We would like to thank the reviewers for their insightful and constructive comments and efforts towards improving our manuscript. We present our point-to-point responses as follows:

Reviewer #1

General comments:
The manuscript presents modelling results to evaluate the potential of replacing arable crops by forage crops to reduce eutrophication problems in the Canadian Prairies. It approaches the topic from a hydrological perspective by investigating to which degree the different crops affect runoff formation causing nutrient losses. This topic fits the scope of HESS. The manuscript reads well and is generally easy to follow. Nevertheless there are a number of critical issues that need to be resolved before the manuscript is ready to be published.

Unbalanced discussion and literature review. The Introduction and the Discussion is not very balanced regarding potential advantages and disadvantages of forage crops. Advantages of forage crops are highlighted, disadvantages such as observed increased nutrient concentrations in runoff are neglected despite referring to articles (Liu et al., 2014) that point out these aspects in very clear manners (see below). A more comprehensive discussion is needed to provide the reader with broad and differentiated arguments. It might be also useful to touch upon the question what such a large-scale land use change might imply for the agricultural sector. I am aware that the authors aren't the specialists for that aspect. Nevertheless, it may be useful to at least refer to that aspect to avoid naive views on the problem. This broader view may also be relevant for asking relevant questions for hydrological research in the future to address the topic from a more interdisciplinary perspective.

Reply: Both the introduction and the discussion sections have revised to expand the arguments about nutrient concentration in runoff as well as large scale implications to the agricultural sector.

The revision is as follows:

Introduction:
The Red River Valley in Manitoba has historically been the location of many large overland flooding events and is one of the largest sources of water and nutrients

to Lake Winnipeg. In recent decades the frequency of flooding, the intensification of agricultural activities in the basin, and environmental implications on associated water courses have come into increased focus (Benoy et al., 2016; Mccullough et al., 2012; Rattan et al., 2017; Painter et al., 2021; Cordeiro et al., 2017). Since the mid-1990s, an increase in runoff during the spring snowmelt season and frequency of spring flooding has been observed in the Red River Valley (Ehsanzadeh et al., 2012; Schindler et al., 2012). This combined with the amplified nutrient availability as a result of the intensification of agricultural production in the region is considered to be the major driver of the eutrophication of Lake Winnipeg ((Mccullough et al., 2012; Schindler et al., 2012; Yates et al., 2012). Conversion of some portions of land from annual cropping systems to perennial forages in intensive agricultural basins has been proposed as means to increase agricultural system resilience in frequently flooded locations, increase carbon sequestration, increase infiltration, and water retention (Kharel et al. 2016; Hutchinson et al. 2007). However, the hydrologic changes associated with broad scale conversion of large portions of the Red River Valley to perennial forages remain understudied and the potential mechanisms for any changes remain to be defined.

From a hydrological perspective, previous studies carried out in cold regions suggest that nutrient export from crop land is mainly driven by snowmelt runoff (Corriveau et al., 2013; Uusi-Kamppa et al., 2012; Cade-Menun et al., 2013). Therefore, reduction in nutrient loads could be achieved through reducing agricultural runoff (Li et al., 2011; Liu et al., 2014). Hydrological alterations that reduce runoff volume could also help to address downstream flooding problems, which are also a significant challenge associated with the flat topography of the Canadian Prairies under intensive agriculture (Bower, 2007; Manitoba Conservation and Water Stewardship, 2014). Several major floods have occurred in recent years in the Canadian Prairies, causing concern over causal factors ranging from climate change to agricultural management practices (Buttle et al., 2016).

Conversion from cropland to perennial forages has been observed to cause fundamental changes in the hydrology of small Canadian Prairie drainage basins such as increases in snow trapping, snowmelt infiltration to frozen soils, and annual evapotranspiration, as well as decreased soil moisture; together, these changes have been attributed to causing reduced runoff and declining wetland storage (van der Kamp et al., 2003). However, changes in hydrology have been mainly described as a result of field-scale observations in Saskatchewan and were made outside the higher rainfall and warmer climate of the Red River Valley of Manitoba, which also has high incidence of clay soils. These differences make it difficult to extrapolate the impact of forage conversion to broader scales due to the role of landscape physiography (e.g., soils texture, topography) and climate on hydrology (van der Kamp et al., 2003).

