Environmental and Economic Consequences of Tile Drainage Systems in Canada

Paper prepared for CAPI

by

Vivekananthan Kokulan
CAPI Doctoral Fellow 2017-2019
PhD Candidate, Biogeochemistry Research Group
Dept. of Geography and Environmental Management
University of Waterloo

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The Canadian Agri-Food Policy Institute

960 Carling Avenue, CEF

Building 49, Room 318

Ottawa, ON K1A 0C6

Telephone: 613-232-8008

Fax: 613-232-8008

www.capi-icpa.ca

1. Agricultural drainage in a changing climate

Drainage is a natural process that occurs in any landscape and is a key component of water cycling. This process is crucial in cropped systems as it reduces waterlogging conditions and facilitates plant growth. However, natural drainage is less effective on many farmlands due to soils with lower hydraulic conductivities, soil compaction, and poor relief. Therefore, a substantial proportion of agricultural lands, which, in most cases are vulnerable to waterlogged conditions, rely on artificial drainage systems. Around 11 % of the world's agricultural cropland is artificially drained. In North America, 27 % of the agricultural lands in the United States and 14 % of Canadian croplands are artificially drained (ICID, 2018).

Agricultural drainage can either be surface or subsurface. Surface drainage is often facilitated by using naturally existing in-farm swales and depressions to reroute or store water. Surface drainage can further be enhanced by improving the conditions of near-farm ditches. In contrast, subsurface drainage is enhanced through the installation of tile drains, which are perforated plastic or clay tubes installed in the vadose zone (unsaturated soil profile). Other artificial subsurface drainage systems are mole drainage, interceptor drains and ground water pumps. In general, tile drains reduce waterlogged conditions and the occurrence of overland flow by removing excess water from the vadose zone (thus enhancing water infiltration), improve soil aeration by keeping water table at desired depth, and facilitate improved crop growth and extended cropping and grazing seasons (King et al., 2015). The demand for agricultural drainage has increased recently to tackle uncertainties in precipitation patterns that are anticipated under a changing climate.

1.1. Subsurface drainage as a cause for environmental issues

Even though agronomically effective, tiles can also be the cause of several environmental problems. Enhancing drainage tiles may increase the edge of field runoff leading to increased risk of downstream flooding (Rahman et al., 2014). In addition, tile drainage can function as subsurface conduits for agricultural nutrients such as nitrogen (N) and phosphorus (P), which are crucial sources for algal blooms and subsequent eutrophication in surface water bodies (King et al., 2015). Scientific literature has also reported occurrences where tiles have been the sources for pathogens and other chemicals such as pesticides, veterinary antibiotics and heavy metals (Kladivko et al., 2010). The benefits and risks of tile drainage vary substantially according to regional climate, soils, management and tile configuration (e.g., King et al., 2015; Plach et al., 2018b). Therefore, regional and field scale studies must evaluate the impact of tile drains on both agronomy and environment relative to soils, management and tile configuration.

In Canada, extensive research on tile drainage has been done in Ontario and Quebec whereas little literature is available from other provinces (Christianson et al., 2015, 2016). Currently there is no literature that exclusively looks at the impacts of tile drainage from a pan-Canadian perspective. This paper has three objectives: (1) The first part of this study reviews the impact of tile drainage on edge of field runoff and agrochemical pollution in Canada; (2) The second part details the best management practices that can reduce tile nutrient losses without compromising the productivity; and (3) The last part of this study identifies and outlines research gaps and their practical importance in a changing climate from a policy perspective. Outcomes of this study will be useful for Canadian farmers, researchers and policy makers in identifying and adopting tools to increase the efficiency of subsurface drainage while minimizing its negative impacts.

