Final Report

1. **Project title:** Revising the crop nutrient uptake and removal guidelines for Western Canada (ADF 2119018)

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3. **Abstract/Summary:**

The project objective was to develop new estimates for crop nutrient uptake and removal, based on analyses of grain and biomass samples collected from commercial fields and values from existing literature. Through the collaborative efforts of Nutrien Ag Solutions and Manitoba Agriculture, over 2200 grain and biomass samples were collected from across the three prairie provinces from 2020 to 2022, and analyzed for macronutrient (N, P, K, S) and micronutrient (Cu, B, Zn) uptake. Results confirmed that some of the nutrient uptake and removal values are aligned with existing estimates (e.g., CFI Nutrient Uptake and Removal Guidelines for Western Canada, 2001) whereas others needed revision. Importantly, existing ranges for nutrient removal do not capture the full extent of the observed variability in nutrient uptake and removal, underscoring the importance of using any uptake and removal estimates together with regular soil testing for informing fertilizer management decisions. The survey provided new uptake and removal estimates for micronutrients (boron, copper, and zinc).

Additionally, we conducted a review of existing literature and research relevant to Western Canada. In addition to peer-reviewed publications, online university repositories were searched for relevant theses and dissertations. Other databases included the ministries of agriculture and commodity groups from across the prairies. Research groups also were contacted for raw field data. We developed a list of criteria to include (or exclude) sources of information with the goal of only

using data deemed relevant and robust. Together, these sources proved to be a rich source of information for corn, oat, wheat, winter wheat, canola, soybean, faba bean, lentil, and pea; however, search criteria were not met for barley, durum, flax, mustard, and chickpea, and these were not included. The data accessed for some crops was abundant. For example, for spring wheat, we acquired 2596 N, 858 P_2O_5, 84 K_2O, 372 sulfur, 84 boron, 116 copper, and 196 zinc data points. In contrast, we found only 24 data points for oat for each of the nutrients (i.e.,168 total data points).

When comparing the literature values, which represent data largely from small-plot experiments, to the survey data, the literature-based yield data were frequently within 10% of the survey data for wheat, oat, canola and lentil, but were lower for corn (124 versus 150 bu·acre^{-1}) and higher than the survey yields for the remaining crops. It is probable that yield losses in commercial harvesting operations versus hand-harvested research plots account for the higher yields reported in the literature.

In general, the literature revealed similar or lower estimates for nutrient removal (i.e., nutrient in the grain) than from the survey with a few notable exceptions, one of which was S removal in canola. Whereas the survey estimate (mean) was 0.19 lb S·bu^{-1} canola, the literature-based estimate was 0.42 lb S·bu^{-1}. Given the importance of S in canola production, and the variance in the estimated removal, we conclude that it is prudent to opt for a higher estimate of S removal to avoid potential deficiencies. Similar results were observed for S removal in flaxseed. Additionally, survey values for potassium removal in soybean were lower than the literature-based estimates (mean 0.89 lb K_2O·bu^{-1} versus 1.29 lb K_2O·bu^{-1}), which may warrant further investigation.

A survey of nutrient uptake of forages (alfalfa, clover, forage grass, barley silage, corn silage) in the published and grey literature was conducted. Although a number of relevant reports were accessed, parameters reported in the various studies were inconsistent, including growth stage at which biomass or nutrient uptake was determined. Moreover, although some studies included nutrient uptake, the vast majority focused on yield, and far fewer studies included both yield and nutrient uptake. Ultimately, we were unable to compile consistent and coherent data to justify any modifications to the existing nutrient uptake and removal guidelines for forages published in the 2001 CFI guidelines.

4. Key Messages:

- Regular soil testing is a critical tool for assessing current soil nutrient status and determining appropriate fertilizer application rates to achieve crop yield goals.

- Nutrient removal estimates are an additional tool for assessing nutrient addition required to maintain or build soil fertility levels. Crops are not able to extract all the total nutrient available in the soil (i.e., soil plus added fertilizer) and thus estimates of available nutrient(s) should be greater than estimates of nutrient removal to maintain soil nutrient levels.

- Revised nutrient removal values developed specifically for crops grown in Western Canada provide estimates of nutrient removal, although it is essential to recognize that due to known variability in the data (including weather-associated variability), these estimates provide guidance but should not be viewed as prescriptive. A reference table summarizing the nutrient removal data is included in the Appendix (Table A1).

- For some crops and nutrients, lower grain concentrations observed in the current survey suggests that management practices and modern varieties have resulted in improved nutrient use efficiency on a per bushel basis, although higher yields remove more nutrient on a per acre basis.

- Although the survey data indicates lower sulphur (S) removal by canola (and flax seed) than previous estimates, given the importance of S in canola production, and the variance in the estimated removal, it is prudent to opt for a higher estimate of S removal than suggested by the survey data to avoid potential S deficiencies.

- An on-line calculator and an Excel-based calculator have been developed. The calculators use the 75th percentile of the survey data as the nutrient coefficient, with the goal of limiting the risk of underestimating nutrient removal (Appendix Table A4). The 75th percentile represents that point at which 75% of the survey values were below the coefficient value and 25% of the values were above the coefficient value.

5. Introduction:

Nutrient uptake and removal guidelines are an invaluable resource for farmers and agronomists alike. Soil testing remains a valuable tool for determining the levels of available and, in some cases, potentially available nutrients in the soil; however, nutrient uptake and removal guidelines provide an additional layer of information regarding crop nutrient requirements. Knowledge of potential uptake and removal can be used to help balance the nutrients removed when the grain is harvested against nutrients replaced as fertilizer, helping to ensure consistently high yield goals and sustainable cropping systems.

There is a growing interest in utilizing multiple sources of information beyond soil testing for developing nutrient management plans for subsequent crops. This interest is driven in part by the economic reality of soaring fertilizer costs, and the desire to closely match crop requirements with nutrient inputs, thereby reducing unnecessary fertilizer inputs without compromising yield goals. The desire to more closely match fertilizer inputs and crop yield goals goes hand-in-hand with environmental goals, reducing the likelihood of potential environmental losses. Indeed, nutrient uptake and removal guidelines are an integral part of 4R fertilizer management practices (i.e., right source, right rate, right time, and right place) which help farmers identify management practices that keep nutrients in the field for crop uptake, thereby aligning economic and environmental goals.

Although many on-line resources and published nutrient uptake and removal guidelines are available, these guidelines typically are not specific to Western Canada. For example, The International Plant Nutrient Institute (IPNI) Canada provides crop nutrient uptake estimates (http://www.ipni.net/article/IPNI-3296), last modified May 2014, and cautions that "*Reported nutrient uptake coefficients may vary regionally depending on growing conditions. Use locally available data whenever possible*." Importantly, the data used in their resources (including an i-OS app and web-based version) are not specific to Saskatchewan, or Western Canada, with most data originating from other continents. Additionally, many of the available nutrient removal calculators are based either on the IPNI data, or on the early Western Canada Fertilizer Association guidelines, revised in 1992 (and presumably based on research conducted in the 80's), and again in 2001 by the Canadian Fertilizer Institute (CFI) (https://www.canolacouncil.org/download/2042/canola-watch/14659/20110309_fpj_aut11_beckie-et_-al_-2). The revisions at that time, however, retained the original data, reporting it as a 10% ± range for each nutrient and crop. Since then, many different nutrient uptake and removal apps have become available (e.g., Nutrien eKonomics Nutrient Removal Calculator at https://nutrien-ekonomics.com/ROItools/calculators; Mosaic Crop Nutrition Nutrient Removal Calculator at https://www.cropnutrition.com/nutrient-management), with many reformatting portions of the original CFI or IPNI guidelines, but none have taken on a full revision and expansion of the original CFI nutrient uptake and removal guidelines.

Importantly, few of the existing guidelines include micronutrient estimates for crops commonly grown in Western Canada. Over the years, there have been a number of studies examining response of various crops to micronutrient application in Western Canada, but until now, a comprehensive survey of micronutrient uptake and removal by commercially grown crops has not been available. Interest in understanding micronutrient uptake has been growing and questions have arisen regarding potential micronutrient depletion, particularly as crop yields climb (Statistics Canada 2019 https://www150.statcan.gc.ca/) with improved management, continuous cropping, and higher yielding crop varieties.

Our project aimed to develop new nutrient uptake and removal guidelines for 14 annual crops based on both measured values from seed and straw samples collected across Western Canada. Additionally, as further confirmation, we compared our measured estimates with data in the published and grey literature (i.e., unpublished) from Western Canada, where available. Building on the previous guidelines, the revised guidelines include removal and uptake estimates for both macro (N, P_2O_5, K_2O, S) and micronutrients (Cu, Zn, B) for annual crops. Additionally, we examined the existing values for forage dry matter production (alfalfa, clover, forage grass, barley silage, corn silage) based on values published in the scientific and grey literature.

The second year of sample collection coincided with the 2021 drought, and as a consequence, we limited sample collection in 2021 to 20% of our original plans. However, this gave us the opportunity to compare data collected in a drought year versus data collected in both 2020 and 2022. Very fortuitously, these comparisons between years revealed that although drought had an impact on crop yields, the removal and uptake (i.e., concentration) remained relatively unaffected by the drought conditions beyond the variability that was associated with "normal" years, which indicates that single nutrient coefficients provide suitable estimates of nutrient uptake, irrespective of the year or climatic conditions.

6. Objectives and the Progress Towards Meeting Each Objective:

Objectives (Please list the original objectives and/or revised objectives. A justification is needed for any deviations from the original objectives)	Progress (e.g., completed/not completed)
1) Determine and revise estimates of the nutrient uptake and removal guidelines of crops commonly grown in western Canada a) Collect data on nutrient concentrations for current crop varieties by analyzing seed and biomass samples collected across western Canada from commercial fields. b) Compile existing data from the literature.	1a) Completed 1b) Completed 1c) Completed. Based on our literature search, we conclude that there is not sufficient justification for revising the

c) Update existing values for forage dry matter production (alfalfa, clover, forage grass, barley silage, corn silage).	existing values for forage dry matter production.
2) Develop a user friendly on-line and mobile app for determining nutrient uptake and removal estimates	2) An Excel-based calculator is included as an attachment to this report. A link to an on-line calculator is also available.

7. Methodology:

Grain and Biomass Sample Collection (Objective 1a)

Nutrient uptake and removal guidelines for 14 crops (barley, corn, durum, oats, spring wheat, winter wheat, canola, flax, soybean, mustard, chickpea, dry bean, lentil, field pea) were investigated and revised based on grain and biomass samples collected from commercial fields in 2020 to 2022. In addition, we added faba bean to our study, largely because of the availability of samples, and the seeded acres. We originally planned to access grain samples through the Canadian Grain Commission but as indicated in our proposal, this sample source was not confirmed when the project was proposed. Unfortunately, the Canadian Grain Commission ultimately declined to provide samples. As an alternative, the samples were collected by Nutrien Ag Solutions agronomists across the three prairie provinces under the leadership of Lyle Cowell (Manager, Agronomy Solutions, Northeast Saskatchewan). Additionally, John Heard (Manitoba Agriculture) coordinated the collection of samples from across Manitoba.