However, from a nutrient export perspective, research also suggests that conversion from cropland to perennial forages could result in increased nutrient losses in the years directly following conversion. For example, a field experiment carried out by Liu et al. (2014) observed increased P and NH_3 losses from perennial forages planted on former cropland and attributed this pattern to increased concentrations following nutrient release from forage residue due to freezing. Likewise, Cade-Menun et al. (2013) found that significantly more N in pasture runoff than crop land, and there were no significant difference in total phosphorus loss in runoff between crop and pasture land.

These conflicting perspectives suggest that comprehensive studies integrating long-term land use (e.g., land cover and land management), climate, and physiography (e.g., soil properties, topography, and drainage conditions) are still required to improve the understanding of the impacts to the water quality in the Lake Winnipeg basin. Full investigation of nutrient export is complex at large spatial scales requiring available data on nutrient management practices adopted at field scale (e.g., fertilizer application rates, times, source; Mikkelsen, 2011) in addition to understanding of drivers of both the watershed nutrient dynamics controlling concentration and hydrological dynamics controlling runoff volumes. Research to more fully define those factors controlling nutrient dynamics in the region is ongoing (e.g. Liu et al. 2019), and continued research is required before the influence of forage conversion on nutrient source can be accurately represented in a modelling framework. Particularly, the relative importance of freeze-thaw release of nutrients from frozen vegetation, stratification of nutrients near the soil surface, and legacy of past nutrient inputs can't be differentiated in those observational studies cited above. However, assessing hydrological dynamics at these scales is more feasible due to the availability of ancillary data (e.g., soils databases and weather records (Cordeiro et al., 2018; Cordeiro et al., 2019) and hydrometrics observations (ECCC, 2018).

.....

Discussion:

During our study period, surface runoff under annual crop contributed 72.2% of the stream discharge, which was consistent with previous studies performed in this region (Dibike et al. 2012; Glozier et al. 2006). Under the perennial forages' scenario, this contribution was decreased to 54.4%. This reduction in surface runoff, combined with an increase in evapotranspiration, resulted in reduced annual discharge from perennial forages simulated by CRHM at basin scale, which agrees with hydrological observations at field-scale in the Canadian Prairies (van der Kamp et al., 2003). Reduced overland flow in perennial forages is primarily caused by enhanced infiltration (Rachman et al., 2004; Self-Davis et al., 2003; Tricker, 1981). Through measuring infiltration to fine-loamy soils during snowmelt in Saskatchewan using single-ring infiltrometers, van der Kamp et al. (2003) found that the infiltrability of the frozen soil was much higher in grassland than cultivated fields. Their results at most of the infiltration test locations showed that the frozen soil in the grassed areas had infiltration rate in excess of the typical snowmelt rates (i.e., ≤10 mm hr-1) while all the infiltration tests on frozen soil in cultivated fields indicated an infiltrability considerably less than the typical snowmelt rate. Enhanced infiltrability in perennial forages was attributed to the development of macropores, such as root holes, desiccation cracks, and animal burrows (van der Kamp et al., 2003). The results demonstrated that the model simulations presented here were able to capture the increased infiltration in frozen soils due to macropore formation under forage.

Higher soil moisture content for perennial forages in some years (i.e., 1994-1996, 2002-2006, and 2011) is contrary to the trends reported by field investigations in the Canadian Prairies (Christie et al., 1985; van der Kamp et al., 2003) where grasses had lower soil moisture than cultivated fields. Such contrasts could be due to the more western and drier locations and short period of field investigations [1990 and 2000 by van der Kamp et al. (2003) and seemingly 1975 and 1981 by Christie et al. (1985)], which may not cover the full range of climate conditions including very dry and wet years experience in Manitoba. Thus, the impact of perenial forages on soil moisture may not be unequivocal as suggested by previous short-term field research, and this land cover may show variation between periods of low and high soil moisture dictated by antecedent conditions. These differences in soil moisture may also be a result of differences in ET calculation, although the mean annual precipitation in the present study (560 mm) is larger than those reported by Christie et al. (1985) for Lethbridge, Alberta (350-400 mm) and van der Kamp et al. (2003) for the St. Denis National Wildlife Area, Saskatchewan (358 mm).

……

Additionally, there are a number of parameters for which it seems that the authors have subjectively chosen numerical values (e.g. stomatal resistance, L. 331 - 332). Given that the water balance at the soil surface has a major impact on the model result I had expected to see a sensitivity analysis for parameters that the authors have selected based on their expert judgement.