2. Tile drainage in Canadian agriculture

Tile drains have been adopted by Canadian farmers since the mid-19th century. Initially, clay pipes were installed in hand dug trenches. However, tile drains are now installed with tile plows assisted by advanced surveying techniques such as Real Time Kinematics Global Navigation Satellite Systems (RTK GNSS). Historically, tile drainage systems were most extensively installed in the Canadian regions of Southern Ontario and Southwestern Quebec, in intensively farmed fields. For example, around 45 % of the Southern Ontario crop lands have been tiled. In Western Canada particularly in Alberta, tile drains have been historically used to overcome the salinity issue via flushing through tile drains (Broughton and Jutras, 2013). Substantial proportions of British Colombian and Nova Scotian farmlands have also been tile-drained. Although tile drainage has not historically been used in the Canadian Prairies, an increasing frequency of multiday spring and summer storms in these regions (Shook and Pomeroy, 2012) has caused farmers in provinces such as Manitoba and Saskatchewan to install tile drains at an accelerated rate to tackle the unprecedented waterlogging conditions in their crop fields (Cordeiro and Ranjan, 2012; Kokulan et al., 2019a). Installation of tile drains effectively modifies the vadose zone's[1] physical, chemical and biological properties, thus modifying field hydrology and biogeochemical processes.

2.1. Edge of field runoff

Tile drains can modify both the volume and pathways of runoff at the edge-of-field. The removal of excess vadose zone water by tile drainage increases the effective soil hydraulic conductivity resulting in suppression of surface runoff. However, this suppression of overland flow often depends on the regional climate and soil types. For example, tile flow accounted for 73 % of the total flow in a clay loam soil and 86 % of the total flow in a sandy loam soil in a two-year study conducted in Quebec (Eastman et al., 2010). In southern Ontario, Canada, Plach et al. (2019) reported that ~80% of annual runoff at the edge-of-field occurred through tile drains in a range of soil textures. In contrast, little flow travelled through tile drains in the nearly flat southern Manitoban agricultural landscapes underlain by clay rich soils, and overland flow dominated instead (Kokulan et al., 2019b). Indeed, 72-89 % of annual runoff occurred as overland flow.

The timing of runoff through tile drains also differs across Canada. For example, larger tile outflows have been observed in Ontario throughout the non-growing season and tile drains often do not flow during the growing season (Van Esbroeck et al., 2016; Woodley et al., 2018). In contrast, tiles rarely flowed in summer and never in winter in the Canadian prairies (Kokulan et al., 2019b) because conditions were either too dry or too cold. Substantial tile flow was only observed after the thawing of soil-ice layer in the Canadian Prairies.

It is not clear if, and to what extent, tile drainage may impact the volume of runoff exiting fields as few studies actively compared tiled and non-tiled fields. There is a possibility of increased edge of field runoff due to tile drains which in turn will increase the downstream flooding; however, none of the reviewed studies have evaluated this concept. This in an area where additional research is needed.

[1] The vadose zone is the area that extends from the ground surface to the regional groundwater table.

2.2. Phosphorus losses

Despite the dominance of tile drains as a flow path in some landscapes, overland flow appears to be the major runoff pathway for edge-of-field phosphorus (P) losses in Canadian landscapes where both overland and tile flow prevail. Overland flow was responsible for more than 90 % of annual P losses in the nearly flat southern Manitoban landscapes with clay rich soils over a three-year period (Kokulan et al., 2019b). In a five-year study in Ontario, substantial amounts of P were lost via overland flow even though tile drainage was responsible for the majority of annual runoff (Van Esbroeck et al., 2016; Plach et al., 2019). Nevertheless, tile drains can be the crucial edge-of-field P pathway in landscapes with minimal overland flow (Tan and Zhang, 2011; Plach et al., 2019).

