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Inadequacy of agricultural best management practices under warmer climates

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Abstract

Agricultural best management practices (BMPs) are often implemented to reduce nutrient transport from farmland to downstream waterbodies. However, under the scenario of a changing climate, nutrient transport processes may be altered and BMPs may not be as effective. Using an ensemble of downscaled climate projections under moderate and high radiative forcings, we perform a hybrid climate assessment of BMPs in a large, flat, and primarily agricultural watershed in the Canadian Prairies. We quantify the total nitrogen delivery under current and future climate scenarios, with and without BMPs. Our findings reveal that BMP combinations, which are currently sufficient under historical climate conditions, may become inadequate to handle increased nitrogen under future climate conditions. We examine the enhancement of BMPs, conditioned to mean ensemble projections. Although updated combinations of BMPs show improvements in both the magnitude and cost of nitrogen removal compared to historical practices, their efficiency systematically declines as temperature rises. The decline rate of BMP efficiency is significantly larger under the high radiative forcing. Even by implementing all considered BMPs, we show that, at least under some realizations of future climate, the historical status-quo nitrogen state, in which no BMP is implemented, cannot be maintained. Our study demonstrates the reduced effectiveness of BMPs as the climate warms. To combat this, we recommend the immediate implementation of updated BMPs to slow down the build up of nitrogen. However, in innovations in physical, chemical, and biological remediation technologies would be needed in long term to control nitrogen loads coming from farmlands.

1. Introduction

Nitrogen is one of the essential elements for crop growth (Mariotti *et al* 2008). However, most nitrogen exists in a stable gaseous form; therefore, there is limited availability of the 'reactive' nitrogen required for plant growth (Hutchinson 1944). This limitation was 'fixed' in the early 20th century by the seminal work of Haber and Bosch, who suggested an industrial solution for producing synthetic reactive nitrogen (Ellis 2018). The invention of fertilizers resulted in the so-called 'Green Revolution' that significantly increased the amount of food produced and supported a 3-fold increase in the human population since the 1950s (Khush 1999). At present, maintaining global food security is somehow unimaginable without nitrogen-rich fertilizers (Liang 2022); however, nitrogen applied to farmlands can be transported by runoff to water resources. Moreover, global food production systems rely heavily on livestock farming, which amplifies nitrogen levels in water bodies through the discharge of animal waste and food.

High nitrogen content in water poses risks to both human health and ecosystems and has now evolved into a global challenge to water security (Zimmerman *et al* 2008, Mekonnen and Hoekstra 2015, Strokal *et al*

2019). A common strategy to reduce nitrogen transport from farmlands is through implementing best management practices (BMPs) (Meals *et al* 2010, Liu *et al* 2017). There are guidelines for selecting BMPs based on their implementation costs and effectiveness under historical conditions (Maringanti *et al* 2009, Shen *et al* 2023a). Nevertheless, changing natural and anthropogenic conditions can impact nitrogen loading and the effectiveness of BMPs selected under historical conditions (Xie *et al* 2015, Walters and Babbar-Sebens 2016, Qiu *et al* 2020). In particular, climate change can affect physical, chemical, and biological processes controlling nitrogen export (Panagopoulos *et al* 2011, Liu *et al* 2019). For instance, rising temperatures reduce diffusion, increase the decomposition of organic matter, enhance nitrogen volatilization from soil and water bodies, intensify nitrogen release from sediments and vegetation into water bodies, and accelerate eutrophication (Shen *et al* 2023b, Ficklin *et al* 2010, Nazari-Sharabian *et al* 2019). Changes in precipitation characteristics can also influence the nitrogen delivery by altering soil erosion, leaching, surface runoff, and sediment suspension and transport (Howarth *et al* 2006, Lychuk *et al* 2021).

Given the high costs of long-term monitoring, quantifying the impact of climate change on BMPs' performance relies heavily on assessments made by water quality models (Wallace *et al* 2017, Kim *et al* 2021, Plunge *et al* 2022, Yang *et al* 2022). These assessments are often scenario-led and utilize projections of global climate models (GCMs) under future pathways for greenhouse gas emissions and human development (Meinshausen *et al* 2011, 2020). There are alternative scenario-neutral frameworks that do not rely on GCM projections (Bussi *et al* 2017, Yang *et al* 2017). Such studies show that implementing a combination of BMPs may counteract climate-change induced increases in nitrogen loadings (Woznicki and Nejadhashemi 2014, Ghimire *et al* 2021). However, it has been noted that BMP selection must be guided by local knowledge due to small scale changes in nitrogen export and responses to climatic changes (Bosch *et al* 2014, Johnson *et al* 2022).

There are methodological limitations to both scenario-led and scenario-neutral climate change assessments. While GCMs are valuable tools for understanding future climate, they are affected by a large cascade of uncertainty (Wilby 2017). Although scenario-neutral frameworks avoid these specific uncertainties, they include other sources of uncertainty (Nazemi *et al* 2020), and cannot indicate when trade-offs and critical conditions occur (Mahdian *et al* 2023). Even without considering the uncertainties in representing future climate, BMP assessments using water quality models remain highly uncertain due to the complex interplay of varying climatic conditions and heterogeneities in responses to BMPs, which are not well represented in water quality models. In addition, the scarcity of multi-year monitoring data limits the parameterization and validation of BMP representations in water quality models (Lintern *et al* 2020). As a result, there is a need for rigorous sensitivity analyses that are often overlooked. Apart from these methodological constraints, there are limited studies that look into the reliability of BMPs and explore whether they remain viable solutions in a warmer world (Chaubey *et al* 2010).

In this paper, we address these methodological and epistemological gaps in the Qu'Appelle River Basin (QARB), a 55 700 km^2 watershed in Saskatchewan, Canada. With a total area ∼1.3 times the Netherlands, the QARB has a critical role in North American grain and cattle production (FAO 2010, Statistics Canada 2016), and is currently facing a range of water quality challenges related to nitrogen management (Waiser *et al* 2011). Due to its flat terrain, slow water movement and shallow wetlands, water tends to stay in the watershed for a long time and therefore the residence time of the nutrients dissolved in the water is relatively high in the QARB (Costa *et al* 2021). As climate warms and agricultural production grows, the catchment will be saturated faster compared to steeper watersheds (Baulch *et al* 2019). Therefore, the QARB could exemplify a global tipping point of highly agricultural regions that are facing excessive nitrogen surplus, and could demonstrate how regional transformation of nitrogen cycles, which have supported booming socio-economic activities for decades, could ultimately reach an unprecedented rate and threaten both humans and the environment.

