Opportunities to reduce nitrous oxide emissions from horticultural production systems in Canada1

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REVIEW

Opportunities to reduce nitrous oxide emissions from horticultural production systems in Canada[1]

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Abstract: Horticultural systems, specifically vegetable production systems, are considered intensive agricultural systems as they are characterized by high nitrogen (N) fertilizer application rate, frequent tillage, and irrigation operations. Accordingly, horticultural production in temperate climates is prone to N losses — mainly during post-harvest (during fall and winter) or pre-plant (spring) periods — such as N_2O emissions and nitrate leaching. The risk for N losses is linked to low crop N use efficiency (NUE) combined with a narrow C:N and high N content of crop residues. Here we reviewed the studies conducted in Canada and similar climates to better understand the risk of N_2O emission and potential agronomic management strategies to reduce N_2O emissions from horticultural systems. Current knowledge on N_2O emissions from horticultural systems indicate that increasing crop NUE, modifying the amount, type, time, and rate of N fertilizer inputs, and adopting cover crops in crop rotations are some of the effective approaches to decrease N_2O emissions. However, there is uncertainty related to the efficiency of the existing N_2O mitigation strategies due to the complex interactions between the factors (soil characteristics, type of plant species, climatic conditions, and soil microbial activity) responsible for N_2O production from soil. Little research on N_2O emissions from Canadian horticultural systems limits our ability to understand and manage the soil N_2O production processes to mitigate the risk of N_2O emissions. Thus, continuing to expand this line of research will help to advance the sustainability of Canadian horticultural cropping systems.

Key words: greenhouse gas emissions, nitrogen use efficiency, vegetable, fruit, temperate climate.

Résumé : On range les systèmes horticoles, surtout la production maraîchère, dans l'agriculture intensive, car ces systèmes exigent l'application d'une grande quantité d'engrais azotés (N), des labours fréquents et l'irrigation. C'est pourquoi, dans les climats tempérés, l'horticulture est propice aux pertes de N — essentiellement après la récolte (à l'automne et en hiver) ou avant la plantation (au printemps) — par les dégagements de N_2O ou la lixiviation. Le risque des pertes de N est lié à la piètre assimilation de cet élément par la culture combinée au faible rapport C:N et à des résidus agricoles riches en N. Les auteurs ont passé en revue les études effectuées au Canada et dans des régions au climat similaire pour mieux cerner le risque des émissions de N_2O par les systèmes horticoles et les stratégies de gestion agronomiques qui concourraient à les réduire. Actuellement, ce qu'on sait des dégagements de N_2O par les productions horticoles indique qu'amener la culture à mieux assimiler l'azote, modifier la quantité d'engrais azotés, la nature de l'engrais ainsi que son taux et le moment d'application, de même qu'intégrer des cultures abri aux assolements sont quelques moyens efficaces permettant de réduire les dégagements de N_2O. Néanmoins, un doute plane quant à l'efficacité des stratégies actuelles visant à atténuer les émissions de N_2O en raison des interactions complexes entre les facteurs à leur origine (propriétés du sol,

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espèce végétale, conditions climatiques, activité de la microflore tellurique). Le peu de recherches sur le volume de N_2O libéré par les systèmes horticoles au Canada nous empêche de comprendre et de maitriser vraiment les mécanismes qui produisent ce gaz dans le sol en vue d'en réduire le volume libéré. En conséquence, poursuivre les recherches de ce genre contribuera à faire progresser la pérennité de l'horticulture au Canada. [Traduit par la Rédaction]

Mots-clés : émissions de gaz à effet de serre, utilisation efficace de l'azote, légumes, fruits, climat tempéré.

Introduction

Nitrous oxide, a potent greenhouse gas with 298 times greater warming potential than CO_2 (IPCC 2007), is produced in the soil primarily through processes of nitrification and denitrification (Bremner et al. 1997). Nitrous oxide production potential of a soil generally increases with an increase in soil nitrogen (N) availability (Bouwman et al. 1996). Therefore, agricultural activities which increase soil N inputs, such as use of synthetic N fertilizers, significantly contribute to increasing soil N_2O emissions (Bouwman et al. 1996). Due to a steady increase in global fertilizer N consumption, N_2O emissions from agricultural soils are expected to increase by 35% to 60% by 2030 (US EPA 2011).

Horticultural (vegetable and perennial fruit) crops constitute an integral component of a healthy diet. The benefits of vegetable and perennial fruit consumption in reducing malnutrition and associated health problems (WHO 2003) has resulted in a significant expansion of the global vegetable and perennial fruit production (FAO 2017). Like global trends, in Canada, planted area of perennial fruit crops increased by 3.3% from 2011 to 2020 period (Statistics Canada 2021*a*, 2021*b*). Unlike perennial fruit crops, planted area of field vegetable crops decreased by 4.8% over the 2011 to 2020 period (Statistics Canada 2021*a*, 2021*b*). Regardless, farm gate value of perennial fruit ($1.17 billion CAD) and field vegetables ($1.33 billion CAD) has increased in Canada (Statistics Canada 2021*a*, 2021*b*). Partly due to high economic and nutritive value of vegetable and perennial fruit crops, certain cropping systems are subjected to large amount of N fertilizer inputs (Chen et al. 2005; Thompson et al. 2007), which poses an enhanced risk of N loss to the environment (Agneessens et al. 2014; Di and Cameron 2002). For instance, globally, about 220 kg $N{\cdot}ha^{-1}$ is applied to vegetable crops in each growing season (Rashti et al. 2015). Likewise, in Canada, approximately 200 to 250 kg $N{\cdot}ha^{-1}$ is applied to cabbage, broccoli, and cauliflower (Congreves and Van Eerd 2015). Intensive soil management, low crop N use efficiency (NUE), and high N fertilizer inputs to horticultural crops typically result in high amounts of residual soil mineral N in horticultural fields at harvest (Di and Cameron 2002). As a result, horticultural systems have a greater risk of fertilizer-induced N_2O emissions than grain cropping systems (Dalal et al. 2003; Ju et al. 2006; Xiong et al. 2006; Lin et al. 2010; Diao et al. 2013; Rashti et al. 2015; Cheng et al. 2017;). Therefore, studying N_2O dynamics from horticultural systems is crucial to reduce adverse effects on soil and environmental quality, optimize N fertilizer management, and develop N_2O emission mitigation strategies.

