1}, $P<0.05$, Fig. 2-11). When all three seasons were combined, as with direct emissions alone, total N_2O emissions from CSA (1.53 kg N ha^{-1}) were significantly higher than from PCU-1 (0.97 kg N ha^{-1}). In 2008 and 2009, fertilizer induced N_2O emissions accounted for 0.50 and 0.30% of applied N in CSA, 0.12 and 0.17% of applied N in PCU-1 and 0.42 and 0.22% of applied N in PCU-2, respectively.

DISCUSSION

Fertilizer application rates designed to meet the high N demand of a crop like potato present a challenge for minimizing N losses. This is particularly true when

fertilizer is applied to coarse-textured soils where high rates of NO_3^- leaching have been observed (Errebhi et al., 1998; Delgado et al., 2001; Zvomuya et al., 2003). Under these field conditions, PCUs have been shown to reduce NO_3^- leaching (Zvomuya et al., 2003, Wilson et al., 2010), as well as potentially reduce direct N_2O emissions (Hyatt et al., 2010). However, as far as we know, this is the first study in potatoes to compare the effects of more than one PCU with CSA on NO_3^-leaching. It is also uncommon to estimate potential indirect N_2O flux by applying an emission factor to water samples, and as far as we know, this study is the first to compare multiple PCUs in this way. Total N_2O flux, the sum of direct and estimated indirect emissions, can then be evaluated to determine a given treatment's effectiveness at managing N_2O in this agro-ecosystem.

A reliable estimate of total N loss requires a good NO_3^- leaching determination, which in turn is dependent on an accurate water balance calculation. We evaluated two different ET estimation models used to determine the potential ET component of the water balance. The JH alfalfa-reference model (Jensen and Haise, 1963) has been used extensively in Minnesota, as well as in other states, to calculate ET for irrigation scheduling (Wright, 2002; Al-Kaisi and Broner, 2009). For this study we used a version of JH modified with Minnesota specific elevation and temperature range factors (Killen, 1984). The FAO 56 PM grass-reference model (Allen et al., 1998) was the second model examined. Both models utilize daily air temperature and solar radiation data to derive ET. The PM model additionally incorporates wind speed and humidity data.

The FAO 56 PM method is recommended as the sole standard method for determining ET (Allen et al., 1998). However, researchers continue to utilize other

models, including JH, as they often times depend on fewer weather data inputs, allow for practical, direct comparison with previous work, or have been found through use to accurately predict ET under the narrow set of conditions applicable to a specific site. Recent studies have used the JH model to calculate ET in crops as diverse as potato, corn, peanut, and sugarcane, as well as for the development of automated irrigation systems (Delgado et al., 2001; Derby et al., 2004; Rowland et al., 2005; Wiedenfeld and Enciso, 2008; Han et al., 2009).

For our study, cumulative ET calculated using JH ranged from 45.6% (2007 & 2008) to 49.4% (2009) of PM. In various comparison studies of ET models, PM was consistently ranked higher with regards to accuracy than JH (e.g. Jensen et al., 1990; Irmak et al., 2003; Irmak et al., 2008) In a comparison of 13 ET models and direct measurement of ET by weighing lysimeters, Jensen *et al.* (1990) showed that JH predicted 85% of the ET measured by the lysimeters, as compared to 101% from PM. They ultimately ranked PM 1st and JH 10th of 13 models for daily estimates of ET and recommended using the PM model for daily or longer ET estimation periods (Jensen et al., 1990). Because of this, and because of the disparate results obtained by us with the two methods, we have chosen PM as the preferred ET estimation method for this study

Using the PM model, ET, along with rainfall and irrigation, was assumed to be consistent across all treatments. Because of this, treatment effects on drainage were not examined in this study. It is, however, possible that drainage in the control treatment may be slightly underestimated. Hyatt *et al.* (2010) reported that yield from the control plots was significantly less than the fertilized treatments. Our results show that the control

treatments also supported, on average, lower above ground biomass. Reduced total biomass in the control suggests reduced ET and increased drainage when compared with fertilized treatments.

Treatments were also evaluated for soil water NO_3^- concentrations, which were not found to be significantly affected by fertilizer type during the sampling season (Fig. 2-5). However, when water samples collected the following spring were analyzed, water from PCU-1 in the 2008 field (i.e. collected spring 2009) displayed significantly higher concentrations of NO_3^- than any of the other treatments. In an in situ study of PCU-1 and PCU-2 N release (Hyatt et al., 2010), PCU-1 was shown to have a slower release rate. This was perhaps due to differences in coating thickness or composition resulting in a release peak from PCU-1 occurring after that of PCU-2. In that same study, Hyatt *et al.* also found that by the end of the 2008 season, PCU-1 had only released 58% of the fertilizer N contained within the prills. This high residual fertilizer amount suggests that fertilizer could remain within prills beyond the application season. In each spring we often saw prills from both PCU treatments that had overwintered in the field which could still contain soluble fertilizer. It is possible that the high spring soil water NO_3^- concentrations from the 2008 fields are due to residual N that was released during snow melt. More work is needed to determine the significance of this post-season N contribution and identify differences among treatments.

Through analysis of soil water NO_3^- concentrations, estimated drainage, and environmental factors, our results indicate that a given rainfall event's magnitude and timing with respect to fertilizer application tended to be the strongest indicators of

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potential major leaching (taken as an average of > 1 kg N ha^{-1} day^{-1}). Errebhi *et al.* (1998) and Wilson *et al.* (2010) also found that if soil N levels were high, a rainfall event preceded within 24 hr by irrigation was a predictor of significant leaching in loamy sands planted to potato. The singular major leaching event in 2007 took place on 11 Aug. Despite not being proceeded by irrigation and occurring late in the season when much of the N had already been taken up by the crop , the 55 mm of rainfall recorded on that date still triggered major leaching. In 2008, two major leaching events occurred before any irrigation was applied for the year. However, both dates experienced rainfall > 20 mm. The remaining two major leaching dates for 2008 also received about 20 mm of rain, but were preceded within 24 hr by irrigation. Later rainfall dates, including one that experienced nearly 73 mm of water accumulation (2 Sept.), occurred after the final irrigation date and did not lead to major leaching. However, it is possible that by this late in the season, much of the available N had been utilized by the crop or lost through leaching, as by this point in the PCU treatments more than 91% of the season's cumulative leaching had occurred. In 2009, the first rainfall event > 20 mm for the season was preceded by irrigation, but did not produce major leaching. The next four events > 20 mm, however, did result in major leaching, the first two of which were preceded by irrigation or rainfall and the last two which produced nearly 55 and 40 mm of precipitation, respectively.

In 2007 and 2009 when major leaching occurred, daily leaching averages were strongly influenced by N levels in the CSA treatment water samples. In both years, major leaching events began with the first rainfall event > 20 mm after the final split application

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of CSA fertilizer. In 2007, no rainfall events > 20 mm occurred during the entire period that CSA was split applied. In 2009, there was only a single rainfall event during the same period, which occurred the day after the first application date. It is possible that irrigation and smaller rainfall events moved CSA fertilizer into the soil and created a high soil N condition. Leaching was then initiated with subsequent > 20-mm rainfall events. In contrast, a much wetter spring in 2008 with multiple rainfall events > 20 mm occurring between planting and the end of fertilizer application, resulted in major leaching prior to the start of irrigation and during the split CSA application timeframe. In this season, major leaching was not defined by N concentrations in the water from a single fertilizer treatment.

In our study, there was no statistical difference among treatments in cumulative leaching seasonally or over the entire 3-season study period (Table 2-3). Contrast analysis, however, suggested a statistical difference between the control and fertilized treatments. Others found similar mixed results or no significant differences when examining potatoes grown in coarse textured soil and fertilized with conventional soluble N, PCU and sulfur coated urea (Errebhi et al., 1998; Waddell et al., 2000; Zvomuya et al., 2003; Wilson et al., 2010). Hyatt *et al*. (2010) reported that irrigation water for this study contributed the equivalent of 34, 33, and 24 kg ha^{-1} N in 2007, 2008, and 2009 respectively. In addition, rainwater was also found on average to contain the equivalent of 3 kg ha^{-1} N in 2007 (data not presented). It is possible that periodic addition of N rich water may have obscured statistical differences between individual treatments if water

sampling occurred shortly after irrigation or rainfall. Cumulative leaching from the control was consistently numerically lower than any fertilizer treatment.

Leaching in the control plots was higher in 2008 than 2007 or 2009. Rainfall events, which introduce more water in a shorter time period than irrigation, occurred more often and earlier in 2008, when compared with the other two seasons. Fertilizer leaching loss may have occurred in the control plots before sufficient recovery by the crop. Zebarth and Rosen (2007) state that by the end of the combined sprouting and vegetative growth stages (< 55 days after planting), only 20% of potato crop N uptake has occurred. Additionally, the 2008 field was planted the previous year to rye and mustard and fertilized with 34 kg N ha^{-1}, whereas the 2007 and 2009 fields were preceded by unfertilized rye. This site history may also provide an explanation for additional N available for leaching early in the 2008 season in the control plots.

Fertilizer induced leaching, calculated as the difference in leaching between fertilized and control plots, was higher in 2009 than 2007 or 2008. In contrast to 2008, the majority of the major rainfall events in 2009 occurred late in the season (> 15 July). By this time, much of the residual N present in the control plots may have been taken up by the crop, creating a greater disparity between these and the fertilized plots with respect to total N leached during an event. In addition, over 100 mm more drainage occurred in 2009 when compared with 2007 or 2008.

Our results indicate that a single pre-plant application of PCU results in similar amounts of NO_3^- leaching in potato as the more field intensive method of using multiple split applications of conventional fertilizers. As water drainage was taken to be consistent

across treatments and N was applied in all fertilized treatments at an equal rate, similar leaching implies similar crop N uptake. This is supported by measured vine, tuber, and total N uptake amounts, which were not significantly different between the PCU-1 treatment and CSA in all seasons, with the exception of the vine uptake in 2009. Additionally, N concentrations in the vines and tubers were not significantly different between the PCU-1 treatment and CSA with the exception of the vines in 2008. Similarly, Wilson *et al*. (2010) found no difference in vine, tuber, or total plant (sum of vine and tuber) N content by potato plants grown under split applied conventional fertilizers and PCU at four rates and two fertilizer timings. Waddell *et al*. (1999) found that there was also no difference in total N uptake by potato plants when fertilized by split applied urea or sulfur coated urea fertilizer at 224 kg N ha^{-1}.

N use efficiency was also not significantly different among treatments in any season or across the three season period for any of the NUE metrics with the exception of PUE in 2008 which was significantly different at *P*<0.01 (Table 2-5). In that case, PUE of PCU-2 was significantly lower than that of CSA. Hutchinson *et al.* (2003) in a Florida potato study on sandy soil, found significantly higher NUE (as PFP) in polymer coated fertilizer treatments at an application rate of 112 kg N ha^{-1} when compared with AN + urea at the same rate. However at higher rates (i.e. 224 kg N ha^{-1}), closer to what was applied in our study, Hutchinson *et al.* (2003) did not see any significant differences in NUE between polymer coated and conventional N treatments. Wilson *et al.* (2010) also found no difference Russet Burbank potato NUE (using NupE – referred to as 'N

uptake') between PCU and comparable split applied conventional fertilizer at four rates and two fertilizer timings.

Potential NO_3^- leaching data allows for an estimation of possible indirect N_2O emissions which can then be compared to direct N_2O emissions data (presented in Hyatt et al. 2010) and total emissions predicted. Paired T-test analysis found direct N_2O emissions to be significantly higher than the indirect in each season and for the entire 2007-2009 study. Because of this, differences among treatments with respect to total N_2O emissions followed those reported by Hyatt *et al*. (2010) for direct emissions fairly closely. At most, the addition of the indirect emissions moderated the total flux numbers, resulting in weak statistical differences being strengthened slightly for the 2009 season and the entire 2007-2009 study, while causing their disappearance altogether for 2007. There were no changes in statistical relationships for 2008 (Fig. 2-11).

Indirect N_2O emissions calculated using the default IPCC indirect emission factor of 0.75% of NO_3^- leached were between 8.9 and 25.5% of measured direct emissions. This is much lower than the values estimated by Koga *et al*. (2006) for a Japanese potato study where it was concluded that indirect N_2O emissions were comparable to direct emissions. However in that study, nitrate leaching was not directly measured, but rather estimated by multiplying a 30% nitrate leaching factor (from Eggleston et al., 2006) to applied fertilizer N. In our findings, cumulative N leached was found to be between 1.2 and 17.9% of applied N.

Additionally, the uncertainty range given by the IPCC for the emission factor is quite broad, with endpoints representing the 95% confidence interval at 0.05%, for the

lower end, and 2.5%, for the upper end (Eggleston et al., 2006). By exploring these two extremes we can gain a better understanding as to the potential implications of a realistic emission factor on estimated N_2O emissions. With the 0.05% emission factor, indirect emissions were calculated to between 0.6 and 1.7% of direct, whereas with a 2.5% factor, the values were increased to between 30.0 and 84.9%. These are significant differences ($P<0.0001$) and clearly illustrate that depending on the emission factor chosen and amount of nitrate leached, indirect N_2O flux can be seen as either a very minor component or nearly an equal contributor as direct to total N_2O emissions.

Changing the emission factor in our study resulted in no changes in statistical relationships in 2007. However, in 2008, both the upper and lower factors caused a loss of significant difference. In 2009 and for the 2007-2009 period, the upper factor amplified differences, while in 2009, the lower reduced differences (P value from < 0.05 to <0.10).

CONCLUSIONS

In this 3-yr study, the JH method of ET determination estimated markedly lower ET values when compared with the PM model. Because of this, and due to a number of comparison studies of ET models where PM was consistently ranked higher than JH (e.g. Jensen et al., 1990; Irmak et al., 2003; Irmak et al., 2008), we recommend using the PM model whenever the existence of a complete dataset, including relative humidity and wind-speed, allow.