We are particularly interested in knowing (1) the changes in nitrogen depositions due to climate change, and (2) the impact of updating BMPs, i.e. BMP adaptation, on excess nitrogen under changing climate scenarios given the uncertainties involved. To tackle the methodological gaps noted above, we apply a so-called hybrid assessment framework that combines the strengths of scenario-led and scenario-neutral frameworks in a unified assessment. On the one hand, we quantify the catchment's nitrogen delivery by considering a range of changes in temperature and precipitation using a scenario-neutral approach. We also evaluate the performance of BMPs selected based on historical climate scenarios (hereafter historical BMPs) under these changing climate conditions. On the other hand, we use an ensemble of downscaled projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring *et al* 2016, O'Neill *et al* 2016) to identify new combinations of BMPs that can improve water quality under future climate (hereafter adapted BMPs). We compare the performance of adapted BMPs with historical practices, both in terms of magnitude of nitrogen removal and the cost of implementation. We introduce a set of measures to allow systematic comparisons between

BMPs and to highlight the role of climate change on the reliability of BMPs in the QARB.

2. Methods

2.1. Case study

The QARB is home to one-third of Saskatchewan's population, and agriculture is the main socio-economic activity in the basin (Andreichuk 2017). Hydrologically, the QARB is the contributing catchment to the Qu'Appelle River and encompasses a river network covering 14 779 sub-catchments that drain into twelve tributaries (figure 1), from which Indian Head Creek has the least number of sub-catchments (81) and the Moose Jaw River has the highest count (3408). The basin can be segmented into upstream (Zone 1), midstream (Zone 2), and downstream (Zone 3), each shown in a different color in figure 1 (Akomeah *et al* 2019).

Zone 1 includes the Ridge and Iskwao Creeks and has the smallest number of cattle and cropland areas. Therefore, it maintains the lowest deposition of total nitrogen (TN) in the whole basin—see table 2. Zone 2, located in the central part of the QARB, has the largest catchment area (28 533 km^2; nearly the size of Albania) and includes the six tributaries of the Moose Jaw River, Wascana, Last Mountain, Loon Creeks, and Jumping Deer creeks (Water Security Agency 2008, Roste and Baulch 2018). This zone is characterized by the largest croplands and cattle production farms in the QARB. Zone 3 covers the tributaries of the Indian Head, Redfox, Pheasant, Pearl, and Ekapo creeks (Water Security Agency 2013). Table 1 provides an overview of the total, effective, and cropland areas, as well as number of cattle heads in each zone.

Grain farmers in the QARB often employ fertilizer to enhance crop yield, leading to an accumulation of TN in the soil (Van Meter *et al* 2018). Moreover, cattle farms (corrals) generate manure, urines and residual feed that contain nitrogen (Hooda *et al* 2000, Chen *et al* 2018). Nitrogen from these nonpoint sources is transported to streams through surface runoff during snowmelt and rainfall events (Boyer *et al* 2018). As a result, water quality in the QARB has significantly degraded (Costa *et al* 2020). In addition, wetlands in this area have been drained to expand farmland (McRae 2013, Ducks Unlimited Canada 2022). Wetland drainage has contributed to nutrient delivery to water bodies, given that wetlands can remove a large proportion of TN from runoff (39%–48%; Jordan *et al* 2011, Untereiner *et al* 2015).

The climate of the QARB has undergone significant change over the past several decades. Regionally, there have been increases in long-term annual temperature (∼2 °C) and precipitation (∼7%) from 1948 to 2016 across the Canadian Prairies (Zhang *et al* 2019). Previous studies based on CMIP5 projections show continued increases in temperature (1.5 °C to 6.5 °C) and precipitation (5% to 15.3%) in the region throughout the 21st century (Zhang *et al* 2019). Specifically, for the QARB, an average increase of between 3.15 °C and 4.6 °C for temperature and 6.4% to 8% for precipitation are projected using 24 CMIP5 climate models for the period 2051–2080 as compared to 1976–2005 (Climate Atlas of Canada 2024). High air temperatures can activate nitrogen compounds in the soil and water (Bai *et al* 2012). Increased precipitation can result in increasing surface runoff, leaching, and soil erosion and intensify the transportation of nitrogen to the streams (Ballard *et al* 2019, Wu *et al* 2022).

2.2. Water quality model and BMP representation

Given the current nitrogen state of the QARB (see table 2) and the multifaceted nature of warming climate, a comprehensive assessment is required to determine the nitrogen state of the QARB and the role of BMPs in the region. Nitrogen management has been challenging in the QARB, due to lack of data and known limitations in water quantity and quality models in prairie regions (Mekonnen *et al* 2015, Akomeah *et al* 2022, Baron *et al* 2024). To address these limitations and provide an assessment tool using available information, Hassanzadeh *et al* (2019) introduced the SD-Qu'Appelle model for water quality assessment in the QARB. The SD-Qu'Appelle emulates the United States Geological Survey's SPAtially Referenced Regression On Watershed attributes model (SPARROW; Schwarz *et al* 2006, Morales-Marín *et al* 2015, García *et al* 2016), which calculates the long-term nutrient delivery as a series of additive/multiplicative exponential functions. In brief, the SD-Qu'Appelle calculates the annual average TN delivery from tributary j as a sum of TN delivery from all contributing sub-catchments $I(j)$. The TN delivery from each sub-catchment $i \in I(j)$ is a non-linear function of point and non-point TN sources, considering attenuations associated with landscape, climate, and aquatic processes:

$$TN_j = \sum_{i \in I(j)} \Bigg[\{((a_{1j}N_{1i} + a_{2j}N_{2i} + a_{3j}N_{3i}) \times A_i \times \exp\{t_jT_i + p_jP_i + w_jW_i + l_jL_i + f_jF_i\}) + b_jB_i\} \times \exp\left\{\frac{-0.5s_jS_i}{V_i}\right\} \times \left(\frac{1}{1+\frac{q_j}{Q_i}}\right)\Bigg] \quad (1)$$

where N_{1i}, N_{2i}, and N_{3i} represent non-point TN contributions from sub-catchment i to tributary j due to fertilizer, spread manure, and cattle corrals (feedlots), respectively. A_i represents the effective sub-catchment area. Factors influencing non-point TN export from land to water are air temperature (T_i), precipitation (P_i), wetland coverage (W_i), land slope