Reply: While CHRM makes provision for expert knowledge during parameterization, an objective parameterization was used in the present study. Stomatal resistance, mentioned by the reviewer, was defined based on Beven (2011), which is within the range reported in the literature, as indicated in the manuscript. The major issue with this parameter is that it is dynamic in nature, while its representation in the model is static. We agree with the reviewer that this limitation creates some uncertainty in the ET estimates, as acknowledged in the manuscript. Therefore, a sensitivity analysis has been conducted for the revised manuscript. The stomatal resistance values used in the analysis were 25 (lower limit reported in the literature), 50 (Beven, 2011), 75 (equidistant value), and 100 s m^{-1} (upper limit reported in the literature).

Detailed comments:

- L. 17: “resulting in lower water yield and concomitant export of nutrients”: From a nutrient balance perspective: where would the nutrients not lost end up in the system?

Reply: The nutrient would buildup in the soil and be potentially uptaken by vegetation. Alternatively, nutrients could also be lost through other pathways depending on its form (e.g., N gaseous emissions).

- L. 17: A related aspect: what are the nutrient budgets for the two alternative crops (fertilization rates, yield export)? This is important for the long-term effect of any given crop choice.

Reply: It is expected that lower nutrient application to forage land would lead to reduced nutrient loss compared to annual crop land. The nutrient budget of perennial forages could also differ, depending on management (e.g., native, and tame pastures, which differ in nutrient inputs, for example). These aspects are complex and out of the scope of the manuscript. That said, CRHM is under continuous development and has been recently added a nutrient module (Costa et al., 2021). The authors expect to further investigate the nutrient balance of the two alternative land uses using the newly developed CRHM modules in the future.

- L. 29: Introduce abbreviation upon first use.

Reply: Correction has been made as suggested.

- L. 33: Which nutrients? N or P or both?

Reply: It indicates both N and P. We have included additional references (Mccullough et al., 2012; Schindler et al., 2012; Yates et al., 2012), report the increasing trend of N and P loading to Lake Winnipeg in the past few decades.

- L. 35: Which kind of intensification took place?

Reply: Agriculture intensification has taken place in the Lake Winnipeg region since the early 1800s. In Manitoba, wheat and barley production has increased from ~1×10^9 kg yr^{-1} and 0.3-0.5×10^9 kg yr^{-1} in 1910s to 5×10^9 kg yr^{-1} and 2×10^9 kg yr^{-1} in the 1980s, respectively. Potato production has increased by almost 10-fold to 1×10^9 kg yr^{-1} due to increased demand for processed food (Honey and Oleson, 2006; Bunting et al., 2016). Canola production has increased from $<1.2\times10^4$ ha in 1961 to 1.15×10^6 ha in 2004. Hog population has increased by 500% and fodder crops increased 275-1000% during 1981-2000 (Bunting et al., 2016).

- L. 37 – 38: The way of referencing is somewhat misleading. As written, the citation evokes the impression that Liu et al. (2014) proposed this conversion (based on their scientific findings). However, these authors describe that “Conservation initiatives on the Canadian Prairies are attempting … by promoting conversion of annual cropland to perennial forages” (Liu et al., 2014, p. 1645). Actually, the authors formulate based on their empirical findings some warnings regarding this suggested conversion: “When nutrients are released from plant residues by freezing, the introduction of perennial forages to a crop rotation may increase P losses in surface runoff during snowmelt.” (Liu et al., 2014, p. 1654). Such a framing puts this manuscript into quite a different perspective.

Reply: The introduction section has been expanded to reflect the balanced approach suggested by the reviewer in the general comment.

- L. 39: Agronomic practices are neglected.

Reply: Agronomic practices, namely, nutrient management, are now mentioned in a new paragraph added to the introduction section.

- L. 41 – 42: This sentence gives the impression that conversion to perennial crops were a better alternative than arable crops. However, given the findings cited above (Liu et al., 2014), this implicit assessment is not necessarily true.

Reply: The introduction section has been expanded to reflect the balanced approach suggested by the reviewer in the general comment. Specifically, the revised introduction now discusses both hydrology and nutrient dynamics as drivers of water quality issues.

L. 68 – 69: How is it possible to achieve "physical realism of hydrological processes without the need of parameter calibration to achieve accurate simulations."? This holds especially true for parameters such as soil hydraulic parameters at the spatial scale of HRUs. The statement is also in contradiction with (He et al., 2021), which states: "… were initialized based on the soil textures in WGC basin, and then slightly adjusted using trial and error based on the NSE and logNSE values of the streamflow simulation in the calibration period." (He et al., 2021, p. 5).

