Use of a Nitrogen Budget to Predict Nitrogen Losses in Processing Butternut Squash with Different Nitrogen Fertilization Strategies

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Abstract. With rising input costs and environmental concerns, growers are seeking methods to minimize nitrogen (N) inputs and off-field N losses while maintaining crop yields. Field studies on processing butternut squash (*Cucurbita moschata* Duchesne ex Poir.) were conducted in 2004–2007 at 11 locations in Ontario, Canada, to determine the optimal N rate and estimate potential N losses. Preplant broadcast ammonium nitrate was applied at five rates between 0 and 220 kg N/ha. In contrasting years (i.e., cool/wet versus warm/dry versus average), 64% of sites were nonresponsive to N fertilizer as indicated by no differences in marketable squash yield. In responsive sites, the most economical rate of N (MERN) was between 105 and 129 kg N/ha of N fertilizer, indicating that the Ontario-recommended rate of 110 kg N/ha seems appropriate for responsive sites. At 110 kg N/ha, no yield advantage resulted from using a controlled-release N (CRN) or split-applying ammonium nitrate at preplant and vine elongation at 65 + 45 kg N/ha, respectively, compared with the same amount applied preplant. Apparent N losses (N inputs – N outputs) at harvest were 83 and 29 kg N/ha greater at a fertilizer application rate of 220 kg N/ha than at 0 and 110 kg N/ha, respectively. At 110 kg N/ha, crop removal balance and apparent N loss calculations suggest relatively low risk of N loss from the field during the growing season and after harvest, respectively. However, environmental and economical risks would be minimized if nonresponsive sites could be identified before N fertilizer application.

Agriculture is a fundamental part of a natural legacy sustaining a healthy economy, society, and environment. However, the intensification of agricultural production, similar to other primary industries, often results in the degradation of air, water, and soil resources. The increased pressure to protect consumers and the environment has facilitated the development of new legislation regarding nutrient management and drinking water source protection in Canada and elsewhere (Beegle et al., 2000). The scientific basis behind these regulations, with respect to protecting the environment, has not been rigorously assessed or validated. For instance, Ontario's nutrient management recommendations are based on the premise that the N rate that provides maximum yield is also appropriate from an environmental per-

spective. However, previous production research generally has relied heavily on agronomic and economic objectives with little regard for the environment or nutrient use efficiency (Beegle et al., 2000).

An important sector of the Canadian economy is the production of field vegetables for fresh and processing markets, which in 2007 accounted for nearly \$267 million in farm value in the province of Ontario alone (Mailvaganam, 2008). Vine crops such as cucumbers, squash, pumpkins, and zucchini averaged ≈\$20 million annually in farm gate value in Ontario from 2004 to 2007 (Mailvaganam, 2008). However, over the past 20 years, farm gate value for field vegetables has not increased proportionally to increases in production costs such as fuel, fertilizer, and pesticides (OMAFRA, Ontario Ministry of Agriculture, Food and Rural Affairs, 2008). Thus, growers are seeking methods to minimize fertilizer input costs while maximizing economic returns.

There may be opportunities to lower N input costs in cucurbitaceous crops because excessive N fertility leads to vegetative growth at the expense of fruit yield. Thus, many vine crop growers are cognitive not to overapply N fertilizer. Nevertheless, it is difficult to predict the optimal N rate resulting from variable and unknown weather conditions as well as differences resulting from soil fertility, crop variety,

and previous production practices (Tremblay and Bélec, 2006). When N is applied over the MERN, growers sustain economic losses. In addition, overfertilization may lead to harmful environmental effects (Zebarth et al., 2009). Hochmuth (2003) suggests that optimum N rates for most vegetables are known, but there has been no N fertilizer response study in a temperate climate on processing or fresh market butternut squash. There have been only a few N fertilizer studies on large-fruit cucurbitaceous crops (Bhella and Wilcox, 1989; Dweikat and Kostewicz, 1989; Goreta et al., 2005; Hegde, 1988; Mohammad, 2004a; Zotarelli et al., 2008), and fewer studies have evaluated potential N losses (Mohammad, 2004b; Zotarelli et al., 2008). None of these studies were conducted in climatic or soil conditions similar to those in Ontario. Therefore, there is a need to evaluate butternut squash yield response to N fertilization while evaluating environmental and economic implications.