Despite the high economic value of horticultural crops, there is limited research quantifying N_2O emission from horticultural systems in Canada. For instance, sweet corn, green peas, green beans, carrots are the major field grown vegetable crops in Canada — planted on more than 7000 ha (Statistics Canada 2021*a*, 2021*b*). However, no studies have quantified N_2O emissions from these horticultural crops in Canada (Table 1). The mismatch between commercial crop production trends in Canada and studies that evaluate the risk of N_2O emission presents a conspicuous knowledge gap. Based on a literature search including areas with similar climate to Canada, we review the factors leading to high N_2O emissions and suggest a framework to guide the needed future N_2O emission research for horticultural production systems. Our objectives are to (*a*) evaluate the risk of N_2O emission by way of analysing what is known about N cycling in horticultural systems, (*b*) synthesize management strategies which show promise in minimizing N_2O emissions from these systems, and (*c*) highlight future research needs for better understanding of N_2O dynamics in Canadian horticulture.

Materials and Methods

Studies related to N_2O emissions from horticultural crops were collected from peer reviewed articles available on Web of Science and Google Scholar platform using keywords 'greenhouse gas emission', 'N_2O emission', 'horticulture', 'vegetable', 'fruit', 'temperate climates', and 'Canada'. In this study, we have focused on crop growing season emissions from field grown horticultural crops and thus N_2O emissions from the greenhouse and laboratory studies were not included. Although it is important to include N_2O emissions during the non-growing season to better predict the N_2O risk from agricultural systems (Wagner-Riddle et al. 2017), studies quantifying N_2O emissions during the non-growing season are scant. During the non-growing season when the soil is frozen, thawing, and snow covered, there is a greater potential for N_2O emissions (Dörsch et al. 2004; Regina et al. 2004; Maljanen et al. 2007; Chen et al. 2018;). The exact mechanism contributing to large N_2O emissions during the non-growing season (snow-melt period) in cold climates is not clear

Table 1. Summary of growing season N_2O emissions from horticultural crops in Canada.

Crop type		Location	Soil type	Study site/ treatment year	N fertilizer source	N fertilizer application rate kg N·ha^{-1}	Growing season N_2O-N emission kg·ha^{-1}	N_2ON/ applied N^a g·kg^{-1} fertilizer N	Reference
Annual	Onion	Sherrington, QC	Organic	4	NH_4NO_3	91–99	0.17–7.19	1.90–79.0	Lloyd et al. 2019
	Tomato	Sherrington, QC Palichuk Farms, ON	Sandy loam, Loamy sand	8	NH_4NO_3	195	2.47–5.98	12.7–30.5	Edwards et al. 2018; Lloyd et al. 2019
	Potato	Carberry, MB	Clay loam, loamy fine sand	12	Urea	80–240	0.26–3.06	2.20–17.6	
				5	ESN^b	100–200	0.82–1.87	4.60–13.3	Gao et al. 2013 and 2017
		Fredericton, NB	Loam, coarse loam, sandy loam	3	ESN	193	0.44–1.00	2.28–5.18	Zebarth et al. 2012
				12	NH_4NO_3	193–200	0.09–2.20	1.14–11.0	Burton and Grant 2008; Snowdon et al. 2013; Zebarth et al. 2012
	Lettuce	Montreal, QC	Organic	12	NH_4NO_3	50–150	3.60–40.2	50.0–804	Rochette et al. 2010
	Squash	Vancouver, BC	Sandy	2	Manure	151	0.39–0.46	2.60–3.00	Maltais-Landry et al. 2019
Perennial	Blueberry^c	Westham Island, BC	Silty clay loam	1	$(NH_4)_2SO_4$	110	2.75	25.0	Pow et al. 2020
	Cranberry	Saint-Louis-de Blandfort, QC	Sandy	4	NH_4NO_3	43–49	0.06–0.16	1.20–3.60	Lloyd et al. 2019
	Grapes^c	Summerland, BC	Sandy loam	12	Urea/Compost	40	0.43–0.99	10.8–24.8	Fentabil et al. 2016*a*
	Apple	Summerland, BC	Loamy sand	12	$Ca(NO_3)_2$	63–127	0.32–0.93	3.1–12.4	Fentabil et al. 2016*b*

[a] Values reported were calculated by dividing the growing season N_2O emissions by the amount of N fertilizer application rate.

[b] ESN, Environmentally Smart N (44-0-0), a form of slow-release N fertilizer.