Reply: The paradigm for development of CRHM has been to rely on parameterization based on knowledge of the basin. That said, parameter calibration can still be performed in CHRM. This statement has been removed in the revised version of the manuscript.

- L. 129: What are possible reasons for the poor performance under drier conditions?

Reply: The poor performance in simulating low flow is recognized as a common issue for many hydrological models. The reasons vary from region (location and/or size), season, to lead time (Nicolle et al., 2014). Cordeiro et al. (2017), studying the same basin, suggested that variable typological controls at the landscape level (e.g., preferential flow) could be one of reasons influencing the hydrological regime under the dry conditions, which are difficult to represent in model simulations. Those authors stress that these hypotheses remain to be investigated.

- L. 138 – 144: This seems to indicate that a major change was introduced apriori to the model structure!? Does this not lead to the situation that the model results simply reflect the initial hypothesis?

Reply: The module structures between annual crop and perennial forage models were the same. The introduction of the ‘fallstat_correction’ parameter was a technical way to mimic a hydrological premise of perennial forages observed in field research in the Canadian Prairies, namely, to reduce or prevent the formation of ice lenses in those landscapes and to increase infiltration through macropore formation. The objective of the manuscript was to assess the large-scale hydrological implications of this premise to other components of the water balance. We acknowledge that the extend of this hydrological premise depends on antecedent conditions and, therefore, we used an uncertainty framework to capture this uncertainty. We also acknowledge that the methodology adopted in the present study (i.e., falsification of the ‘fallstat’ parameter) was meant as a ‘proof-of-concept’ approach, but a more rigorous model representation of this process based on field research is warranted. This last sentence has been included in the discussion section of the revised manuscript.

L. 140: the use and motivation for the parameter “fallstat” is obscure to me. Should the degree of saturation of the soil not result from the water balance simulations of the antecedent period? “Defining” a degree of saturation will generally induce a water balance error, wouldn’t it? Please explain and clarify.

Reply: In the current representation of CHRM, replacing annual crops with perennial forages would change the hydrological effect of the above-ground vegetation cover (e.g., snow trapping), but would cause no difference in the subsoil hydrology. In order to mimic the known subsoil alterations (i.e., prevention of ice lenses formation), the parameter “fallstat” was falsified. This parameter handles the infiltration into frozen soil for the following spring as determined from soil properties and soil moisture variables (Gray et al., 2001). The value 0% of “fallstat” indicates the soil is cracked and the infiltration flow is unlimited. The value 100% of “fallstat” indicates the soil is completely saturated and infiltration is restricted. Intermediate values of this parameter characterized limited infiltration. The original range of “fallstat” values used in the simulations (i.e., 30%-70%) characterizes the limited infiltration range of infiltration (Gray et al., 2001). However, this range has been expanded to between 0% and 70%, as suggested by the reviewer.

- L. 145 – 146:] I suggest to extend the range between 0 and 70\%. This allowed to assess the vegetation effects on SWE separately from the effects on soil properties (i.e. infiltration capacity).

Reply: We have extended the range of fallstat from 30%-70% to 0-70%, as suggested. The results have been updated accordingly, while the conclusion remains similar after the expansion of scenarios.

- L: 174 - 180: How have the meteorological point data extrapolated in space?

Reply: The data was not extrapolated in space. Rather, a single weather file was applied to the entire area. This was due to the fact that the study area does not have a weather station within. Also, no single weather station had all the meteorological variables required to force the model. Therefore, we combined the data from nearby stations. As stated in section 2.4, we obtained temperature, wind speed, and relative humidity from the Portage Southport Airport station, while solar radiation was acquired from the station located at the Winnipeg International Airport, and precipitation was acquired from the weather station in Marquette. Precipitation was only available in a daily time-step and was disaggregated to an hourly time-step using the R package HyetosMinute (Kossieris et al., 2013; Koutsoyiannis and Onof, 2001).

- L. 210, Fig. 3 (and following): The figures differentiate between the two crops with green and red colors. Given that about 8% of the male population is color blind, I strongly recommend to change the color code and potentially also use different symbols to avoid readability problems.

Reply: Figures 3 through 9 were reformatted, as suggested.

- L. 235: Can the larger SWE for forage crops be fully explained by reduced sublimation? It seems that transport and wind erosion would not cause such differences because in a scenario with one land use only (arable crop or forage only), any transport and erosion would lead to snow deposition somewhere else in the catchment without a net change of the surface water balance. Can you comment on that?