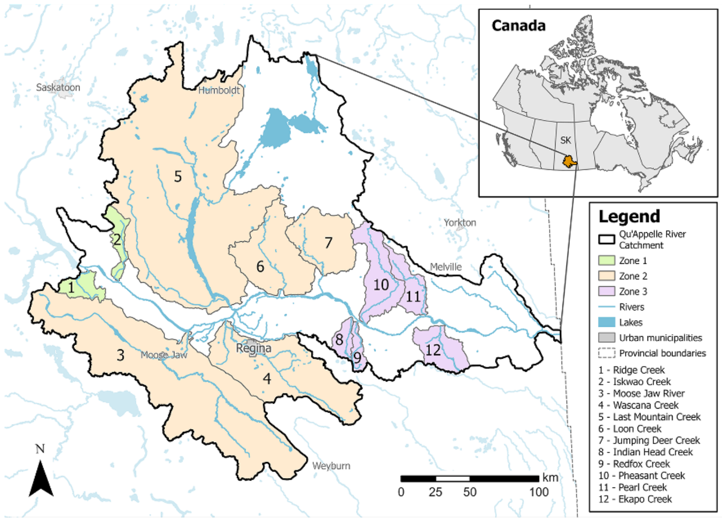

Figure 1. Qu'Appelle River Basin, Saskatchewan, Canada and its main tributaries at the basin's upstream (tributaries 1–2; Zone 1), midstream (tributaries 3–7; Zone 2), and downstream (tributaries 8–12; Zone 3). The map is adapted from Hassanzadeh *et al* (2019); reused with permission from Elsevier: license # 5903221322488'.

Table 1. Catchment and farming characteristics in Zones 1, 2, and 3 in the QARB.

Features	Zone 1	Zone 2	Zone 3
Total area (km^2)	1153	28 533	5933
Effective drainage area (km^2)	507	10 264	2318
Cropland area (km^2)	341	5686	1189
Wetland coverage (km^2)	77	2691	416
Number of cattle	4500	68 000	14 000
Average land slope	0.027	0.028	0.030
Average soil permeability (in/hr)	1.69	1.49	1.89
Average stream length (km)	1.31	1.32	1.36
Average streamflow velocity (m/s)	0.21	0.22	0.21

(L_i), and permeability (F_i). B_i is the total point-source TN, e.g. from urban and rural communities. Variables influencing aquatic TN transport are streamflow length (S_i), velocity (V_i), and lake/reservoir hydraulic loads (Q_i). The a_j, t_j, p_j, w_j, l_j,f_j, b, s_j, and q_j are the free parameters and are identified in each tributary through calibration. The TN delivery from the tributaries in each zone are then summed up to provide the total TN (ton/year) per zone. Required data for model development are obtained from Saskatchewan's Water Security Agency (www.wsask.ca), an organization responsible for water management in the province. The model is validated by historical observations of TN and verified by the original SPARROW model (Hassanzadeh *et al* 2019). The model is built in a System Dynamics environment (Forrester 1994, Hassanzadeh 2019), providing a simple interface to engage with stakeholders (Malard *et al* 2017).

Using the SD-Qu'Appelle model, a suite of five BMPs related to land, stream, and land-to-stream delivery has been identified through extensive consultations with local stakeholders and government agencies in the QARB (see Bradford *et al* 2020). These BMPs include holding ponds (HPs), wetland conservations (WCs), flow controls (FCs), storage dams (SDs), and grassing ditches (GDs) and are represented in the SD-Qu'Appelle model by a set of coefficients, described by Hassanzadeh *et al* (2019)—see equation (S1) in the supplementary materials for the representation of these BMPs within the structure of the SD-Qu'Appelle model. These practices are commonly applied in the Canadian Prairies and have been identified as effective BMPs in the region (Baulch *et al* 2019, Liu *et al* 2022)—see section S1 in the supplementary materials for a review on the use and efficiency of these BMPs in the prairies as well as the values chosen for their corresponding coefficients in the model. As BMP assessments in this study are solely model based, our results heavily depend on how BMPs are represented within the model structure and how the value of BMP coefficients are chosen. As a result, we provide a formal sensitivity analysis by studying the partial derivatives of TN with respect to each of the BMP coefficients. This analysis is provided in section S2 in the supplementary materials.

Table 2. Historical BMPs and their cost-effectiveness in the three zones of QARB based on Zammali *et al* (2021).

Item	Zone 1	Zone 2	Zone 3
Selected BMP portfolio	FCs, GDs, WCs, HPs	WCs	HPs, WCs, GDs
TN without BMPs (ton/year)	12	286	51
TN reduction with BMPs (%)	58	81	88
Cost of implementation ($/year)	1.6 M	51 M	9.9 M
Abatement cost ($/kg TN removal)	229	220	221

Zammali *et al* (2021) enhanced the SD-Qu'Appelle model to calculate the capital costs and construction/operation costs based on governmental records. Through cost-effectiveness analysis, they identified a BMP portfolio for reducing TN with a feasible annualized cost for each zone during the historical period. Table 2 summarizes the results obtained by Zammali *et al* (2021) for the historical TN before BMP implementation (hereafter status-quo scenario), the historical BMPs selected in each zone, their percentage of TN removal, and their associated annualized costs.

2.3. BMP adaptation and climate change impact assessment

Using a scenario-neutral approach, we aim to identify the TN response to climate change, both with and without the implementation of historical BMPs. We use a precipitation range of −15% to +40%, slightly broader than the projected range of −12% to +38% obtained by downscaled CMIP6 projections for the QARB, to allow for more comprehensive sampling. For temperature, we also apply a range of −1 °C to +8.5 °C, which is broader than the projected range of 0.75 °C to +8.3 °C, to allow for capturing the impacts of both cooling and warming. Figure S1 in the supplementary materials compares these ranges with those based on downscaled CMIP6 models. We utilize an increment of 0.5 °C for temperature change and 5% for precipitation to create a matrix of 240 climate futures. These scenarios are fed to the SD-Qu'Appelle to quantity the impact of changing climate on TN.