The original goal was to collect approximately 100 grain/seed samples (typically 500 g) of each of the 15 crops in each of two years, with the actual number of samples for each crop collected within each province adjusted to reflect relative acreage of each (based on total acreage estimates). Consequently, crops such as mustard, with limited acreage, had fewer samples collected than canola, wheat, and barley (Table 1). Additionally, in response to the severe drought in 2021, grain and biomass sample collection was reduced to 20% of what was initially planned, with the remaining 80% collected in 2022. Efforts were made to collect samples from all three prairie provinces (Fig. 1), and the location of each sample collected was recorded. Samples were collected from producers, and information about the samples (location, crop, variety, fertilizer application, previous crop, and estimated yield) was recorded. Biomass samples were collected in 2021 and 2022. No biomass samples were collected in 2020 due to employment and mobility restrictions associated with COVID protocols at the University of Saskatchewan.

Plant tissue (i.e., biomass) samples were collected in 2021 at Agri-Arm sites (Irrigation Crop Diversification Corporation (Outlook), Indian Head Agricultural Research Foundation (Indian Head), Southeast Research Farm (Redvers), Conservation Learning Centre (Prince Albert), and at University of Saskatchewan research plots (Saskatoon), and from a commercial farm at Central Butte, SK. Additional samples were collected in 2022 at these sites and at NARF (Melfort), WARC (Scott) and from multiple commercial fields at or near Kindersley, Weyburn, Naicam, Tisdale, Prince Albert, Bow Island, Alberta, and 62 locations across southern Manitoba.

Table 1. Number of biomass and grain samples collected across Western Canadian prairies from the 2020 to 2022 growing seasons.

	Biomass				**Grain**			
Crop	**2020**	**2021**	**2022**	**Total**	**2020**	**2021**	**2022**	**Total**
Barley	-	6	13	19	102	32	67	201
Corn	-	4	20	24	34	4	21	59
Durum	-	0	15	15	44	12	3	59
Oats	-	46	62	108	86	19	61	166
Wheat	-	11	48	59	155	42	124	321
Winter wheat	-	3	0	3	9	2	0	11
Canola	-	13	47	60	204	49	120	373
Flax	-	1	15	16	62	8	19	89
Soybeans	-	3	18	21	60	7	30	97
Mustard	-	0	0	0	9	2	4	15
Chickpea	-	0	1	1	34	4	0	38
Dry bean	-	4	33	37	38	3	20	61
Faba bean		4	15	19	26	4	7	37
Lentils	-	1	5	6	86	13	7	106
Peas	-	17	23	40	95	32	43	170
Total	**-**	**113**	**315**	**428**	**1044**	**233**	**526**	**1803**

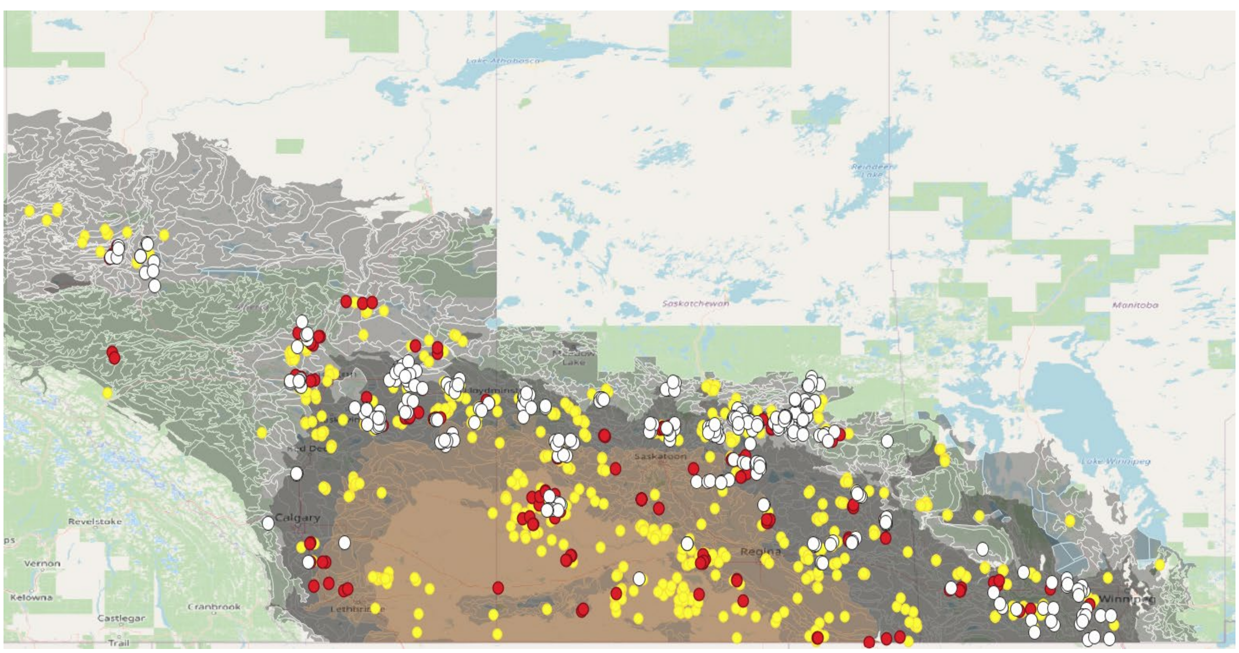

Figure 1. Grain sample collection locations in 2020 (yellow), 2021 (red) and 2022 (white).

Biomass sample collection in both 2021 and 2022 was conducted by agronomists, producers, and by U of S staff, under the direction of Dr. Gazali Issah. Typically, two 1-m strips of biomass were hand-harvested for each biomass sample, and total yield was adjusted to reflect row-spacing. Biomass samples were collected at growth stages prior to maturity at which maximum nutrient uptake is normally achieved (Table 2). Sample information (location, crop, variety, fertilizer application, previous crop, and estimated yield) was recorded. Whole samples were dried in a forced air oven, ground, and analyzed for both macro and micronutrients.

Table 2. Target growth stages for biomass sampling for the determination of maximum total nutrient uptake.

Crop	Growth stage	Reference
Canola, mustard, flax	Mid to end of pod forming growth stages (before leaf drop for canola)	Mahli et al., 2004a
Cereals	Late milk to ripening stage	Mahli et al., 2004b
Soybeans, pulses	Mid pod formation to early seed-filling stages, R6 (full seed) for soybean	Mahli et al., 2004c Manitoba Pulse Growers Staging Guide https://www.manitobapulse.ca/wp-content/uploads/2015/03/Soybean-GROWTH-STAGING-Guide_June-2018_WR.pdf
Corn	Milk to dough kernel stage (R3-R5)	Bender et al. (2013); John Heard (pers. comm.)
Dry bean	Full seed stage (R7)	Heard and Brolley (2006). Manitoba Pulse Growers Dry Bean Staging Guide https://www.manitobapulse.ca/wp-content/uploads/2017/08/Dry-Bean-Growth-Staging-Guide-_WR.pdf

Nutrient Analyses

Both grain and biomass samples were oven-dried at 60 °C to a constant weight to determine moisture content. The samples were ground to pass through a 2 mm sieve using a Wiley mill (Thomas Scientific, Swedesboro, NJ). Both biomass (<2 mm) and grain samples were further ground to a fine powder (<250 µm) using a Cyclone Sample Mill grinder (Udy Corporation, Fort Collins, CO, USA). Oil seeds grain samples were ground using Retsch Ultra Centrifugal Mill ZM 200 (Retsch GmbH Company, Haan, Germany).

In 2020, grain samples were digested using H_2SO_4-H_2O_2 and N content was determined colorimetrically using an auto-analyzer (Technicon Autoanalyzer II) (Thomas et al., 1967). In subsequent years, N content was determined by dry combustion using a Thermo FLASH 2000 Organic Elemental Analyzer (Thermo Fisher Scientific Inc., Bremen, Germany 2016) (Natural Resources Analytical Laboratory, University of Alberta).

Phosphorus, potassium, sulfur, copper, zinc, and boron were determined using ICP-MS. Briefly, approximately 0.25 g sample was digested in HNO_3-HCl using a Mars Microwave digester according to the CEM procedure, Microwave Digestion of Feed Grains (CEM, 2022). Following the digestion, samples were analyzed using an ICP-MS (model: ICAP-RQ, S/N ICAPRQ00250, Thermo Fisher Scientific (Bremen)–GmbH, Hanna-kunath-Str. 11, 28199 Bremen, Germany), using the Ked (Kinetic Energy Discrimination) cell mode for all analyses.

Following nutrient content analysis, the moisture contents for each crop were adjusted to the recommended threshold set by the Canadian Grain Commission. All nutrient concentration ($lb \cdot bu^{-1}$) values are reported at the Canadian Grain Commission recommended moisture contents (minimum "tough", https://www.grainscanada.gc.ca/en/grain-quality/grain-grading/grading-factors/moisture-content/tough-damp-ranges.html).

The data sets for each crop were trimmed by removing extreme outliers. Where data were not normally distributed, extreme outliers were identified using Tukey's rule (i.e., extreme outliers more than three times the interquartile range (IQR)–either below Q1 - 3IQR, or above Q3 + 3IQR. Mean and standard deviation were determined on trimmed data, as were median and Quartile 1 and Quartile 3 values.

Data in this report are presented using Imperial units for the purpose of comparing the current results with previous "Nutrient Uptake and Removal by Field Crops" guidelines published by CFI (available at https://www.canolacouncil.org/download/2042/canola-watch/14659/20110309_fpj_aut11_beckie-et_-al_-2) and other nutrient removal calculators available on-line (e.g., IPNI nutrient calculator at https://www.ipni.net/app/calculator/home). Dry bean and soybean were not included in the original CFI estimates for western Canada, and instead we referred to the CFI Nutrient Uptake and Removal for Field Crops, Eastern Canada (1998) (Heard 2022, pers comm.). Dry bean yields are reported in bushels/acre for comparability (and not CWT hundredweights).