One possible method to optimize crop yields with less fertilizer may be to split-apply N fertilizer or to use products that alter the release of nitrate (NO_3^-) such as CRN fertilizer containing urease and/or nitrification inhibitors (Guertal, 2000; Wiedenfeld, 1986). The applicability of these methods in cucurbitaceous crops or crops grown without irrigation in a climate where evapotranspiration typically exceeds rainfall during the growing season is unknown. Thus, the suitability of CRN or split N application for squash production in Ontario should be evaluated.

To estimate the potential environmental impact of N fertilization, an N budget or mass balance (inputs versus outputs) approach is needed (Follett, 2001; Vos, 1996). This approach may lead to options for improving N management in crop production systems (Vos, 1996; Zebarth et al., 2009; Zhu et al., 2005). Knowledge of N dynamics and balance calculations is crucial (Vos, 1996) to design legislation that serves both agricultural and environmental interests. Clearly, agronomic, economic, and environmental issues must be addressed properly if progress is to be made with respect to the development of agricultural best management practices that improve the use of applied nutrients by crops and reduce potential environmental contamination. To meet these objectives, an N fertilizer processing butternut squash yield response study was conducted on typical soil types to 1) determine the MERN; 2) evaluate the impact of timing and N source on yield; and 3) estimate a total N balance to assess the potential environmental consequences of N fertilization.

Materials and Methods

Experimental design. In 2004–2007, field experiments on processing butternut squash were conducted at the University of Guelph Ridgetown Campus and at grower sites in southwestern Ontario. The sites were selected to represent soils typical of squash production in Ontario (Table 1). The experimental design

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Table 1. Selected rotation and soil characteristics at 11 experimental sites of processing butternut squash in Ontario, Canada during 2004–2007.

Site ^y	Yr	Previous crop	Sand:silt:clay ^z (%)	OM (%)	pH	Cation exchange capacity (MEQ/100 g)	Preplant nutrients (mg·kg ⁻¹)					
							NO ₃ ⁻ -N	NH ₄ ⁺ -N	Phosphorus	Potassium	Calcium	Magnesium
Harwich ^x	2004	Corn	24:60:16	4.3	7.5	26	45	9.1	33	141	4290	396
Louisville ^x	2004	Soybeans	4:48:48	4.8	7.2	39	27	6.8	33	211	6470	551
Ridgetown	2005	Soybeans	51:33:16	5.3	7.3	55	17	7.3	53	110	4893	203
Fairview	2005	Soybeans	36:56:8	2.2	7.6	36	13	10	47	160	3140	201
Louisville ^x	2005	Winter wheat + manure ^w	19:56:25	3.1	7.6	33	17	8.7	45	184	5868	219
Ridgetown	2006	Soybeans	72:21:7	3.2	6.2	64	6.8	2.8	33	150	1394	72
Fairview	2006	Soybeans	33:53:14	2.7	7.8	30	22	12	19	112	5132	203
Louisville	2006	Corn + manure	21:56:23	2.5	7.6	24	54	13	65	206	5721	276
Ridgetown	2007	Soybeans	51:29:20	4.4	5.6	23	25	4.7	25	103	3164	398
Fairview	2007	Seed corn	18:59:23	3.1	7.8	26	15	1.6	29	156	3810	588
Louisville ^x	2007	Winter wheat	9:57:34	2.5	7.8	30	14	0.8	12	117	4963	398

^zSoil sample depth 15 cm for all parameters except NO₃⁻-N and NH₄⁺-N, which was 30 cm.

^ySites with the same name were in different fields but under similar rotation and production practices.

^xSites where squash yield was responsive to N fertilizer.

^wManure was solid beef manure broadcast incorporated at ≈3 Mg·ha⁻¹ the fall before squash production.

was a randomized complete block with four replications at two to three sites each year. Sites were in different locations each year, but those sites with the same name were under the same production and rotation practices (Table 1). Squash cv. Supreme was seeded between 28 May and 21 June 2004–2007 at 19,700 plants/ha with 1.5 m between plant rows and 0.33 m between plants. Plots were 8 m long and 4.6 m or three rows wide. Ammonium nitrate fertilizer was broadcast by hand and incorporated before planting at 0, 65, 110, 220, and x kg N/ha, where x was 165 kg N/ha in 2004 and 30 kg N/ha in all other years. In 2004 and at Louisville sites, N fertilizer was not incorporated because of constraints of working in large commercial fields. Two additional N treatments were included to compare the relative effects of timing of application and CRN. A split N application of ammonium nitrate at 65 + 45 kg N/ha was applied preplant, as described, and broadcast by hand before vine elongation, which occurred between 28 June and 26 July 2004–2007. A urea-based CRN fertilizer containing the urease inhibitor N-(n-butyl) thiophosphoric triamide and dicyandiamide, a nitrification inhibitor (SuperU®; Agrotain International L.L.C., St. Louis, MO), was preplant broadcast incorporated at 110 kg N/ha. Other than N, all fertilizers were applied based on soil testing and typical Ontario production practices were followed for pest control and other field operations (OMAFRA, Ontario Ministry of Agriculture, Food and Rural Affairs, 2008). Air and soil temperature and precipitation data were collected at all sites, but only data from Ridgetown are presented because the data set was the most complete and representative (Table 2). All sites were within a 20-km radius of Ridgetown.