In parallel, we implement a scenario-led framework to delineate pathways for BMP adaptation corresponding to consecutive 30 year projections from 2025 to 2095 (e.g., 2025–2054, 2026–2055…, and 2066–2095). For this purpose, we use the ensemble 20 downscaled CMIP6 models under Shared Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5, respectively (O'Neill *et al* 2017, Riahi *et al* 2017). These SSPs correspond to moderate and high radiative forcing respectively and have been frequently used as bases in recent impact assessment studies (Bian *et al* 2021, Dawadi *et al* 2022, Crévolin *et al* 2023). Downscaled climate projections under these two SSPs were obtained from National Aeronautics and Space Administration's (NASA) Earth Exchange Global Daily Downscaled Projections (Thrasher *et al* 2021, 2022) that provides bias-corrected and spatially downscaled projections of CMIP6 models at a spatial resolution of 0.25 degrees. The list of climate models used is provided in table S1 in the supplementary materials. The mean ensemble of downscaled projections under each radiative forcing is employed to identify new combinations of BMPs through cost-effective analysis at every 30 year horizon from 2025 to 2095. Repeating this analysis for each zone at every 30 year sequence delineates an adaptation pathway under each future radiative forcing. Future costs of BMP implementation are estimated by applying a flat 2% inflation rate per year. These identified BMPs, along with their projected cost and effectiveness in TN removal, are presented to local stakeholders through multiple workshops and are finalized with their approval. We also used individual ensemble members to address the sensitivity of the adapted BMPs, conditioned to other possible realizations of the future climate.

To systematically assess the impact of climate change and the role of BMP adaptation on the TN state, a set of performance measures are defined. We start with investigating the impact of climate change on the status-quo TN export from each zone. To do so, we calculate the relative difference between TN (ton/year) under changing climate ΔC with no BMP, $\mathrm{TN}(C_0+\Delta C,\mathrm{null})$, and status-quo state, $\mathrm{TN}(C_0,\mathrm{null})$:

$$R_0(\Delta C,\mathrm{null}) = \frac{\mathrm{TN}(C_0+\Delta C,\mathrm{null})-\mathrm{TN}(C_0,\mathrm{null})}{\mathrm{TN}(C_0,\mathrm{null})}\times 100. \quad (2)$$

Values of $\mathrm{TN}(C_0,\mathrm{null})$ for each zone are reported in table 2. Positive values of R_0 show that ΔC has caused an increase in TN, leading to degraded water quality conditions. Similarly, the impacts of BMPs on TN under a given changing climate condition ΔC can be quantified by calculating the percentage of difference in TNs with BMPs, $\mathrm{TN}(C_0+\Delta C,\ \mathrm{BMP})$, and no BMP, $\mathrm{TN}(C_0+\Delta C,\mathrm{null})$:

$$R_1(\Delta C,\mathrm{BMP}) = \frac{\mathrm{TN}(C_0+\Delta C,\mathrm{BMP})-\mathrm{TN}(C_0+\Delta C,\mathrm{null})}{\mathrm{TN}(C_0+\Delta C,\mathrm{null})}\times 100. \quad (3)$$

Negative values of R_1 denote the positive impact of BMPs on reducing TN. The magnitude of R_1 for historical BMPs in each zone, $R_1(0, \mathrm{BMP}_0)$, is reported in table 2; but the values should be negative to denote reduction. Finally, to see whether BMPs can mask the impacts of climate change, we quantify the percentage of relative difference between $\mathrm{TN}(C_0 + \Delta C, \mathrm{BMP})$ and $\mathrm{TN}(C_0, \mathrm{null})$:

$$R_2(\Delta C, \mathrm{BMP}) = \frac{\mathrm{TN}(C_0 + \Delta C, \mathrm{BMP}) - \mathrm{TN}(C_0, \mathrm{null})}{\mathrm{TN}(C_0, \mathrm{null})} \times 100. \quad (4)$$

Positive values of R_2 indicate that, despite the implementation of BMPs, TN values under changing climate conditions would still be higher than the status-quo historical levels with no BMP implementation. In that regard, it is crucial to evaluate how BMP adaptations perform under changing climate conditions. To address this, we first quantify the changes in efficacy of a given BMP under changing climate conditions as:

$$R_{\mathrm{eff}}(BMP|\Delta C) = \frac{R_1(\Delta C, \mathrm{BMP}) - R_1(0, \mathrm{BMP})}{R_1(0, \mathrm{BMP})} \times 100. \quad (5)$$

Positive values of $R_{\mathrm{eff}}(\mathrm{BMP}|\Delta C)$ denote a condition in which the given BMP has higher efficiency under changing climate ΔC. In parallel, the role of BMP adaptations under a given changing climate condition ΔC can be measured by the relative difference between the efficiency of updated BMPs, $R_1(\Delta C, \mathrm{BMP}_{\mathrm{new}})$, and the historical BMP under the same climatic changes, $R_1(\Delta C, \mathrm{BMP}_0)$:

$$R_{\mathrm{eff}}(\Delta\mathrm{BMP}|\Delta C) = \frac{R_1(\Delta C, \mathrm{BMP}_{\mathrm{new}}) - R_1(\Delta C, \mathrm{BMP}_0)}{R_1(\Delta C, \mathrm{BMP}_0)} \times 100. \quad (6)$$

Positive values of $R_{\mathrm{eff}}(\Delta\mathrm{BMP}|\Delta C)$ show conditions in which BMP adaptations provide better efficiency in removing TN than historical BMPs. Finally, the overall impact of BMP implementation under changing climate ΔC can be assessed by comparing the efficacy of updated BMPs under climate change with the historical BMP under historical climate:

$$R_{\mathrm{eff}}(\Delta\mathrm{BMP}, \Delta C) = \frac{R_1(\Delta C, \mathrm{BMP}_{\mathrm{new}}) - R_1(0, \mathrm{BMP}_0)}{R_1(0, \mathrm{BMP}_0)} \times 100 \quad (7)$$

$R_1(0, \mathrm{BMP}_0)$ is the efficacy of historical BMPs under no change. Positive $R_{\mathrm{eff}}(\Delta\mathrm{BMP}, \Delta C)$ denotes that new BMPs are more efficient under change than the historical BMPs under no climate change.