The nutrient concentration ($lb \cdot bu^{-1}$) values were estimated by dividing the nutrient removals estimated using equations (1) to (4) below:

$$\text{Nutrient removal } \left(\text{lb N/S ac}^{-1}\right) = \text{dry matter/grain yield } \left(\text{lb ac}^{-1}\right) \times \frac{\text{concentration (\%)}}{100\ \%} \tag{1}$$

$$\text{Nutrient removal } (\text{lb } P_2O_5 \text{ ac}^{-1}) = \text{dry matter/grain yield } \left(\text{lb ac}^{-1}\right) \times \frac{\text{P concentration (\%)}}{100\ \%} \times 2.29 \tag{2}$$

$$\text{Nutrient removal } (\text{lb } K_2O \text{ ac}^{-1}) = \text{dry matter/grain yield } \left(\text{lb ac}^{-1}\right) \times \frac{\text{K concentration (\%)}}{100\ \%} \times 1.20 \tag{3}$$

$$\text{Nutrient removal } (\text{lb B/Cu/Zn ac}^{-1}) = \text{dry matter/grain yield } \left(\text{lb ac}^{-1}\right) \times \frac{\text{concentration (ppm)}}{1,000,000} \tag{4}$$

Literature search for nutrient uptake and removal of annual crops (Objective 1b)

Published literature on nutrient uptake and removal from 2001 up to 31 May 2022 was searched using Web of Science Core Collection (WoS CC) by Thomson Reuter, Scopus by Elsevier, and Google Scholar. The search terms included 'crop nutrient uptake' OR 'soil nutrient supply' AND 'prairies' OR 'western Canada' AND 'crops.' A second search was done using the keywords: 'nutrient removal' AND 'prairies' OR 'western Canada' AND 'crops.' Online repositories of the Universities within Alberta, Saskatchewan, and Manitoba were searched for theses and dissertations that measured nutrient uptake and removal for the major crops under consideration. Another search was done in the databases of ministries of agriculture and commodity groups for studies that assessed nutrient uptake and removal. Laboratory groups involved in agronomy and soil management-related work and principal investigators were contacted for raw field data. The criteria used to include or exclude data in this review were as follows:

1. When manuscripts did not report nutrient uptake and removal data, they had to report nutrient concentration (percentage or $\mu g \cdot g^{-1}$) along with yield (grain, straw, or total biomass) to compute nutrient uptake/removal ($kg \cdot ha^{-1}$).
2. When manuscripts reported % protein, except where there is an explicit conversion factor, %N is deduced from the % protein using a conversion factor of 6.25.
3. Only replicated and randomized studies under field conditions were considered. Treatments or combinations of treatments with manure application or under saline conditions were not included.
4. When manuscripts/raw data reported harvest index (HI) and either total biomass or grain/straw yield, the other is computed from the two indices.
5. Where the raw data had information on the harvested area (number of rows and row spacing), the yield (straw, grain, biomass) was computed and expressed on a $kg \cdot ha^{-1}$ basis.
6. Where manuscripts and reports had uptake and removal data in a range, an average of the upper and lower limits is used together with the reported yield.

The word 'uptake' refers to total nutrient uptake in harvested (grain) and residue (straw) portions, whereas 'removal' is harvested seed/grain only. Uptake and removal values were normalized to $lb \cdot bu^{-1}$ for the crops.

Update existing values for forage dry matter production (alfalfa, clover, forage grass, barley silage, corn silage) (Objective 1c)

Published literature and on-line repositories containing information relevant to forage production were searched using the approach described above. Specifically, searches were carried out using the Web of Science Core Collection (WoS CC) by Thomson Reuter, Scopus by Elsevier, and Google Scholar. The search terms included 'nutrient uptake' OR 'soil nutrient supply' AND 'prairies' OR 'western Canada' AND either 'forage*'or each of the individual forages (i.e., alfalfa, clover, forage grass, barley silage, corn silage). Another search was done of the databases of the Saskatchewan Ministry of Agriculture and commodity groups for studies that assessed nutrient uptake and removal of the various forages. Although a number of relevant reports were accessed via these searches, the wide variability in parameters reported in the various studies—including growth stage at which yield, or nutrient uptake was determined—limited the utility of the data for our purposes. Moreover, although some studies included nutrient uptake levels, the vast majority of the studies focused on yield data, and far fewer studies included both yield and nutrient uptake. Ultimately, we were unable to compile consistent and coherent data to justify any modifications to the existing nutrient uptake and removal guidelines for forages published in the 2001 CFI guidelines. We note that the 2001 CFI guidelines are consistent with the current Government of Manitoba guidelines (https://www.gov.mb.ca/sd/eal/registries/5659steinbach/crop_nutrient_removal.pdf) and published Fertilizer Canada guidelines for 4R Nutrient Stewardship (https://fertilizercanada.ca/wp-content/uploads/2017/11/Forages_v3.pdf). Other nutrient removal estimates are available from the Government of Saskatchewan (Forage Crop Production Guide https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/forage-production-annual-native-perennial/forage-crop-production), although these latter estimates do not identify the forage species.

8. Results and Discussion:

Macronutrient removal in the seed/grain

Mean yields and macronutrient removals are reported in Table 3, and corresponding median values are reported in the appendices (Table A2). In addition to the 14 crops originally proposed, faba bean was included in the analyses based on acreage and availability of samples. The data are presented in Imperial units to provide a direct comparison with the 2001 CFI estimates. The mean yield for each crop is presented in parentheses and bolded, together with the range in yield in parentheses. For example, for barley, the mean yield for all three years (2020-2021) was 79 bu·acre^{-1}, and the yields ranged from 49 to 105 bu·acre^{-1} based on a total of 201 samples. In comparison, the 2001 CFI barley yield estimate was 80 bu·acre^{-1}. For some crops (durum, winter wheat, mustard, and chickpea), the 2001 CFI guidelines did not include these crops and thus no CFI yield estimates are available for comparison.

Average yields (2020-2022) determined by the survey of several crops were higher than the 2001 estimates including corn (150 vs 100 bu·acre^{-1}), oats (113 versus 100 bu·acre^{-1}), spring wheat (62 versus 40 bu·acre^{-1}), canola (43 versus 35 bu·acre^{-1}), flax (30 versus 24 bu·acre^{-1}), and dry bean (42 versus 30 bu·acre^{-1}), with the remaining crop yields remaining relatively unchanged (i.e., similar or within 10% of the 2001 estimates). Although the divergence in yields may reflect, in part, the development of new varieties together with management strategies that have enhanced yield potential since the publication of the 2001 yield estimates, comparisons with reported crops yields in Saskatchewan (https://dashboard.saskatchewan.ca/agriculture/rm-yields/rm-yields-data#rm-yields-tab) indicate that mean yields based on the current survey are in some instances higher than the current Saskatchewan RM averages (e.g., barley 55 bu·acre^{-1}, oat 74 bu·acre^{-1}, spring wheat 42 bu·acre^{-1}, canola 32 bu·acre^{-1}, flax 21 bu·acre^{-1}, lentil 1281 lb·acre^{-1}, pea 33 bu·acre^{-1}).

Data was collected over three growing seasons, each of which had different growing conditions. In particular, the 2021 growing season was marked by a drought across all three prairie provinces. Although growing season precipitation varied between years, the data indicate that variations in seed nutrient concentration (i.e., nutrient removal on a per bushel basis) associated with the drought in 2021 fell within the overall variation in the data set (e.g., Fig. 2). Consequently, all data were combined over the three years of the project. Others have reported no association between crop yield and nutrient concentration. For example, Villamil et al. (2019) examined P and K uptake in corn, soybean and wheat in Illinois and based on over 5000 grain samples and similarly concluded that grain concentration of P and K were not related to field crop yields.

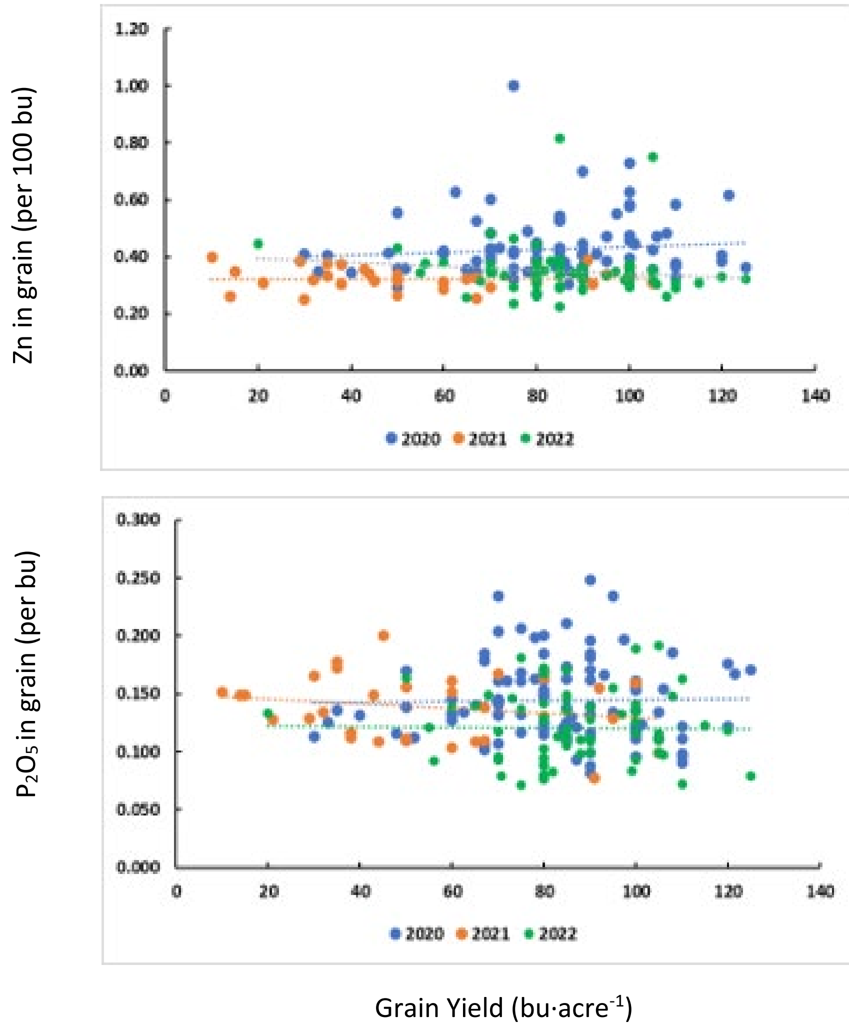

Figure 2. Scatter plot showing the relationship between zinc concentration in the grain and crop yield, and phosphorus concentration in the grain and yield of barley. Similar non-significant relationships were observed for other nutrients and crops.

Nutrient uptake is expressed as pounds (lb) nutrient per bushel produced, and thus reflects a concentration (i.e., nutrient per bushel) rather than being a yield dependent estimate of nutrient uptake (i.e., total uptake). In most cases, the new estimates of macronutrient removal (in the seed and/or grain) were lower than the 2001 CFI estimates, although there were notable exceptions (Table 3). For example, nitrogen removal values for oats and lentil was higher than the CFI estimates, although the N removal in oats was within 10% of the 2001 CFI estimate (Fig. 3). Estimates of P_2O_5 and K_2O removal were consistently less than the CFI estimates, with the exception of K_2O removal in dry bean (0.93 lb $K_2O \cdot bushel^{-1}$ versus the previous CFI estimate 0.83 lb $K_2O \cdot bushel^{-}$

[1]). Sulphur removal values similarly were lower (or similar) in the survey than previous CFI estimates with the exception of soybean, for which the survey data indicated higher S removal (0.17 lb S·bushel^{-1}) versus the CFI estimate (0.10 lb S·bushel^{-1}).

Others have reported reduced P and K removal estimates relative to earlier estimated reference values. For example, Villamil et al. (2019) examined P and K uptake in corn, soybean and wheat in Illinois and, based on a survey of over 5000 grain samples, also reported approximately 12% lower removal rates than previous reference values. As in the current study, the exact origin of the Illinois reference values are unknown, and Villamil et al. (2019) concluded that the lower grain nutrient concentrations associated with improved varieties and management clearly demonstrated that per-bushel nutrient removal had not increased with time, although greater yields necessarily resulted in greater total nutrient removal, irrespective of the lower nutrient concentrations in the grain. Our survey results similarly suggest a reduction in nutrient concentration in the grain for most crops and macronutrient combinations, which may reflect greater nutrient use efficiency associated with current varieties and management practices. However, because the details of the origin of the 2001 CFI estimates are not known (e.g., it is not known whether the data was derived from research plots or commercial fields), the revised survey estimates may simply provide data more closely related to commercially produced crops.