During the 3 consecutive yrs of this study, cumulative NO_3^- leached was found to be between 1.2 and 17.9% of applied fertilizer N, which is much lower than the IPCC recommended value of 30% of applied N (Eggleston et al., 2006). In general, leaching was low during the three year period. The mean cumulative indirect N_2O emissions for this period were estimated to be 0.17, 0.14, and 0.20 kg N ha^{-1} with a CSA and two different PCU products (PCU-1 and PCU-2), respectively, using the default IPCC emission factor of 0.75%. These values were significantly lower than measured direct emissions, but not significantly different among N fertilizer treatments.

Biomass N uptake and N concentrations were not significantly different between the PCU-1 and CSA treatments in most cases. This suggests that PCU can supply N to potato at amounts consistent with best management practices recommendations as represented by the CSA treatment. This was also supported by the fact that treatments were found to be highly consistent with respect to their NUE's.

Total N_2O emissions were found to be significantly different among treatments and a fertilization system utilizing PCU can potentially reduce total N_2O emissions when compared with CSA. The uncertainty range for the indirect emission factor, however, provides the possibility that indirect emissions could be anywhere from 0.6 to 84.9% of direct emissions. This underscores the need for further study into quantifying indirect N_2O emissions from agricultural systems.

In all, our results show that N application strategies utilizing PCU have the potential to match the NUE's seen under CSA while maintaining, if not reducing, NO_3^- leaching - thereby also reducing total N_2O emissions in potato.

REFERENCES

Allen, R.G, L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. Food and Agricultural Organization of the United Nations, Rome.

Al-Kaisi, M.M., and I. Broner. 2009. Crop Water Use and Growth Stages. Colorado State Univ. Cooperative Extension. Rept. No. 4.715. 4 p.

Benson, V.S., J.A. VanLeeuwen, J. Sanchez, I.R. Dohoo, and G.H. Somers. 2006. Spatial analysis of land use impact on ground water nitrate concentrations. J. Environ. Qual. 35:421-432.

Brown, J.R. (ed.). 1998 Recommended chemical soil test procedures for the North Central Region. Doc. SB 1001. Missouri Agric. Exp. Stn., Columbia.

Burton, D.L., B.J. Zebarth, K.M. Gillam, and J.A. MacLeod. 2008. Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. Can. J. Soil Sci. 88:229-239.

Carlson, R.M., R.I. Cabrera, J.L. Paul, J. Quick, and R.Y. Evans. 1990. Rapid direct determination of ammonium and nitrate in soil and plant tissue extracts. Commun. Soil Sci. Plant Anal. 21:1519-1529.

Cassman, K.G., G.C. Gines, M.A. Dizon, M.I. Samson, and J.M. Alcantara. 1996.
Nitrogen-use efficiency in tropical lowland rice systems: contributions from
indigenous and applied nitrogen. Field Crop. Res. 47:1-12.

Derby, N.E., F.X.M. Casey, R.E. Knighton, and D.D. Steele. 2004. Midseason nitrogen
fertility management for corn based on weather and yield prediction. Agron. J.
96:494-501.

Delgado, J.A., R.R. Riggenbach, R.T. Sparks, M.A. Dillon, L.M. Kawanabe, and R.J.
Ristau. 2001. Evaluation of nitrate-nitrogen transport in a potato-barley rotation.
Soil Sci. Soc. Am. J. 65:878-883.

Eggleston H.S., L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds). 2006. 2006 IPCC
Guidelines for National Greenhouse Gas Inventories. National Greenhouse Gas
Inventories Programme. IGES, Japan. Available at www.ipcc-
nggip.iges.or.jp/public/2006gl/index.html (verified 14 Apr. 2011).

Errebhi, M., C.J. Rosen, S.C. Gupta, and D.E. Birong. 1998. Potato yield response and
nitrate leaching as influenced by nitrogen management. Agron. J. 90:10-15.

Errebhi, M., C.J. Rosen, F.I. Lauer, M.E. Martin, and J.B. Bamberg. 1999. Evaluation of
tuber-bearing *Solanum* species for nitrogen use efficiency and biomass
partitioning. Am. J. Potato Res. 76:143-151.

Firestone, M., and E. Davidson. 1989 Microbiological basis of NO and N_2O production
and consumption in soil. P. 7-21. *In* M. Amdreae and D. Schimel (ed.) Exchange
of trace gases between terrestrial ecosystems and the atmosphere. John Wiley &
Sons, Chichester, UK.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, *et al*. 2007.
Changes in atmospheric constituents and in radiative forcing. P. 131-234. *In* S.
Solomon *et al*. (ed.) Climate Change 2007: The Physical Science Basis.
Cambridge Univ. Press, Cambridge, UK.

Haile-Mariam, S., H.P. Collins, and S.S. Higgins. 2008. Greenhouse gas fluxes from an
irrigated sweet corn (*Zea mays* L.) – potato (*Solanum tuberosum* L.) rotation. J.
Environ. Qual. 37:759-771.

Han, Y.J., A Khalilian, T.O. Owino, H.J. Farahani, and S. Moore. 2009. Development of
Clemson variable-rate lateral irrigation system. Comput. Electron. Agr. 68:108-
113.

Horneck, D.A., and R.O. Miller. 1998. Determination of total nitrogen in plant tissue. *In*
Y.P. Kalra (ed.) Handbook of reference methods for plant analysis. CRC Press,
Boston.

Hutchinson, C., E. Simonne, P. Solano, J. Meldrum, and P. Livingston-Way. 2003.
Testing of controlled release fertilizer programs for seep irrigated Irish potato
production. J. Plant Nutr. 26: 1709-1723.

Hyatt, C.R., R.T. Venterea, C.J. Rosen, M. McNearney, M.L. Wilson, and M.S. Dolan. 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. Soil Sci. Soc. Am. J. 74:419-428.

IPCC. 1997. Intergovernmental Panel on Climate Change. Revised 1996 IPCC guidelines for national greenhouse gas inventories reference manual, vol. 3. Available at www.ipcc-nggip.iges.or.jp/public/gl/invs6.html (verified 14 Apr. 2011).

Irmak, S., R.G. Allen, and E.B. Whitty. 2003. Daily grass and alfalfa-reference evapotranspiration estimates and alfalfa-to-grass evapotranspiration rations in Florida. J. Irrig. Drain. E.-ASCE. 129:360-370.

Irmak, A., S. Irmak, and D.L. Martin. 2008. Reference and crop evapotranspiration in south central Nebraska. I: Comparison and analysis of grass and alfalfa-reference evapotranspiration. J. Irrig. Drain. E.-ASCE. 134:690-699.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed.). 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70., Am. Soc. Civil Engrs. New York.

Jensen, M.E., and Haise, H.R. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. Drain. Div. 89:15-41.

Killen, M.A. 1984. Modification of the checkbook method of irrigation scheduling for use in Minnesota. M.S. thesis. Univ. of Minnesota, St. Paul.

Koga, N., T. Sawamoto, and H. Tsuruta. 2006. Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, northern Japan. Soil Sci. Plant Nutr. 52:564-574.

Kraft, G.J. and W. Stites. 2003. Nitrate impacts on groundwater from irrigated-vegetable systems in a humid north-central US sand plain. Agr. Ecosyst. Environ. 100:63-74.

Lewandowski, A.M., B.R. Montgomery, C.J. Rosen, and J.F. Moncrief. 2008. Groundwater nitrate contamination costs: A survey of private well owners. J. Soil Water Conserv. 63:153-161.

Lesczynski, D.B. and C.B. Tanner. 1976. Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potato. Am. Potato J. 53:69-78.

Mosier, A., C Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput. 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycl. Agroecosys. 52:225-248.

MRCC. 2010. Midwestern Regional Climate Center. Climate of the Midwest. Available at http://mrcc.isws.illinois.edu/climate_midwest/maps/mn_mapselector.htm (verified 14 Apr. 2011). Illinois State Water Survey, Champaign, IL.

Nevison, C. 2000. Review of the IPCC methodology for estimating nitrous oxide emissions associated with agricultural leaching and runoff. Chemosphere – Global Change Sci. 2:493-500.

NRCS. 2002. Natural Resources Conservation Service. Soil Survey of Sherburne County, MN. United States Government Printing Office, Washington, DC. Available at soildatamart.nrcs.usda.gov/Manuscripts/MN141/0/sherb_MN.pdf (verified 14 Apr. 2011).

Rosen, C.J., and P.M. Bierman. 2008. Best management practices for nitrogen use: Irrigated potatoes. Publ. 08559. Univ. of Minnesota Ext. Serv., St Paul.

Rowland, D.L., R.B. Sorensen, K.S. Balkcom, and M.C. Lamb. 2005. Estimating stem water flow in peanut (Arachis hypogaea L.) under different irrigation methods. Peanut Sci. 32:81-90.

Rupert, M.G. 2008. Decadal-scale changes of nitrate in ground water of the United States, 1988-2004. J. Environ. Qual. 37:S-240-S-248.

Ruser, R, H. Flessa, R. Russow, G. Schmidt, F. Buegger, and J.C. Munch. 2006. Emission of N_2O, N_2 and CO_2 from soil fertilized with nitrate: Effect of compaction, soil moisture and rewetting. Soil Biol. Biochem. 38:263-274.

Sawamoto, T., Y. Nakajima, M. Kasuya, and H. Tsuruta. 2005. Evaluation of emission

    factors for indirect N_2O emission due to nitrogen leaching in agro-ecosystems.

    Geophys. Res. Lett. 32:L03403.

Shock, C.C., A.B. Pereira, and E.P. Eldredge. 2007. Irrigation Best Management

    Practices for Potato. Am. J. Potato Res. 84:29-37.

Stalham, M.A. and E.J. Allen. 2001. Effect of variety, irrigation regime and planting date

    on depth, rate, duration and density of root growth in the potato (*Solanum*

    tuberosum) crop. J. Agr. Sci. 137:251-270.

Stegman, E.C., A. Bauer, J.C. Zubriski, and J. Bauder. 1977. Crop curves for water

    balance irrigation scheduling in S.E. North Dakota. Res. Report No. 66

    Agricultural Experiment Station, North Dakota State Univ.

USEPA. 2010. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2008. EPA

    430-R-10-006. Available online at

    http://epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-

    2010_Report.pdf (verified 14 Apr. 2011.). USEPA, Washington, DC.

Vallejo, A, U.M. Skiba, L. García-Torres, A. Arce, S. López-Fernández, and L. Sánchez-

    Martín. 2006. Nitrogen oxides emission from soils bearing a potato crop as

    influenced by fertilization with treated pig slurries and composts. Soil Biol.

    Biochem. 38: 2782-2793.

Venterea, R.T. 2007. Nitrate-driven nitrous oxide production under aerobic soil conditions: Kinetics and biochemical controls. Global Change Biol. 13:1798-1809.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 1999. Irrigation and nitrogen management effects on potato yield, tuber quality, and nitrogen uptake. Agron. J. 91:991-997.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation- and nitrogen-management impact on nitrate leaching under potato. J. Environ. Qual. 29:251-261.

Wendt, K. 2003. Determination of Nitrate/Nitrite by Flow Injection Analysis (Low Flow Method). QuikChem Method 10-107-04-1-A. Lachat Instruments, Milwaukee.

Wiedenfeld, B and J. Enciso. 2008. Sugarcane responses to irrigation and nitrogen in semiarid south Texas. Agron. J. 100:665-671.

Wilson, M.L., C.J. Rosen, J.F. Moncrief. 2009b. Potato response to a polymer-coated urea on an irrigated, coarse-textured soil. Agron. J. 101:897-905.

Wilson, M.L., C.J. Rosen, J.F. Moncrief. 2010. Effects of polymer-coated urea on nitrate leaching and nitrogen uptake by potato. J. Environ. Qual. 39:492-499.

Wright, J. 2002. Irrigation scheduling: Checkbook method. FO-01322. Univ. of Minnesota Ext. Serv., St. Paul.

Zebarth, B.J. and C.J. Rosen. 2007. Research perspective on nitrogen BMP development for potato. Am. J. Potato Res. 84:3-18.

Zebarth, B.J., Y. Leclerc, and G. Moreau. 2004. Rate and timing of nitrogen fertilization of Russet Burbank potato: Nitrogen use efficiency. Can. J. Plant Sci. 84:845-854.

Zebarth, B.J., T.R. Tarn, H. de Jong, and A. Murphy. 2008. Nitrogen use efficiency characteristics of andigena and diploid potato selections. Am. J. Potato Res. 85:210-218.

Zvomuya F, C.J. Rosen, and J.C. Miller, Jr. 2002. Response of Russet Norkotah Clonal Selections to Nitrogen Fertilization. Am. J. Potato Res. 79:231-239.

Zvomuya F, C.J. Rosen, M.P. Russelle, and S.C. Gupta. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. J. Environ. Qual. 32:480-489.

Table 2-1. Selected chemical properties of site soils. Samples were collected before establishing treatments (in April of each year) from the upper 0.15 m, except for inorganic N samples, which were collected from the upper 0.6 m. Methods of analysis from Brown (1998). Means with standard errors in parentheses are shown (n = 2-5).

	2007	2008	2009
		--	
pH	6.7 (0.04)	6.2 (0.13)	4.9 (0.03)
		% by weight	
organic matter	1.5 (0.07)	2.0 (0.03)	2.4 (0.03)
		$\mu g\ g^{-1}$	
Bray-P	32 (2.3)	32 (1.9)	23 (1.9)
K	88 (7.0)	110 (2.0)	66 (2.6)
SO_4	not done	2.0 (0)[†]	5.0 (1.0)
B	0.20 (0)[†]	0.21 (0.01)	0.28 (0.01)
Ca	720 (49)	810 (6.0)	335 (65)
Mg	140 (9.0)	140 (2.0)	40 (5.5)
Zn	0.67 (0.03)	0.70 (0)[†]	1.35 (0.05)
Fe	19 (0.70)	29 (0.20)	114 (9.90)
Cu	0.30 (0.04)	0.41 (0.01)	0.50 (0)[†]
Mn	4.9 (0.17)	7.2 (0.05)	37.6 (4.25)
NH_4^+-N	1.8 (0.10)	2.5 (0.39)	1.6 (0.13)
NO_3^--N	1.3 (0.11)	2.2 (0.14)	1.4 (0.09)

[†]All replicates had same result.