Soil mineral N and plant total N content were determined for 0, 110, and 220 kg N/ha treatments as well as the split treatment in 2005–2007. These N rates were selected for evaluation because they encompass the range of rates tested and the Ontario-recommended N rate of 65 + 45 kg N/ha (OMAFRA, Ontario Ministry of Agriculture, Food and Rural Affairs, 2008). It was assumed that N variables for all other treatments would be intermediary.

Crop measurements. Over the growing season, squash plants were trained to prevent vines from growing in other plots by moving vines at the plot border toward the center of the plot. Between 12 Sept. and 24 Oct. 2004–2007, the entire plot area was harvested and fruit was sorted into marketable and culls according to Ontario processing industry standards for size and quality (OPVG, Ontario Processing Vegetable Growers, 2007). Harvest area and either fresh fruit or cull weights were used to calculate marketable and total yield, respectively. Optimal N rates for processing butternut squash were determined based on the quadratic N dose–yield response equation and the MERN (Rashid and Voroney, 2005). The MERN values were calculated using the following equation: MERN = [b – (F/P)]/2c where F was fertilizer cost at \$1/kg, P was the mean processing squash selling price of \$98/Mg, and b and c were the linear and quadratic coefficients, respectively, from the quadratic N dose–yield response curve for each site (Rashid and Voroney, 2005).

At harvest, above-ground vegetative biomass (i.e., leaves and vines) was collected from 0.5-m² quadrats and five representative squash fruits were sliced, weighed, and dried at 60 °C for total N analysis. After determining dry weights, a representative sample of dried plant tissue was ground in a Wiley mill through a 2-mm diameter opening mesh screen. Total N content in plant biomass was determined by dry combustion method (McGill and Figueiredo, 2008) using a LECO CN determinator (LECO Corporation, St. Joseph, MI) at an Ontario-certified laboratory (A&L Canada Laboratories Inc., London, Ontario, Canada). Percent total N content data were converted to kg N/ha based on above-ground plant vegetative (leaves and vines) and reproductive tissues dry weights.

Soil mineral nitrogen measurements. Soil inorganic N concentration [NO₃⁻-N and ammonium-N (NH₄⁺-N)] was determined on one composite soil sample taken from at least five 3.5-cm diameter cores (typically seven to 10 cores) to 75- or 90-cm depths from each block before planting (Table 1) and from each plot of selected treatments at the time of

Table 2. Monthly mean air temperature and total rainfall at Ridgetown, Ontario, Canada, in 2004–2007 and the 30-year mean.

Month	2004	2005	2006	2007	30-yr mean
<i>Air temperature (°C)</i>					
May	14.5	11.7	14.2	17.9	13.6
June	18.3	22.1	18.2	21.6	18.8
July	20.4	22.4	21.8	23.6	21.5
Aug.	18.8	21.6	19.8	23.4	20.6
Sept.	17.7	18.6	17.2	18.6	16.8
Oct.	11.5	11.3	12.6	16.9	10.6
Mean	16.9	18.0	16.6	18.9	15.6
<i>Rainfall (mm)</i>					
May	138	36	84	79	77
June	98	29	55	64	82
July	128	64	98	83	93
Aug.	68	40	76	101	105
Sept.	18	81	110	42	93
Oct.	47	11	132	70	55
Total	497	261	554	438	505

split N application and at harvest. In the field, soil cores were divided into 15- or 30-cm increments, homogenized by depth, sealed in plastic bags, and put into a cooler for transport. Samples were frozen at –20 °C, stored, and sent for analysis at an Ontario-certified laboratory (Agri-Food Laboratories Ltd., Guelph, Ontario, Canada).

Soil NO₃⁻-N and NH₄⁺-N were extracted with KCl and quantified colorimetrically (Maynard et al., 2008) with cadmium reduction and the phenate method, respectively, using an auto analyzer (Technicon Auto Analyzer II, Tarrytown, NY). Preplant soil characteristics and bulk density were evaluated according to accredited standards (Gregorich and Carter, 2008) on composite 15-cm depth soil cores sampled from the entire trial area as described by Van Eerd and O'Reilly (2009).