[c] Data reported in the table are seasonal N_2O emissions; however, annual N_2O emissions for blueberry and grapes were 3.90 kg N_2O-N·ha^{-1} and 0.95–1.74 kg N_2O-N·ha^{-1}, respectively.

but might be related to the freeze-thaw induced effects on soil aggregate disruption (Chai et al. 2014), microbial cell lysis (Freppaz et al. 2007), microbial community dynamics (Kumar et al. 2013), and denitrification (Wagner-Riddle et al. 2008). Crop growing season N_2O emissions data were summarised based on the crop, and rate and source of N applied to the crops. To compare N_2O emission potential between annual and perennial horticultural crops, N_2O emissions were normalized by N application rates. Vegetable crops reviewed in this study were classified based on their edible part. For instance, tomato and squash were classified as fruit vegetables, potato was classified as tuber vegetable, onion was classified as bulb vegetable, and lettuce was classified as leafy vegetable. Based on the literature search on N_2O emissions from field grown horticultural crops in Canada (Table 1 and Supplementary Table S1[2]), 14 studies were found where seasonal N_2O emissions were mainly evaluated in fruit (tomato and squash), tuber (potato), bulb (onion), and leafy (lettuce) vegetables, and perennial fruit crops (grapes, blueberry, and cranberry). The purpose of identifying the Canadian horticultural studies quantifying N_2O emissions was to clearly indicate the scarcity of the N_2O emissions data in Canada, to highlight the conspicuous gaps between the horticultural crop production trends and knowledge related to N_2O emissions, and to direct future research. In addition, findings from the previously published research in Canada and similar climates on N cycling, water dynamics, crop residue quality, and soil management in horticultural crop production were reviewed to draw predictions regarding the risk of N_2O production and emission from Canadian horticultural systems.

Analyzing the risk of N_2O production and emission in horticultural production

Although research is scant, there is a handful of studies on N_2O emissions from Canadian horticultural production systems (Table 1 and Supplementary Table S1[2]); the regions and crop types studied match the major growing regions for key horticultural crops in Canada. For example, Ontario is the major commercial producer of tomato, onion, and lettuce—for which N_2O dynamics have been studied for all these crop types (Table 1). Manitoba and Prince Edward Island are main producers of potato, this corresponds to the horticultural N_2O studies of this region (Table 1). Likewise, blueberry, cranberry, and grape production are mainly located in Nova Scotia, Quebec, and British Columbia, respectively — matching the N_2O studies shown in Table 1.

Linking N cycling to the risk of N_2O production and emission in horticultural systems

Nitrogen inputs and use as related to N_2O risk

Generally, the risk of N_2O emissions increases linearly with an increase in N fertilizer application rates (Gao et al. 2013; Shcherbak et al. 2014; Yang et al. 2019) when N fertilizer is applied at the rate less or equal to the crop requirement (Gregorich et al. 2005). When N fertilizer application rate exceeds 150 $kg \cdot ha^{-1}$ (typically crop N requirements) (Shcherbak et al. 2014; Tenuta et al. 2019; Wang et al. 2020), which is frequently observed in cabbage, potato, carrot, onion, radish, garlic, lettuce, melon, and cauliflower (see meta-analysis by Rashti et al. 2015), N_2O emissions increase exponentially (Snyder et al. 2009). A recent global metadata analysis from vegetable crops showed that 1.41% (CI: 1.19%–1.64%) of fertilizer applied N is lost in form of N_2O emissions (Yang et al. 2019). A study by Suter et al (2021) reported that about 10 $kg\ N \cdot ha^{-1} \cdot yr^{-1}$ was lost as N_2O from a celery production system. In Atlantic Canada, fertilizers alone contributed to 70% N_2O emissions from potato production system (Snowdon et al. 2013; Zebarth et al. 2012). It is important to note that sweet corn occupies the greatest (17%) land acreage among the vegetables in Canada (Agriculture and Agri-Food Canada 2019). Therefore, abundant supply of N in soil due to high N fertilizer application (150 to 200 $kg\ N \cdot ha^{-1}$) to sweet corn suggests that considerable N_2O emissions may be derived from sweet corn production systems (Yang et al. 2019).

Several Canadian studies indicate that annual vegetable crops have greater N_2O emission potential than perennial fruit crops. For examples, 79 $g\ N_2O\text{-}N \cdot kg^{-1}$ fertilizer N for onions was reported by Lloyd et al (2019) from mineral soils and 50 to 804 $g\ N_2O\text{-}N \cdot kg^{-1}$ fertilizer N for lettuce was reported by Rochette et al (2010) under organic soil; 25 $g\ N_2O\text{-}N \cdot kg^{-1}$ fertilizer N for blueberries was found by Pow et al (2020);10.4 to 24.8 $g\ N_2O\text{-}N \cdot kg^{-1}$ fertilizer N for grapes was found by Fentabil et al (2016*a*), and 3.1 to 12.4 $g\ N_2O\text{-}N \cdot kg^{-1}$ fertilizer N for apples was reported by Fentabil et al (2016*b*). Drained organic soils act as a major source of N_2O emissions mainly due to accelerated rate of organic matter decomposition and mineralization of organic N (Duguet et al. 2006); hence, high N_2O emissions were observed from lettuce grown on organic soils (Rochette et al. 2010). Greater N_2O emissions from vegetable production systems than perennial fruit crops are mainly due to higher rates of N fertilizer inputs to vegetable crops (Table 1). For instance, N fertilizer application to blueberry usually ranges from 75 to 100 $kg\ N \cdot ha^{-1}\ year^{-1}$ (Larco et al. 2013) which is less than broccoli (≥293 $kg\ N \cdot ha^{-1}$; Congreves and Van Eerd 2015). Lower N fertilizer rates and perennial nature of fruit crops along with deeper root

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[2] Supplementary data are available with the article at https://doi.org/10.1139/cjps-2021-0107.

penetration results in a more efficient utilization of soil N and contributes to lower N_2O emissions from perennial fruits than vegetable crops.