Table 2-2. Timing and rate of fertilizer applications used with conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2) and control treatments.

Treatment	Pre-planting	Planting[†]	Emergence[‡]	Post-emergence[§]	Total[¥]
kg N ha^{-1}					
2007					
CSA	0	45	112	5 x 22.5	270
PCU-1	225	45	0	0	270
PCU-2	225	45	0	0	270
2008 and 2009					
CSA	0	45	112	4 x 28	270
PCU-1	225	45	0	0	270
PCU-2	225	45	0	0	270
Control	0	0	0	0	0

[†]All fertilized treatments received 45 kg N ha^{-1} starter as diammonium phosphate.

[‡]Emergence applications consisted of 100% urea.

[§]Post-emergence applications consisted of 50% urea and 50% NH_4NO_3.

[¥]All treatments received additional inputs equivalent to 34, 33, and 24 kg N ha^{-1} in 2007, 2008, and 2009, respectively, from NO_3^- contained in irrigation water.

Table 2-3. Daily N concentration in water samples, cumulative N leached, and fertilizer induced leaching (mean with standard error in parentheses) in plots fertilized using conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control (presented for daily concentration and cumulative leaching only). In the entire table, within each column, values with the same uppercase letter are not significantly different at $P < 0.05$; in cumulative N leached, within each row, values for individual years with the same lowercase letter are not significantly different at $P < 0.05$; no letters indicate no significant difference.

Daily N Concentration			
Fertilizer Effects	2007	2008	2009
	mg N L^{-1} Water		
p value	0.74	0.02	0.12
CSA	4.93 (0.74)	13.05 (1.80) **B**	5.62 (0.71) **B**
PCU-1	4.66 (0.83)	14.65 (1.76) **B**	3.92 (0.58) **B**
PCU-2	4.53 (0.62)	10.33 (1.77)**AB**	5.60 (0.81) **B**
Control	3.22 (0.54)	7.42 (1.74)**A**	1.76 (0.22)**A**
Date Effects p value	< 0.0001	< 0.0001	< 0.0001
(fert x date) p value	0.09	0.17	0.21

Cumulative N Leached				
Fertilizer Effects	2007	2008	2009	2007-2009
	Kg N ha^{-1}			
p value	0.36	0.60	0.18	0.13
CSA	9.87 (1.92)	28.29 (14.50)	23.28 (1.36)	20.48 (5.05)
PCU-1	**a** 6.40 (1.76)	**b** 30.93 (1.23)	**a** 12.99 (3.94)	16.77 (3.89)
PCU-2	11.17 (5.90)	34.40 (2.49)	27.50 (9.86)	26.00 (4.63)
Control	**a** 5.37 (2.28)	**b** 25.80 (2.83)	**a** 6.31 (0.19)	12.49 (3.49)
Date Effects p value				0.0003
(fert x date) p value				0.75
Contrast Control vs. Rest p value	0.3434	0.5435	0.0557	0.0498

Fertilizer Induced N Leaching			
Fertilizer Effects	2007	2008	2009
	Kg N ha^{-1}		
p value	0.17	0.56	0.69
CSA	4.50 (1.92)	2.49 (14.50)	16.97 (1.36)
PCU-1	1.03 (1.76)	5.13 (1.23)	6.69 (3.94)
PCU-2	5.80 (5.90)	8.60 (2.49)	21.19 (9.86)

Table 2-4. Nitrogen concentration and accumulation in vines and tubers (mean with standard error in parentheses) in plots fertilized using conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control. Within each column and year, values with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, lowercase letters indicate $P < 0.10$; no letters indicate no significant difference.

	N Concentration		N Uptake		
	Vine	Tuber	Vine	Tuber	Total
	%		kg N ha^{-1}		
2007					
CSA	1.12 (0.13)	1.21 (0.15) **b**	42.02 (7.05) **B**	182.75 (18.38) **BC**	224.77 (24.71) **C**
PCU-1	1.19 (0.06)	1.18 (0.03) **b**	33.82 (8.41) **B**	193.16 (8.56) **C**	226.98 (4.61) **C**
PCU-2	1.14 (0.10)	0.82 (0.12) **a**	31.84 (1.03) **B**	127.52 (14.10) **B**	159.36 (13.07) **B**
Control	1.14 (0.03)	0.86 (0.05) **a**	10.70 (1.64) **A**	78.39 (4.37) **A**	89.09 (5.74) **A**
2008					
CSA	1.01 (0.09) **A**	0.98 (0.03) **AB**	38.93 (7.58)	171.47 (11.14) **B**	210.40 (4.82) **B**
PCU-1	1.61 (0.15) **B**	1.00 (0.10) **AB**	42.89 (1.87)	177.46 (27.70) **B**	220.34 (27.45) **B**
PCU-2	1.44 (0.09) **B**	1.16 (0.02) **B**	54.59 (11.18)	190.23 (16.00) **B**	244.82 (26.49) **B**
Control	1.36 (0.11) **AB**	0.86 (0.02) **A**	24.16 (5.32)	104.91 (0.63) **A**	129.07 (5.83) **A**
2009					
CSA	1.53 (0.18)	1.42 (0.06) **C**	50.43 (7.10) **C**	249.61 (22.38) **B**	300.04 (18.20) **C**
PCU-1	0.96 (0.09)	1.36 (0.09) **BC**	21.53 (2.50) **BC**	241.21 (11.14) **B**	262.74 (12.51) **BC**
PCU-2	1.16 (0.14)	1.25 (0.02) **B**	36.50 (7.84) **AB**	216.34 (13.41) **B**	252.84 (6.02) **B**
Control	1.17 (0.05)	0.76 (0.02) **A**	9.54 (0.73) **A**	81.05 (4.81) **A**	90.59 (5.33) **A**
2007-2009					
CSA	1.22 (0.11)	1.20 (0.08) **B**	43.80 (4.01) **B**	201.27 (15.13) **B**	245.07 (16.54) **B**
PCU-1	1.25 (0.11)	1.18 (0.06) **B**	32.74 (4.03) **B**	203.94 (13.13) **B**	236.69 (11.00) **B**
PCU-2	1.26 (0.08)	1.11 (0.07) **B**	42.12 (5.81) **B**	184.35 (15.03) **B**	226.46 (17.36) **B**
Control	1.23 (0.05)	0.83 (0.02) **A**	14.80 (2.85) **A**	88.12 (4.62) **A**	102.92 (7.12) **A**

Table 2-5. Nitrogen use efficiencies (mean with standard error in parentheses) in plots fertilized using conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2) and control. Within each column and year, values with the same letter are not significantly different at $P < 0.10$; no letters indicate no significant difference.

	Efficiency Index[†]				
	NUpE	AUE	PUE	NHI	PFP
	%	g g^{-1}			kg kg^{-1}
2007					
CSA	50.25 (9.15)	32.65 (1.25)	69.18 (11.54)	0.77 (0.02)	305.70 (4.36)
PCU-1	51.07 (1.71)	34.00 (2.25)	66.59 (4.12)	0.83 (0.06)	317.00 (10.54)
PCU-2	26.03 (4.84)	30.58 (1.02)	122.59 (27.40)	0.69 (0.07)	285.14 (12.89)
2008					
CSA	34.23 (1.79)	30.46 (1.62)	89.01 (2.35) **b**	0.80 (0.11)	283.80 (10.26)
PCU-1	37.91 (10.17)	26.04 (3.57)	73.48 (10.78) **ab**	0.75 (0.08)	295.08 (8.75)
PCU-2	46.98 (9.81)	25.60 (6.39)	53.24 (4.19) **a**	0.75 (0.06)	279.67 (15.09)
2009					
CSA	77.57 (6.74)	34.76 (6.62)	44.02 (4.78)	0.80 (0.05)	284.42 (26.24)
PCU-1	63.76 (4.63)	31.71 (1.85)	50.09 (3.59)	0.93 (0.01)	298.79 (1.00)
PCU-2	60.09 (2.23)	33.33 (4.04)	55.16 (5.00)	0.83 (0.05)	293.99 (17.54)
2007-2009					
CSA	52.65 (7.64)	31.58 (2.29)	68.00 (7.69)	0.79 (0.03)	291.31 (8.98)
PCU-1	49.55 (5.43)	29.54 (2.15)	63.46 (4.94)	0.84 (0.04)	303.62 (5.21)
PCU-2	45.12 (6.08)	28.57 (3.09)	70.28 (12.74)	0.77 (0.04)	286.41 (8.30)

[†]NUpE = N uptake efficiency, AUE = Agronomic use efficiency, PUE = Physiological use efficiency, NHI = N harvest index, and PFP = Partial factor productivity.

Table 2-6. Direct and potential indirect N_2O emissions (mean with standard error in parentheses) and linear regression R^2 values (direct vs. potential indirect emissions) for plots fertilized using conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control (presented for 2008 and 2009 seasons only). Within each column, values with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, lowercase letters indicate $P < 0.10$; no letters indicate no significant difference.

	2007		2008		2009		2007-2009		R^2
	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	
p value	0.10	0.70	0.10	0.85	0.07	0.12	0.04	0.46	
CSA	0.89 **b** (0.03)	0.07 (0.01)	2.10 **b** (0.60)	0.21 (0.11)	1.09 **b** (0.04)	0.17 (0.01)	1.36 **B** (0.26)	0.15 (0.04)	0.0274
PCU-1	0.61 **a** (0.14)	0.05 (0.01)	1.06 **ab** (0.13)	0.23 (0.01)	0.82 **ab** (0.25)	0.10 (0.03)	0.83 **A** (0.11)	0.13 (0.03)	0.1649
PCU-2	0.69 **ab** (0.09)	0.08 (0.04)	1.85 **ab** (0.28)	0.26 (0.02)	0.84 **ab** (0.07)	0.21 (0.07)	1.13 **AB** (0.20)	0.20 (0.04)	0.2510
Control	--	--	0.79 **a** (0.13)	0.19 (0.02)	0.42 **a** (0.03)	0.05 (0.00)	--	--	0.8173
Date Effects p value							0.02	0.01	
(fert x date) p value							0.48	0.85	
R^2	0.0052		0.0000		0.0667		0.1476		
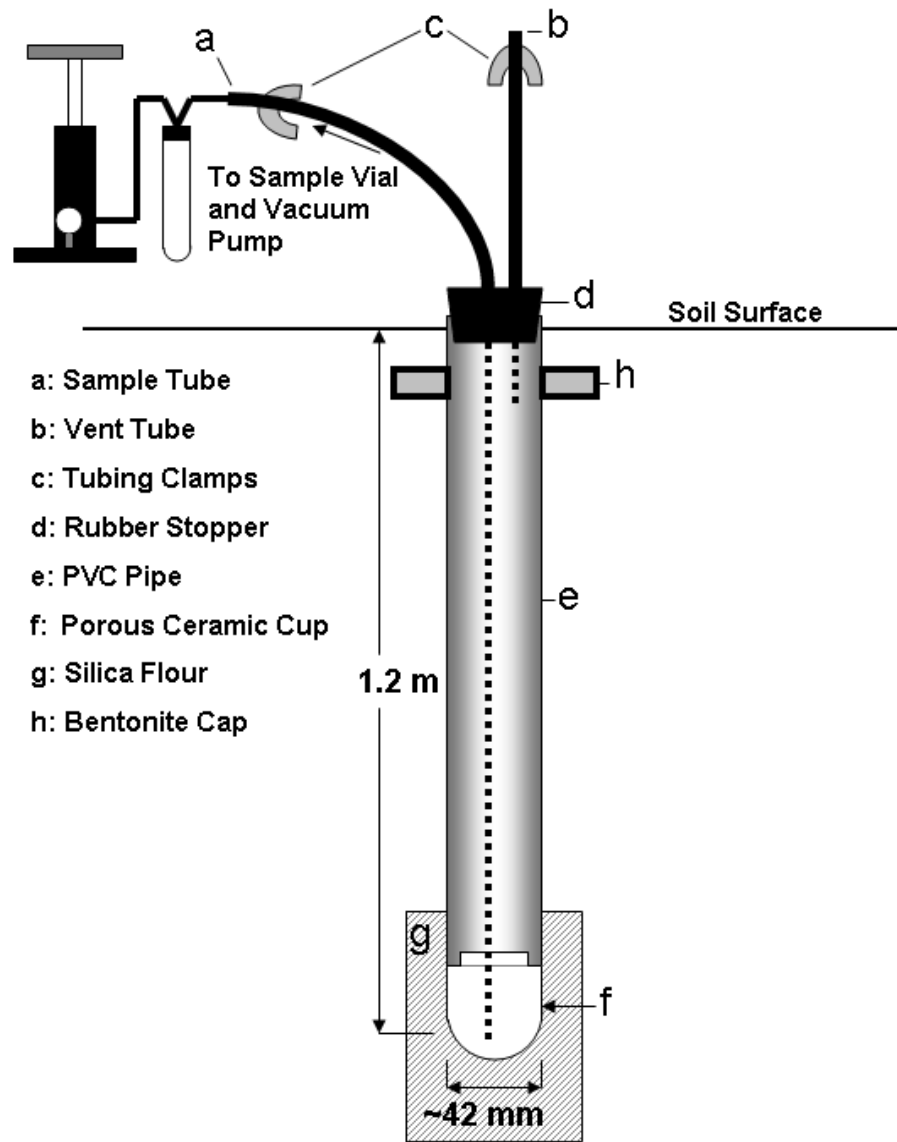
Figure 2-1. Suction cup lysimeter design and installation summary.