Nitrogen budget. An estimated N budget was developed with soil and plant N data and expressed in kg N/ha. The amount of plant N derived from the soil over the growing season was estimated by the total N accumulated in the above-ground portion of plants grown in the 0 kg N/ha treatment. Plant N content in above-ground plant vegetative and reproductive tissues were presented as crop residue

Table 3. Effect of nitrogen (N) fertilizer on processing butternut squash yield at 11 experimental sites in Ontario, Canada during 2004–2007.

Regression of squash yield response to preplant ammonium nitrate fertilizer					Optimal preplant N rate (kg N/ha)		Squash yield (Mg·ha ⁻¹)			
Site	Yr	Equation	Significance level ^z		MERN ^y	Maximum yield	Zero N	Fertilizer at 110 kg N/ha		
			L	Q				Preplant	Split ^x	CRN ^w
Harwich	2004	y = 25.3 + 0.03N + 0.00004N ²	0.1	0.1	>>220 ^v	>>220	25.3	29.9	27.2	24.5
Louisville	2004	y = 21.2 + 0.06N–0.0003N ²	NS	*	129	155	21.8	24.3	26.5	25.3
Ridgetown	2005	y = 19.5 + 0.011N–0.0001N ²	NS	NS	—	—	18.4	18.3	18.5	17.3
Fairview	2005	y = 35.7 + 0.065N + 0.00011N ²	*	*	N/A ^u	N/A	36.9	28.7	36.2	35.2
Louisville	2005	y = 29.5 + 0.08N–0.0003N ²	NS	0.1	105	123	28.6	31.0	31.3	32.1
Ridgetown	2006	y = 30.9 + 0.032N–0.0001N ²	NS	NS	—	—	31.0	31.5	31.6	30.4
Fairview	2006	y = 28.6 + 0.012N–0.00009N ²	NS	NS	—	—	28.2	26.9	29.9	32.6
Louisville	2006	y = 46.1–0.09N + 0.0004N ²	NS	0.1	N/A	—	47.5	43.6	39.9	43.8
Ridgetown	2007	y = 25.2 + 0.018N–0.0001N ²	NS	NS	—	—	23.8	24.2	23.0	24.7
Fairview	2007	y = 36.8–0.12N + 0.0003N ²	*	**	N/A	N/A	35.4	27.5	29.7	33.6
Louisville	2007	y = 24.8 + 0.080N–0.0003N ²	NS	*	115	123	25.5	26.6	25.4	27.0

^zL, linear; Q, quadratic; ns, 0.1, *, **, ***non-significant or significant at $P \leq 0.1, 0.05, 0.01$, or 0.001 , respectively ($n = 20$). Non-significance indicates that the most economical rate of N or maximum yield was predicted to be zero N fertilizer.

^yMost economic rate of N (Rashid and Voroney, 2005) $MERN = [b - (F/P)]/2c$; where F was fertilizer cost at \$1/kg, P was the mean processing squash selling price of \$98/Mg, and b and c were the linear and quadratic coefficients, respectively, from the quadratic N yield response curve for each site.

^xSplit treatment was ammonium nitrate fertilizer broadcast-applied preplant and in-season before vine elongation at 65 and 45 kg N/ha, respectively.

^wControlled-released nitrogen (CRN) fertilizer was a urea-based fertilizer containing the urease inhibitor N-(n-butyl) thiophosphoric triamide and dicyandiamide, a nitrification inhibitor, was preplant broadcast at 110 kg N/ha.

^v>>220 positive linear or curvilinear response indicates that optimal N rates were higher than rates tested.

^uN/A indicates a significant negative linear or convex quadratic curve; therefore, the MERN and maximum yield optimal N rates were predicted as zero N fertilizer.

(i.e., N remaining in the field) and crop removal (i.e., N removed from the field as marketable fruit), respectively. Total N input was the sum of soil-derived plant N and N fertilizer applied. Soil mineral N content as NO_3^- -N and NH_4^+ -N was to the 30-cm depth. Soil mineral N at harvest and crop residue and crop removal N contents were summed together to determine total N output. Apparent N loss or the quantity of N that could not be accounted for, and therefore presumably lost over the growing season, was the difference between N input and output. Crop removal balance was the difference between the quantity of fertilizer N applied and crop N removal.