The tendency of tile drains to be significant exporters of P depends in a range of factors. Soils with higher soil test P are more likely to desorb P to runoff and drainage water (e.g. Plach et al., 2018a; Duncan et al., 2017). However, the threshold P value varies between soils depending on their P sorption capacity and P saturation. For example, clayey soils can retain more P over sandy soils due to their higher P sorption capacity. In addition, the tendency of P release by soils also depends on soil P pool in which most of the P is retained. For example, P retained in reducible form (higher oxides of Fe and Mn) may become available during anoxic conditions through reductive dissolution reactions. On the other hand, P is often stable and rarely released to runoff water when bound to calcium and magnesium. Recent work (Plach et al., 2018b) has shown that soils across Ontario retain P in different forms, which has implications for the vulnerability of those fields to lose P via tile drains. However, the existence of preferential flow pathways in soils often overrides the natural tendency of the soils to retain P in their matrix. Tile P losses through preferential flow paths are critical in clay-rich soils due to the existence of macropores (Grant et al., 2019), which can be present as either desiccation cracks or biopores. Preferential flow tile P losses have been reported in Ontario and Quebec clayey and loamy soils at times accounting for majority of tile P losses (Michaud et al., 2018; Tan and Zhang, 2011). On the contrary, Kokulan et al (2019a, b) did not find direct surface-tile connectivity in Manitoban vertisols despite their tendency to form cracks.

Farm operations such as tillage methods and nutrient application can affect P in tile runoff. In fine textured soils, conservation practices such as no-till operations have been found to increase preferential flow-attributed tile P losses by preserving the macropore network (King et al., 2015; Jarvie et al., 2017). In such cases, practices such as minimum till are recommended to disrupt the macropore network and to reduce subsequent P losses (Zhang et al., 2017). However, the effects of no-till are not consistent across the landscape. For example, no significant difference was observed in tile P loads between annual disk till and minimum till in non-macroporous soils like sandy loams (Lam et al., 2016) and silt loams (M. Macrae, University of Waterloo. Unpublished data). Fertilizer and manure application methods such as broadcasting can also result in higher tile P losses mainly though preferential flow, whereas the subsurface placement of fertilizer can reduce P losses (Grant et al., 2019; Qi et al., 2018).

The form of nutrient application (manure vs fertilizer) may also influence tile P losses (Macrae et al., 2007). In general, manure applications contain more P than mineral fertilizers as manure requirements are calculated based on N requirements. Furthermore, in clayey soils, increased preferential flow connectivity has been observed in manure applied plots, which may further increase the possibility of tile P losses (Ali et al., 2018). Indeed, tile P losses may be further exacerbated, especially when manure application is accompanied with zero tillage (Zhang et al., 2017). Kinley et al (2007) observed higher tile P losses from several Nova Scotian fields that received swine and poultry manure. On the contrary, Wang et al (2018) have found solid cattle manure more resistant to P losses when compared to inorganic fertilizers and liquid cattle manure. Continuous fertilization could further increase tile P losses (Zhang et al., 2015). Improved knowledge of the relative contributions of manure and inorganic P fertilizer to edge-of-field losses are needed. Moreover, research is needed on whether periodic assessments of soil test P and variable rate P application (avoid applying on P enriched areas) may considerably decrease tile P losses.

2.3. Nitrogen losses

Nitrate (NO_3^-) ions are not only sensitive to crop management practices but also have the potential to leach through the soil matrix. Therefore, tile drainage often contributes to increased N losses. For example, 40-50 % of annual nitrate losses were attributed to tile drainage in vertisols of Southern Manitoba where tiles were responsible for only 11-28% of annual flow (Kokulan et al., 2019b). Tile drainage (54-58 %) and groundwater resurgence (39-45 %) were responsible for the majority of the nitrate loads in an agricultural catchment in Quebec whereas surface runoff was only responsible for 3 % of the total nitrate loads (Michaud et al., 2018).

LikeP, fertilization is one of the primary reasons for increased tile N losses. Elevated tile N concentrations were seen even with recommended N rates (Philips et al., 1982). Farms that receive organic inputs like poultry and swine manure are likely to lose more N through tile drains (Kinley et al., 2010; Smith and Kellman, 2011). Fields that receive herbicides such as glyphosate also have resulted in elevated tile N losses potentially due to increased mineralization (Fuller et al., 2010). Rainfall events following fertilizer application may also exacerbate tile N losses (Kokulan et al., 2019b). Unlike P, tile N has been shown to be lower in no till cultivation as increased volatilization and denitrification result in aerial N losses (Fuller et al., 2010).