Figure 2-2. (a) Soil water inputs; (b) solar radiation and air temperatures; (c) evapotranspiration (ET) as calculated using the Jensen-Haise (JH) and FAO 56 Penman-Monteith (PM) equations; (d) daily water drainage and soil water deficit determined using JH and PM; and (e) cumulative water drainage for 2007. Arrows indicate planting (P), vine kill (VK), and timing of fertilizer applications with conventional split application, which occurred at emergence (E), and five times after emergence. Stars indicate dates where an average of ≥ 1 kg N ha^{-1} leached in 24-h. Polymer-coated ureas were added in a single preplant application. Total seasonal precipitation and irrigation as a percentage of total inputs are given in (a) and seasonal mean air temperature and radiation are given in (b). Cumulative ET and cumulative drainage is given in (c) and (e), respectively. Values for (c) and (e) are reported for each ET model and their difference.
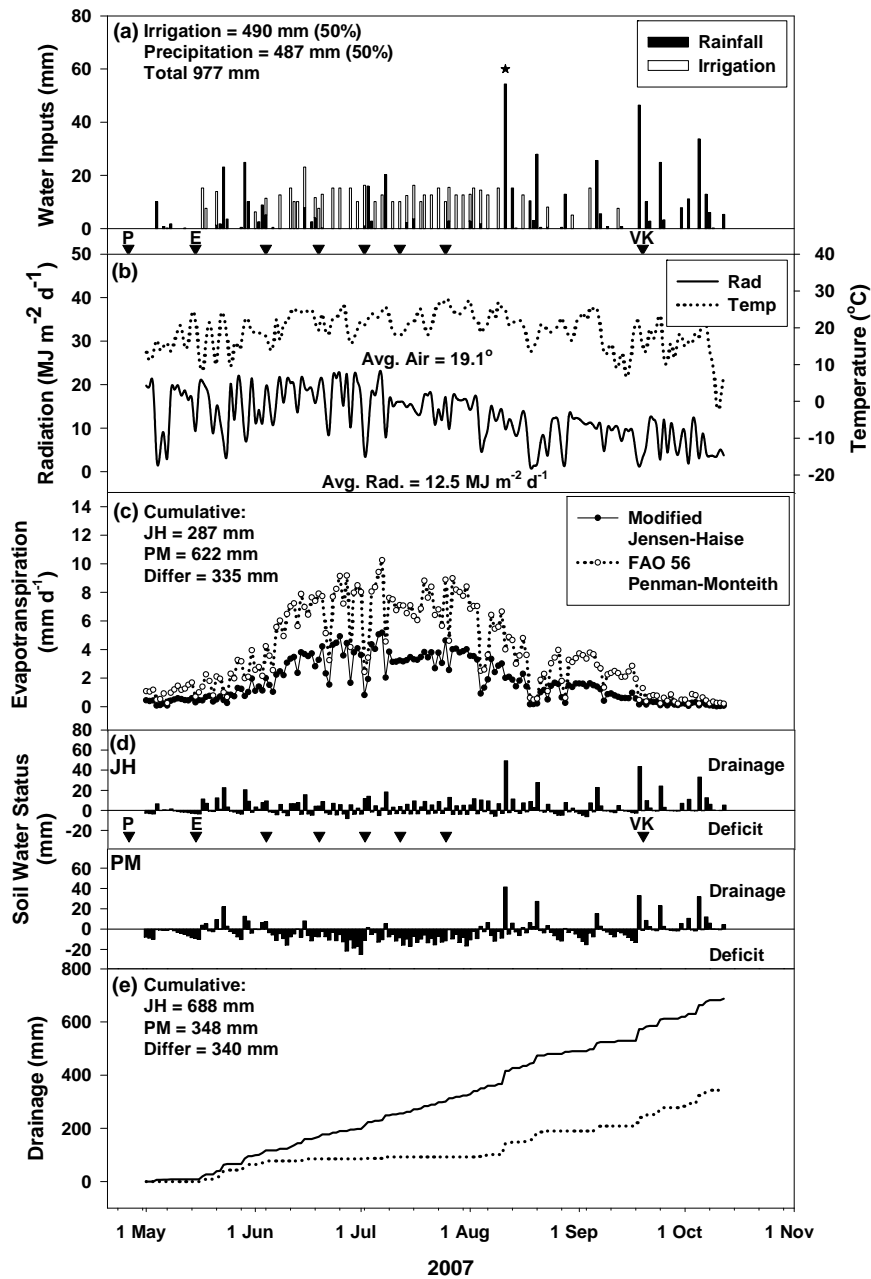
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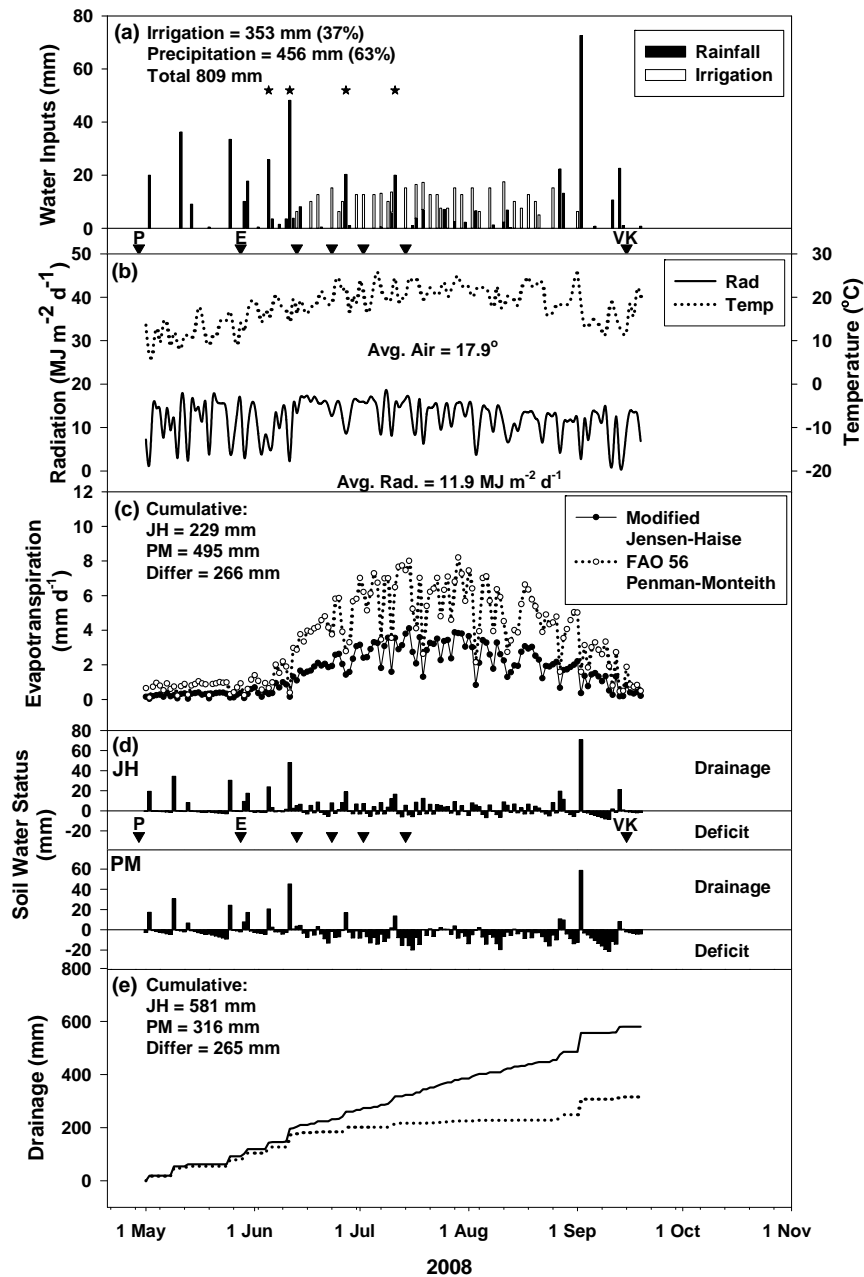
Figure 2-3. (a) Soil water inputs; (b) solar radiation and air temperatures; (c) evapotranspiration (ET) as calculated using the Jensen-Haise (JH) and FAO 56 Penman-Monteith (PM) equations; (d) daily water drainage and soil water deficit determined using JH and PM; and (e) cumulative water drainage for 2008. Arrows indicate planting (P), vine kill (VK), and timing of fertilizer applications with conventional split application, which occurred at emergence (E), and four times after emergence. Stars indicate dates where an average of ≥ 1 kg N ha^{-1} leached in 24-h. Polymer-coated ureas were added in a single preplant application. Total seasonal precipitation and irrigation as a percentage of total inputs are given in (a) and seasonal mean air temperature and radiation are given in (b). Cumulative ET and cumulative drainage is given in (c) and (e), respectively. Values for (c) and (e) are reported for each ET model and their difference.
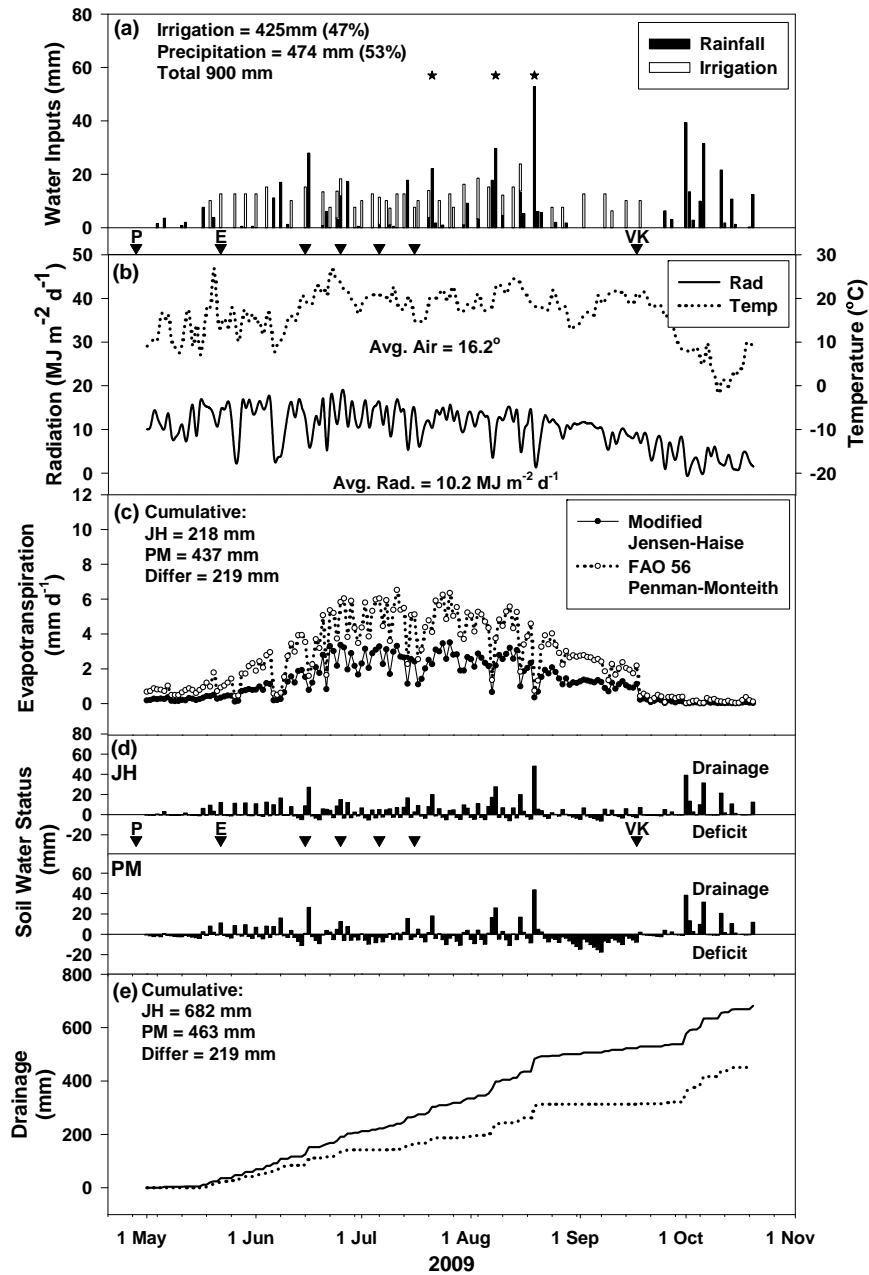
Figure 2-4. (a) Soil water inputs; (b) solar radiation and air temperatures; (c) evapotranspiration (ET) as calculated using the Jensen-Haise (JH) and FAO 56 Penman-Monteith (PM) equations; (d) daily water drainage and soil water deficit determined using JH and PM; and (e) cumulative water drainage for 2009. Arrows indicate planting (P), vine kill (VK), and timing of fertilizer applications with conventional split application, which occurred at emergence (E), and four times after emergence. Stars indicate dates where an average of ≥ 1 kg N ha^{-1} leached in 24-h. Polymer-coated ureas were added in a single preplant application. Total seasonal precipitation and irrigation as a percentage of total inputs are given in (a) and seasonal mean air temperature and radiation are given in (b). Cumulative ET and cumulative drainage is given in (c) and (e), respectively. Values for (c) and (e) are reported for each ET model and their difference.