As was the case for all the macronutrients, improved yields relative to the 2001 CFI estimates for many crops necessarily means that greater nutrient removal is occurring on a per acre basis, irrespective of the “per bushel” removal values. It is important to note that crop yields reported for the survey data were variable from year to year and within years, reflecting differences in overall growing conditions.

Although the survey results were generally lower than previous CFI estimates, the degree of variability in the nutrient concentration values was considerably higher for all macronutrients (as revealed by boxplots), relative to the estimated range in the CFI estimates (Figs. 3-6). The 2001 CFI estimates were presented as a range, which was calculated from earlier nutrient removal values published in 1992 by the Western Canada Fertilizer Association and represented a mean value ± 10%. Survey data in Figs. 3-6 are presented as boxplots, in which the green box represents the middle 50% of the data surrounding a median value (i.e., 25% of the data is above and 25% of the data falls below the median within the green boxes), and the whiskers represent the largest (upper whisker) and lowest (lower whicker) data values that are within 1.5 times the interquartile range (i.e., the range of the data within the box itself). The size of the box and associated whiskers represents the variability in the data values. The current survey data indicates that the variability in nutrient removal can be significantly greater than ± 10% of median value, underscoring the need to view nutrient removal estimates as useful guidance (when paired with a soil test), but not as prescriptive values. Notable variation in nutrient removal was observed for potassium removal by winter wheat and soybean, and S removal by mustard. Estimates for both winter wheat and mustard are based on a more limited number of samples (n=11 and n=17, respectively) than other crops.

Table 3. Average (mean) macronutrient removal in the grain (lbs per bushel of grain produced) ± standard deviation, and grain yield (bushels per acre) estimated across Western Canadian prairies in 2020, 2021, and 2022 growing seasons compared with CFI estimates (mean ± standard deviation). Bolded values are the average grain yields and nutrient removal from 2020-2022.

Crop **(x̄)** (Current yield range)	CFI x̄ crop yield bu per acre	Nitrogen (N)		Phosphorus (P_2O_5)		Potassium (K_2O)		Sulphur (S)	
		Survey	**CFI**	**Survey**	**CFI**	**Survey**	**CFI**	**Survey**	**CFI**
		---lbs per bushel of grain produced---							
Barley **(79)** (49-105), *n=201*	80	**0.86** (± 0.28)	0.97 (0.88-1.06)	**0.36** (±0.07)	0.42 (0.38-0.46)	**0.26** (± 0.07)	0.32 (0.29-0.34)	**0.07** (± 0.01)	0.09 (0.08-0.10)
Corn **(150)** (111-181), *n=59*	100	**0.94** (± 0.62)	0.97 (0.87-1.07)	**0.36** (±0.04)	0.44 (0.39-0.48)	**0.23** (± 0.07)	0.28 (0.25-0.30)	**0.053** (± 0.004)	0.07 (0.06-0.07)
Durum **(50)** (29-72), *n=59*	(-)	**1.64** (± 0.58)	- -	**0.50** (± 0.10)	- -	**0.30** (± 0.07)	- -	**0.10** (± 0.02)	- -
Oat **(113)** (69-157), *n=166*	100	**0.65** (±0.22)	0.62 (0.55-0.68)	**0.25** (±0.05)	0.26 (0.23-0.28)	**0.17** (± 0.04)	0.19 (0.17-0.20)	**0.05** (±0.01)	0.05 (0.04-0.05)
Wheat **(62)** (41-83), *n=310*	40	**1.38** (± 0.28)	1.50 (1.35-1.65)	**0.49** (± 0.09)	0.59 (0.53-0.65)	**0.31** (± 0.22)	0.44 (0.40-0.48)	**0.10** (0.01)	0.12 (0.10-0.13)
W. Wheat (**53**) (42-83), *n=11*	(-)	**1.55** (± 0.49)	- -	**0.51** (± 0.11)	- -	**0.50** (± 0.37)	- -	**0.10** (0.02)	- -
Canola **(43)** (31-55), *n=373*	35	**1.68** (± 0.32)	1.93 (1.74-2.11)	**0.67** (± 0.15)	1.04 (0.94-1.14)	**0.35** (± 0.07)	0.52 (0.46-0.57)	**0.19** (± 0.06)	0.32 (0.29-0.34)
Flax **(30)** (19-43), *n=89*	24	**1.89** (± 0.42)	2.12 (1.91-2.33)	**0.63** (± 0.13)	0.65 (0.58-0.71)	**0.42** (± 0.11)	0.61 (0.54-0.67)	**0.12** (± 0.03)	0.23 (0.21-0.25)
Mustard (**17**) (12-22), *n=15*	(-)	**2.26** (± 0.31)	- -	**0.75** (± 0.19)	- -	**0.45** (± 0.07)	- -	**0.42** (± 0.26)	- -
Soybean **(40)** (27-53), *n=96*	50[¥]	**2.99** (± 0.19)	3.87 (3.74-4.00)	**0.74** (± 0.17)	0.84 (0.8-0.88)	**0.89** (± 0.36)	1.39 (1.38-1.4)	**0.17** (± 0.05)	0.10
Chickpea **(32)** (18-45), *n=38*	(-)	**2.26** (± 0.44)	- -	**0.51** (± 0.05)	- -	**0.73** (± 0.11)	- -	**0.12** (± 0.01)	- -
Dry bean **(42)** (36-51), *n=61*	30[¥]	**1.99** (± 0.32)	2.50 -	**0.61** (± 0.09)	0.83 -	**0.93** (± 0.16)	0.83 -	**0.12** (± 0.01)	0.17 -
Faba bean **(50)** (31-67), *n=37*	50	**2.70** (± 0.51)	3.42 (3.08-3.76)	**0.67** (± 0.11)	1.22 (1.10-1.34)	**0.83** (± 0.18)	1.04 (0.94-1.14)	**0.12** (± 0.02)	0.14 (0.12-0.16)
Lentil **(28)** (19-39), *n=106*	30	**2.44** (± 0.51)	2.03 (1.83-2.23)	**0.56** (± 0.11)	0.62 (0.57-0.67)	**0.63** (± 0.15)	1.09 (0.97-1.20)	**0.12** (± 0.02)	0.15 (0.13-0.17)
Pea **(50)** (29-73), *n=170*	50	**1.75** (± 0.39)	2.34 (2.10-2.58)	**0.47** (± 0.10)	0.69 (0.62-0.76)	**0.55** (± 0.17)	0.71 (0.64-0.78)	**0.10** (± 0.01)	0.13 (0.12-0.14)

[¥]CFI estimates for yield, nutrient uptake and removal based on the Nutrient Uptake and Removal for Field Crops, Eastern Canada 1998, for soybean and dry bean only.
[ƒ]Denotes standard deviation.

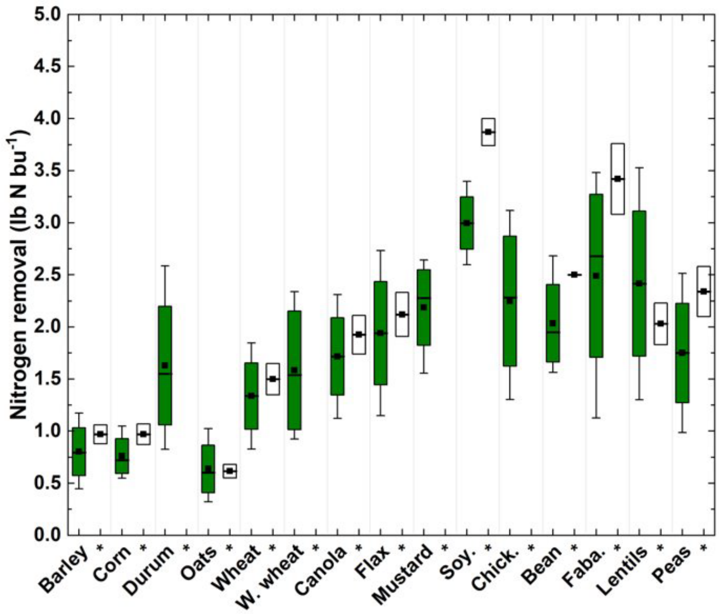

Figure 3. Removal of nitrogen in the seed/grain. Boxplots in green represent the survey data with the mid-line representing the median. The corresponding 2001 CFI removal estimates are presented as white boxes representing the estimated variation with the mean value in the centre. The CFI estimates for soybean and dry bean are based on the Eastern Canada 1998 guidelines.

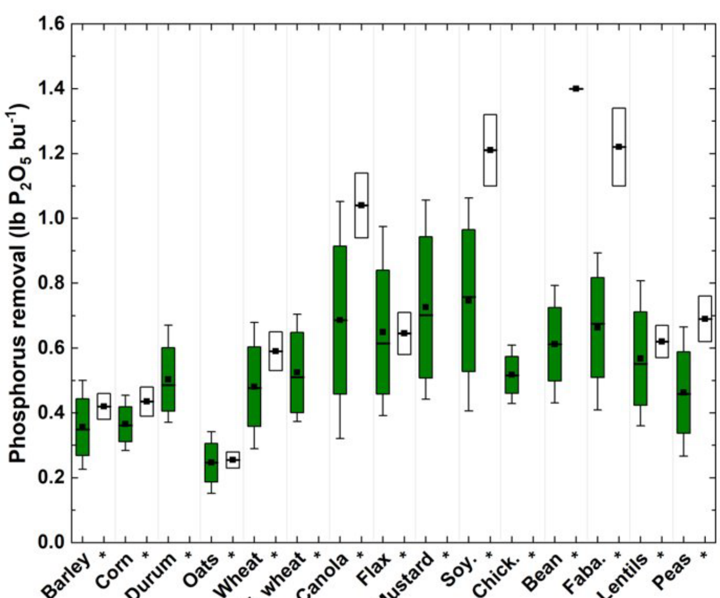

Figure 4. Removal of phosphorus (P_2O_5) in the seed/grain. Boxplots in green represent the survey data with the mid-line representing the median. The corresponding 2001 CFI removal estimates are presented as white boxes representing the estimated variation with the mean value in the centre. The CFI estimates for soybean and dry bean are based on the Eastern Canada 1998 guidelines.

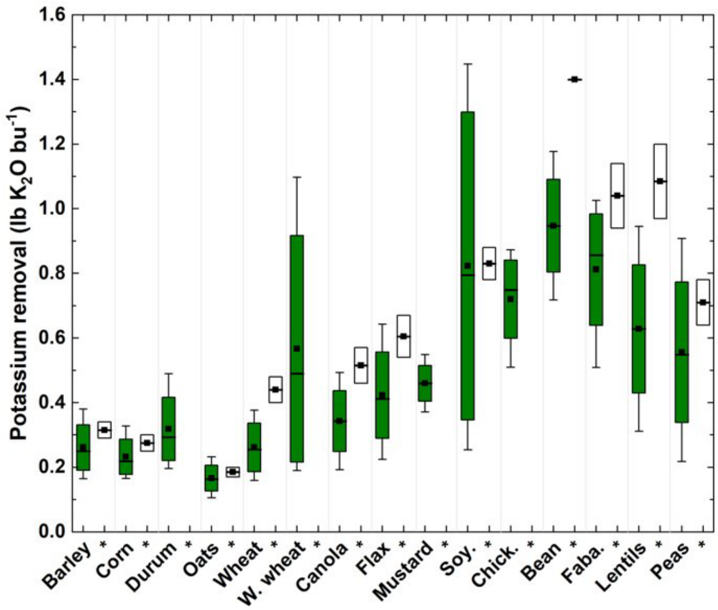

Figure 5. Removal of potassium (K_2O) in the seed/grain. Boxplots in green represent the survey data with the mid-line representing the median. The corresponding 2001 CFI removal estimates are presented as white boxes representing the estimated variation with the mean value in the centre. The CFI estimates for soybean and dry bean are based on the Eastern Canada 1998 guidelines.