Reply: The larger SWE in perennial forages is a result of the great ability of this vegetation cover to trap snow due to its increased height compared to crop land, which is harvested and has a shorter stubble height.

- L. 285: The assumption of constant nutrient concentrations contradicts the empirical findings by Liu et al., (2014) reporting substantial increase of several nutrients upon a change from arable crops to perennial forage. This puts the results in quite a different perspective.

Reply: The discussion section has been extensively revised and, as a result, this statement has been removed.

- L. 285 – 302: This section seems biased in that only results are reported that favor a transition from arable to forage crops. Conflicting findings are neglected despite the fact that one of such papers (Liu et al., 2014) is cited.

Reply: As stated above, the discussion section has been extensively revised and provides a more balanced argument highlighting the interaction between hydrology and nutrient release to water quality outcomes.

- L. 312 - 313: The mechanism of how the macropore flow is mimicked by the model is not very clear. Please provide more (technical) details.

Reply: As stated previously, the fallstat parameter was indented to mimic the hydrological effect of macropore flow (i.e., enhanced infiltration). This representation was meant as a 'proof-of-concept' approach to assess the overall implications to different water balance components, but a more rigorous model representation of this process based on field research is warranted.

- L. 330 - 340: These aspects should be investigated with a sensitivity analysis. This should be straightforward and would provide more robust information how relevant this parameter might be for the overall results.

Reply: As stated in the reply to the general comments, a sensitivity analysis has been conducted for the revised manuscript. The stomatal resistance values used in the analysis were 25 (lower limit reported in the literature), 50 (Beven, 2011), 75 (equidistant value), and 100 s m^{-1} (upper limit reported in the literature).

- L. 348 - 349: This outcome seems rather trivial: empirical evidence at field scale has been conceptually be incorporated into the model and applied to a larger scale. Therefore, the model results are no independent test whether the local observations hold true if scaled up.

Reply: That particular sentence has been removed in the revised manuscript.

References:

Bunting, L., Leavitt, P., Simpson, G., Wissel, B., Laird, K., Cumming, B., St. Amand, A., and Engstrom, D.: Increased variability and sudden ecosystem state change in Lake Winnipeg, Canada, caused by 20th century agriculture, Limnol. Oceanogr., 61, 2090-2107, 2016.

Beven, K.J.: Rainfall-Runoff Modelling: The Primer. Wiley, West Sussex, UK, 2011.

Costa, D., Pomeroy, J. W., Brown, T., Baulch, H., Elliott, J., and Macrae, M.: Advances in the simulation of nutrient dynamics in cold climate agricultural basins: Developing new nitrogen and phosphorus modules for the Cold Regions Hydrological Modelling Platform, J. Hydrol., 603, 10.1016/j.jhydrol.2021.126901, 2021.

Gray, D. M., Toth, B., Zhao, L., Pomeroy, J. W., & Granger, R. J. Estimating areal snowmelt infiltration into frozen soils. Hydrological processes, 15(16), 3095-3111, 2001.

Honey, J. and Oleson, B.: A century of agriculture in Manitoba, a proud legacy, Credit Union Central of Manitoba, 2006.

McCullough, G. K., Page, S. J., Hesslein, R. H., Stainton, M. P., Kling, H. J., Salki, A. G., and Barber, D. G.: Hydrological forcing of a recent trophic surge in Lake Winnipeg, J. Great Lakes Res., 38, 95-105, 2012.

Nicolle, P., Pushpalatha, R., Perrin, C., François, D., Thiéry, D., Mathevet, T., Le Lay, M., Besson, F., Soubeyroux, J. M., Viel, C., Regimbeau, F., Andréassian, V., Maugis, P., Augeard, B., and Morice, E.: Benchmarking hydrological models for low-flow simulation and forecasting on French catchments, HESS, 18, 2829-2857, 10.5194/hess-18-2829-2014, 2014.

Schindler, D. W., Hecky, R. E., and McCullough, G. K.: The rapid eutrophication of Lake Winnipeg: Greening under global change, J. Great Lakes Res., 38, 6-13, 10.1016/j.jglr.2012.04.003, 2012.

Yates, A. G., Culp, J. M., and Chambers, P. A.: Estimating nutrient production from human activities in subcatchments of the Red River, Manitoba, J. Great Lakes Res., 38, 106-114, 10.1016/j.jglr.2011.04.009, 2012.