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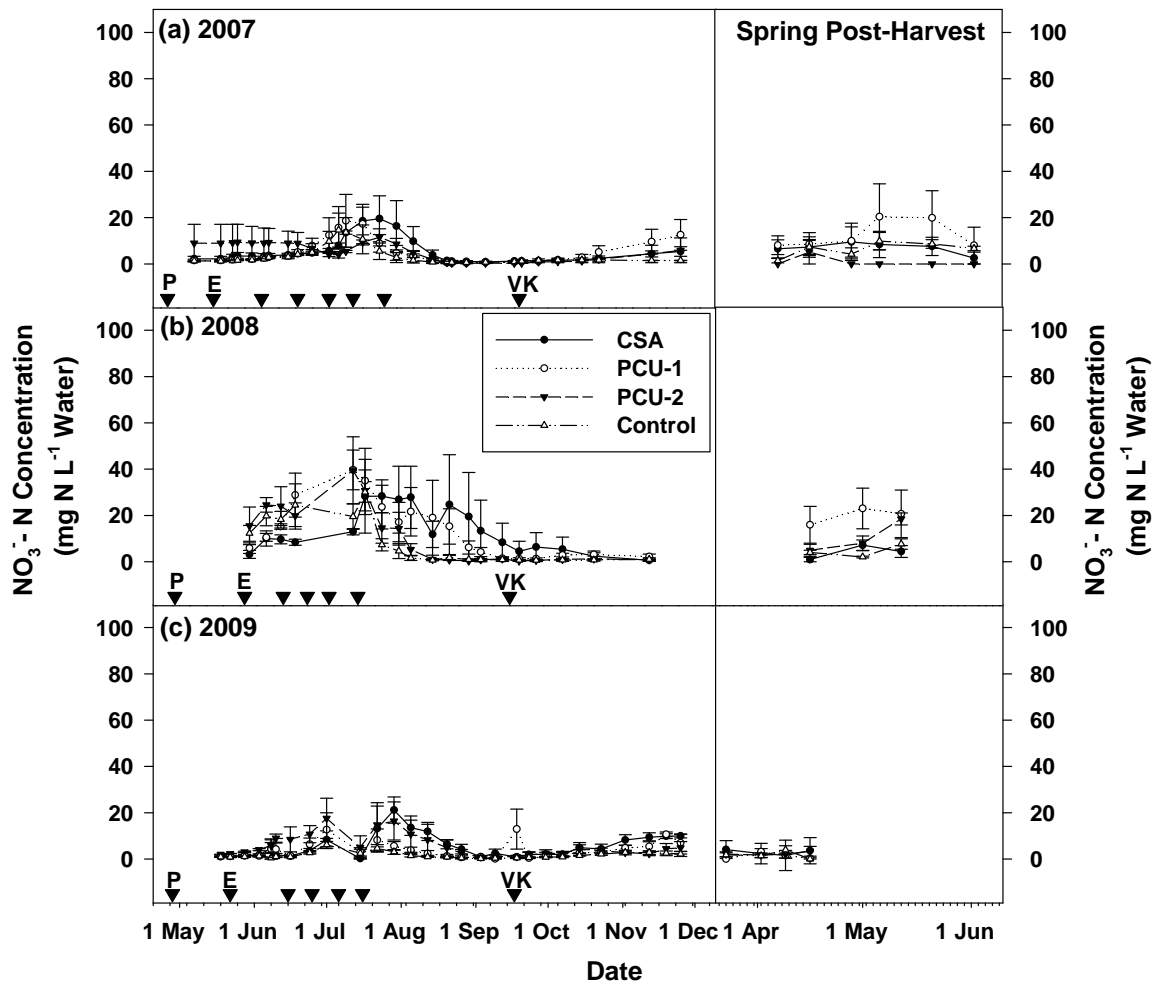
Figure 2-5. Soil water NO_3^- concentrations in potatoes fertilized with conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control from samples collected at a 120 cm depth with suction cup lysimeters. Results are presented for (a) 2007, (b) 2008 and (c) 2009, as well as the same fields the following spring. Arrows indicate planting (P), vine kill (VK), and timing of fertilizer applications with conventional split application, which occurred at emergence (E), and (a) five or (b&c) four times after emergence. The PCUs were added in a single preplant application.

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Figure 2-6. Daily sub-rootzone NO_3^- leaching in 2007 in potatoes fertilized with conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control using the Jensen-Haise (JH) and FAO 56 Penman-Monteith (PM) equations to determine daily crop evapotranspiration (a&b) and cumulative seasonal N leached (c&d). Arrows indicate planting (P), vine kill (VK) and timing of fertilizer applications with CSA, which occurred at emergence (E) and five times after emergence. The PCUs were added in a single preplant application**.**

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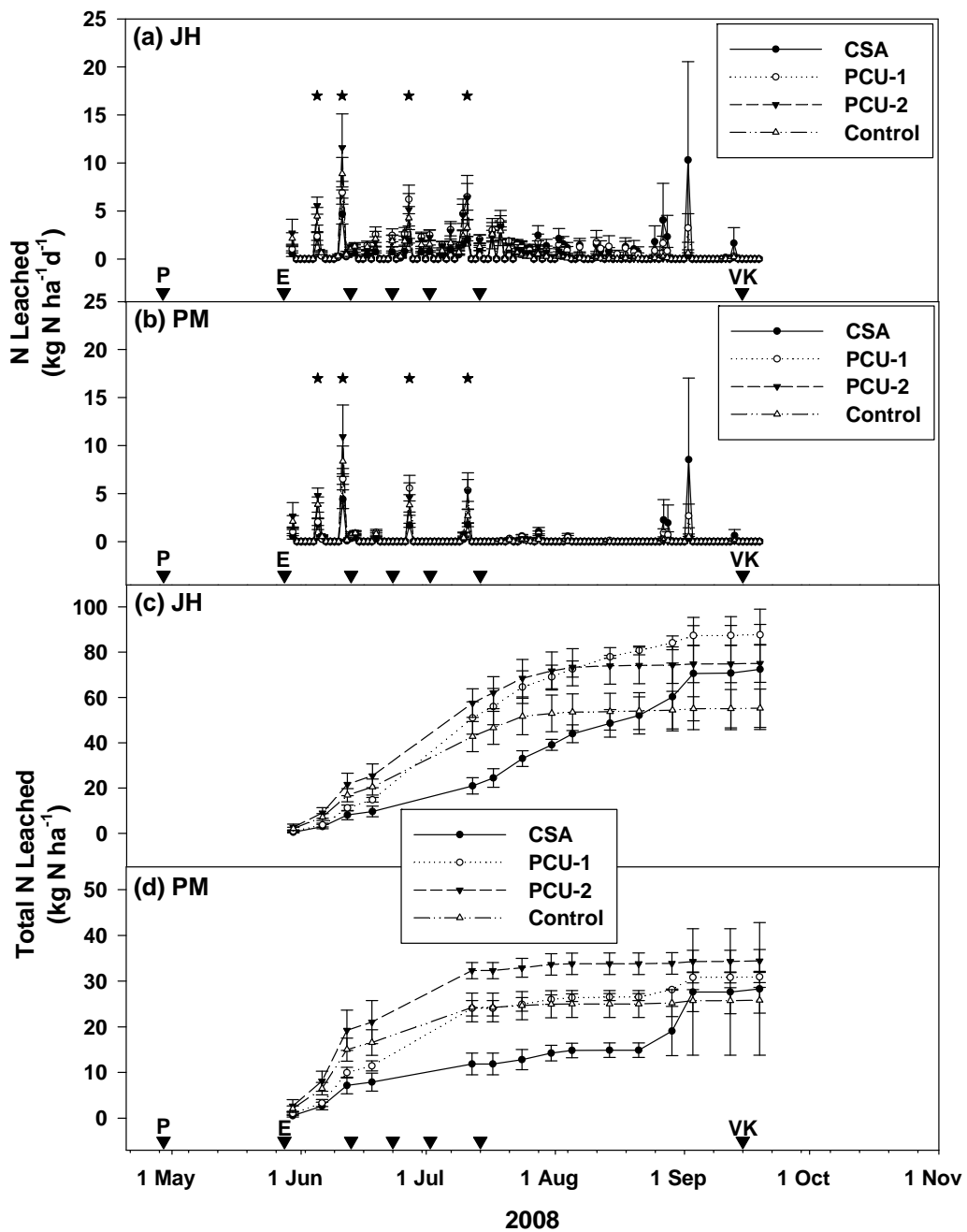
Figure 2-7. Daily sub-rootzone NO_3^- leaching in 2008 in potatoes fertilized with conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control using the Jensen-Haise (JH) and FAO 56 Penman-Monteith (PM) equations to determine daily crop evapotranspiration (a&b) and cumulative seasonal N leached (c&d). Arrows indicate planting (P), vine kill (VK) and timing of fertilizer applications with CSA, which occurred at emergence (E) and four times after emergence. The PCUs were added in a single preplant application.
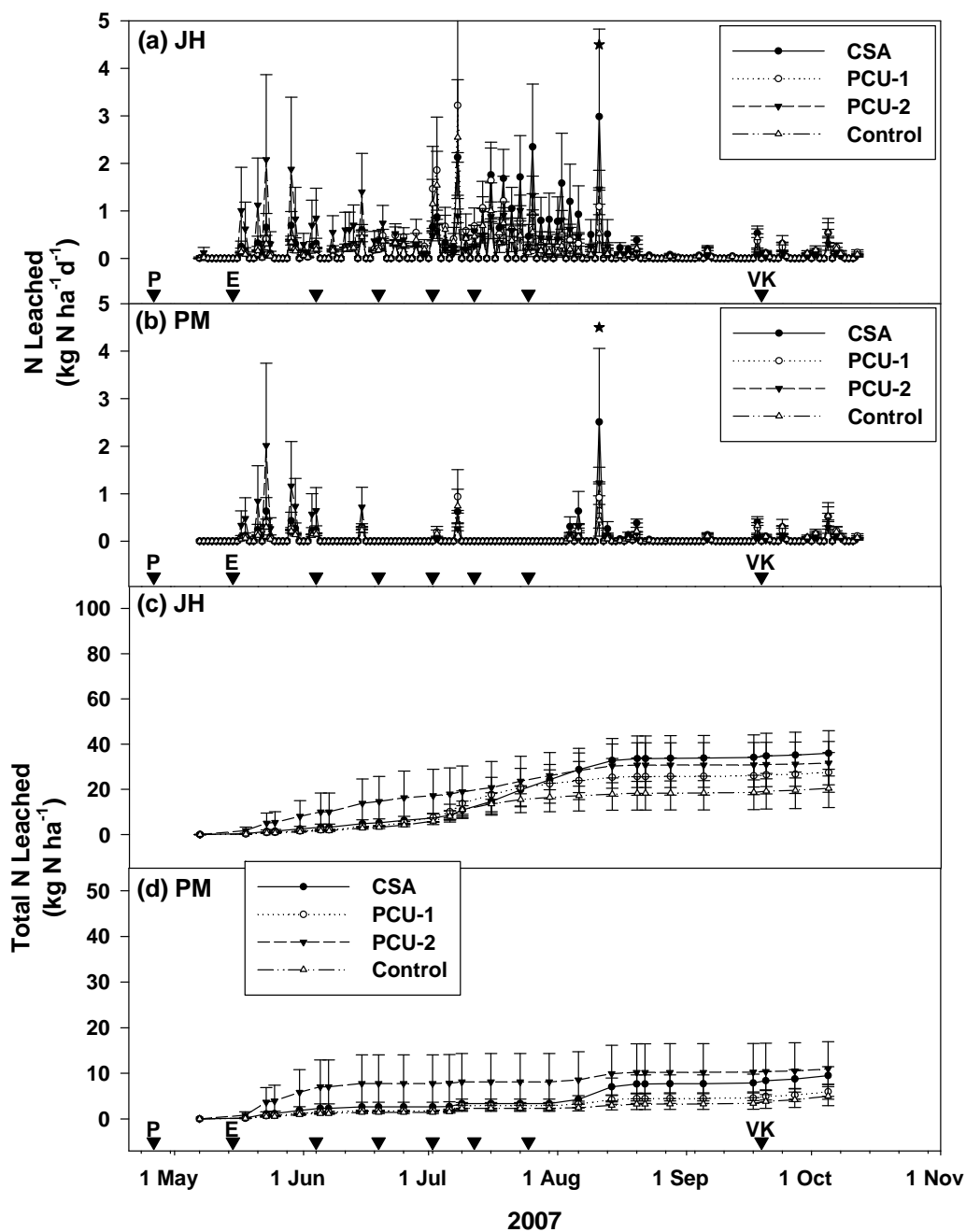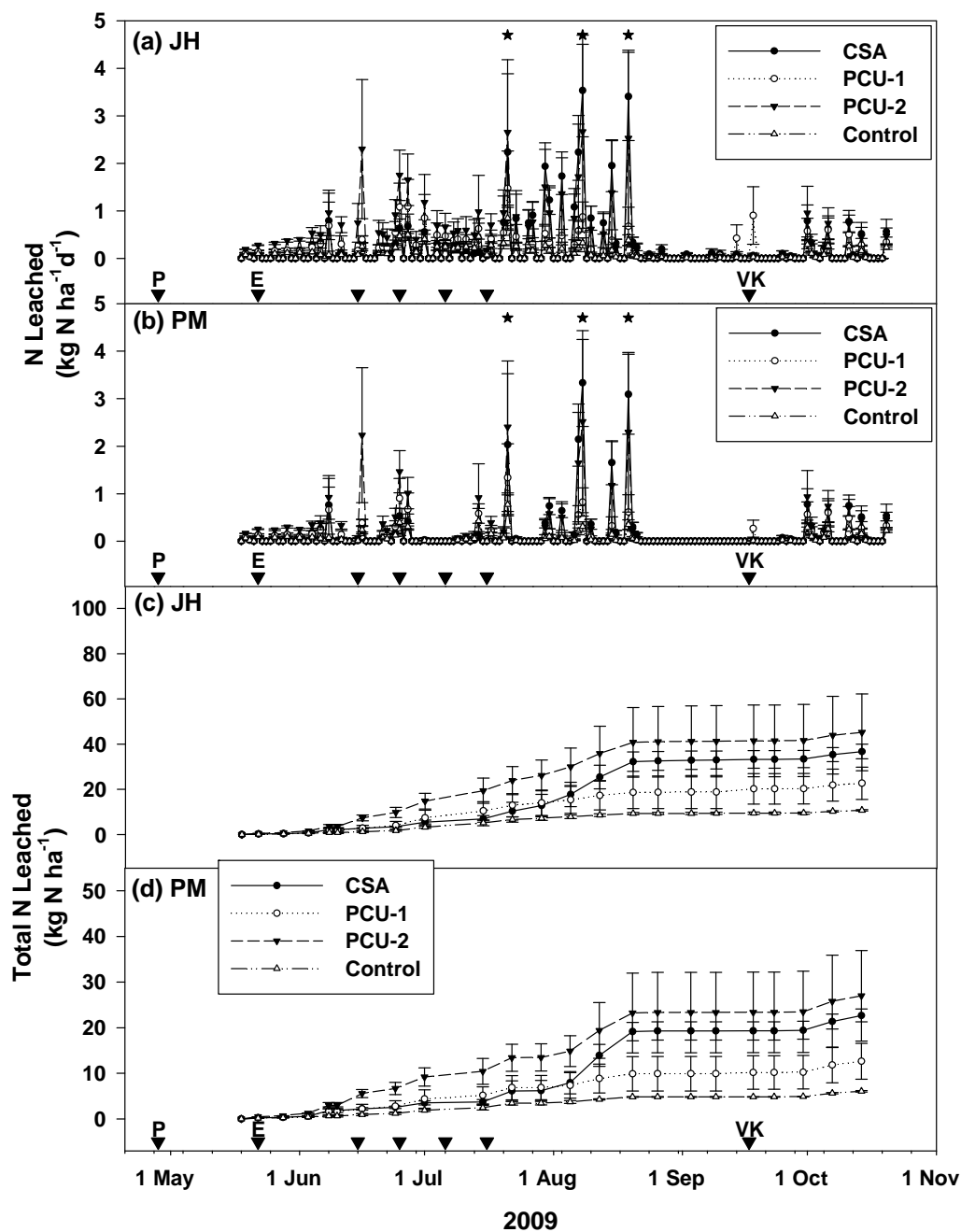
Figure 2-8. Daily sub-rootzone NO_3^- leaching in 2009 in potatoes fertilized with conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control using the Jensen-Haise (JH) and FAO 56 Penman-Monteith (PM) equations to determine daily crop evapotranspiration (a&b) and cumulative seasonal N leached (c&d). Arrows indicate planting (P), vine kill (VK) and timing of fertilizer applications with CSA, which occurred at emergence (E) and four times after emergence. The PCUs were added in a single preplant application.