Statistical analyses. To maintain a balanced data set for analyses, data from 2004 were analyzed separately from those of all other years because only one location in 2004 had a complete data set for yield, soil, and plant variables. All data were subjected to analysis of variance using Type I sums of squares in PROC GLM model (SAS Version 9.1; SAS Institute Inc., Cary, NC) to determine the effect of site, N rate, year, and their interactions on the parameter of interest. The N fertilizer rate response for yield, plant N concentration and content, and soil N content was fitted to linear and quadratic models using PROC REG model (SAS Version 9.1). Homogeneity and normality were evaluated using residual plots and the Shapiro-Wilk normality test. Data were pooled if there was no location-by-year interaction. Means separation was determined using Tukey-Kramer multiple comparison procedure. The Type I error rate (α) was set at 0.05.

Results and Discussion

The growing season was cool with sufficient rainfall in 2004, warm and dry in 2005 and 2007, and nearly average air temperature and rainfall during most of the 2006 growing

Fig. 1. In 2004–2007, processing butternut squash plant nitrogen (N) accumulation at harvest expressed as percent nitrogen concentration (A) and on a dry weight basis (B) in response to preplant broadcast ammonium nitrate. The split treatment was two applications at 65 and 45 kg N/ha applied preplant and before vine elongation, respectively. Data averaged across site years with bars representing SE of means. NS, *, ***Nonsignificant or significant at $P \leq 0.05$ or 0.001 , respectively ($n = 126$).

season, but the fall had higher precipitation than climatic norms (Table 2). As is typical of the region, processing butternut squash was not irrigated.

Squash yield response to nitrogen fertilizer. Mean total and marketable yield over the 4 years was 31.5 and 29.2 Mg·ha⁻¹. Yields were representative of squash production in the region. For instance, in Ontario during 2004–2007, typical grower processing squash yield was 34 Mg·ha⁻¹, and local food processors estimate manufacturing production on a average grower yield of 27 Mg·ha⁻¹ (E.C. Roddy, personal communication).

In only four of the 11 sites tested was there a significant positive yield response to N fertilizer (Table 3). Another three fields had a significant correlation between marketable yield and N fertilizer, but the quadratic response was either convex or the linear response was negative indicating a MERN of 0 kg N/ha. Thus, in seven of 11 sites, squash yield was nonresponsive to N fertilizer. Pumpkin (*Cucurbita pepo* L.) yield did not respond to increasing N fertilizer rates (Reiners and Riggs, 1997), but it is not known if these sites were nonresponsive to N fertilizer because a zero N fertilizer treatment was not included. When grown on sandy soil and/or under irrigation or fertigation, other studies have shown a positive yield response to N rates in squash (Mohammad, 2004a), zucchini squash (*Cucurbita pepo* var. *melo* Alef.) (Dweikat and Kostewicz, 1989; Zotarelli et al., 2008), muskmelon (*Cucumis melo* L.) (Bhella and Wilcox, 1989), and watermelon (*Citrullus lanatus* Matsum & Nakai) (Goreta et al., 2005).

At all sites, there was no difference in squash yield when 110 kg N/ha was preplant or split-applied or when the source was ammonium nitrate or CRN (Table 3). Likewise, with potatoes (*Solanum tuberosum* L.) and peppers (*Capsicum annuum* L.), there was no consistent yield advantage between preplant CRN and split application of N fertilizer (Guertal, 2000; Hendrickson et al., 1978).

Other than the Harwich site in 2004, which had a linear positive N yield response, all other responsive sites had MERN values between 105 and 129 kg N/ha for processing butternut squash (Table 3). Maximum yields were achieved at N rates 7% to 20% higher than MERN values. Although MERN or similar economic N evaluations have been used in field corn (*Zea mays* L.) (Rashid and Voroney, 2005) and broccoli (*Brassica oleracea* L.) (Bakker et al., 2009a), no such analyses have been conducted in cucurbitaceous crops other than machine-harvested cucumbers by Van Eerd and O'Reilly (2009). In horticultural production, MERN and the N rate for maximum yield are often similar (Bakker et al., 2009a) as a result of the relative high selling price of the crop compared with N fertilizer costs.

Ontario's recommendation of 110 kg N/ha for squash production (OMAFRA, Ontario Ministry of Agriculture, Food and Rural Affairs, 2008) is appropriate for responsive sites. However, there was no squash yield

response to N fertilizer in seven of 11 trials; hence, in 64% of the sites, the recommended rate was too high, ineffective, and costly. Real economical and environmental savings could be realized if nonresponsive fields and/or weather conditions likely to result in no yield response could be identified before N fertilizer application (Tremblay and Bélec, 2006; Zebarth et al., 2009). Without this knowledge, growers are likely to apply too much fertilizer to minimize the perceived risks of lower yield with too little N fertilizer (Hochmuth, 2003).

