Adapting Nitrogen Fertilization to Unpredictable Seasonal Conditions with the Least Impact on the Environment

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ADDITIONAL INDEX WORDS. **chlorophyll meter, SPAD, Dualex, Greenseeker, saturation index, saturated reference plot, water quality, runoff, leaching**

SUMMARY. **Weather is the primary driver of both plant growth and soil conditions. As a consequence of unpredictable weather effects on crop requirements, more inputs are being applied as an insurance policy. Best management practices (BMPs) are therefore about using minimal input for maximal return in a context of unpredictable weather events. This paper proposes a set of complementary actions and tools as BMP for nitrogen (N) fertilization of vegetable crops: 1) planning from an N budget, 2) reference plot establishment, and 3) crop sensing prior to in-season N application based on a saturation index related to N requirement.**

Over the recent years, protection of water and air quality has increased in importance. In Canada, the Agricultural Policy Framework (Agriculture and Agri-Food Canada, 2005) sets a number of goals for environmental protection: reduce water contamination from nutrients, pathogens, and pesticides; reduce agricultural risks to soil health and reduce soil erosion; limit particulate emissions, odors, and greenhouse gases; ensure compatibility between biodiversity and agriculture. These goals will be achieved in part by the implementation of BMPs that will reduce use of pesticides and fertilizers. For growers, the challenge of using minimal input for maximal return in a context of largely unpredictable seasonal weather conditions is considerable. Nitrogen management is a good example of the challenges facing vegetable growers. Nitrogen supply is important to secure an abundant harvest of good quality horticultural products. Unfortunately, nitrate-N (NO_3-N) from agricultural operations has been traced as a contaminant of both aquatic ecosystems and drinkable water supply. Dinitrogen oxide (N_2O) is also known as a "greenhouse gas" potentially issued from non-optimal fertilization practices. BMP of N fertilization should aim at balancing and timing application rate to meet crop needs, protecting the nutrients from losses, by using professional judgment and a group of approaches such as water, irrigation, fertilizer and manure management, soil testing, spreader calibration and application restrictions, cover crops, conservation tillage, and the presence of buffer zones close to sensitive areas. Nutrient management BMPs are available from institutions which are regional in scope hence connecting well with the realities they target in their recommendations. For field crops in Canada, BMPs are normally obtained from provincial governments or recognized groups such as Certified Crop Advisors (Prairie Certified Crop Adviser Board, 2004) or Production Clubs (Clubs conseils en agroenvironnement, 2006) hiring agronomists (Ordre des agronomes du Québec, 2005).

According to Cassman et al. (2003), the key challenge for higher-yielding crops is to meet the greater N requirements while concurrently increasing N use efficiency and reducing the reactive N load attributable to agriculture. There is no contradiction in trying to achieve a high yield while preserving the environment since lower crop yields leave more N in the soil or crop residues after harvest (Vagstad et al., 1997). Residual soil mineral N after harvest (as an indicator for potential nitrate leaching during fall and winter) increases also substantially at N rates exceeding optimal N rate (Olfs et al., 2005; Vagstad et al., 1997). Because of the intensive nature of their production, vegetable crops are more at risk of leading to nutrient contamination of the environment. In a survey of mineral N content of soils used for vegetable production in Quebec, Tremblay and Beaudet (2004) found maximum levels of 202 (Fig. 1A) and 519 kg·ha^{-1} NO_3-N (Fig. 1B) in spring and fall samples, respectively, in the 0- to 30-cm layer. Crops particularly prone to increase NO_3-N over a growing season were broccoli (*Brassica oleracea* var. *italica*), carrot (*Daucus carota* ssp. *sativus*), sweet corn (*Zea mays* var. *rugosa*), and sweet pepper (*Capsicum annuum*). Except for pickles (*Cucumis sativus*) and tomato (*Lycopersicon esculentum*), all crops were subjected to N applications (Table 1) on average higher than the current official recommendations for vegetables (Centre de référence en agriculture et agroalimentaire du Québec, 2003). These, in spite of a recent re-edition, have not changed for decades. Carrot, sweet pepper, cauliflower (*B. oleracea* var. *botrytis*), cabbage (*B. oleracea* var. *capitata*), and broccoli were the crops with the most discrepancies between growers practices and recommendations. It is not possible to conclude which growers or recommendations are wrong. An initiative is currently going on in Quebec to establish new guidelines based on trial results, recommendations of neighboring provinces and states, and environmental risks. Based on the residual NO_3-N concentration left in the soil at fall, Tremblay and Beaudet (2004) stated that carrot, cauliflower, broccoli, sweet corn, and sweet pepper N fertilizer recommendations in Quebec should be revisited in priority.