Nitrate concentrations in tile water often exceed the recommended thresholds for drinking water (< 10mg N/ L) rotation and continuous cropping systems with corn (Bolton et al., 1970; Woodley et al., 2018) potentially due to poor crop N use efficiencies (Tan et al., 2002). These losses can further be exacerbated in cropping systems where a leguminous cover crop is being ploughed in addition to fertilization (Woodley et al., 2018). Therefore, N fertilizer rates should be adjusted when a legume crop is cultivated. Management practices like straw mulching may also reduce nitrate leaching into tile for a certain period (Milburn et al., 1997). However, long term studies are absent.

3. Ways to minimize tile nutrient losses to environment without compromising productivity

3.1. The 4R Principle

The 4R principle is centered around adapting fertilizer application to optimize the productivity with little environmental impact. The 4 Rs stand for right fertilizer source, right rate, right time and right place. For example, a high proportion of soluble P fraction leads to elevated P losses from raw manure application. Therefore, generating low P manure or processed manure with lower available P fractions might be a solution (Kumaragamage and Akinremi, 2018). Following P fertilizer application rates based on soil test P levels not only reduces runoff P, but also boosts economic returns.

Timing of fertilization is also a major concern as fall application of manure often results in increased nutrient losses during winter runoff in Ontario, Quebec and Nova Scotia. Therefore, applying fertilizers in spring is recommended. Even if they are applied in spring, a subsequent rainfall could lead to major runoff nutrient losses. Therefore, the fertilizers have to be mixed (right place) with soil for better retention and crop growth. Subsurface banding of P fertilizers or applying as P fertilizers liquids has the potential to reduce tile P losses by limiting the contact between P and preferential flowpaths (Grant et al., 2019). However, these conditions may vary with region and management options. Therefore, formulating regional 4R strategies considering managemental options could aid in better crop production with minimal environmental impacts (King et al., 2018).

3.2. Controlled drainage

Controlled drainage (CD) is a best management practice (BMP) where water table depths are regulated by an adjustable raised structure at the tile outlet. Maintaining desirable water depths through CD has agronomic and environmental advantages (Crabbe et al., 2012; Sunohara et al., 2016). However, these benefits may vary with regional climate, soils and management. For example, increased soybean and corn yields were reported under CD when compared to free drainage (FD) in Ontario (Crabbe et al., 2012; Ng et al., 2002; Sunohara et al., 2016). On the contrary, higher yields were observed in FD in Manitoban sandy loams over CD in potato cultivation potentially due to deeper tile depths (Satchithanantham et al., 2012). However, CD can significantly reduce P loads due to controlled flow (Corderio et al., 2014; Sunohara et al., 2016; Tan and Zhang, 2011). Controlled drainage also reduces P losses when combined with a wetland reservoir (Tan et al., 2007) and wood chip bioreactors with alum-based drinking water plant residues (Gottschall et., 2016). In contrast, Valero et al (2007) observed high P losses in CD, which they attributed to increased P solubility due to higher water table positions.

Controlled drainage with sub-irrigation (CDS) was found to be effective in reducing nitrate concentrations and loads when compared to FD in a variety of soil textures ranging from sandy loams to clay loams (Cordeiro et al., 2014; Drury et al., 1996; Ng et al., 2002; Sunohara et al., 2016). Further reductions in nitrates were seen when CDS was combined with another best management practice such as conservation tillage (Drury et al., 1996), cover crops (Drury et al., 2014), recycling through a wetland reservoir (Tan et al., 2007), woodchip denitrification bioreactors (Husk et al., 2018) and woodchip bioreactors with alum-based drinking water treatment plant residues (Gottschall et al., 2016). However, reduction of nitrate in CDS may increase leaching of nitrate into groundwater, lateral seepage into drainage ditches and gaseous N emissions (Sunohara et al., 2014). An increase in surface runoff nitrate loads was also observed with CDS but the combined losses (surface runoff +CDS) were still smaller when compared to FD (Drury et al., 1996). In addition, increased antibiotic concentrations were observed in CDS effluent (Frey et al., 2015) and in the ditches that received CDS outflows (Wilkes et al., 2019) potentially due to the reduction of flow and absence of dilution. However, antibiotics in the CDS water may be reduced with a woodchip bioreactor with 10% alum-based drinking water plant residues (Gottschall et al., 2016).