Plant nitrogen. For all plant N variables, the only significant interaction was site by year. There was a positive linear and quadratic relationship between N fertilizer rate and percent N concentration in squash vegetative and

reproductive tissue, respectively (Fig. 1A). Fruit N content was ≈111 kg N/ha, which was similar to values observed in zucchini squash (Zotarelli et al., 2008). There was a significant positive linear relationship of plant N content, expressed on a dry weight/ha basis, with total above-ground tissue and vegetative tissue but not in reproductive tissues (Fig. 1B). Clough et al. (1992) similarly observed differences in N content in vegetative yellow squash tissue, but reproductive tissue did not respond to N fertilization. Overall, these observed relationships of plant N and N fertilizer applied were consistent with results in cucurbitaceous crops (Mohammad, 2004a; Van Eerd and O'Reilly, 2009) and other vegetable crops (Bakker et al., 2009b; Van Eerd, 2007).

Fig. 2. In 2006 (A) and 2007 (B) at Ridgetown, Fairview, and Louisville locations, the effect of preplant ammonium nitrate fertilizer against soil nitrate–nitrogen concentration (mg·kg⁻¹) in 0- to 30-cm depth taken at the time of split nitrogen fertilizer application, ≈1 month after processing butternut squash planting. Bars represent SE of means. NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively ($n \geq 10$).

The partitioning of dry matter or N content between vegetative and reproductive biomass can be characterized as the harvest index and harvest N index, respectively. Mean harvest index and harvest N index were 60.0% and 64.8% at 110 kg N/ha, respectively, and there were no differences in the indices between preplant and split fertilizer applications. There was a negative linear relationship with the quantity of N fertilizer applied and both harvest index and harvest N index. The regression equations for harvest index and harvest N index (y variable) were $y = 60.3 - 0.022x$ ($r^2 = 0.9822$) and $y = 65.8 - 0.032x$ ($r^2 = 0.9859$), respectively, where x = N fertilizer rate. Zucchini squash grown in sand culture displayed a convex quadratic response of harvest index to N supply (Huett and Dettmann, 1991). In contrast, from 2004–2006 in Ontario, N fertilization had no effect on harvest index or harvest N index of machine-harvested cucumbers (Van Eerd and O'Reilly, 2009). The observed differences between machine-harvested cucumbers and squash grown in the same climate and soil conditions may be the result of differences in season length (6 weeks versus greater than 4 months, respectively), population density (131,000 versus 19,700 plants/ha, respectively), and physiological maturity at harvest (reproductive versus plant senescence, respectively). Most likely, stage of development at harvest was the strongest influencer because the partitioning of resources from vegetative to reproductive tissues would be more pronounced in squash compared with machine-harvested cucumber. In peppers, harvest index and harvest N index were not influenced by quantity or timing of N applications (Van Eerd, 2007).

Soil mineral nitrogen. At the time of planting (i.e., end of May to mid-June), mean soil NO_3^- -N in the 0- to 30-cm depth was 23.4 $\text{mg}\cdot\text{kg}^{-1}$ (Table 1), which is typical for the time of year in warm, productive soils. Similar soil mineral N content was observed by other researchers in Ontario (Bakker et al., 2009b; Rashid and Voroney, 2005). At all sites except for Ridgetown in 2007, there was a significant positive linear relationship between N fertilizer and soil NO_3^- -N concentration at the time of in-season fertilization (Fig. 2). Although there was a significant positive correlation (Fig. 3), only 20% and 7.8% of the variability in squash marketable yield could be explained by soil NO_3^- -N at the time of in-season fertilization at 0- to 30-cm depth in 2006 and 2007, respectively. Thus, soil NO_3^- -N (Fig. 3) and soil mineral N (data not shown) at the time of in-season fertilization does not appear to be an adequate indicator of the need for N fertilization of squash grown in Ontario. In contrast, with soil NO_3^- -N concentrations between 1 and 24 $\text{mg}\cdot\text{kg}^{-1}$, there was good agreement between preplant and in-season NO_3^- -N and between field corn relative yield and the MERN for field corn in Ontario (Rashid and Voroney, 2005). The applicability of detecting N fertilizer nonresponsive sites in corn based on preplant or in-season soil NO_3^- -N level and

Fig. 3. In 2006 (A) and 2007 (B) at three locations each year, the relationship of processing butternut squash marketable yield and soil nitrate–nitrogen concentration ($\text{mg}\cdot\text{kg}^{-1}$) in 0- to 30-cm depth taken at the time of in-season nitrogen fertilizer application, ≈ 1 month after squash planting. +,***Significant at $P \leq 0.1$ or 0.01, respectively ($n \geq 36$).

the ability to estimate N responsiveness in any given year has been debated (Tremblay and Bélec, 2006; Zebarth et al., 2009).