Vegetable crops are so diverse that regionally fit and documented BMPs are not always available. In a perfect world, BMPs for vegetable crops would be studied and calibrated by species over

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Acknowledgments: We want to thank the crop nutrition and management team at HRDC, synAgri, Yara, the staff at the L'Acadie experimental farm, Stéphanie Jacquet, the agronomists who specialized in horticulture at MAPAQ and Production clubs.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha^{-1}	0.8922

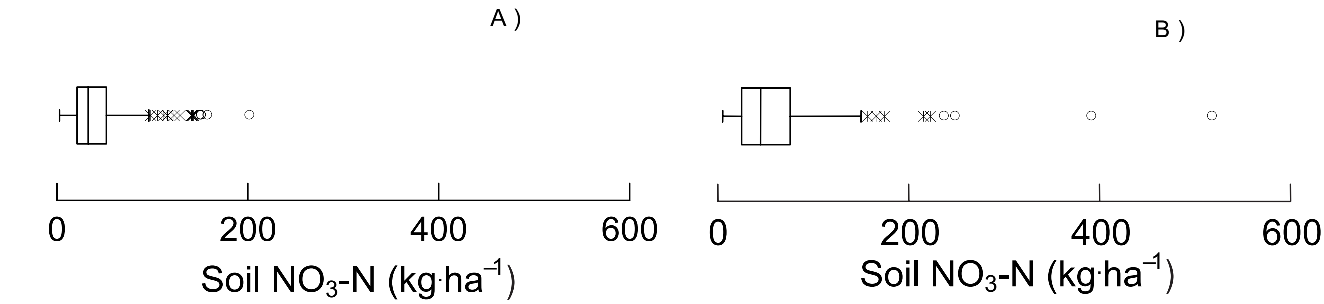

Fig. 1. Box plots of nitrate-nitrogen (NO_3-N) in Quebec's mineral soils sampled [0–30 cm (11.8 inches)] (A) prior to crop establishment (Spring 2001, 2002, or 2003; total of 344 fields) or (B) after harvest (Fall 2001 and 2002; total of 170 fields). The center vertical line marks the median of the sample. The length of each box shows the range within which the central 50% of the values fall, with the box edges at the first and the third quartiles. Asterisks and empty circles show extreme values (1 kg·ha^{-1} = 0.8922 lb/acre).

a number of years and field conditions. Where the critical mass of production exists over a localized set of growing conditions, such personalized BMPs can be researched and implemented. However, given the wide variety of vegetable crops and production as well as the reduction in public funding for applied research, realistic alternatives are found in generic approaches to nutrient requirement accounting and diagnosis. Despite their limitations, the implementation of generic concepts is often sufficient to challenge and force adjustments to practices only inherited from the past. Moreover, by acknowledging their strengths and weaknesses, some concepts can be used in association. This is the case, in our opinion, of two generic components of BMP for N management of vegetables that can be summarized in the words "plan" and "sense."

Plan prior to crop establishment

Nitrogen budget calculation is a BMP that can balance N supply and use by all components of the plant–soil system. Tremblay et al. (2001) have proposed a guide to implement the budget approach to the planning of N fertilization of vegetable crops in Canada. This calculation consists of the estimation of all significant inputs and outputs of N in the soil–plant system; the difference of which leads to the actual need in fertilizer N. Soil analysis, soil type, crop, and amendments history are information required for the development of such N budget calculation. A proper evaluation of these natural N pools is central to the evaluation of mineral N contributions (Dharmakeerthi et al., 2005) and leaching risks (Vagstad et al., 1997). Where needed, more adapted regional estimates of inputs or outputs can be obtained from extension groups, dealers, or provincial advisors. Computerized versions of N budget planning are available in the form of decision-making systems for vegetables (Goodlass et al., 1997), such as WELL-N (Rahn et al., 1996) or equivalent ones throughout Europe (Rahn et al., 1999), also for agronomic crops (Meynard et al., 2002). Using the N-Expert system developed in Germany, Chen et al. (2005) have generally reported no significant yield reduction as compared to conventional practice but a significant decrease in residual N_{min} (NO_3-N + ammonium-N) at harvest. For crops with limited N requirements (N uptake for average yield lower than 150 kg·ha^{-1}; Tremblay et al., 2001), there is normally no N application performed after sowing or planting. This planning operation constitutes then the only opportunity for adjusting N fertilization to fit the needs of the crops with minimum losses to the environment. For crops with higher N requirements, N application is often split in one or several applications during crop growth, giving the opportunity to adjust for seasonal conditions.