3.3. Recycling drainage water

Re-routing tile effluent to retention structures like in-farm retention ponds or constructed wetlands is also a viable alternative to control edge of field tile nutrient losses. This retained water can be recycled for irrigation during water demanding periods. P and N losses were reduced and yields were boosted during dry years when CDS effluent was recycled through a wetland reservoir in Ontario (Tan et al., 2007) and Quebec (Kroeger et al., 2007). However, re-irrigating constructed wetland water to raw crops should be done with caution as another study observed increased E. coli in a retention pond during warmer days (Havestock et al., 2017). This is another area that requires further research.

3.4. Using caution with no till cultivation

Increased P losses in macroporous soils through preferential pathways are an issue especially in no till systems where the soil structural development is enhanced (Williams et al., 2018; Zhang et al., 2017). Conversely, conventional tillage may loosen up soil particles and encourage nutrient and sediment loss through overland flow. Therefore, current research recommends minimum conservation tillage or reduced tillage where only the top soil is tilled annually or bi-annually to disturb surface-tile connectivity. If not, subsurface fertilizer placement methods such as subsurface fertilizer injection may help in reducing P losses in no tillage fields (Williams et al., 2018).

4. Suggestions for future research and policy making

Despite wide use of tile drainage in Canadian agriculture and research being done regarding its agronomic potential and environmental impacts, important gaps and questions still remain.

4.1. Need for region-specific research

Factors that influence tile flow and nutrient losses vary with regional climate, soils and management. Significant work has been done on drainage tiles from Ontario and Quebec. These works are important considering the wide adaptation of tile drains in these provinces and their locations close to the Great Lakes. However, certain findings of these studies cannot be applied to areas like Canadian Prairies where tile drainage is expanding. For example, larger tile outflows that are frequently observed in Ontario during winter months were not seen in Manitoba due to frozen soils (Kokulan et al., 2019b; Plach et al., 2019). Therefore, further research is needed especially from the regions where tile drainage is expanding to correctly assess their economic and environmental feasibility.

4.2. Need for long term water quality monitoring programs

In a changing climate with increasing weather uncertainty, short-term monitoring of hydrologic responses often fails to capture extreme events and long-term trends in hydrologic responses. Currently, long term tile drainage studies are lacking. Long term monitoring programs also aid in identifying changes in runoff composition with adaptation or modification of a particular management practice.

4.3. Simultaneous monitoring of agrochemicals in tile effluent

Even though both P and N are responsible for water quality issues, only a handful of studies have simultaneously monitored the trends of both nutrients in tile water. In soil profile, the majority of P is moved through preferential flow pathways whereas nitrate-N is mainly transported through soil matrix. Therefore, strategies that are taken to reduce one nutrient in tile flow may exacerbate the losses of another nutrient. Therefore, studies that include simultaneous measurements of both N and P nutrients are recommended to evaluate the efficiency of management strategies.

Studies focusing on other agrochemicals (e.g. pesticide residue) and antibiotics in agricultural drainage are also encouraged as there are not many Canadian studies that have addressed this.

In addition, overland flow is the greater contributor for P loss and its importance as a major hydrologic pathway cannot be understated. Therefore, studies that look into tile and control drainage should also monitor the overland flow for runoff and nutrient losses.

4.4. Controlled drainage and water recycling

Research done in Canada shows controlled drainage combined with another best management practice such as bioreactors or sub-irrigation could reduce edge of field nutrient loads without compromising crop yield. However, the suitability of controlled drainage in agricultural regions underlain by groundwater aquifers should be evaluated due to nitrate leaching concerns. Automated lifting stations are increasing in popularity in regions with little slope such as Southern Manitoba. Their efficacy on water management and quality should be evaluated. In addition, the efficiency of retention and re-cycling facilities such as retention ponds and constructed wetlands in reducing edge of field nutrient losses should also be evaluated.

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