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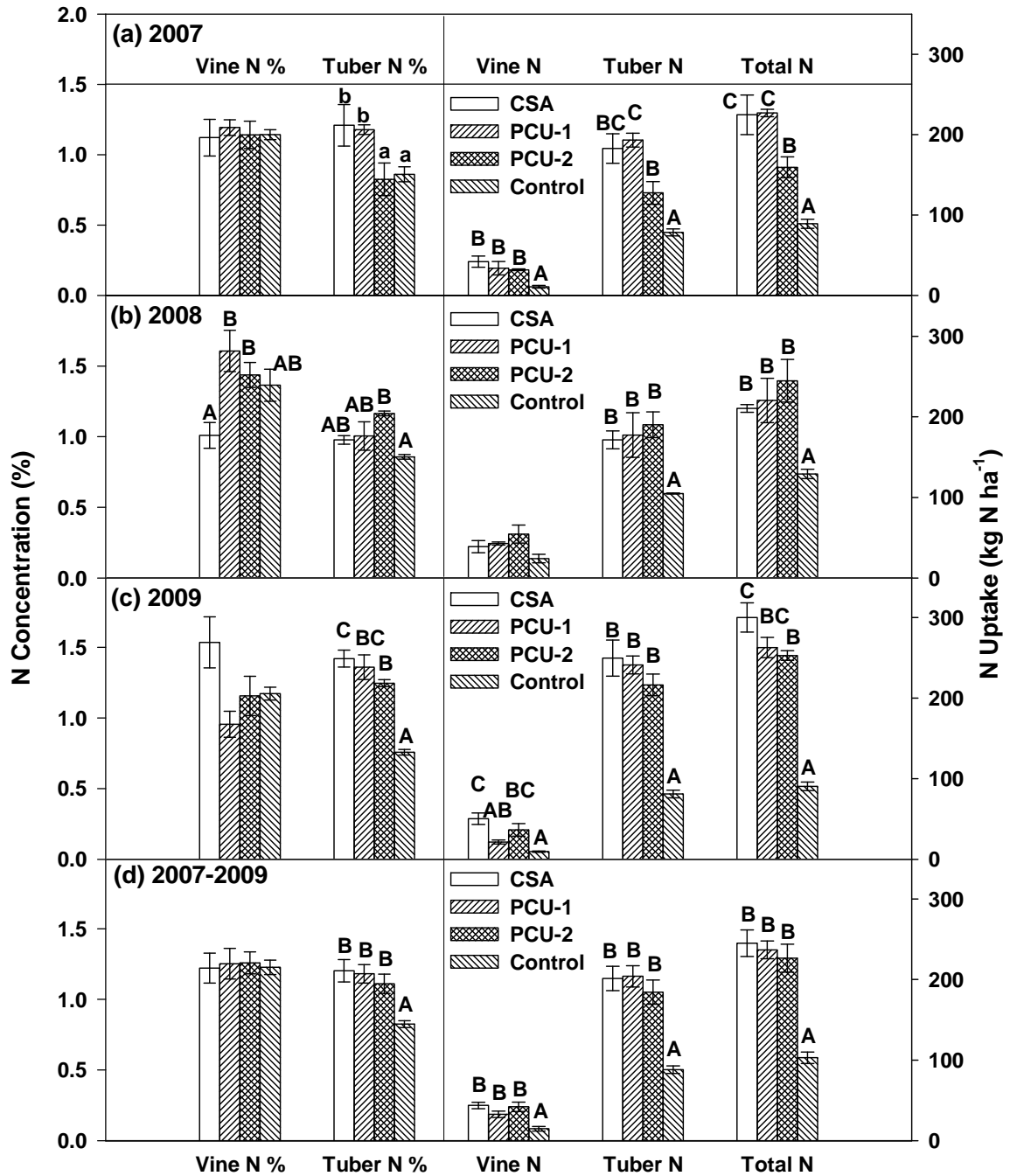
Figure 2-9. Nitrogen concentration and accumulation in vines and tubers for the (a) 2007, (b) 2008, and (c) 2009 seasons, and (d) combined 2007-2009 period in plots fertilized using conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2) and an unfertilized control. Within each time period and metric, bars with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, lowercase letters indicate $P < 0.10$; no letters indicate no significant difference.

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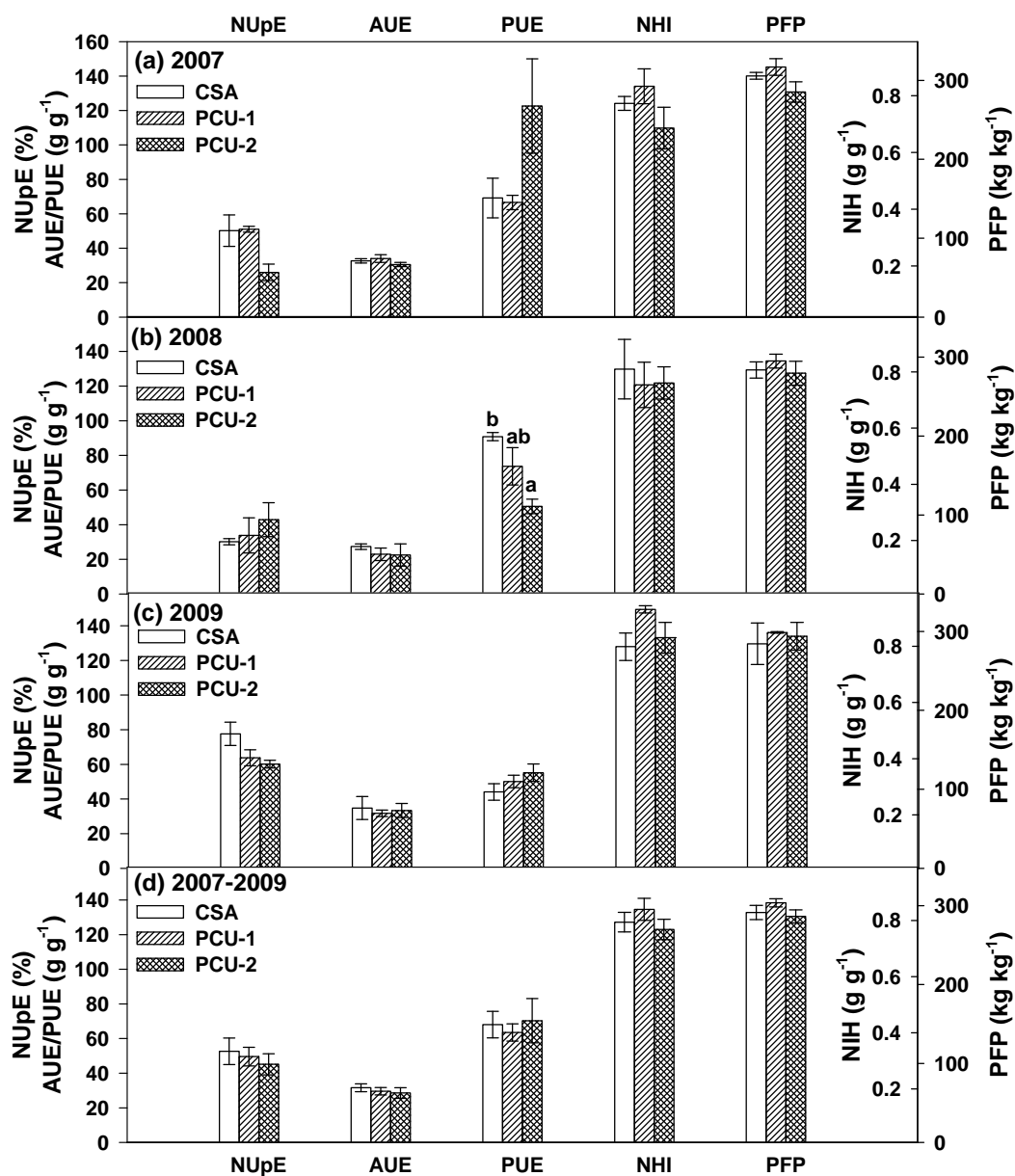
Figure 2-10. Nitrogen use efficiencies for the (a) 2007, (b) 2008, and (c) 2009 seasons, and (d) combined 2007-2009 period in plots fertilized using conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2). NUpE = N uptake efficiency, AUE = agronomic use efficiency, PUE = physiological use efficiency, NHI = N harvest index, and PFP = partial factor productivity. Within each time period and index, bars with the same letter are not significantly different at $P<0.10$; no letters indicate no significant difference.
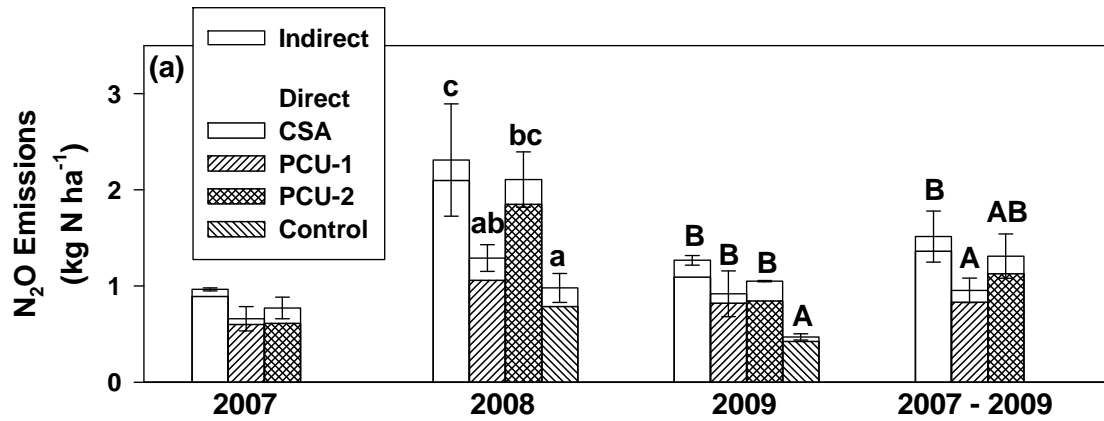
Figure 2-11. Total seasonal cumulative N_2O emissions in plots fertilized using a conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and an unfertilized control. Mean values for direct and indirect emissions are shown individually. Standard error bars are calculated by treatment for the mean of total emissions (n = 3). Values during the study period (2007-2009) are shown only for the fertilized treatments. Within each time period, bars with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, lowercase letters indicate $P < 0.10$, no letters indicate no significant difference.

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Overall Conclusions

TUBER YIELD

Tuber yields from the PCU treatments did not differ significantly from those of the CSA. These results were paralleled by aboveground biomass production data which also showed no significant differences in vine growth among fertilized treatments. As PCU is typically used with a single application, this indicates that N fertilization strategies utilizing PCUs can maintain potato yields while reducing equipment field time and personnel costs associated with CSA.