3. Results and discussion

3.1. The impact of climatic change and performance of historical BMPs

To understand the baseline state of TN in the QARB under changing climate conditions, we perturbed the historical 30 year average temperature and precipitation at each zone, using a simple delta method (Hatami and Nazemi 2021, 2022), and fed the perturbed climate into SD-Qu'Appelle without considering BMPs. The results are shown in figure 2, in which the grids related to historical climate are highlighted by black squares—see the exact values of TN under changing climate in each zone in table S2 in the supplementary materials. This figure clearly shows the excessive impact of changing climate on TN export, with a significantly stronger role for temperature compared to as precipitation. Figure S2 in the supplementary materials illustrate that the greatest impact of precipitation changes occurs in Zone 2 and at a warming of 8.5 °C, leading to an ~6.5% increase in TN.

Given such extensive increases in TN export under changing climate, there is an urgent need for nitrogen management in the QARB. As a first step, we measure the efficacy of historical BMPs in each zone (BMP_0; see table 2) using $R_0(\Delta C, \mathrm{null})$, $R_1(\Delta C, \mathrm{BMP}_0)$, $R_2(\Delta C, \mathrm{BMP}_0)$ and $R_{\mathrm{eff}}(\mathrm{BMP}_0|\Delta C)$. This analysis is depicted in figure 3 from left to right, respectively—see the numerical values for each grid in tables S3–S6 in the supplementary materials. As expected, $R_0(\Delta C, \mathrm{null})$ reveals the sensitivity of TN export to a warming climate. In fact, a 1 °C rise in temperature leads to a 20% increase of TN in the QARB zones (see the values in table S3 in the supplementary materials). Based on $R_1(\Delta C, \mathrm{BMP}_0)$, it can be observed that, while historical BMPs still reduce TN, their overall efficacy declines considerably as temperature rises. Table S4 in the supplementary materials shows that Zone 2 exhibits the highest sensitivity to a warming climate, with a 78% variation in TN reduction, followed by 46% in Zone 3 and 20% in Zone 1.

Results for $R_2(\Delta C, \mathrm{BMP}_0)$ reveal critical thresholds beyond which the implementation of historical BMPs is no longer sufficient to maintain the historical status-quo of TN levels. These thresholds are 3.5 °C for Zones 1 and 2, and 5 °C for Zone 3, after which the values of $R_2(\Delta C, \mathrm{BMP}_0)$ are positive (see table S5 for the numerical values in the supplementary materials). As previously noted, positive values of $R_{\mathrm{eff}}(\mathrm{BMP}_0|\Delta C)$ indicate that the historical BMP demonstrates higher efficiency under changing climate conditions. This scenario only occurs under historical temperature but with lower precipitation, or when there is a decrease in temperature as illustrated in table S6 in the supplementary materials. The overlayed 30 year downscaled projections, under

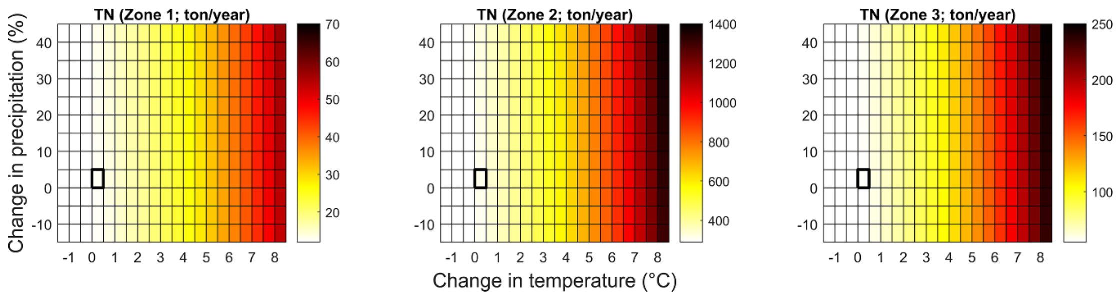

Figure 2. Zonal TN delivery (ton/year) in the QARB under changing climate conditions, assuming no BMP implementation. In each panel *x* and *y* axes show changes in 30 year temperature (°C) and precipitation (%), respectively. The highlighted grids show the historical climate condition.

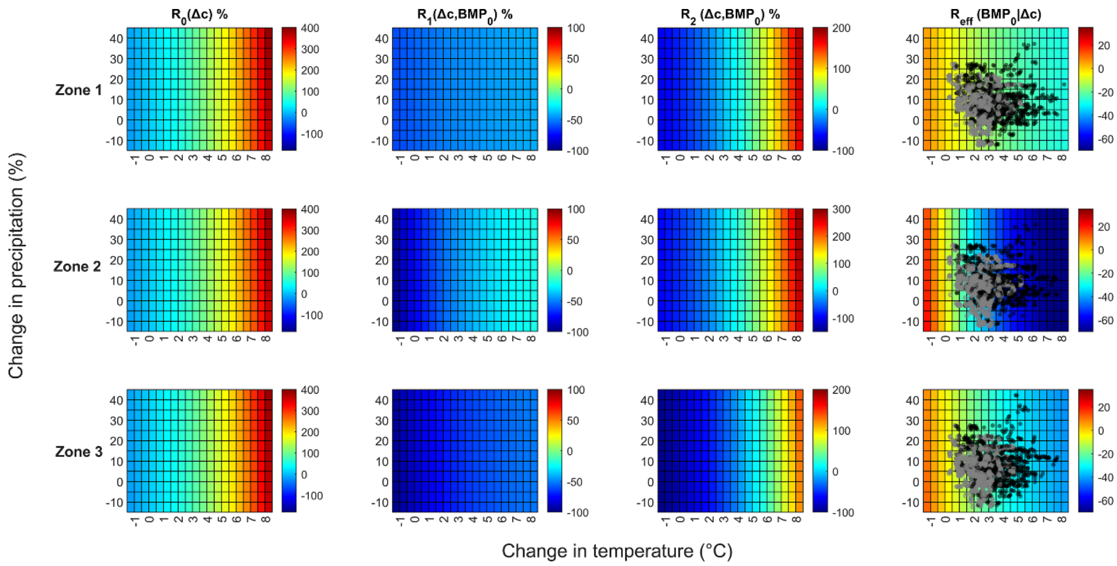

Figure 3. Indications of change in TN export from Zones 1–3 under changing climate conditions, quantified from left to right by relative ratios of $R_0\,(\Delta C, \text{null})$, $R_1\,(\Delta C, \text{BMP}_0)$, $R_2\,(\Delta C, \text{BMP}_0)$ and $R_{\text{eff}}\,(\text{BMP}_0|\Delta C)$. Dots in the right column show future downscaled projections from 20 CMIP6 models under SSPs 2–4.5 (gray) and 5–8.5 (black). See equations (2)–(5) for definitions of the considered ratios.