Crop N use efficiency (NUE) reflects the ability of plants to obtain N from soil and is largely a function of soil's capacity to supply N and crop's capacity to uptake, store, and translocate N among plant parts (Baligar et al. 2001). Horticultural crops are often characterized by low NUE (Thompson et al. 2020). For instance, Neto et al (2008) reported that NUE of pear trees ranged between 6% to 33% in the first three years. A review by Congreves and Van Eerd (2015) revealed that vegetable crop NUE was 37.3% for broccoli (Toivonen et al. 1994; Zebarth et al. 1995; Bowen et al. 1999; Bakker et al. 2009*a*, 2009*b*;) and 38.5% for cabbage (Zebarth et al. 1991; O'Halloran 1998). Benincasa et al (2011) reported NUE in tomato as 57%, sweet pepper as 28%, and lettuce as 39%. Likewise, NUE for sweet corn was observed to be <50% (Zhu 2000). A meta-analysis of greenhouse-grown crops by Gu et al (2019) reported that leafy vegetables (avg. 14%) had lower crop NUE relative to stem (avg. 45%) and fruit (avg. 26%) vegetables; thus, leafy vegetable production systems were prone to higher N_2O emissions. Similarly, the normalized average N_2O emissions among perennial fruit and vegetable crops reviewed in this study were in the order of cranberry < squash < potato < grapes < tomato < onion < blueberry <<< lettuce (Table 1). Here, the greatest N_2O emissions observed for lettuce (leafy vegetable) were attributed to production on organic soil with a high-water table. Higher crop NUE values indicate greater plant N uptake of the mineral N available in the soil; hence, indicative of a potential reduction in N_2O emissions (Cui et al. 2012). Therefore, increasing crop NUE is needed for potentially reducing risk of N_2O emissions.

Crop residues for nitrification and denitrification

Vegetable crop residues remaining in the field after harvest are rich in N, but N content in crop residue vary with crop types (Congreves and Van Eerd 2015). For instance, crop residue N content in brussels sprout (138 $kg\ N\cdot ha^{-1}$; Whitmore 1996) and cabbage (115 $kg\ N\cdot ha^{-1}$; Whitmore 1996) is relatively higher than tomato (26 $kg\ N\cdot ha^{-1}$; Van Eerd et al. 2014; Chahal and Van Eerd 2019), sweet corn (28–49 $kg\ N\cdot ha^{-1}$; O'Reilly et al. 2012), leeks (54 $kg\ N\cdot ha^{-1}$; Whitmore 1996), spinach (35 $kg\ N\cdot ha^{-1}$; Whitmore 1996), squash (51–75 $kg\ N\cdot ha^{-1}$; Van Eerd 2018), peppers (30–40 $kg\ N\cdot ha^{-1}$; Van Eerd 2007) and cucumber (91–126 $kg\ N\cdot ha^{-1}$; Van Eerd and O'Reilly 2009). Unlike annual vegetable crops, N inputs to soil by crop residues (i.e., fallen leaves) from perennial fruit crops are dependent on the age of tree (Neto et al. 2009). For instance, N content of fallen leaves of pear trees varied from 1.0 $kg\ N\cdot ha^{-1}$ (1-y old tree) to 5.8 $kg\ N\cdot ha^{-1}$ (6-y old tree) (Neto et al. 2009). Therefore, N input to soil from senescent leaves of perennial fruit trees is much less than from vegetable crop residue. Typically, the risk of N_2O production increases with an increase in N content of the crop residue; therefore, annual vegetable cropping systems have an increased risk of post-harvest N_2O emissions compared with perennial fruit crops.

Unlike crop residue N content, a negative relationship exists between crop residue C:N and N_2O production potential (Huang et al. 2004; Shan and Yan 2013). The majority of Brassica vegetable crops have a low C:N ratios (<25:1; Congreves and Van Eerd 2015). When these crop residues are returned to soil, soil microbial activity is increased, the residues undergo rapid mineralization, and the potential for N_2O production and emission is increased (Vigil and Kissel 1991). Contrary to low C:N of crop residue, when returning residue with high C:N (such as tomato with C:N up to 45), N immobilization will occur resulting in a reduction in N_2O production and emission potential from soil (Hu et al. 2019). In perennial fruit trees, the C:N of senescent leaves (dependent on age of tree) is greater than vegetable crop residues. For instance, C:N of senescent leaves in young and old pear trees was 28:1 and 32:1, respectively (Neto et al. 2009). Tagliavini et al (2004) reported that the C:N of senescent leaves of mature apple trees was 35:1. Higher crop residue C:N of perennial fruit trees suggest soil N immobilization and slower decomposition than vegetable crop residue; therefore, indicate a potential reduced risk of N_2O production and emission from perennial fruit production systems. In a soil incubation study that evaluated C and N processing from four different horticultural soils, soils under a legacy of intensive vegetable cropping produced the highest N_2O emissions (Arcand and Congreves 2020).