Acknowledge the need for adjustments within season

Seasonal fluctuations of plant available N are particularly spectacular in tropical conditions (Wong and Nortcliff, 1995). In temperate conditions as well, N production and losses can be significant. Ammonia losses after application of organic manures might often exceed 50% of the total N content, depending on the type of manure, the application technique, and seasonal conditions (Olfs et al., 2005). The amount of plant available N at a given growth stage and the rate at which N accumulates are heavily dependent on weather (Dharmakeerthi et al., 2005). Vagstad et al. (1997) as well as Schweigert et al. (2004)

Table 1. Nitrogen (N) applied from both mineral and organic sources in commercial vegetable fields surveyed in Quebec in 2001–03.

	Fields	N				
	(no.)	Minimum	Maximum	Median	Mean	Recommended[z]
		(kg·ha^{-1})[y]				
Broccoli	19	75	256	135	148	135
Cabbage	6	113	178	156	150	135
Carrot	10	77	238	100	146	80
Cauliflower	17	81	504	124	175	135
Pickles	15	66	233	105	113	115
Pumpkin	17	63	312	120	121	115
Sweet corn	16	25	222	115	121	80–150
Sweet pepper	18	104	285	178	183	140
Tomato	14	40	244	94	104	135

[z]Official recommendation by the Centre de référence en agriculture et agroalimentaire du Québec (2003).
[y]1 kg·ha^{-1} = 0.8922 lb/acre.

reported on the determinant impact of temperature and precipitation on soil mineral N content. One of the limitations of the budget approach is the difficulty of properly estimating N credits and debits because fertilizer needs greatly vary according to season (Beauchamp, 2004; Kay et al., 2004). Van Es and Melkonian (2004) state that field corn (*Zea mays*) growers do not appreciate temporal processes determining seasonal N needs and use "insurance fertilizer" based on the worst-case scenario. Unfortunately, most of the time, this extra amount is not used by the crop and contributes to environmental problems.

According to Olfs et al. (2005), N-recommendation programs based on yield goals are inappropriate because all the relevant interactions of weather with crop growth, N-turnover processes in the soil, and losses from the soil–plant system are not considered. Beauchamp (2004) states that the inorganic fraction of N coming from manure may "disappear" immediately following manure application only to "reappear" slowly later. This and other uncertainties related to soil characteristics and conditions make sufficiently accurate predictions of manure N availability an enigma. Best N management practice needs to consider the soil and crop status at each relevant point in time during the vegetation period to readjust the N-application strategy (Olfs et al., 2005). According to Van Es and Melkonian (2004), early seasonal conditions are the ones critical to determine fertilizer N needs. For field corn in New York state, this occurs before late June, when the crop enters its rapid growth phase. Prior to this time, the accumulated N (often amounting to 50–80 $kg \cdot ha^{-1}$) is highly susceptible to leaching and denitrification when heavy rainfall occurs. In summer, evapotranspiration rates are very high and soil water saturation rarely occurs.

Sense the soil and the crop

Average data are unable to cope with the variability of soil N supply (Goodlass et al., 1997). Recommendation systems actually measuring soil mineral N contents are the most accurate. Quick soil extraction (Hartz, 1994) and determination techniques (Sims et al., 1995) exist to provide assessment of actual NO_3-N content of fields. When this information is

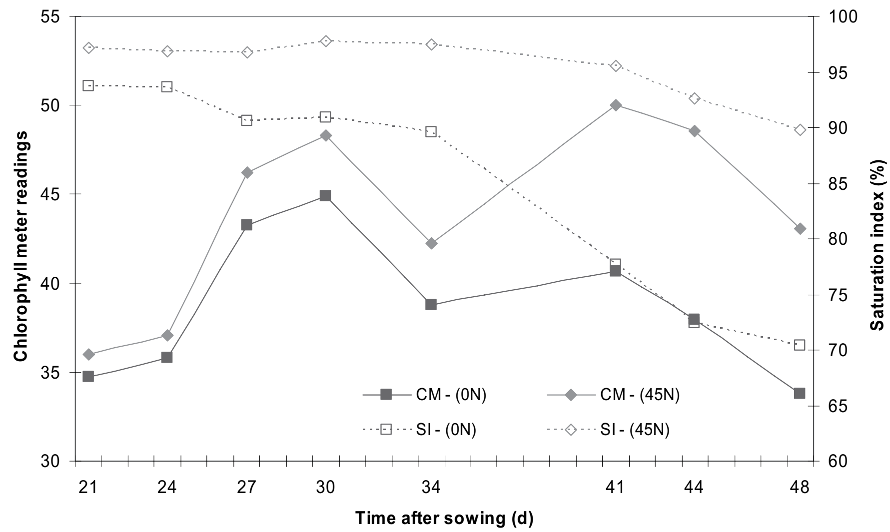

Fig. 2. Chlorophyll-meter (CM) readings and saturation index (SI) of field corn with 0 (0 N) or 45 $kg \cdot ha^{-1}$ (45 N) of nitrogen (N) in the starter fertilizer as a function of time after sowing. The SI is calculated by dividing chlorophyll-meter readings by those obtained on well-fertilized reference plots which received a total of 225 $kg \cdot ha^{-1}$ of N at sowing (1 $kg \cdot ha^{-1}$ = 0.8922 lb/acre).