SSP2-4.5 (gray) and SSP5-8.5 (black) show that such thresholds will likely be exceeded across QARB.

3.2. Role of BMP adaptation

Considering the future climate conditions quantified by the means of multi-model ensembles under SSPs 2–4.5 and 5–8.5, we adapted the BMPs across the three zones of QARB. Figure 4 summarizes the result, in which projections for SSPs 2–45 and 5–85 are shown by blue and red colors, respectively. The top and middle rows display the ensemble ranges of 30 year projections from 2025 to 2095 (areas) along with the corresponding ensemble means (lines). Scenario-led projections show the possibility for substantially warmer and wetter climate by the end of the 21st century across all zones, particularly under the SSP5–8.5. While both temperature and precipitation projections exhibit large uncertainty, the uncertainty is more significant for precipitation, as both drier and wetter climate are consistently seen among projections, particularly under SSP2–4.5. The new combination of BMPs, based on the mean ensemble projections and cost-effectiveness analysis, are shown in the bottom row under SSPs 2–4.5 (blue) and 5–8.5 (red). Although BMP pathways differ for each zone and scenario, they all converge to implementation of all the five BMPs by the end of the 21st century.

We assess new combinations of BMPs through three ratios introduced in equations (2), (3), and (6) as well as the cost of TN removal per unit of nitrogen mass. The results are presented in figure 5. From left to right, the results for $R_0\,(\Delta C^{*}, \text{null})$, $R_1\,(\Delta C^{*}, \text{BMP}_{\text{new}})$, $R_{\text{eff}}\,(\Delta\text{BMP}|\Delta C^{*})$, and the abatement costs are demonstrated. ΔC^{*} is used here to denote that changes in historical climate are derived from downscaled climate projections. Like figure 4, blue and red bands show the results for SSP2–4.5 and SSP5–8.5, respectively; the solid blue and red lines are their corresponding ensemble means. As expected, and shown in figure 3, a warming climate

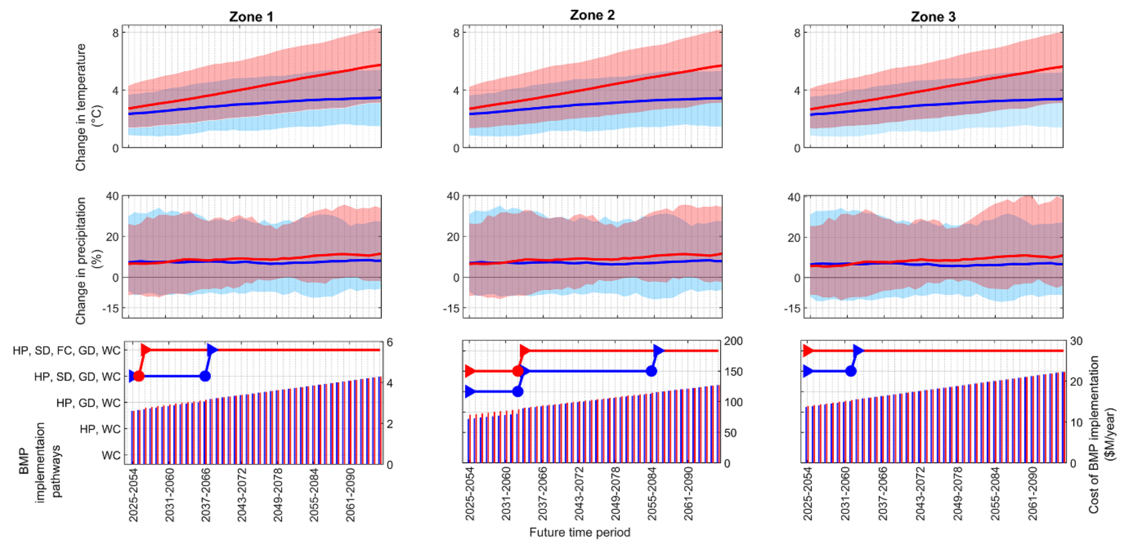

Figure 4. Projected changes in 30 year annual temperature (top row) and precipitation (middle row) in Zones 1–3, using ensembles of downscaled GCMs under SSP2–4.5 (blue bands) and SSP5–8.5 (red bands), along with their corresponding ensemble means (solid lines). Left and right *y* axes on the bottom row show pathways for BMP adaptations (paths) along with their cost of implementation (bars) for SSP2–4.5 (blue) and SSP5–8.5 (red) respectively.