Crop residue mineralization increases the concentration of dissolved organic C and inorganic N in soil, which stimulates N_2O emissions (Muhammad et al. 2011). Due to low C:N of vegetable crop residue, it is anticipated that approximately 60% of vegetable crop residue (82% of leaf-blades and 42% of stems) might decompose within 3 to 9 weeks after addition to soil (De Neve and Hofman 1996, 1998). A meta-analysis by Chen et al (2013) reported that increased amount of labile organic C inputs at crop harvest were positively associated with an increase in N_2O emissions. Residue C content and decomposability act as a sink for oxygen. Availability of labile and organic C substrates stimulate microbial respiration leading to oxygen depletion, and production of anaerobic conditions which favor N_2O emissions (Chen et al. 2013; Duan et al. 2018). On the contrary, addition of high C containing residues to a soil which is not limiting in C (preferably high C:N) might not stimulate denitrification (Risk et al. 2013; Sehy et al. 2004). As concluded in Chen et al (2013), the interaction between residue quality and soil moisture content are major factors mediating soil denitrification potential. For instance, with the addition of corn crop residue amendments (high C:N), N_2O emissions were greatest when water filled pore space was between 34% and 77% (Abalos et al. 2013). However, when water filled pore space was ≥90%, addition of crop residue decreased N_2O emissions (Chen et al. 2013). Decrease in N_2O emissions was perhaps attributed to a shift in the $N_2O:N_2$ ratio with an increase in reduced conditions in soil. In soils amended with crop residues, the reduction in soil oxygen concentration is severe mainly due to rapid microbial degradation (Chen et al. 2013). Under these conditions, N_2O reductase enzyme (an oxygen intolerant enzyme) becomes active and results in the reduction of N_2O to N_2 (Bouwman 1998; Chen et al. 2013). Therefore, presence of crop residues when the water filled pore space is ≥90% might contribute in reducing N_2O emissions. Overall, the body of research suggests that vegetable production presents a higher risk for N_2O emissions than perennial fruit production systems.

Periods with high moisture availability

Regional water balance

Regional annual water budget is a major factor determining the need for irrigation and the potential losses of N to environment. For instance, eastern Canada normally receives greater amount of rainfall during crop growing season than western Canada (western Canada being the Prairie region), except pacific coastal regions (Zhang et al. 2019). Because of greater total precipitation in eastern Canada than the Prairies, N_2O emissions per unit area are expected to be greater in eastern Canada than the Prairies. The pacific coastal region, however, receives a similar or greater amount of precipitation than eastern Canada. For grain crops, Rochette et al (2018) established an exponential relationship between N_2O emissions and growing season precipitation based on a nation-wide database. Furthermore, from the regional annual water budget of southwestern Ontario (Fallow et al. 2003), it is clear that the risk for N loss is less during mid to late growing season (July to September) mainly due to greater evapotranspiration than precipitation. But, during the non-growing season, precipitation generally exceeds evapotranspiration, suggesting potential for an increase in soil moisture content and prevalence of anaerobic conditions in soil which poses an increased risk of N_2O emissions.

Irrigation

Water deficit conditions decrease crop yield due to reduction in plant growth and development (Abdelkhalik et al. 2020; Patanè and Cosentino 2010). Therefore, due to the high value of horticultural crops, frequent irrigation is usually practiced. Also, vegetable crops tend to be grown on sandy soils to facilitate crop harvest especially if wet soil conditions occur at harvest. Sandy soils are prone to drought conditions mainly due to low water holding capacity (Ladányi et al. 2021); thus, irrigation is done to meet the horticultural crop water demand. For horticultural crop production systems, commonly used irrigation systems are sprinkler, drip irrigation, and surface irrigation (consisting of flood and furrow irrigation) in Canada (Statistics Canada 2021*a*, 2021*b*). Soil water content varies based on the method chosen to irrigate the horticultural crops. For example, sub-surface drip irrigation supplies the water directly into the crop roots, sprinkler irrigation sprays the water over the crop canopy; in surface irrigation, water flow over the soil surface occurs by gravity (Statistics Canada 2021*a*, 2021*b*). In surface irrigation, surface soil is saturated by water before the water reaches to deeper depths; therefore, there is a greater potential for N_2O production in surface irrigation. Ideally irrigation, regardless of the method, is based on the plant water demand. Intermittent application of water can increase the frequency of dry-wet cycles — events which are known to increase N_2O production and emission (Congreves et al. 2018; Ning et al. 2019). For instance, N_2O emissions were 70% lower with drip than furrow irrigation (Sanchez-Martin et al. 2008). Likewise, several studies have reported lesser N_2O emissions under drip than furrow irrigation (Kallenbach et al. 2010; Sanchez-Martin et al. 2010). Since the soil pore space is filled with water only at the locations where drippers are fixed, denitrification occurs at a relatively smaller area with drip than furrow irrigation (Trost et al. 2013). In addition to the type of irrigation, the risk of N_2O emissions is dependent on the frequency of irrigation (Fentabil et al. 2016*b*). Nitrous oxide emissions decreased by 27% with a reduction in irrigation frequency (Fentabil et al. 2016*b*). Also, fertigation (when large amounts of N fertilizer are applied with irrigation)(Yao et al. 2019) or application of N fertilizer immediately after irrigation increases the potential for N_2O emissions (Ning et al. 2019). Regardless of the different irrigation methods adopted in horticultural systems, the magnitude of N_2O production is unclear. Therefore, future research to comprehensively evaluate the N_2O production and emission due to irrigation methods from horticultural systems is needed.

Mulching

Various types of mulching materials are used in horticultural crop production such as organic materials (e.g., plant products), synthetic materials (e.g., plastic films) and specialized type of materials (e.g., stones, gravel). The type of mulching material used for crop production influences soil hydrothermal properties. For example, plastic film mulches conserve greater amount of soil moisture than organic mulches (Ogundare et al. 2015). Increased soil temperature and moisture under plastic film mulch promotes soil microbial activity and accelerates the decomposition of plant residues and organic matter (Lee et al. 2019; Wang et al. 2016), which favors the release of greenhouse gases from soil, such as N_2O emissions (Steinmetz et al. 2016). Although plastic film mulches increase N_2O emissions (Cuello et al. 2015; Lee et al. 2019; Zhao et al. 2020), the amount of N_2O

emitted with the use of plastic films in horticultural systems is regulated by the characteristics of plastic films (Wang et al. 2021).