obtained prior to crop establishment it can be used as a measurement of one component of the available-N pool in the budget, the NO_3-N content. Depending on field characteristics and history, this pool may be significant (Fig. 1A). Later in the season, however, weather conditions may have greatly influenced soil N mineralization and losses. At this point, mineral NO_3-N content assessment can be used to monitor this part of the pool again in order to make adjustments to fertilization (Lorenz et al., 1989). Alternatively, such results can be used as a threshold to trigger N fertilization in a presidedress testing (PSNT) format (Hartz et al., 2000; Heckman, 2002; Heckman et al., 2002; Krusekopf et al., 2002), with positive effects on N use efficiency and reduction of N losses (Breschini and Hartz, 2002). However, soil tests have their shortcomings (short timing between soil testing and fertilizer application, higher labor requirements, and generally high prediction errors), which limit the adoption of this method by farmers (Van Es and Melkonian, 2004).

Alternatively to soil, measurements of the crop itself can be used as an indicator of its N requirements (Schroder et al., 2000). Although several indicators, such as sap tests, can be used, handheld chlorophyll meters are particularly well suited for that purpose (Westerveld et al., 2004). Handheld, tractor-based, aerial or satellite imagery are all platforms potentially usable to derive chlorophyll-based information. Sensing a crop for nitrogen (N) status is also possible with other instruments (Tremblay, 2004) including the Dualex (FORCE-A, Orsay, France), which provides information on the polyphenolic status of the crop (Goulas et al., 2004). The calibration of chlorophyll meter measurements with N fertilizer needs has always been difficult because of the wide variations in values of leaf chlorophyll estimation due to soil, water supply, growing stages, sampling procedures, cultivar and seasonal effects. Hence, the observance of a strict sampling protocol is required (Olfs et al., 2005). Absolute recommendation schemes can be derived from field trials (e.g., 100 trials used in Germany to derive variety-specific correction factors for chlorophyll readings; Olfs et al., 2005) but an alternative is the establishment of overfertilized reference plots that integrate at least in part the confounding effects of factors other than N status (location, cultivars, dates, etc.) (Raun et al., 2005; Tremblay, 2004). The reference plot approach has been suggested as a solution to the variation of absolute diagnostic values (Fox et al., 2001; Peterson et al., 1993; Schroder et al., 2000). According to this approach, plots (limited in size) receiving extra amount of N fertilizer at sowing constitute an internal standard against which measurements taken in the rest of the field can be compared in the form of a ratio called saturation index (SI). The lower the saturation index, the higher is the discrepancy between non N-deficient plants and the rest of the field, and the more N is required to complete the growing season. The reference plot is the most efficient way of relating crop diagnosis to actual in-season fertilizer recommendation. By using reference plots, virtually all the sources of variations hampering the use of diagnostic-based fertilization systems are eliminated. Figure 2 compares raw chlorophyll meter readings to the saturation index over time. On day 34, the operator probably selected a different leaf or section of the leaf that demonstrated much lower chlorophyll content, and the raw readings showed an unexplained drop detracting from the general trend. Should only the data on this particular day be used to decide how much N should be applied, the raw reading would have led to amounts way beyond what the saturation index would have likely suggested. This illustrates that saturation index actually nullifies the factors affecting the instrument readings, but the N status. The saturation index constitutes an important improvement in the reliability of crop N diagnosis in commercial conditions. The relative status of the crops to be fertilized as compared to a well-fertilized reference plot has been shown to be a good indicator of the potential effect of supplemental N application in a given season and location. The real challenge of plant-based recommendation methods is to translate the result obtained into actual fertilizer recommendation (Olfs et al., 2005). Calibration algorithms based on N-response trials and saturation index can be used.

The Canadian Fertilizer Institute summarizes BMP for fertilizer management by the formula "right rate, right time, right place." According to Olfs et al. (2005), optimal N rate varies considerably between years and fields, and is not related to yield. The main reason for the variability among years is the changing and unpredictable weather, while the differences among and within fields are related to soil conditions. It is desirable to delay the decision on the total amount of N required as long as reasonable because it allows farmers to adapt the N application to the actual growing conditions. The BMP package consisting of 1) an appropriate planning through N budget, 2) reference plot establishment, and 3) crop sensing prior to in-season N application constitutes a sound strategy to get the most out of unpredictable seasonal conditions with the least impact on the environment. Applying this strategy, the use of "insurance fertilizer" will be gradually phased out to a large extent as growers gain confidence in their control on the N supplied to, and needed by the crop during a given growing season.

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