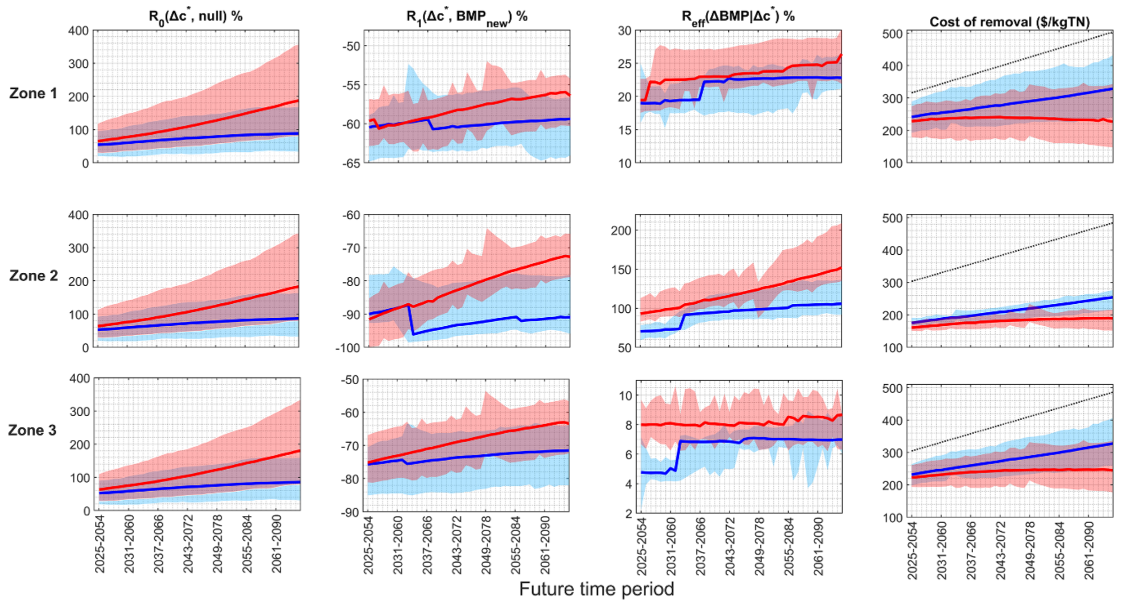

Figure 5. Notions of change in TN export from Zones 1–3 under projected downscaled climate, obtained from 20 CMIP6 models under SSPs 2–4.5 (blue) and 5–8.5 (red). From left to right, columns show the results for $R_0\,(\Delta C^*, 0)$, $R_1\,(\Delta C^*, \mathrm{BMP}_{\mathrm{new}})$, $R_{\mathrm{eff}}\,(\Delta \mathrm{BMP}|\Delta C^*)$, and the cost of removal. Solid colored lines denote ensemble means. The dotted black lines in the right column show the cost of removal related to historical BMPs.

leads to a consistent increase in TN across all zones. Simulations from SSP2–4.5 and SSP5–8.5 highlight the significant impact of additional warming under high radiative forcing. By the end of the 21st century, the mean ensemble of TN export increases substantially from below 100% under SSP2–4.5 to above 200% across all zones under SSP5–8.5. That said, it is evident that the uncertainty in TN export is considerably greater under high radiative forcing. The impact of BMP adaptation on the TN export under projected changes can be monitored by $R_1\,(\Delta C^*, \mathrm{BMP}_{\mathrm{new}})$. According to the mean ensemble projections, TN export could reduce by 57%–96%, depending on the zone and the radiative forcing scenario. In general, the reduction rate is higher under the moderate radiative forcing; however, note that these reduction rates come with large uncertainty, as represented by the envelopes. Nevertheless, the effectiveness of BMPs diminishes as temperature rises towards the end of the century, particularly under SSP5–8.5.

Positive values of $R_{\mathrm{eff}}\,(\Delta BMP|\Delta C^*)$ in figure 5 highlight that the adapted BMPs consistently provide higher efficacy compared to the historical BMPs in QARB zones. The most significant improvement is

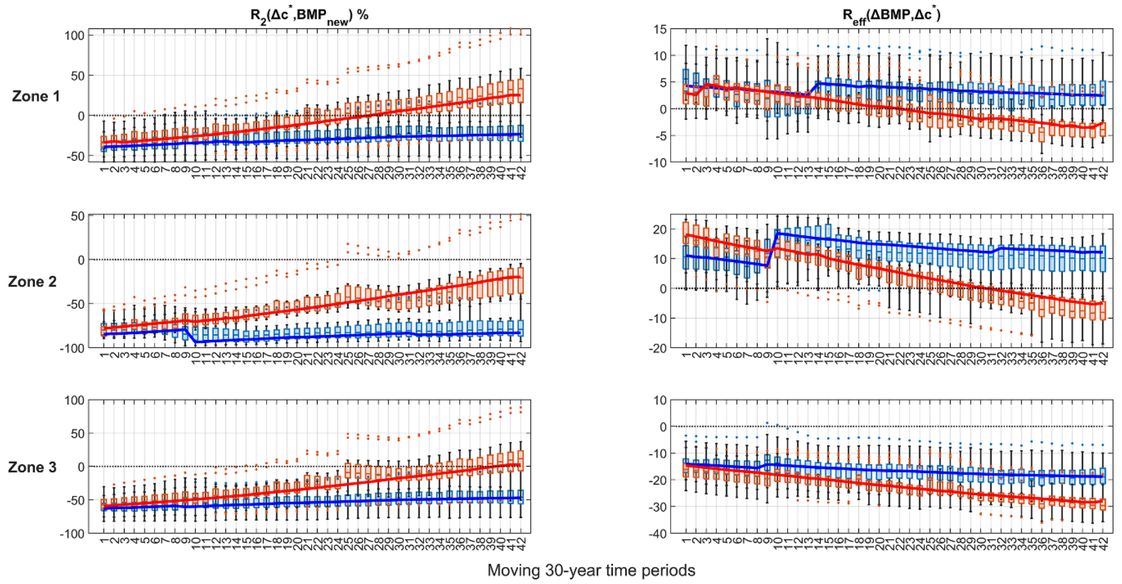

Figure 6. Indications of efficacy for updated BMPs in three zones of the QARB quantified by $R_2\,(\Delta C^{*}, \mathrm{BMP_{new}})$ and $R_{\mathrm{eff}}\,(\Delta \mathrm{BMP}, \Delta C^{*})$, and characterized by an ensemble of 20 downscaled GCM projections (boxplots) and their ensemble mean (solid lines) under SSPs 2–4.5 (blue) and 5–8.5 (red).

observed in Zone 2, where multiple additional BMPs were added to the single historical BMP (see table 2). The relative improvement in TN removal due to BMP adaptation becomes more pronounced under higher warming rates, particularly under high radiative forcing. The higher performance of updated BMPs is also evident by analyzing the removal costs shown in the right column. Despite uncertainty in abatement costs, updated BMPs show strictly lower costs compared to the historical BMP (dotted black lines), in all zones and under both scenarios. As the slope of dotted lines represents inflation, it is evident that by updating the BMPs, the growth in removal costs becomes less than the inflation rate, particularly under high radiative forcing. In fact, based on the mean ensemble projection obtained in Zone 1 under SSP 5–8.5, the abatement cost by the end of the century could be less than the cost at the beginning of the simulation period.