Organic mulches are adopted for many reasons including regulating soil temperature in crop production. Organic mulches regulate soil temperature by increasing soil temperature in the spring and reducing soil temperature during summer and increasing during winter season. Thus, soil temperature fluctuation is reported to be minimum with organic mulches (Abouziena and Radwan 2015). Despite the benefits of organic mulches, decomposition of organic mulches over time might release N (Valenzuela-Solano and Crohn 2006; Xu et al. 2017), and trigger N_2O emissions. However, it has been reported that mechanism of N_2O emissions from organic mulches are complex because emissions are dependent on the mulch's biochemical properties influencing soil moisture adsorption and absorption (Chen et al. 2017), decomposition potential, and soil C and N contents (Xu et al. 2017). Fentabil et al (2016*a*) found lower N_2O emissions with woodchips than without mulch in a grape vineyard. Mulched treatment had greater soil water and organic C content, and lesser soil nitrate concentration than non-mulched control suggesting that mulching created anaerobic conditions with increased organic C and soil moisture; thus, favoured the production of N_2 over N_2O (Fentabil et al. 2016*a*). In contrast to Fentabil et al (2016*a*), Huang et al (2020) reported that organic mulches have the potential to trigger N_2O emissions under heavily fertilized conditions by accelerating residue decomposition and providing organic C to soil microbes. Therefore, in addition to N fertilizer application rate and type of production system (annual vs. perennial), type of mulching materials used in crop production plays a major role in determining the risk of N_2O losses from horticultural crops.

Management strategies to enhance fertilizer N use efficiency and potentially mitigate N_2O emissions

Crop rotation for annual cropping systems

Crop rotation is one of the important strategies for effectively maintaining and increasing soil fertility, crop yield, and environmental sustainability (Benincasa et al. 2017). Nevertheless, to achieve the benefits (to enhance soil health, soil biology, and nutrient availability) from a well-designed crop rotation (Agneessens et al. 2014), the potential mechanisms through which crop rotations sustain horticultural crop production must be considered. For instance, inclusion of leguminous crops (cover crop or main crop) in crop rotations has demonstrated to be an effective practice for supplying N to the succeeding crop and reducing the application of synthetic N fertilizers to the following crop (Hirel et al. 2011; Coombs et al. 2017; Farneselli et al. 2018; Perrone et al. 2020). Several studies have reported that rotating shallow rooted crops (such as leek) with deep-rooted (such as white cabbage) vegetable crops helps to reduce soil mineral N by 100 kg N·ha^{-1} from 1 to 2.5 m depth (Thorup-Kristensen 2006; Xie et al. 2017) and reduce the potential of N_2O loss from soil. It was also observed that N_2O emissions were greater from leguminous cover crops at low N fertilizer rates and vice-versa; non-legume cover crops increased N_2O emissions with an increase in N fertilizer rates suggesting the importance of both C and N for denitrification (Basche et al. 2014; Davis et al. 2019; Machado et al. 2021).

Including cover crops in the rotation

Adoption of cover crops in horticultural production systems is a promising option to potentially reduce fall nitrate leaching (Van Eerd 2018), increasing N availability to the subsequent crop (O'Reilly et al. 2012; Belfry et al. 2017), soil microbial activity (Blanco-Canqui et al. 2015), and overall soil quality (Norris and Congreves 2018; Chahal and Van Eerd 2019). In temperate climates, such as Canada, cover crops are often seeded after the main crop harvest in fall. This period of cover crop growth (fall) usually coincides with the period of high concentration of soil nitrate mainly from readily mineralizable vegetable crop residue with high N content (Congreves and Van Eerd 2015). Therefore, cover crops take up the residual soil mineral N (O'Reilly et al. 2012; Hill et al. 2016; Van Eerd 2018; Chahal and Van Eerd 2021), potentially reducing fall and winter N_2O losses to the environment. Generally, living cover crops can reduce the soil water content via transpiration (Basche et al. 2014) but after cover crop termination, N_2O production potential is increased mainly due to the increase in soil water content with the presence of cover crop residues that help to increase soil water holding capacity (Dabney 1998). Moreover, decomposition of cover crop residues releases labile C and inorganic N substrates which are favorable for denitrification (Kaspar and Singer 2011). Although the benefits of cover crops in increasing N availability for the subsequent crop and improving crop NUE have been documented (Farzadfar et al. 2021), cover crop impacts on N_2O production potential are not clearly understood (Cavigelli and Parkin 2012). For instance, a meta-analysis by Gu et al (2019) revealed that integrating leguminous and non-leguminous cover crop species in fruit orchards increased N_2O emissions mainly due to increasing soil N availability due to biological N fixation by legumes and addition of organic C by non-legumes. However, Marques et al (2018) reported that grass cover crop species decreased N_2O emissions in a vineyard. Therefore, the efficiency of cover crops in increasing or decreasing N_2O emissions and other N losses is largely dependent on the cover crop type, planting and termination date, seeding rate, climatic conditions, and soil type (Weinert et al. 2002; Thorup-Kristensen 2006; Nett et al. 2011; Van Eerd 2018).

Planting time of cover crops is another important aspect to determine effectiveness of cover crops in reducing the risk of N_2O emissions. Due to short growing season in temperate climates, early planting of cover crops has been demonstrated to be an effective strategy for mitigating N_2O emissions mainly due to an increase in N uptake by cover crops associated with an increase in cover crop biomass accumulation. For instance, early fall planting of cover crops in a vegetable production system increased cover crop biomass and N accumulation (Van Eerd 2018). Late harvesting of main crops reduces the time for cover planting and establishment; thus, decreases the effectiveness of cover crops in providing benefits related to reducing fall and winter N_2O losses. A study by Congreves et al (2013) reported that cover crops did not reduce N losses when planted after broccoli (due to late harvest of broccoli in Ontario). Therefore, in temperate climates, the cover crop benefits on reducing N losses and effectively managing N fertility are generally limited to vegetable crops harvested in summer or early fall.