At harvest, soil mineral N was affected significantly by location, N rate, and depth but not by year and the only significant interactions were year by N rate and year by depth. At harvest, there was a significant positive linear relationship between N fertilizer and soil mineral N in all years (Fig. 4A) and in all soil depths (Fig. 4B). This relationship was consistent with results observed in cucurbits (Mohammad, 2004a; Van Eerd and O'Reilly, 2009) and corn (Halvorson et al., 2005). On average, there was 49 and 152 kg N/ha more soil mineral N in 0- to 90-cm depth at squash harvest with the 110 and 220 kg N/ha treatments, respectively, than with the non-fertilized control treatment. This result suggests inefficient use of N fertilizer and that considerable quantities of soil mineral N would be susceptible for loss from the field after squash

harvest, particularly in the 220 kg N/ha treatment.

In all years except 2005, soil mineral N at harvest was not different if 110 kg N/ha was preplant- or split-applied (Fig. 4). In 2005, soil mineral N at harvest was lower with the split application compared with preplant N application. This result was unexpected because 2005 was warmer and drier than climatic norms, suggesting little opportunity for N loss through denitrification or leaching. Overall, there was little advantage to split-applying N fertilizer in N fertilizer-responsive and -nonresponsive sites. Similarly, in machine-harvested cucumbers (Van Eerd and O'Reilly, 2009) and broccoli (Bakker et al., 2009b; Bowen et al., 1999), there were no differences in soil mineral N at harvest when N was applied preplant or in season.

Estimated nitrogen budget. All data were pooled over site years because there were no two-way or three-way interactions for all N

Fig. 4. Relationship of soil mineral nitrogen concentrations ($\text{mg}\cdot\text{kg}^{-1}$) at processing butternut squash harvest against preplant broadcast ammonium nitrate fertilizer. Data averaged across location and depth in 2005–2007 (A) and location and years for each sampling depth: 0–30, 30–60, and 60–90 cm (B). The split treatment was two applications at 65 and 45 kg N/ha applied preplant and before vine elongation, respectively. Bars represent SE of means. **, ***Significant at $P \leq 0.01$ or 0.001, respectively ($n = 108$).

Table 4. Estimated nitrogen (N) balance sheet for processing butternut squash at nine experimental sites in Ontario, Canada during 2005–2007.^z

N balance parameters		N treatments				P value
		0	110	220	Split ^y	
		(kg N/ha)				
N inputs						
N fertilizer		0	110	220	110	
Soil-derived plant N	From 0 N treatment	156	156	156	156	
Total input		156	266	376	266	
N outputs						
Crop N removal	N in harvested fruit	105 a	114 a	111 a	116 a	0.4236
Crop residue N	N in vegetative tissues	51 a	65 b	75 c	63 b	0.0004
Soil mineral N	0- to 30-cm soil depth	62 a	95 b	169 c	77 ab	<0.0001
Total output		218 a	274 b	355 c	256 b	<0.0001
N balance						
Apparent N loss	Inputs – outputs	–62 a	–8 b	21 c	10 bc	<0.0001
Crop removal balance	Fertilizer – crop removal	–105 a	–4 b	109 c	–6 b	<0.0001

^zData were means with SE and four replications at each site ($n = 36$). Treatment means within rows followed by different letters were significantly different ($P \leq 0.05$) based on Tukey-Kramer multiple range test.

^ySplit treatment was broadcast ammonium nitrate applied preplant and in-season before vine elongation at 65 and 45 kg N/ha, respectively.

budget variables, except soil mineral N in the 0- to 30-cm depth at harvest. Nitrogen treatment had a significant effect on all N balance variables except crop N removal (Table 4; Fig. 1B) where N budget variables displayed a $0 < 110 < 220$ kg N/ha trend (Table 4). There were no differences in N balance variables between 110 kg N/ha preplant and split treatments (Table 4). Thus, the value of split applying N at 110 kg N/ha in squash is questionable considering the lack of effect on N dynamics, the lack of yield advantage, and the increased time and cost commitments involved.