NITROGEN UPTAKE AND NITROGEN USE EFFICIENCY

Biomass N uptake and N concentrations were not significantly different between the PCU-1 and CSA treatments in most cases. This suggests that PCU can supply N to potato at amounts consistent with best management practices recommendations as represented by the CSA treatment. NUEs were also not significantly different among fertilized treatments at $P<0.05$. Only PUE (Physiological Use Efficiency), a measure of the plant's ability to utilize recovered N for biomass production, showed a difference at $P<0.10$. This difference occurred between CSA and PCU-2 and indicates that CSA may hold a slight advantage in the production of total biomass (vines + tubers in kg) per unit of applied fertilizer when compared with PCU-2. However, this advantage does not carryover to any the other NUE indices or the PFP (partial factor productivity), an economic index comparing tuber yield per unit of applied fertilizer. In light of this, it

does not appear that crops fertilized by PCU at the N rate tested are any more or less

efficient at utilizing applied nitrogen then those under CSA.

EVAPOTRANSPIRATION

The JH model of ET determination modified for Minnesota specific conditions

and used regularly for irrigation scheduling was found to significantly underestimate ET

when compared with the FAO 56 PM model. This finding was consistent with a number

of other studies that compared un-modified versions of JH with various PM derivatives

(Jensen et al., 1990; Irmak et al., 2003; Irmak et al., 2008). To avoid this underestimation,

the PM model should be used whenever a complete input factor dataset that includes

relative humidity and wind-speed is available.

NITRATE LEACHING

Over the 3-yr study period, cumulative NO_3^- leached was found to be between 1.2

and 17.9% of applied fertilizer N, depending on treatment. Despite being gathered from a

coarse-textured, well drained soil, these results are far lower than the IPCC recommended

value of 30% of applied N used to estimate NO_3^- leaching (Eggleston et al., 2006). This

may partially be due to lower rainfall amounts in 2007 and 2009 (85 and 67% of

average). However, the IPCC default value may need to be reevaluated under a range of

cropping systems, including irrigated potato, to more closely reflect actual conditions.

Leaching was also not significantly different among fertilized treatment types. This

indicates that the use of a single pre-plant application of PCU carries the same benefit of providing N in parallel with crop demand and thereby reducing excess supply susceptible to leaching as does CSA.

DIRECT NITROUS OXIDE EMISSIONS

N_2O emissions measured directly on field with static chambers were significantly higher from a CSA treatment when compared with a PCU product (PCU-1). Mean cumulative growing season N_2O emissions were 1.36, 0.83, and 1.13 kg N ha^{-1} yr^{-1} with CSA and two different PCU products (PCU-1 and PCU-2), respectively. These emissions only represented 0.1 to 0.5 % of applied fertilizer, after accounting for emissions from the unfertilized control treatment. This is comparable to emissions seen in other agronomic crops in finer texture soils with lower fertilization rates (Venterea et al., 2010). These results suggest that the use of PCU products can potentially reduce direct N_2O emissions when compared with CSA.

INDIRECT NITROUS OXIDE EMISSIONS

Mean estimated cumulative indirect N_2O emissions, as with NO_3^- leaching, were not statistically different among fertilized treatments. However, the values of 0.17, 0.14, and 0.20 kg N ha^{-1} calculated using the IPCC default emission factor of 0.75% for CSA, PCU-1, and PCU-2, respectively, were significantly lower than measured direct N_2O emissions (1.36, 0.83, and 1.13 kg N ha^{-1} yr^{-1}, respectively). Because the uncertainty

range for the indirect emission factor is so broad (0.05% to 2.5%, 95% confidence),

indirect emissions could be anywhere from 0.6 to 84.9% of direct N_2O emissions. In

order to narrow this uncertainty factor, much more work is needed in quantifying indirect

N_2O emissions from various agricultural systems, including irrigated potato grown in

coarse textured soils.

TOTAL NITROUS OXIDE EMISSIONS

Total N_2O emissions were found to be significantly different among treatments

and ranged from 0.5 to 3.3 kg N ha^{-1} in the fertilized treatments. Depending on the

emission factor chosen for calculating indirect N_2O emissions, total emissions can be

made up of nearly equal parts direct and indirect flux (54.1 and 45.9%, respectively), or

indirect N_2O emissions can be seen as a very minor component of total N_2O emissions

when compared with direct (0.6% of total). However, at the IPCC default emission

factor, statistical relationships among treatments due to total flux closely mirrored those

of direct N_2O emissions, with emissions from the CSA treatment significantly higher than

those of PCU-1 over the entire 3-yr study period. This suggests that a fertilization system

utilizing PCU can potentially reduce total N_2O emissions when compared with CSA.

Bibliography

Addiscott, T.M., A.P. Whitmore, and D.S. Powlson. 1991. Farming, fertilizers and the
   nitrate problem. CAB International, Wallingford, UK.

Agrium, 2009a. A new generation in smart nitrogen: ESN Controlled-release fertilizer.
   Potato. Available at
   http://www.agriumat.com/agtech/includes/esn_potato_fact_sheet.pdf (verified 14
   Apr. 2011). Agrium Inc., Calgary, AB, Canada.

Agrium, 2009b. ESN Smart Nitrogen: A smarter source of nitrogen, a smarter way to
   grow. Potato. Available at
   http://www.smartnitrogen.com/pdf/10915%20ESNPotatoInfoSheet_LR.pdf
   (verified 14 Apr. 2011). Agrium Inc., Calgary, AB, Canada.

Allen, R.G, L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration -
   Guidelines for computing crop water requirements - FAO Irrigation and drainage
   paper 56. Food and Agricultural Organization of the United Nations, Rome.

Al-Kaisi, M.M., and I. Broner. 2009. Crop Water Use and Growth Stages. Colorado State
   Univ. Cooperative Extension. Rept. No. 4.715. 4 p.

Bennett K. and P. O'Rourke. 2002. Crop profile for potatoes in Minnesota. Available at
   http://www.ipmcenters.org/cropprofiles/docs/MNpotatoes.pdf (verified 14 Apr.
   2011). North Central Pest Management Center, St. Paul.

Benson, V.S., J.A. VanLeeuwen, J. Sanchez, I.R. Dohoo, and G.H. Somers. 2006. Spatial analysis of land use impact on ground water nitrate concentrations. J. Environ. Qual. 35:421-432.

Brown, J.R. (ed.). 1998 Recommended chemical soil test procedures for the North Central Region. Doc. SB 1001. Missouri Agric. Exp. Stn., Columbia.

Bruening D. 1996. Potato survey: Central Sands 1995. Available at http://www.mda.state.mn.us/en/sitecore/content/Global/MDADocs/protecting/soil protection/fanmappotato.aspx (verified 14 Apr. 2011). Minnesota Department of Agriculture: Farm Nutrient Management Assessment Program, St. Paul.

Bucher, M. and J. Kossmann. 2007. Molecular physiology of the mineral nutrition of the potato. p. 311-329. *In* Vreugdenhil, D. *et al.* (ed.) Potato biology and biotechnology: Advances and perspectives. Elsevier. New York.

Burton, D.L., B.J. Zebarth, K.M. Gillam, and J.A. MacLeod. 2008. Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. Can. J. Soil Sci. 88: 229-239.

Burton, W.G. 1989. The Potato. 3rd Ed. John Wiley & Sons, Inc. New York.

Carlson, R.M., R.I. Cabrera, J.L. Paul, J. Quick, and R.Y. Evans. 1990. Rapid direct determination of ammonium and nitrate in soil and plant tissue extracts. Commun. Soil Sci. Plant Anal. 21:1519-1529.

Cassman, K.G., G.C. Gines, M.A. Dizon, M.I. Samson, and J.M. Alcantara. 1996. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crop. Res. 47:1-12.

Cheng, W., S. Sudo, H. Tsuruta, K. Yagi, and A. Hartley. 2006. Temporal and spatial variations in N_2O emission from a Chinese cabbage field as a function of type of fertilizer and application. Nutr. Cycling Agroecosyst. 74: 147-155.

Clark, B. and J.B. Forster. 2009. Ecological Imperialism and the Global Metabolic Rift: Unequal Exchange and the Guano/Nitrates Trade. Int. J. Comp. Sociol. 50:311-334.

Coyne, M.S. 2008. Biological denitrification. p. 201-254. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Dean, B.B. 1994. Managing the potato production system. Food Products Press, imprint of The Haworth Press, Inc. New York.

Derby, N.E., F.X.M. Casey, R.E. Knighton, and D.D. Steele. 2004. Midseason nitrogen fertility management for corn based on weather and yield prediction. Agron. J. 96:494-501.

Delgado, J.A., and A.R. Mosier. 1996, Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. J. Environ. Qual. 25:1105-1111.

Delgado, J.A., R.R. Riggenbach, R.T. Sparks, M.A. Dillon, L.M. Kawanabe, and R.J. Ristau. 2001. Evaluation of nitrate-nitrogen transport in a potato-barley rotation. Soil Sci. Soc. Am. J. 65: 878-883.

Dobbie, K.E., and K.A. Smith. 2003. Impact of different forms of N fertilizer on N_2O emissions from intensive grassland. Nutr. Cycling Agroecosyst. 67: 37–46.

Eggleston H.S., L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds). 2006. 2006 IPCC
Guidelines for National Greenhouse Gas Inventories. National Greenhouse Gas
Inventories Programme. IGES, Japan. Available at www.ipcc-
nggip.iges.or.jp/public/2006gl/index.html (verified 14 Apr. 2011).

Erisman, J.W., A. Bleeker, J. Galloway, and M.S. Sutton. 2007. Reduced nitrogen in
ecology and the environment. Environ. Pollut. 150:140-149.

Erisman, J.W., M.S. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter. 2008. How a
century of ammonia synthesis changed the world. Nat Geosci. 1:636-639.

Errebhi, M., C.J. Rosen, S.C. Gupta, and D.E. Birong. 1998. Potato yield response and
nitrate leaching as influenced by nitrogen management. Agron. J. 90:10-15.

Errebhi, M., C.J. Rosen, F.I. Lauer, M.E. Martin, and J.B. Bamberg. 1999. Evaluation of
tuber-bearing *Solanum* species for nitrogen use efficiency and biomass
partitioning. Am. J. Potato Res. 76:143-151.

FAOSTAT. 2010. Food and Agriculture Organization of the United Nations. FAOSTAT.
Available at http://faostat.fao.org/site/339/default.aspx (verified 14 Apr. 2011).
Rome.

Firestone, M., and E. Davidson. 1989. Microbiological basis of NO and N_2O production
and consumption in soil. p. 7-21. In M. Andreae and D. Schimel (ed.) Exchange
of trace gases between terrestrial ecosystems and the atmosphere. John Wiley &
Sons, Chichester, UK.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, *et al*. 2007.
Changes in atmospheric constituents and in radiative forcing. P. 131-234. *In* S.

Solomon *et al*. (ed.) Climate Change 2007: The Physical Science Basis.

Cambridge Univ. Press, Cambridge, UK.

Gaskell, M., and R. Smith. 2007. Nitrogen sources for organic vegetable crops. Horttechnology. 17:431-441.

Gopal, J., and R. Ortiz. 2006. True Potato Seed. p. 557-585. *In* J. Gopal and S.M.P. Khurana (ed.) Handbook of potato production, improvement, and postharvest management. Food Products Press, imprint of The Haworth Press, Inc. New York.

Govindakrishnan, P.M. and A.J. Haverkort. 2006. Ecophysiology and agronomic management. p. 179-229. *In* J. Gopal and S.M.P. Khurana (ed.) Handbook of potato production, improvement, and postharvest management. Food Products Press, imprint of The Haworth Press, Inc. New York.

Hadi, A., O. Jumadi, K. Inubushi, and K Yagi. 2008. Mitigation options for N_2O emission from a corn field in Kalimantan, Indonesia. Soil Sci. Plant Nutr. 54: 644-649.

Haile-Mariam, S., H.P. Collins, and S.S. Higgins. 2008. Greenhouse gas fluxes from an irrigated sweet corn (*Zea mays* L.) – potato (*Solanum tuberosum* L.) rotation. J. Environ. Qual. 37: 759-771.

Halvorson, A.D., S.J. Del Grosso, and F. Alluvione. 2010. Tillage and nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Sci. Soc. Am. J. 74: 435-445.

Halvorson, A.D., S.J. Del Grosso, and C.A. Reule. 2008. Nitrogen, tillage, and crop

    rotation effects on nitrous oxide emissions from irrigated cropping systems. J.

    Environ. Qual. 37: 1337-1344.

Han, Y.J., A Khalilian, T.O. Owino, H.J. Farahani, and S. Moore. 2009. Development of

    Clemson variable-rate lateral irrigation system. Comput. Electron. Agr. 68:108-

    113.

Horneck, D.A., and R.O. Miller. 1998. Determination of total nitrogen in plant tissue. *In*

    Y.P. Kalra (ed.) Handbook of reference methods for plant analysis. CRC Press,

    Boston.

Hutchinson, C., E. Simonne, P. Solano, J. Meldrum, and P. Livingston-Way. 2003.

    Testing of controlled release fertilizer programs for seep irrigated Irish potato

    production. J. Plant Nutr. 26: 1709-1723.

Hutchinson, G.L. and G.P. Livingston. 2002. Soil-atmosphere gas exchange. p. 1159–

    1182. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA

    Book Ser. 5. SSSA, Madison, WI.

Hyatt, C.R., R.T. Venterea, C.J. Rosen, M. McNearney, M.L. Wilson, and M.S. Dolan.

    2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide

    emissions in a Minnesota loamy sand. Soil Sci. Soc. Am. J. 74:419-428.

IPCC. 1997. Intergovernmental Panel on Climate Change. Revised 1996 IPCC guidelines

    for national greenhouse gas inventories reference manual, vol. 3. Available at

    www.ipcc-nggip.iges.or.jp/public/gl/invs6.html (verified 14 Apr. 2011).

Irmak, S., R.G. Allen, and E.B. Whitty. 2003. Daily grass and alfalfa-reference evapotranspiration estimates and alfalfa-to-grass evapotranspiration rations in Florida. J. Irrig. Drain. E.-ASCE. 129:360-370.