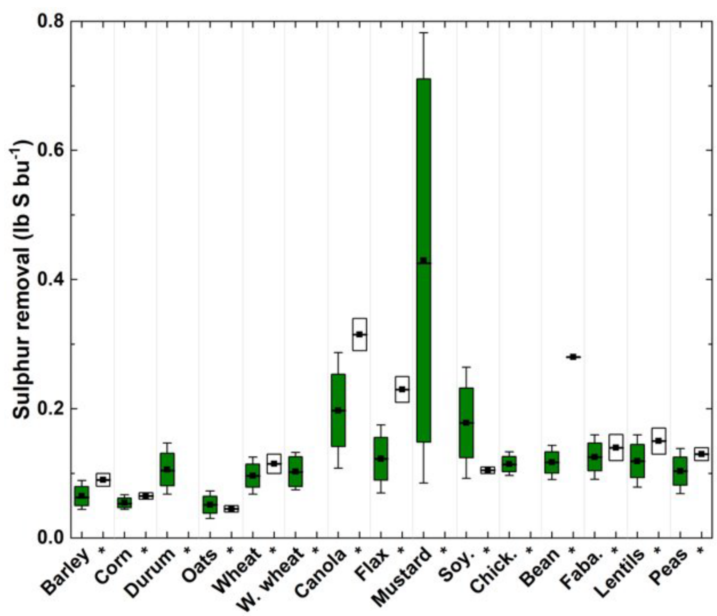

Figure 6. Removal of sulphur in the seed/grain. Boxplots in green represent the survey data with the mid-line representing the median. The corresponding 2001 CFI removal estimates are presented as white boxes representing the estimated variation with the mean value in the centre. The CFI estimates for soybean and dry bean are based on the Eastern Canada 1998 guidelines.

Micronutrient removal in the seed/grain

Average micronutrient removal is reported in Table 4, and median values are reported in the appendices (Table A3). Values are reported “per 100 bushels of grain produced” to account for the numerically low values of micronutrient removal (e.g., B removal in barley grain is 0.00009 lb B per bu, expressed here as 0.009 lbs B per 100 bushels). The 2001 CFI nutrient removal guidelines did not include micronutrient removal values, so these values, collected from across western Canada, represent a new source of information for prairie farmers.

Relative to macronutrients, micronutrient removal was very small numerically. None-the-less, micronutrients are essential to support normal crop growth and development. Data suggest that the micronutrient removal in the grain of the different crops varied between crops (Table 4). Moreover, there was significant variation in micronutrient removal values (Figs. 7-9). Boron removal, in particular, was highly variable for most crops. Others have reported that the requirement for micronutrients such as B are variable between plant species, and genotypes within species (Brdar-Jokanovic, 2020). Thus, the variation we observed may reflect differences in micronutrient requirements both between crops and between different varieties.

Micronutrient removal in soybean was high relative to all other crops. Others similarly have reported high concentrations of micronutrients in soybean relative to other crops. For example, Carter and Gupta (1996) reported B concentrations in soybean grain over 10 times higher than in barley. Boron is transported by passive diffusion and moves with the transpiration stream (Brdar-Jokanovic, 2020) and luxury uptake of boron has reportedly been a concern for Minnesota farmers in both soybean and dry bean (Kaiser, 2017).

Copper removal had less variability in removal values as compared to B, particularly for the cereals. Similarly, Zn removal values were not as variable within the cereals (note the different scales used on the y-axis for the different figures) although Zn removal values for oilseeds and pulses were characterized by considerable variability.

The variability in the removal values is important to consider, particularly when attempting to use these (or other) removal guidelines for nutrient management decisions. We are not able to fully account for the observed variability, other than to conclude that many factors including crop species and variety as well as management practices and climate may affect the uptake of micronutrients in any given year. Thus, micronutrient removal guidelines should be viewed as a tool for assessing nutrient requirements and should not be used for making fertilizer decisions without also conducting soil tests and plant tissue testing to confirm micronutrient deficiencies.

As with macronutrient removal estimates, higher yielding crops are necessarily removing greater quantities of micronutrients on a per acre basis.

Table 4. Average micronutrient removal (in grain) (lbs per 100 bushels of grain produced) and grain yield (bushels per acre) estimated across Western Canadian prairies in 2020, 2021, and 2022 growing seasons compared with CFI estimates. Bolded values are the average grain yields and nutrient removal (± standard deviation) from the 2020-2022 survey.

Crop **(x̄)** (Current yield range)	**Boron (B)**	**Copper (Cu)**	**Zinc (Zn)**
	---------------lbs per 100 bushel grain produced--------------		
Barley **(79)** (49-105), *n=201*[¥]	**0.009** (± 0.008[f])	**0.025** (± 0.010)	**0.129** (± 0.032)
Corn **(150)** (111-181), *n=59*	**0.014** (± 0.002)	**0.010** (± 0.004)	**0.084** (± 0.014)
Durum **(50)** (29-72), *n=59*	**0.009** (± 0.003)	**0.039** (± 0.014)	**0.164** (± 0.031)
Oats **(113)** (69-157), *n=166*	**0.0.004** (± 0.002)	**0.019** (± 0.008)	**0.083** (± 0.024)
Wheat **(62)** (41-83), *n=310*	**0.006** (± 0.003)	**0.029** (±0.011)	**0.171** (± 0.039)
W. Wheat (**53**) (42-83), *n=11*	**0.029** (± 0.030)	**0.038** (± 0.016)	**0.142** (± 0.032)
Canola **(43)** (31-55), *n=373*	**0.048** (± 0.017)	**0.020** (± 0.010)	**0.162** (± 0.033)
Flax **(30)** (19-43), *n=89*	**0.070** (± 0.036)	**0.046** (± 0.020)	**0.198** (± 0.043)
Mustard (**17**) (12-22), *n=15*	**0.048** (± 0.009)	**0.027** (±0.008)	**0.201** (± 0.041)
Soybeans **(40)** (27-53), *n=96*	**0.124** (± 0.066)	**0.058** (± 0.026)	**0.198** (± 0.043)
Chickpeas **(32)** (18-45), *n=38*	**0.049** (±0.008)	**0.046** (± 0.012)	**0.18** (± 0.031)
Dry bean **(42)** (36-51), *n=61*	**0.062** (±0.011)	**0.045** (±0.009)	**0.157** (± 0.021)
Faba bean **(50)** (31-67), *n=37*	**0.060** (± 0.008)	**0.062** (± 0.022)	**0.263** (± 0.064)
Lentils **(28)** (19-39), *n=106*	**0.041** (± 0.014)	**0.047** (± 0.012)	**0.202** (± 0.041)
Peas **(50)** (29-73), *n=170*	**0.044** (± 0.015)	**0.037** (± 0.009)	**0.177** (± 0.040)

[¥] "n" denotes number of samples used in the analyses.

[f] Denotes standard deviation

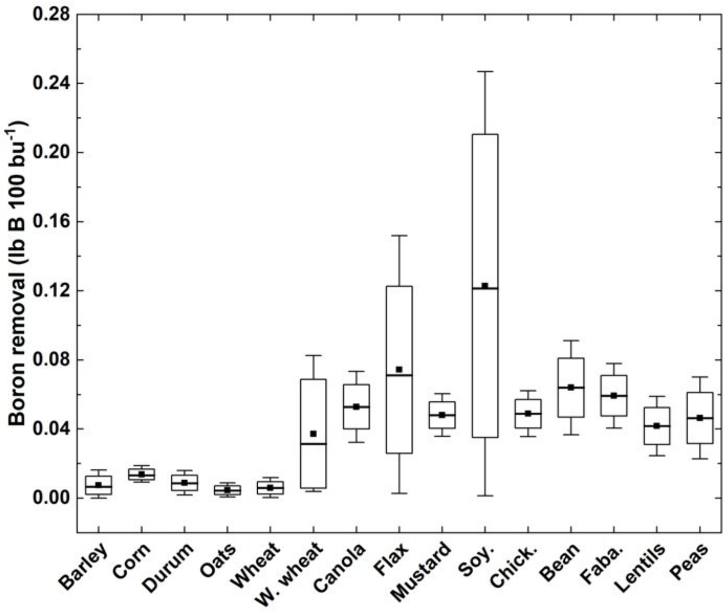

Figure 7. Removal of boron in the seed/grain per 100 bu^{-1}. Boxplots represent the survey data with the mid-line representing the median value, the box limits representing the first (Q1) and third quartile (Q3), and the whiskers representing Q1-1.5*IQR and Q3+1.5*IQR within the min/max of the data set.

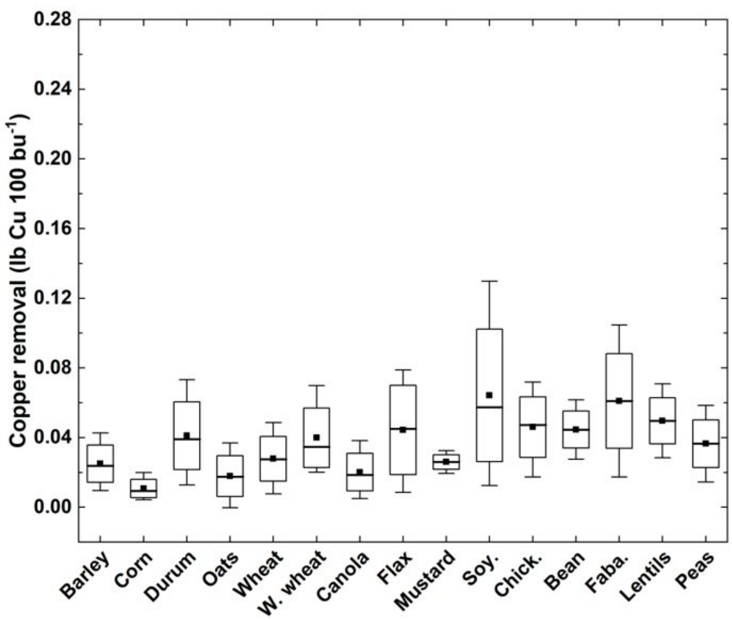

Figure 8. Removal of copper in the seed/grain per 100 bu^{-1}. Boxplots represent the survey data with the mid-line representing the median value, the box limits representing the first (Q1) and third quartile (Q3), and the whiskers representing Q1-1.5*IQR and Q3+1.5*IQR within the min/max of the data set.