Fertilizer N management

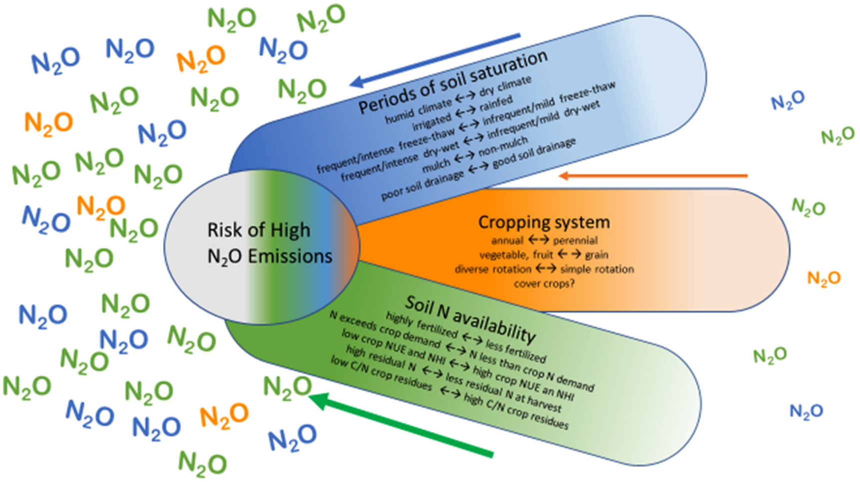
Fertilizer N management to meet the crop yield and quality goals while reducing N losses to the environment is one of the most important decisions for managing soil N fertility (Burns 2006; Snyder 2017) as well as reducing N_2O emissions. Studies by Zebarth and Rosen (2007) and Zebarth et al (2008) reported that decreased supply of N to potato negatively impacted the potato tuber size and biological yield whereas excessive application of fertilizer N increased the potential of N loss, primarily as nitrate leaching and N_2O emissions. Increased application of N above the optimum requirements of crop also decreased crop yield and quality in potato (Zebarth and Rosen 2007), increased nitrate concentration in leafy vegetables (Colla et al. 2018) and increased the potential for N_2O emissions at crop harvest. Therefore, selecting the right rate of fertilizer N is crucial for optimizing N fertility management.

Similarly, application of N fertilizer at the time of peak N demand by the crop is a promising strategy to reduce N_2O emissions. For instance, fertilizer N application to annual horticultural crops is typically done at or before planting. Delaying the N fertilizer application until a few weeks after planting might reduce N_2O production by way of increasing crop NUE. Increases in crop N uptake might reduce the amount of N available for N_2O losses via nitrification and denitrification. Also, the application of N fertilizers at early spring (e.g., prior to crop planting) will increase N_2O emissions due to the presence of wet soil conditions which will stimulate the release of N_2O from soil (Hernandez-Ramirez et al. 2009).

In addition to the timing of fertilizer application, selecting the right method of fertilizer placement is a critical management strategy to minimize N_2O emissions. Although band placement of N fertilizers has shown to increase N uptake by crop roots and crop NUE, N_2O emissions are usually increased with band placement (Engel et al. 2010). Numerous studies have reported that broadcast application of N fertilizers and incorporation of the fertilizer in the soil have lower N_2O emissions than band application (Burton and Grant 2008; Engel et al. 2010; Venterea et al. 2012). To effectively mitigate N_2O emissions from horticultural production systems, we suggest focussing not only on the fertilizer management strategies which increase crop NUE but also considering the interactions between the factors related to soil N_2O production potential.

Choosing the right source (chemical form) of fertilizer N is critical for an effective N management and reducing N_2O emissions (Halvorson et al. 2010; Venterea et al. 2011). Studies by Bouwman et al (2002); Venterea et al (2005), and Engel et al (2010) reported greater N_2O emissions from ammonium than nitrate-based fertilizers. Numerous types of fertilizer N products are available in the market that aim to synchronize N release from fertilizers with the crop N demand (Snyder 2017) and potentially reduce N_2O emissions, such as controlled and slow-release N fertilizers and fertilizers treated with nitrification inhibitors. Slow-release N fertilizers, as the name suggests, release N slowly due to low solubility. Commonly used slow-release N fertilizers are urea formaldehyde, isobutylidene diurea, and triazone. Fertilizer N in slow-release fertilizers undergoes microbial decomposition (e.g., urea formaldehyde) and hydrolysis (e.g., isobutylidene diurea) prior to being available to plants (Morgan et al. 2009). On the other hand, controlled release fertilizers have a physical coating of either sulfur, polymer, or a combination of sulfur and polymer (Morgan et al. 2009). Sulfur coated urea, polymer coated urea, or polymer-sulfur-coated urea are common examples of controlled release N fertilizers (Morgan et al. 2009). The coating of the fertilizer with the highly water insoluble products reduces the penetration of soil water to the fertilizer, limits dissolution of fertilizer, and controls the N release from the fertilizer in the soil (Morgan et al. 2009) and reduces the amount of N in soil available for nitrification and denitrification. The controlled release N fertilizers have successfully reduced N loss and enhanced fertilizer NUE in potato (Zvomuya and Rosen 2001; Ziadi et al. 2011). Regardless of the N release mechanism, research has confirmed the effectiveness of slow and controlled release N fertilizers in reducing nitrate leaching, N_2O production and potentially N_2O emissions in horticultural production systems, specifically on sandy soils (Simonne and Hutchinson 2005). A study conducted by Hyatt et al (2010) in potato production system in Minnesota confirmed a reduction in N_2O emissions with the application of controlled release fertilizers. Nevertheless, due to a short growing period and high N demand of vegetable crops, it is difficult to synchronize the vegetable crop N demand with the fertilizer N release which limits the application of slow and controlled release N fertilizers in vegetable production systems (Van Eerd et al. 2012, 2014).