Irmak, A., S. Irmak, and D.L. Martin. 2008. Reference and crop evapotranspiration in south central Nebraska. I: Comparison and analysis of grass and alfalfa-reference evapotranspiration. J. Irrig. Drain. E.-ASCE. 134:690-699.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed.). 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70., Am. Soc. Civil Engrs. New York.

Jensen, M.E., and Haise, H.R. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. Drain. Div. 89:15-41.

Jumadi O., Y. Hala, A. Muis, A. Ali, M. Palennari, K. Yagi, and K. Inubushi. 2008. Influences of chemical fertilizers and a nitrification inhibitor on greenhouse gas fluxes in a corn (*Zea mays* L.) field in Indonesia. Microbes Environ. 23: 29-34.

Kadam, S.S., S.S. Dhumal, and N.D. Jambhale. 1991. Structure, nutritional composition, and quality. p. 9-35. *In* D.K. Salunkhe, S.S. Kadam, and S.J. Jadhav (ed.) Potato: Production, processing, and products. CRC Press. Boca Raton, Fl.

Killen, M.A. 1984. Modification of the checkbook method of irrigation scheduling for use in Minnesota. M.S. thesis. Univ. of Minnesota, St. Paul.

Koga, N., T. Sawamoto, and H. Tsuruta. 2006. Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, northern Japan. Soil Sci. Plant Nutr. 52:564-574.

Kraft, G.J. and W. Stites. 2003. Nitrate impacts on groundwater from irrigated-vegetable systems in a humid north-central US sand plain. Agr. Ecosyst. Environ. 100:63-74.

Lewandowski, A.M., B.R. Montgomery, C.J. Rosen, and J.F. Moncrief. 2008. Groundwater nitrate contamination costs: A survey of private well owners. J. Soil Water Conserv. 63:153-161.

Lesczynski, D.B. and C.B. Tanner. 1976. Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potato. Am. Potato J. 53:69-78.

MCWG. 2009. Minnesota Climatology Working Group. Minnesota location selector. Available at http://climate.umn.edu/hidradius/radius.asp (verified 14 Apr. 2011). Minnesota State Climatology Office, St. Paul.

MCWG. 2010. Minnesota Climatology Working Group. Minnesota location selector. Available at http://climate.umn.edu/hidradius/radius.asp (verified 14 Apr. 2011). Minnesota State Climatology Office, St. Paul.

Meyer, G.N., C.J. Patterson, H.C. Hobbs, and J.D. Lehr. 1993. Surficial geology, plate 1. *In* G.N. Meyer and J. Jalteisek (ed.) Regional hydrogeologic assessment of the Anoka sand plain: Anoka, Chisago, Isanti and Sherburne Counties, Minnesota. Ser. RHA-1. Minnesota Department of Natural Resources, Division of Waters Regional Assessment. St. Paul.

Mosier, A., C Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput. 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutr. Cycl. Agroecosys. 52:225-248.

MRCC. 2010. Midwestern Regional Climate Center. Climate of the Midwest. Available
at http://mrcc.isws.illinois.edu/climate_midwest/maps/mn_mapselector.htm
(verified 14 Apr. 2011). Illinois State Water Survey, Champaign, IL.

Myrold, D.D., and P.J. Bottomley. 2008. Nitrogen mineralization and immobilization. p.
157-172. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems.
Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

NASS. 2009a. United States Department of Agriculture. National Agricultural Statistics
Service. Potatoes: 2008 summary. Available at
http://usda.mannlib.cornell.edu/usda/nass/Pota//2000s/2009/Pota-09-24-2009.pdf
(verified 14 Apr. 2011). Washington D.C.

NASS. 2009b. United States Department of Agriculture. National Agricultural Statistics
Service. 2007 Census of agriculture: United States summary and state data. AC-
07-A-51. Available at
http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapte
r_2_US_State_Level/usv1.pdf (verified 14 Apr. 2011). Washington D.C.

Nevison, C. 2000. Review of the IPCC methodology for estimating nitrous oxide
emissions associated with agricultural leaching and runoff. Chemosphere – Global
Change Sci. 2:493-500.

NND. 2009. United States Department of Agriculture, Agriculture Research Service.
National Nutrient Database for Standard Reference, Release 22. Available at
http://www.ars.usda.gov/ba/bhnrc/ndl (verified 14 Apr. 2011). Washington D.C.

Norton, J.M. 2008. Nitrification in agricultural soils. p. 173-200. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

NRCS. 2002. Natural Resources Conservation Service. Soil Survey of Sherburne County, MN. United States Government Printing Office, Washington, DC. Available at soildatamart.nrcs.usda.gov/Manuscripts/MN141/0/sherb_MN.pdf (verified 14 Apr. 2011).

Olk, D.C. 2008. Organic forms of soil nitrogen. p. 57-100. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Pack, J.E., C.M. Hutchinson, and E.H. Simonne. 2006. Evaluation of controlled-release fertilizers for northeast Florida chip potato production. J. Plant Nutr. 29: 1301-1313.

Radcliffe, E.B. 2010. Insect control. p. 64-67. *In* Bohl, W.H. and S.B. Johnson. (ed.) Commercial potato production in North America. The Potato Assn. of America. Available at http://potatoassociation.org/documents/A_ProductionHandbook_Final_000.pdf (verified 14 Apr. 2011). Orono, ME.

Rosen, C.J., and P.M. Bierman. 2008. Best management practices for nitrogen use: Irrigated potatoes. Publ. 08559. Univ. of Minnesota Ext. Serv., St Paul.

Rowland, D.L., R.B. Sorensen, K.S. Balkcom, and M.C. Lamb. 2005. Estimating stem water flow in peanut (Arachis hypogaea L.) under different irrigation methods. Peanut Sci. 32:81-90.

Rupert, M.G. 2008. Decadal-scale changes of nitrate in ground water of the United States, 1988-2004. J. Environ. Qual. 37:S-240-S-248.

Ruser, R, H. Flessa, R. Russow, G. Schmidt, F. Buegger, and J.C. Munch. 2006. Emission of N_2O, N_2 and CO_2 from soil fertilized with nitrate: effect of compaction, soil moisture and rewetting. Soil Biol. Biochem. 38: 263-274.

Ruser, R. H. Flessa, R. Schilling, H. Steindl, and F. Beese. 1998. Soil compaction and fertilization effects on nitrous oxide and methane fluxes in potato fields. Soil Sci. Soc. Am. J. 62: 1587-1595.

Russelle, M.P. 2008. Biological dinitrogen fixation in agriculture. p. 281-359. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Salunkhe, D.K. and S.S. Kadam. 1991. Introduction. p. 1-7. *In* D.K. Salunkhe, S.S. Kadam, and S.J. Jadhav (ed.) Potato: Production, processing, and products. CRC Press. Boca Raton, Fl.

SAS Institute. 2003. SAS System for Windows, Release 9.1, SAS Inst., Cary, NC.

Sawamoto, T., Y. Nakajima, M. Kasuya, and H. Tsuruta. 2005. Evaluation of emission factors for indirect N_2O emission due to nitrogen leaching in agro-ecosystems. Geophys. Res. Lett. 32:L03403.

Scavia, D., Rabalais, N.N., Turner, R.E., Justić, Dubravko, and Wiseman, W.J., Jr., 2003, Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load: Limnology and Oceanography, v. 48, p. 951–956.

Scherer T.F., D. Franzen, J. Lorenzen, A. Lamey, D. Aarke, and D.A. Preston.1999. Growing irrigated potatoes. AE-1040. Dakota State Univ. Ext. Serv., North Fargo, ND.

Shaviv, A. 2000. Advances in Controlled Release of Fertilizers. Adv. Agron. 71: 1-49.

Sheridan, R.C. 1979. Chemical fertilizers in southern agriculture. Agr. Hist. 53: 308-318.

Shock, C.C., A.B. Pereira, and E.P. Eldredge. 2007. Irrigation Best Management Practices for Potato. Am. J. Potato Res. 84:29-37.

Shoji, S., J. Delgado, A. Mosier, and Y. Miura. 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. Commun. Soil Sci. Plant Anal. 32: 1051-1070.

Smil V. 2001. Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production. MIT Press, Cambridge.

Smith, K.A., I.P. McTaggart, K.E. Dobbie, and F. Conen. 1998. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. Nutr. Cycling Agroecosyst. 52: 123-130.

Stalham, M.A. and E.J. Allen. 2001. Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (*Solanum tuberosum*) crop. J. Agr. Sci. 137:251-270.

Stegman, E.C., A. Bauer, J.C. Zubriski, and J. Bauder. 1977. Crop curves for water balance irrigation scheduling in S.E. North Dakota. Res. Report No. 66 Agricultural Experiment Station, North Dakota State Univ.

Trenkel, M.E. 1997. Improving fertilizer use efficiency: Controlled-release and stabilized fertilizers in agriculture. Int. Fert. Industry Assoc., Paris.

USEPA. 2008. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2006. EPA 430-R-08-005. Available at http://www.epa.gov/climatechange/emissions/downloads/08_CR.pdf (verified 14 Apr. 2011). USEPA, Washington, DC.

USEPA. 2009. National primary drinking water regulations. Available at http://www.epa.gov/safewater/consumer/pdf/mcl.pdf (verified 14 Apr. 2011). USEPA, Washington D.C.

USEPA. 2010. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2008. EPA 430-R-08-006. Available at http://www.epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_Report.pdf (verified 14 Apr. 2011). USEPA, Washington, DC.

Vallejo, A, U.M. Skiba, L. García-Torres, A. Arce, S. López-Fernández, and L. Sánchez-Martín. 2006. Nitrogen oxides emission from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. Soil Biol. Biochem. 38: 2782-2793.

Van den Berg, R.G. and M.M.J. Jacobs. 2007. Molecular taxonomy. p. 55-76. *In* D. Vreugdenhil (ed.) Potato biology and biotechnology: Advances and perspectives. Elsevier. New York.

Venterea, R.T. 2007. Nitrate-driven nitrous oxide production under aerobic soil conditions: Kinetics and biochemical controls. Global Change Biol. 13: 1798-1809.

Venterea, R.T., M. Burger, and K.A. Spokas. 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. J. Environ. Qual. 34: 1467-1477.

Venterea, R.T., M. S. Dolan, and T.E. Ochsner. 2010. Urea fertilizer decreases N_2O emissions compared to anhydrous ammonia in continuous corn and corn/soybean cropping systems in Minnesota. Soil Sci. Soc. Am. J. 74: 407-418.

Venterea, R.T. and D.E. Rolston. 2000. Nitric and nitrous oxide emissions following fertilizer application to agricultural soil: Biotic and abiotic mechanisms and kinetics. J. Geophys. Res. D: Atmos. 105:15117-15129.

Voroney, P. and D. Derry. 2008. Origin and distribution of nitrogen in soil. p. 1-30. *In* J.S. Schepers and W.R. Raun (ed.) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA-CSSA-SSSA. Madison, WI.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 1999. Irrigation and nitrogen management effects on potato yield, tuber quality, and nitrogen uptake. Agron. J. 91:991-997.

Waddell, J.T., S.C. Gupta, J.F. Moncrief, C.J. Rosen, and D.D. Steele. 2000. Irrigation-and nitrogen-management impact on nitrate leaching under potato. J. Environ. Qual. 29:251-261.

Wagner, S.W., D.C. Reicosky, and R.S. Alessi. 1997. Regression models for calculating gas fluxes measured with a closed chamber. Agron. J. 89: 279-284.

Wendt, K. 2003. Determination of Nitrate/Nitrite by Flow Injection Analysis (Low Flow Method). QuikChem Method 10-107-04-1-A. Lachat Instruments, Milwaukee.

Wiedenfeld, B and J. Enciso. 2008. Sugarcane responses to irrigation and nitrogen in semiarid south Texas. Agron. J. 100:665-671.

Wilson, M.L., C.J. Rosen, and J.F. Moncrief 2009a. A comparison of techniques for determining nitrogen release from polymer-coated urea in the field. HortScience, 44:492–494.

Wilson, M.L., C.J. Rosen, and J.F. Moncrief. 2009b. Potato response to a polymer-coated urea on an irrigated, coarse-textured soil. Agron. J. 101:897-905.

Wilson, M.L., C.J. Rosen, J.F. Moncrief. 2010. Effects of polymer-coated urea on nitrate leaching and nitrogen uptake by potato. J. Environ. Qual. 39:492-499.

Worthington, C.M., K.M. Portier, J.M. White, R.S. Mylavarapu, T.A. Obreza, W.M. Stall, and C.M Hutchinson. 2007. Potato (*Solanum tuberosum* L.) yield and internal heat necrosis incidence under controlled-release and soluble nitrogen sources and leaching irrigation events. Am. J. Potato Res. 84: 403-413.

Wright, J. 2002. Irrigation scheduling: Checkbook method. FO-01322. Univ. of Minnesota Ext. Serv., St. Paul.

Yan, X., Y Hosen, and K. Yagi. 2001. Nitrous oxide and nitric oxide emissions from maize field plots as affected by N fertilizer type and application method. Biol. Fertil. Soils. 34: 297-303.

Zebarth, B.J. and C.J. Rosen. 2007. Research perspective on nitrogen BMP development for potato. Am. J. Potato Res. 84:3-18.

Zebarth, B.J., Y. Leclerc, and G. Moreau. 2004. Rate and timing of nitrogen fertilization of Russet Burbank potato: Nitrogen use efficiency. Can. J. Plant Sci. 84:845-854.

Zebarth, B.J., T.R. Tarn, H. de Jong, and A. Murphy. 2008. Nitrogen use efficiency characteristics of andigena and diploid potato selections. Am. J. Potato Res. 85:210-218.

Zvomuya F, C.J. Rosen, and J.C. Miller, Jr. 2002. Response of Russet Norkotah Clonal Selections to Nitrogen Fertilization. Am. J. Potato Res. 79:231-239.

Zvomuya F, C.J. Rosen, M.P. Russelle, and S.C. Gupta. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. J. Environ. Qual. 32:480-489.

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