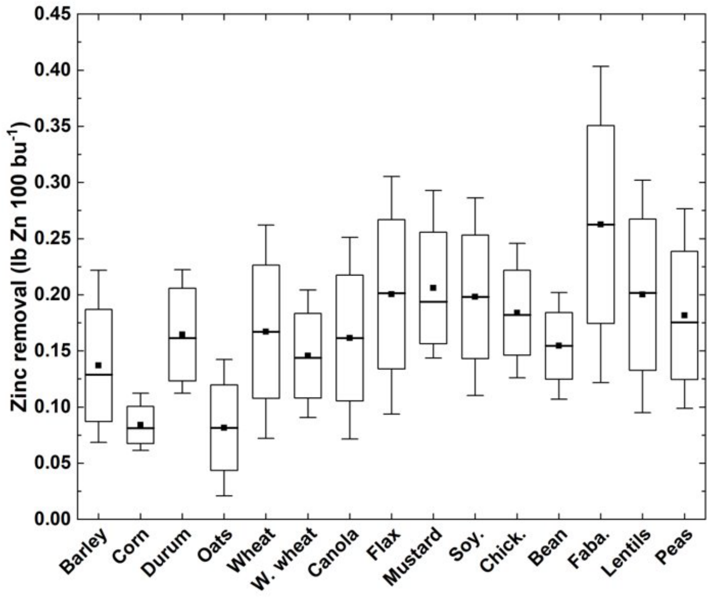

Figure 9. Removal of zinc in the seed/grain per 100 bu^{-1}. Boxplots represent the survey data with the mid-line representing the median value, the box limits representing the first (Q1) and third quartile (Q3), and the whiskers representing Q1-1.5*IQR and Q3+1.5*IQR within the min/max of the data set.

Macro and micronutrient uptake in the biomass

Macro and micronutrient uptake in the biomass of all crops was assessed in 2021 and 2022 (Table 5). The number of biomass samples collected are reported in Table 1. Samples were collected at growth stages intended to correspond to maximum nutrient uptake into the aerial portion of the plant, including any reproductive structures present at the time of sampling. Moreover, whole samples were ground to avoid the possibility that nutrients were unevenly partitioned within plant tissues.

Estimates of both nitrogen and phosphorus uptake in the biomass were either similar to, or less than the 2001 CFI estimates, with the exception of P_2O_5 uptake in soybean (Table 5). In contrast, many of the crops had higher uptake levels of K_2O than previously estimated, with the exceptions of soybean, faba bean and lentil, all of which had slightly lower uptake levels of K_2O than previously estimated.

Survey data indicated that S uptake levels in canola and pea were higher than previous estimates, the oat S uptake level was very similar, whereas all remaining crops removed less S than previously estimated. It is interesting to note that although the S uptake values for canola were greater than the CFI estimates, the removal of S in the grain was less than previous estimates. We conclude that S remains an important nutrient for canola production. Importantly, for all macronutrients, the uptake values were highly variable, likely reflecting both inherent variabilities associated with different crops and varieties and different growing conditions, and the challenges associated with sampling during the growing season and achieving a true "maximum" uptake value. We conclude that the biomass values are at best near approximations of nutrient requirements and should not be used to inform prescriptive fertilizer management decisions.

Micronutrient uptake values in the biomass similarly were highly variable (Table 6), further demonstrating that determining total nutrient uptake is challenging given the judgement required to ensure samples are obtained at a growth stage that fully represents total nutrient uptake. As with the macronutrient removal estimates, these total removal estimates should not be viewed as prescriptive, but rather as an indication of the variability that can be associated with micronutrient removal, both between different crops and also within crops.

Table 5. Average (mean) macronutrient uptake in the whole plant (lb nutrient per bushel of grain produced ± standard deviation). Grain yields (bushels per acre) are based on mean yield estimates from survey samples collected during the 2021-2022 growing seasons. Values are compared with 2001 CFI estimates. Bolded values are the average grain yields (2020-2022) and nutrient removal (± standard deviation). Total number of biomass samples for each crop are reported in the nitrogen column.

Crop **(x̄)** (Current yield range)	(CFI x̄ crop yield)	**Nitrogen (N)**		**Phosphorus (P_2O_5)**		**Potassium (K_2O)**		**Sulphur (S)**	
		Survey	**CFI**	**Survey**	**CFI**	**Survey**	**CFI**	**Survey**	**CFI**
		---------------------------------------lbs per bushel of grain produced---------------------------------------							
Barley **(79)** (49-105)	(80)	**1.00** *(n=19)* [¥] (± 0.35)	1.39 (1.25-1.53)	**0.38** (± 0.15)	0.56 (0.50-0.61)	**1.57** (± 0.50)	1.33 (1.20-1.46)	**0.16** (± 0.04)	0.33 (0.15-0.18)
Corn **(150)** (111-181)	(100)	**1.21** *(n=24)* (± 0.39)	1.53 (1.38-1.68)	**0.60** (± 0.18)	0.63 (0.57-0.69)	**1.28** (± 0.46)	1.29 (1.16-1.41)	**0.12** (± 0.04)	0.15 (0.13-0.16)
Durum **(50)** (29-72)	(-)	**3.14** *(n=15)* (± 1.26)	- -	**1.07** (± 0.47)	- -	**3.33** (± 1.07)	- -	**0.36** (± 0.12)	- -
Oat **(113)** (69-157)	(100)	**1.00** *(n=107)* (± 0.52)	1.07 (0.96-1.19)	**0.30** (± 0.20)	0.41 (0.36-0.45)	**1.65** (± 0.98)	1.46 (1.31-1.60)	**0.14** (± 0.08)	0.13 (0.12-0.14)
Wheat **(62)** (41-83)	(40)	**1.55** *(n=59)* (± 0.76)	2.11 (1.90-2.32)	**0.55** (± 0.20)	0.80 (0.73-0.88)	**2.00** (± 1.29)	1.81 (1.63-2.00)	**0.19** (± 0.09)	0.23 (0.20-0.25)
W. Wheat **(53)** (42-83)	(-)	**1.01** *(n=3)* (± 0.34)	- -	**0.32** (± 0.12)	- -	**1.28** (± 0.35)	- -	**0.16** (± 0.07)	- -
Canola **(43)** (31-55)	(35)	**2.38** *(n=60)* (± 1.26)	3.19 (2.85-3.51)	**0.90** (± 0.50)	1.47 (1.31-1.63)	**2.93** (± 1.42)	2.31 (2.09-2.54)	**0.86** (± 0.57)	0.54 (0.49-0.60)
Flax **(30)** (19-43)	(24)	**2.26** *(n=16)* (± 0.81)	2.89 (2.58-3.17)	**0.80** (± 0.24)	0.83 (0.75-0.92)	**2.92** (± 0.80)	1.81 (1.63-2.00)	**0.30** (± 0.07)	0.56 (0.50-0.63)
Soybean **(40)** (27-53)	(45)	**4.06** *(n=21)* (± 1.21)	5.20 (4.60-5.80)	**1.05** (± 0.37)	0.90 (0.80-1.00)	**3.24** (± 0.70)	3.40 (2.40-4.40)	**0.29** (± 0.08)	0.35 (0.34-0.35)
Chickpea **(32)** (18-45)	(-)	**1.20** *(n=1)* -	- -	**0.26** -	- -	**1.88** -	- -	**0.16** -	- -
Dry bean **(42)** (36-51)	(30)	**2.29** *(n=37)* (± 0.72)	- -	**0.70** (± 0.20)	- -	**2.70** (± 0.97)	- -	**0.19** (± 0.07)	- -
Faba bean **(50)** (31-67)	(50)	**3.04** *(n=19)* (± 1.73)	5.71 (5.14-6.28)	**0.64** (± 0.42)	1.97 (1.78-2.16)	**3.15** (± 2.07)	5.09 (4.58-5.60)	**0.17** (± 0.07)	0.27 (0.24-0.30)
Lentil **(28)** (19-39)	**(**30)	**2.49** *(n=5)* (± 0.38)	3.05 (2.70-3.37)	**0.66** (± 0.21)	0.82 (0.73-0.90)	**2.04** (± 0.55)	2.55 (2.30-2.80)	**0.21** (± 0.07)	0.30 (0.27-0.33)
Pea **(50)** (29-73)	(50)	**2.66** *(n=39)* (± 1.14)	3.06 (2.76-3.36)	**0.70** (± 0.30)	0.84 (0.76-0.92)	**2.97** (± 1.25)	2.73 (2.46-3.00)	**0.37** (± 0.17)	0.25 (0.22-0.28)

[¥] Total number of samples collected for each crop.

Table 6. Average (mean) micronutrient uptake (whole plant) (lb nutrient per 100 bushels of grain produced). Grain yields (bushels per acre) are based on mean yield estimates from samples collected across Western Canadian prairies in 2021-2022 growing seasons. Bolded values are the average grain yields (2020-2022) and nutrient removal (2021-2022) (± standard deviation). Total number of biomass samples for each crop are reported in the nitrogen column.

Crop **(x̄)** (Current yield range)	**Boron (B)**	**Copper (Cu)**	**Zinc (Zn)**
	--------------lbs per 100 bushels grain produced--------------		
Barley **(79)** (49-105)	**0.044** (n=19)[¥] (± 0.020)	**0.087** (± 0.081)	**0.117** (± 0.041)
Corn **(150)** (111-181)	**0.070** (n=24) (± 0.021)	**0.091** (±0.108)	**0.164** (± 0.058)
Durum **(50)** (29-72)	**0.086** (n=15) (± 0.029)	**0.200** (± 0.085)	**0.518** (± 0.291)
Oat **(113)** (69-157)	**0.042** (n=107) (± 0.036)	**0.083** (± 0.044)	**0.086** (± 0.048)
Wheat **(62)** (41-83)	**0.056** (n=59) (± 0.024)	**0.085** (± 0.029)	**0.175** (± 0.058)
W. Wheat (**53**) (42-83)	**0.038** (n=3) (±0.025)	**0.550** (± 0.078)	**0.092** (± 0.039)
Canola **(43)** (31-55)	**0.336** (n=60) (± 0.194)	**0.061** (± 0.055)	**0.203** (± 0.114)
Flax **(30)** (19-43)	**0.364** (n=16) (± 0.109)	**0.094** (± 0.044)	**0.303** (± 0.101)
Soybean **(40)** (27-53)	**0.606** (n=21) (± 0.208)	**0.136** (± 0.121)	**0.313** (± 0.112)
Chickpea **(32)** (18-45)	**0.338** (n=1)	**0.068**	**0.246**
Dry bean **(42)** (36-51)	**0.290** (n=37) (± 0.082)	**0.178** (±0.191)	**0.225** (± 0.060)
Faba bean **(50)** (31-67)	**0.251** (n=19) (± 0.127)	**0.102** (± 0.046)	**0.333** (± 0.236)
Lentil **(28)** (19-39)	**0.232** (n=6) (± 0.032)	**0.084** (± 0.027)	**0.301** (± 0.141)
Pea **(50)** (29-73)	**0.312** (n=39) (± 0.128)	**0.102** (± 0.058)	**0.237** (± 0.105)

[¥] "n" denotes the number of biomass samples collected.