3.3. Reduced effectiveness of updated BMPs under extreme warming

Analyses provided in figure 5 show that updated BMPs can substantially reduce TN export with greater efficiency compared to historical BMPs. However, the performance of updated BMPs declines at higher temperatures towards the end of the 21st century, particularly under high radiative forcing. But is this the whole picture? To answer this question, we simultaneously investigate the absolute efficiency of updated BMPs compared to current status-quo reality under historical climate conditions, represented by $R_2\,(\Delta C^{*}, \mathrm{BMP_{new}})$ and $R_{\mathrm{eff}}\,(\Delta \mathrm{BMP}, \Delta C^{*})$. On the one hand, $R_2\,(\Delta C^{*}, \mathrm{BMP_{new}})$ evaluates whether new BMPs can mask the effects of ΔC^{*} relative to historical conditions. On the other hand, $R_{\mathrm{eff}}\,(\Delta \mathrm{BMP}, \Delta C^{*})$ shows whether updated BMPs can replicate the performance of historical BMPs under historical climate conditions. Figure 6 summarizes our findings with the left and right columns corresponding to $R_2\,(\Delta C^{*}, \mathrm{BMP_{new}})$ and $R_{\mathrm{eff}}\,(\Delta \mathrm{BMP}, \Delta C^{*})$, respectively. In each panel, boxplots and solid lines show respectively the simulations under downscaled projections along with their corresponding ensemble means under moderate (blue) and high (red) radiative forcing scenarios.

While updated BMPs can initially counteract the climate change effects in all zones at the beginning of the century, their efficiency consistently diminishes as the climate warms. This is reflected in the increasing trends in $R_2\,(\Delta C^{*}, \mathrm{BMP_{new}})$, which are significantly larger under SSP2–8.5. Based on mean ensemble projections, Zone 1 demonstrates the fastest rate of reduction of BMP effectiveness, as by the mid-21st century the updated BMPs, which include all five BMPs, fail to maintain even the status-quo TN state under historical conditions. In Zone 3, this reduced effectiveness occurs by the end of the century. In Zone 2, the updated BMPs begin to show signs of minimal effectiveness under some extreme warm projections from the 2050s. Comparing to the performance of historical BMPs under historical climate, updated BMPs consistently fail to replicate the performance of historical BMPs (right column). Zone 3 shows the most extreme case, where updated BMPs strictly undermine historical performance of BMPs from the beginning of the simulation period under both moderate and high radiative forcings. In Zones 1 and 2, such conditions happen earlier and only under high radiative forcing and outbreaks earlier in Zone 1 rather than Zone 2. These findings reveal that, despite implementation of all five BMPs in the three zones (see figure 4), TN reaches a new normal and the water quality in the QARB inevitably declines.

4. Conclusions and further remarks

What are the limitations for BMP adaptations in light of projected warming? And do we need to consider other alternatives to protect the quality of freshwater resources? Our study aims to address these important questions in the QARB, a large and highly farmed region in the Canadian Prairies. Our findings show that changing climate can significantly increase TN export in the QARB. While historical BMPs are able to reduce TN export, they are unable to deliver the current status-quo TN states, in which no BMP is implemented. This means that the increase in TN surpasses the absorption capacity of historical BMPs under changing climate. To identify the role of BMP adaptation, we proposed adaptation pathways for enhancing BMPs, which ultimately converge to the utilization of all five BMPs by the mid 21st century. The simulation results show that, despite improvements in efficacy and cost compared to historical BMPs, adapted BMPs cannot maintain status-quo TN state and will cease to be effective under extreme warming scenarios. The rate and chance of diminished effectiveness in the QARB zones is significantly larger under high radiative forcing. Having said that, although our analysis is at the zonal level, we note that the rate of exhaustion can vary across the tributaries in each zone. This is due to the fact that TN export, and accordingly efficiency of BMPs, highly depends on the intensity of farming activities, wetland coverage and watershed effective area, stream length and flow velocity among other factors. For instance, across Zone 2 of the QARB, in which the most intensive farming takes place, WC has the highest impact on Last Mountain Creek tributary, followed by Moose Jaw, and Wascana, and Loon creeks due to their effective watershed area and drained wetlands.

Does warming climate put an end to the use of BMPs? While our results demonstrate the potential reduced effectiveness of BMPs in the QARB, they also indicate that BMPs can be still effective particularly in the short term. BMP adaptation causes significant reduction in TN export, especially under moderate radiative forcing, and reduces abatement costs. These results are consistent with the findings of Du *et al* (2024), although they were obtained in a different region. As a result, while adapted BMP combinations cannot maintain the current water quality states under warmer conditions, they can still slow down the rate of decline. More broadly, it should be noted that our considered BMPs try to minimize the land-to-water transfer of nitrogen. As climate continues to warm, there is a need to explore additional practices that complement BMPs by targeting nitrogen mitigation at the source. In this regard, new practices could greatly benefit from advanced remediation technologies that leverage physical, chemical, and biological agents (Chakraborty *et al* 2023, Divya *et al* 2023). Implementing smart nitrogen management systems can optimize the timing and amount of fertilizer application based on real-time crop needs, weather patterns, and soil conditions, with the greater goal of reducing nitrogen at its origin (Jariwala *et al* 2022).

Lastly, it should be noted that similar to the majority of the existing literature on impact assessment, our findings heavily depend on how BMPs are represented within the structure of a water quality model (e.g., Giri *et al* 2020, Kim *et al* 2024) and therefore are subject to considerable uncertainty. The sensitivity analyses provided in section S2 of supplementary materials reveals the complex nature of uncertainty in representation of BMP within water quality models even with parsimonious parameterizations. Reducing this uncertainty requires enhanced models that are informed with reliable data. This underscores the need for long-term field monitoring studies to rigorously evaluate the performance of BMPs across a range of climatic scenarios, along with land and aquatic conditions as highlighted by Lintern *et al* (2020). Such monitoring studies are crucial for refining BMP representation in water quality models and for assessing the impact of climate change on BMP effectiveness, especially during heightened and more frequent extreme events (Costa *et al* 2021). We hope our study will lead to more coordinated and integrated efforts towards maintaining water, food, and environmental security in the Canadian Prairies and beyond.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://ds.nccs.nasa.gov/thredds/catalog/AMES/NEX/GDDP-CMIP6/catalog.html.

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Conflict of interest

The authors declare no conflict of interest.

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