Fig. 1. Conceptual diagram listing the major soil and crop factors regulating the risk of N2O emissions from horticultural production systems. [Colour online.]



Although slow and controlled release fertilizers have a greater cost per unit N than conventional mineral fertilizers, there is a possibility that one-time pre-plant application of controlled release fertilizers might contribute in saving time, labour, and cost in horticultural crops in temperate climates (Van Eerd et al. 2014).

Nitrification inhibitors play a significant role in reducing nitrate leaching and N_2O emissions and increasing fertilizer N use efficiency, primarily by slowing down the conversion of ammonium to nitrate (Ruser and Schulz 2015). A study by Scheer et al (2017) reported a reduction in N_2O emissions in beans and broccoli production system by 20%–60% with the addition of nitrification inhibitors. Similar range of decline in N_2O emissions with nitrification inhibitors was reported in other horticultural systems (Pfab et al. 2012; Scheer et al. 2014; Lam et al. 2015; Zhang et al. 2015). It was also reported by Scheer et al (2017) that use of nitrification inhibitors in vegetable production systems might increase N storage in the soil. Nitrification inhibitors when decomposed by soil microbes during nitrification will result in release of nitrate and consequently elevate the post-harvest N_2O emissions. Therefore, N fertilizer adjustments to vegetable production systems might be needed when using nitrification inhibitors to reduce post-harvest N_2O emissions.

Future research needs

Based on the factors reviewed, we suggest the following potential areas for future research:

a. To investigate and estimate the risk of N_2O production from horticultural systems, consideration must be given to the complex interactions between soil properties, climatic conditions, type of crops grown, microbial communities, and N fertilizer management strategies.

b. Since a lot of attention has been given to fertilizer-induced N_2O emissions, future research quantifying the N_2O production potential from the application of organic N sources such as horticultural crop residues, manures and leguminous cover crops to horticultural systems is needed.

c. Although this review focused on field grown perennial fruits and annual vegetables, future work should consider N_2O emissions from other production settings, such as perennial vegetable crop systems (such as asparagus) and greenhouse vegetable production. This would be prudent considering that greenhouse production of vegetables contributes a large share of commercial horticultural production in Canada. Consideration of N_2O emissions from greenhouse vegetable production systems along with field-grown vegetables and perennial fruit crops is required to develop a database/inventory of N_2O emissions from Canadian horticultural systems.

d. Applying improved plant breeding strategies to develop horticultural crop cultivars with increased NUE has potential to decrease N_2O emissions. Cultivars with enhanced NUE will potentially reduce the amount of N available for denitrification and might reduce the reliance of horticultural crops on fertilizer N to achieve economical yield.

e. More research on strategies to reduce N fertilizer rate to horticultural crops when using nitrification inhibitors is needed. This research will benefit the growers by reducing the additional financial costs associated with the nitrification inhibitors while decreasing post-harvest N_2O emissions.

f. Planning crop rotations with cover crops to enhance crop NUE and potentially mitigating N_2O losses would be valuable. Rotating deep-rooted crops with shallow-rooted crops, leguminous crops with high N demanding crops and crops having low C:N crop residue with high N demanding crops are some examples of a well-designed crop rotation.

g. Research quantifying N_2O emissions from the non-growing season is scant; therefore, future research assessing growing and non-growing season emissions is needed to better estimate the risk of N_2O emissions from horticultural systems.

h. Due to low NUE, low C:N and high N content of crop residue in annual vegetable production systems, it is possible that vegetable production systems have a greater risk of N_2O production and emission (Fig 1) than grain crop systems. Therefore, future research comparing magnitude, seasonality, and N_2O production processes from annual vegetable and grain crop systems is needed.

Conclusions

We reviewed the potential soil, crop, and climatic factors to analyze the risk of N_2O production in some horticultural production systems in temperate climates. Main characteristics of horticultural production systems such as high N input, frequent irrigation, low crop NUE, leaving N-rich crop residue in the field after harvest, and narrow C:N of crop residue, potentially contribute in enhancing N_2O emissions. In temperate climates, N_2O emissions are significant during the non-growing season due to the presence of favorable conditions (e.g., presence of labile organic C and N substrates, residual soil mineral N, and high soil moisture). Yet, research that has quantified the magnitude of N_2O production and emission from horticultural cropping systems in Canada is limited. Based on the studies conducted so far in Canada, and elsewhere in similar climates, annual vegetable crops likely present a greater risk of N_2O emission than perennial fruit crops. Studies have shown N_2O emissions increase linearly when the amount of fertilizer N inputs is less than the crop demand; however, an exponential increase in N_2O emissions occurs when N fertilizer additions are more than the crop demand. We suggest that future research systematically analyzing factors (such as soil organic C status, inorganic N, soil moisture and temperature, plant type, N fertilizer application rate, methods, time, and source) known to impact the risk of N_2O emissions must be conducted to extend the results of this review and minimize N_2O losses in horticultural production systems. We also conclude that improved agronomic management strategies, such as using controlled/slow release N fertilizers, nitrification inhibitors, and designing crop rotations and systems aimed at tightening the cycling of N offer a promising opportunity in reducing N_2O losses to the environment.

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