Literature survey for nutrient uptake and removal of annual crops (Objective 1b)

The literature survey was conducted as a supplement to the measured macro and micronutrient uptake and removal values. The published and grey literature provided a vast resource of data, and we were able to use this resource to further support the development of new uptake and removal guidelines. Much of the data collected represents values obtained through small plot studies. Moreover, although the literature was a rich source of data, we were unable to find studies that met our search criteria (described above) for several crops, including barley, durum, flax, mustard, and chickpea, and thus these crops are not included in the analyses. Specifically, although there are research reports and papers available for these crops, specific criteria needed for inclusion in the literature survey were not met. Most commonly, yield data was presented but not with corresponding nutrient data, or the nutrient uptake values did not correspond to maximum nutrient uptake stages, or the vegetative stage was not specifically stated for midseason uptake.

For the crops for which we were able to access data that met our search criteria, we report the mean, together with the number of data points used in the calculation of the mean (Table 7). Importantly, the data represents a collation of several sources, and not all papers or data sources provided data for all nutrients. Consequently, we could not relate all nutrient uptake values to a single corresponding final seed yield for all studies. Thus, for biomass and straw nutrient uptake values, we used the mean grain yields of the studies that measured both biomass and straw uptake to relate the nutrient uptake values to final grain yield, knowing that the grain yields were an average value and were not, in some instances, derived from the same trial.

For corn, oat, canola, soybean and fababean, the literature-derived yield estimates were within 10% of the survey data (Table 7 and Table 3). The average wheat yield based on 2596 data points from the literature, was the same as the yield estimates from the survey data. In contrast, the values from the literature revealed lower yields for corn (124 versus 150 bu·acre^{-1}) but were higher than the reported survey yields for the remaining crops (e.g., winter wheat, 67 versus 53 bu·acre^{-1}; soybean, 49 versus 40 bu·acre^{-1}; and faba bean, 84 versus 50 bu·acre^{-1}). It is likely that yield losses associated with harvesting operations in commercial fields versus hand-harvested research plots account for the divergence in yield estimates in these crops.

With a few exceptions, the literature search revealed similar or lower estimates for nutrient removal (i.e., nutrient in the seed/grain) than those from the survey. A notable exception was the S removal in canola seed for which the survey estimate was 0.19 lb S·bu^{-1}, the CFI estimate was 0.32 lb S·bu^{-1}, and the literature-based estimate was 0.42 lb S·bu^{-1}. Interestingly, the International Plant Nutrient institute Canada reports nutrient removal by canola as 0.25 lb S·bu^{-1} (http://www.ipni.net/article/IPNI-3296, removal estimates last modified May 2014) which is slightly higher than the survey estimate. Given the importance of S in canola production, and the variance in the estimated removal, it may be prudent to opt for a higher estimate of S removal to avoid potential deficiencies. Similarly, the survey estimate of S removal in flax seed of 0.12 lb S·bu^{-1} was lower than both the CFI estimate of 0.23 lb S·bu^{-1}, and the International Plant Nutrient Institute Canada estimate of 0.19 lb S·bu^{-1}.

Table 7. Summary of literature review data (2001-2021) on nutrient uptake (biomass and straw) and removal (grain) from studies and raw data from across Western Canadian prairies. The number in italics is the number of observations (n) used. The bolded values are the average nutrient removal (in grain) and grain yield (bu/ac).

Crop ($\bar{x}$ yield)	**Nitrogen (N)**	**Phosphorus (P_2O_5)**	**Potassium (K_2O)**	**Sulphur (S)**	**Boron (B)**	**Copper (Cu)**	**Zinc (Zn)**
	---------------------lbs per bushel of grain produced-----------------------				------------lbs per 100 bushels of grain produced---------		
Corn							
(**124**) *Grain*	**0.79** (*841*)[1,2]	**0.32** (*72*)[1]	**0.23** (*72*)[1]	**0.05** (*72*)[1]	**0.017** (*72*)[1]	**0.006** (*72*)[1]	**0.075** (*72*)[1]
Biomass	1.19 (*56*)[1]	0.35 (*56*)[1]	0.92 (*56*)[1]	0.08 (*56*)[1]	0.039 (*56*)[1]	0.022 (*56*)[1]	0.215 (*56*)[1]
Straw	-	-	-	-	-	-	-
Oat							
(**122**) *Grain*	**0.63** (*24*)[1]	**0.23** (*24*)[1]	**0.16** (*24*)[1]	**0.05** (*24*)[1]	**0.011** (*24*)[1]	**0.012** (*24*)[1]	**0.067** (*24*)[1]
Biomass	1.05 (*24*)[1]	0.29 (*24*)[1]	1.22 (*24*)[1]	0.11 (*24*)[1]	0.189 (*24*)[1]	0.015 (*24*)[1]	0.097 (*24*)[1]
Straw	-	-	-	-	-	-	-
Wheat							
(**62**) *Grain*	**1.64** (*2596*)[3,4,5,6,7,8,9,10,11,12,13,14,15,16,17]	**0.55** (*858*)[1,3,4,5,8,10,12,18,19]	**0.23** (*84*)[1]	**0.21** (*372*)[1,8]	**0.009** (*84*)[1]	**0.029** (*116*)[1,3]	**0.164** (*196*)[1,3,8]
Biomass	2.11 (*88*)[1]	0.59 (*88*)[1]	1.43 (*88*)[1]	0.17 (*88*)[1]	0.058 (*88*)[1]	0.034 (*88*)[1]	0.161 (*88*)[1]
Straw	0.36 (*557*)[3,4,7,8,10,13]	0.09 (*295*)[3,4,8,10,19]	-	-	-	0.021 (*32*)[3]	0.021 (*32*)[3]
W. wheat							
(**67**) *Grain*	**1.20** (1028)[20,21,22,23,24,25]	-	-	-	-	-	-
Biomass	-	-	-	-	-	-	-
Straw	-	-	-	-	-	-	-
Canola							
(**47**) *Grain*	**1.50** (*718*)[1,6,8,9,10,15,17,26,27]	**0.60** (*434*)[1,8,10,18,19]	**0.42** (*32*)[1]	**0.42** (*320*)[1,18]	**0.068** (*32*)[1]	**0.013** (*32*)[1]	**0.121** (*92*)[1,8]
Biomass	3.49 (*92*)[1,28]	1.07 (*48*)[1]	3.20 (*48*)[1]	0.81 (*92*)[1,28]	0.482 (*48*)[1]	0.037 (*48*)[1]	0.276 (*48*)[1]
Straw	0.24 (*71*)[8,10]	0.07 (*112*)[8,10,19]	-	-	-	-	-
Soybean							
(**49**) *Grain*	**3.23** (*1584*)[1,29,30,31,32,33,34,35]	**0.76** (*1592*)[1,34,36]	**1.29** (*610*)[1,31,32,38]	**0.15** (*60*)[1]	**0.149** (*60*)[1]	**0.055** (*132*)[1,31]	**0.225** (*132*)[1,31]
Biomass	3.44 (*576*)[1,29]	0.58 (*1340*)[1,34,36]	1.30 (*232*)[1,38]	0.46 (*64*)[1]	0.795 (*64*)[1]	0.117 (*64*)[1]	0.380 (*64*)[1]
Straw	0.61 (*144*)[30,32,33,35]	0.23 (*200*)[30,32,33,35,37]	-	-	-	-	-
Faba bean							
(**84**) *Grain*	**2.70** (128)[39]	**0.79** (*128*)[39]	**0.88** (*128*)[39]	**0.13** (*128*)[39]	-	**0.055** (*128*)[39]	**0.241** (*128*)[39]
Biomass	-	-	-	-	-	-	-
Straw	0.27 (128)[39]	0.07 (*128*)[39]	0.61 (*128*)[39]	0.03 (*128*)[39]	-	0.010 (*128*)[39]	0.031 (*128*)[39]
Lentil							
(**27**) *Grain*	**1.99** (*64*)[30,35]	**0.49** (*64*)[30,35]	-	-	-	-	-
Biomass	-	-	-	-	-	-	-
Straw	2.29 (*64*)[30,35]	0.61 (*64*)[30,35]	-	-	-	-	-
Pea							
(**53**) *Grain*	**2.03** (*1058*)[3,8,10,30,40,41]	**0.53** (*762*)[3,8,10,18,19,30,40]	-	**0.22** (*288*)[18]	-	**0.043** (*32*)[3]	**0.165** (*95*)[3,8]
Biomass	-	-	-	-	-	-	-
Straw	0.72 (*434*)[3,8,10,30,40]	0.12 (*474*)[3,8,10,19,30,40]	-		-		

Footnote Table 7:

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9. Conclusions and Recommendations:

This project provides updated uptake and removal guidelines for crops grown in Western Canada. The revised estimates provide updated information for agronomists and producers based on commercially grown crops in Western Canada. The purpose of these estimates is to assist in the development of fertilizer management plans, but not to replace the need for soil testing. As with any nutrient uptake and removal estimates, the estimates are only a single supporting piece of information when developing fertilizer management plans, and should not be viewed as prescriptive, or a replacement for soil testing. At best, the uptake and removal estimates may help in the interpretation of soil test reports and serve as supporting information for developing nutrient replacement or nutrient maintenance fertility strategies. Nutrient uptake and removal estimates should always be used in conjunction with soil testing.

When developing nutrient management strategies for either nutrient replacement or nutrient maintenance in the soil, it is important to recognize that fertilizer use efficiency is never 100%. Moreover, total nutrient uptake and removal levels are dependent on crop yield. Crop varieties, soil fertility and general growing conditions may affect both nutrient uptake and removal. The survey data collected in this study revealed significant variation in uptake for both macro and micronutrients, further underscoring the need to view uptake and removal estimates as supporting information, but not as prescriptive or definitive. Accurate uptake and removal values can only be determined directly on a field-by-field basis via laboratory analyses of the crop of interest.

Importantly, removal estimates are expected to differ from the fertilizer requirements because crops are not able to withdraw all of the nutrients provided by fertilizers. For example, it is estimated that most crops only recover between 10-30% of the phosphorus in first year of application (Saskatchewan Ministry of Agriculture, accessed 2022), whereas nitrogen fertilizer use efficiency has been estimated at approximately 30–50% across the prairies (Mezbahuddin et al. 2020). Manitoba recently released a fertilizer efficiency calculator to help producers and agronomist compare the efficacy of different 4R strategies for enhancing fertilizer use efficiency, available at: www.gov.mb.ca/agriculture/farm-management/production-economics/fertilizer-cost.html.

The nutrient removal tables based on mean values (Tables 3 and 4) have been combined to a single "user-friendly" table that can be used for reference and is attached in the appendices (Table A1). Although this table is provided for information, it is important to recognize that mean values represent the average removal, and does not account for the variability that is certain to exist in commercial fields. Consequently, for the purposes of the nutrient removal calculator provided with this report, we have chosen to base the nutrient coefficients used for the calculator on the 75th percentile (and not the mean) (Appendices, Table A4). The 75th percentile represents the value at which 75% of the observed survey nutrient uptake data fell below this value, and 25% of the observations were above this value. By selecting the 75th percentile for the coefficient, the calculator is more likely to overestimate crop nutrient removal than to underestimate it. Others have used this approach when revising grain nutrient removal values for Illinois (Villamil et al., 2019) and Iowa (Mallarino et al. 2013).