The N inputs for the zero N treatment and the highest N rate tested were 156 and 376 kg N/ha, respectively (Table 4). Nitrogen outputs (the sum of plant N in above-ground vegetative and reproductive tissues and soil mineral N to the 30-cm depth at harvest) were 218 to 355 kg N/ha when N fertilizer was applied at 0 to 220 kg N/ha, respectively. These input and output values were similar to those found in machine-harvested cucumber (Van Eerd and O'Reilly, 2009) and broccoli (Bakker et al., 2009b) grown in Ontario under similar N fertilizer rates.

Nitrogen balance equations provide an indication of potential environmental risk. Apparent N loss values were quite low for all treatments at 21 kg N/ha or less (Table 4). Thus, during the squash season, there was relatively low risk of N loss from the agroecosystem. This result was similar to N budget estimates in vegetable production in Ontario (Bakker et al., 2009b; Van Eerd and O'Reilly, 2009).

Crop removal balance (Table 4) is a component of the N index within Ontario's nutrient management plan, which has a crop removal balance of 35 kg N/ha as a decision point to mitigate N loss by implementing alternative management practices such as reducing N rates and/or planting a cover crop. Fertilizing squash at the MERN or 110 kg N/ha, even in nonresponsive sites, did not exceed the decision point of the N index (Table 4). In contrast, when 220 kg N/ha was applied, crop removal balance was 109 kg N/ha, which represents significant environmental risk. Crop removal balance at all N rates was much lower in squash than in machine-harvested cucumber grown in Ontario in 2004–2006 (Van Eerd and O'Reilly, 2009). The difference is likely the result of timing of harvest at physiological maturity in squash compared with during reproductive growth in machine-harvested cucumbers. Broccoli (Bakker et al., 2009b), which is harvested before crop maturity, had high crop removal balance values similar to machine-harvested cucumbers (Van Eerd and O'Reilly, 2009), indicating greater risk of N loss from the field than observed in processing squash.

Significant quantities, between 62 and 169 kg N/ha, of soil mineral N exist at squash harvest (Table 4), but it is critical to compare values to zero N control treatments when conducting N budget research. Approximately 15 to 107 kg N/ha more soil mineral N was in the 0- to 30-cm depth at harvest

when 110 or 220 kg N/ha of N fertilizer was applied, respectively, compared with the non-fertilized control treatment. Thus, the relative risk of fertilizing at 110 kg N/ha was considerably lower than applying twice as much N fertilizer. Although microbial immobilization is possible, it is assumed that the majority of soil nitrate remaining in the field at squash harvest would be lost through leaching or denitrification over the non-cropping season as a result of significant precipitation (30-year average of ≈ 80 mm/month). With processing butternut squash harvest typically in October, there is little opportunity to plant a cover crop to recover residual N and minimize N losses.

An application rate of 220 kg N/ha is environmentally and economically undesirable as a result of high soil mineral N level at harvest, which was ≈ 74 kg N/ha more than plots receiving 110 kg N/ha. Moreover, compared with 0 or 110 kg N/ha treatments, applying 220 kg N/ha of N fertilizer only minimally increased plant N content and results in unnecessary higher input costs with no yield advantage. These results were similar to other cucurbitaceous crops (Mohammad, 2004b; Van Eerd and O'Reilly, 2009; Zotarelli et al., 2008). Likewise, in The Netherlands, applying N fertilizer at 15% above standard rates was not advised as a result of limited yield returns and increased potential for N loss from the agroecosystem (Vos, 1996).

In responsive sites, the Ontario-recommended rate of 110 kg N/ha was near MERN values and the amount of N fertilizer needed to maximize yield. However, marketable and total processing butternut squash yield was nonresponsive to N fertilizer in 64% of sites. In both responsive and non-responsive sites, applying 110 kg N/ha did not invoke inappropriate environmental risk when compared with the zero N control treatment based on the N balance data (Table 4). However, environmental and economical risks would be reduced if nonresponsive sites could be identified before fertilizer application.

Weather, soil texture and chemical properties, and production practices such as crop rotation and manure application are potential contributors to N responsiveness. It is difficult to identify responsive sites in the spring when N fertilizers are typically applied. Unfortunately, preplant and in-season soil N tests were not predictive of squash-responsive field sites. Although fertilizing for maximum yield has been suggested as an economically and environmentally acceptable practice (Follett, 2001), without the ability to predict seasonal conditions and responsiveness of the site, fertilizing at the MERN is considerably difficult (Tremblay and Bélec, 2006; Zebarth et al., 2009).

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