10. Is there a need to conduct follow-up research?

The removal and uptake of S in canola remains an important concern for canola growers. Given the lower estimates derived from our survey data, further examination of S use by commercially produced canola may be warranted. In particular, an examination of S ranges in different varieties (of both canola and mustard) could be very informative. Additionally, the variance in potassium uptake and removal values in soybean may warrant further investigation. Other than these follow up investigations, we do not see any additional immediate needs for follow-up research with other crops, although the nutrient uptake and removal estimates ought to be revisited as varieties, yield expectations or nutrient use efficiency change.

11. Patents/IP generated/ commercialized products: None

12. List technology transfer activities: Rich – can you add the radio interview and anything else you have?

Issah, Gazali. 2023. Do crop yield influence nutrient uptake and removal in the western Canadian prairies? Soils and Crops Workshop, University of Saskatchewan. March 7-8. Saskatoon, SK.

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Walley, Fran. Revising the Crop Nutrient Uptake and Removal Guidelines for Western Canada. Virtual Presentation at Ag In Motion "Getting on with growing – Vigilance with Crop Care", June 23, 2021.

Yule, Pam. “Project Re-examines the ‘Ins and Outs’ of Crop Nutrient Uptake and Removal” POGA Newsletter Project “The Oat Scoop” November 2021 (interview with Fran Walley).

13. List any industry contributions or support received.

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15. Appendices:

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Table A1: Average (mean) grain yield (bushels per acre) and nutrient removal (in grain) (lbs per bushel of grain produced ± standard deviation) across Western Canadian prairies in 2020, 2021, and 2022 growing seasons. Bolded values are the average grain yields and nutrient removal, and numbers in parenthesis reflect possible range.

Crop (**x̄**) (range)	**Nitrogen (N)**	**Phosphorus (P_2O_5)**	**Potassium (K_2O)**	**Sulphur (S)**	**Boron (B)**	**Copper (Cu)**	**Zinc (Zn)**
	lbs nutrient per bushel grain produced				**lbs nutrient per 100 bu grain produced**		
Barley **(79)** (49-105)	**0.86** (± 0.28[¥])	**0.36** (±0.07)	**0.26** (± 0.07)	**0.07** (± 0.01)	**0.009** (± 0.008)	**0.025** (± 0.010)	**0.129** (± 0.032)
Corn **(150)** (111-181)	**0.94** (± 0.62)	**0.36** (±0.04)	**0.23** (± 0.07)	**0.053** (± 0.004)	**0.014** (± 0.002)	**0.010** (± 0.004)	**0.084** (± 0.014)
Durum **(50)** (29-72)	**1.64** (± 0.58)	**0.50** (± 0.10)	**0.30** (± 0.07)	**0.10** (± 0.02)	**0.009** (± 0.003)	**0.039** (± 0.014)	**0.164** (± 0.031)
Oats **(113)** (69-157)	**0.65** (±0.22)	**0.25** (±0.05)	**0.17** (± 0.04)	**0.05** (±0.01)	**0.0.004** (± 0.002)	**0.019** (± 0.008)	**0.083** (± 0.024)
Wheat **(62)** (41-83)	**1.38** (± 0.28)	**0.49** (± 0.09)	**0.31** (± 0.22)	**0.10** (0.01)	**0.006** (± 0.003)	**0.029** (± 0.011)	**0.171** (± 0.039)
W. Wheat (**53**) (42-83)	**1.55** (± 0.49)	**0.51** (± 0.11)	**0.50** (± 0.37)	**0.10** (0.02)	**0.029** (± 0.030)	**0.038** (± 0.016)	**0.142** (± 0.032)
Canola **(43)** (31-55)	**1.68** (± 0.32)	**0.67** (± 0.15)	**0.35** (± 0.07)	**0.19** (± 0.06)	**0.048** (± 0.017)	**0.020** (± 0.010)	**0.162** (± 0.033)
Flax **(30)** (19-43)	**1.89** (± 0.42)	**0.63** (± 0.13)	**0.42** (± 0.11)	**0.12** (± 0.03)	**0.070** (± 0.036)	**0.046** (± 0.020)	**0.198** (± 0.043)
Mustard (**17**) (12-22)	**2.26** (± 0.31)	**0.75** (± 0.19)	**0.45** (± 0.07)	**0.42** (± 0.26)	**0.048** (± 0.009)	**0.027** (± 0.008)	**0.201** (± 0.041)
Soybeans **(40)** (27-53)	**2.99** (± 0.19)	**0.74** (± 0.17)	**0.89** (± 0.36)	**0.17** (± 0.05)	**0.124** (± 0.066)	**0.058** (± 0.026)	**0.198** (± 0.043)
Chickpeas **(32)** (18-45)	**2.26** (± 0.44)	**0.51** (± 0.05)	**0.73** (± 0.11)	**0.12** (± 0.01)	**0.049** (± 0.008)	**0.046** (± 0.012)	**0.18** (± 0.031)
Dry bean **(42)** (36-51)	**1.99** (± 0.32)	**0.61** (± 0.09)	**0.93** (± 0.16)	**0.12** (± 0.01)	**0.062** (± 0.011)	**0.045** (± 0.009)	**0.157** (± 0.021)
Faba bean **(50)** (31-67)	**2.70** (± 0.51)	**0.67** (± 0.11)	**0.83** (± 0.18)	**0.12** (± 0.02)	**0.060** (± 0.008)	**0.062** (± 0.022)	**0.263** (± 0.064)
Lentil **(28)** (19-39)	**2.44** (± 0.51)	**0.56** (± 0.11)	**0.63** (± 0.15)	**0.12** (± 0.02)	**0.041** (± 0.014)	**0.047** (± 0.012)	**0.202** (± 0.041)
Pea **(50)** (29-73)	**1.75** (± 0.39)	**0.47** (± 0.10)	**0.55** (± 0.17)	**0.10** (± 0.01)	**0.044** (± 0.015)	**0.037** (± 0.009)	**0.177** (± 0.040)

¥ Denotes standard deviation.

Table A2: Median macronutrient removal (in grain) (lbs per bushel of grain produced) and grain yield (bushels per acre) estimated across Western Canadian prairies in 2020, 2021, and 2022 growing seasons compared with CFI estimates. Bolded values are the mean grain yields and median nutrient removal from 2020-2022. Numbers in parentheses represent the first quartile (Q1) and third quartile (Q3) in the data set (i.e., arranging the data set in increasing order, 25% of the data are below Q1, the median splits the data set in half, and 25% of the data are above Q3).

Crop **(x̄)** (min.-max. yield)	(CFI x̄ crop yield)	**Nitrogen (N)**		**Phosphorus (P_2O_5)**		**Potassium (K_2O)**		**Sulphur (S)**	
		Current study	**CFI**	**Current study**	**CFI**	**Current study**	**CFI**	**Current study**	**CFI**
		--------------------------------------lbs per bushel of grain produced---------------------------------------							
Barley **(80)** (10-125), *n=201*	(80)	**0.76** (0.70-0.89)	0.97 (0.88-1.06)	**0.34** (0.31-0.39)	0.42 (0.38-0.46)	**0.24** (0.22-0.28)	0.32 (0.29-0.34)	**0.06** (0.06-0.07)	0.09 (0.08-0.10)
Corn **(150)** (90-191), *n=59*	(100)	**0.72** (0.64-0.80)	0.97 (0.87-1.07)	**0.36** (0.34-0.38)	0.44 (0.39-0.48)	**0.21** (0.19-0.25)	0.28 (0.25-0.30)	**0.05** (0.05-0.06)	0.07 (0.06-0.07)
Durum **(48)** (29-72), *n=59*	(-)	**1.52** (1.29-1.81)	- -	**0.47** (0.44-0.53)	- -	**0.29** (0.24-0.34)	- -	**0.10** (0.09-0.12)	- -
Oat **(118)** (25-180), *n=166*	(100)	**0.57** (0.50-0.71)	0.62 (0.55-0.68)	**0.25** (0.22-0.27)	0.26 (0.23-0.28)	**0.16** (0.15-0.18)	0.19 (0.17-0.20)	**0.05** (0.05-0.06)	0.05 (0.04-0.05)
Wheat **(62)** (15-120), *n=310*	(40)	**1.35** (1.21-1.46)	1.50 (1.35-1.65)	**0.48** (0.43-0.53)	0.59 (0.53-0.65)	**0.24** (0.21-0.27)	0.44 (0.40-0.48)	**0.10** (0.09-0.10)	0.12 (0.10-0.13)
W. Wheat (**46**) (40-110), *n=11*	(-)	**1.54** (1.11-1.97)	- -	**0.46** (0.43-0.59)	- -	**0.29** (0.24-0.74)	- -	**0.10** (0.08-0.12)	- -
Canola **(43)** (7-90), *n=373*	(35)	**1.73** (1.57-1.87)	1.93 (1.74-2.11)	**0.69** (0.59-0.78)	1.04 (0.94-1.14)	**0.35** (0.31-0.38)	0.52 (0.46-0.57)	**0.20** (0.18-0.22)	0.32 (0.29-0.34)
Flax **(30)** (8-70), *n=89*	(24)	**1.92** (1.74-2.14)	2.12 (1.91-2.33)	**0.63** (0.52-0.70)	0.65 (0.58-0.71)	**0.41** (0.35-0.47)	0.61 (0.54-0.67)	**0.13** (0.11-0.14)	0.23 (0.21-0.25)
Mustard (**18**) (8-23), *n=15*	(-)	**2.29** (2.10-2.46)	- -	**0.78** (0.57-0.83)	- -	**0.46** (0.44-0.48)	- -	**0.52** (0.21-0.64)	- -
Soybean **(40)** (11-67), *n=96*	(45)	**2.98** (2.90-3.10)	2.50 (2.00-3.00)	**0.75** (0.65-0.87)	1.21 (1.10-1.32)	**1.05** (0.44-1.15)	0.83 (0.78-0.88)	**0.18** (0.16-0.20)	0.11 (0.10-0.11)
Chickpeas **(30)** (12-60), *n=38*	(-)	**2.24** (1.94-2.62)	- -	**0.51** (0.49-0.54)	- -	**0.75** (0.69-0.81)	- -	**0.12** (0.11-0.12)	- -
Dry bean **(39)** (18-58), *n=61*	(30)	**1.95** (1.76-2.13)	4.20 -	**0.60** (0.57-0.66)	1.40 -	**0.95** (0.89-1.00)	1.40 -	**0.12** (0.11-0.12)	0.28 -
Faba bean **(50)** (25-72), *n=37*	(50)	**2.82** (2.29-3.07)	3.42 (3.08-3.76)	**0.65** (0.61-0.74)	1.22 (1.10-1.34)	**0.88** (0.77-0.94)	1.04 (0.94-1.14)	**0.13** (0.12-0.13)	0.14 (0.12-0.16)
Lentil **(26)** (12-51), *n=106*	(30)	**2.54** (2.14-2.69)	2.03 (1.83-2.23)	**0.56** (0.49-0.62)	0.62 (0.57-0.67)	**0.67** (0.55-0.71)	1.09 (0.97-1.20)	**0.12** (0.11-0.13)	0.15 (0.13-0.17)
Pea **(50)** (8-100), *n=170*	(50)	**1.74** (1.56-1.94)	2.34 (2.10-2.58)	**0.47** (0.41-0.51)	0.69 (0.62-0.76)	**0.59** (0.46-0.64)	0.71 (0.64-0.78)	**0.10** (0.09-0.11)	0.13 (0.12-0.14)

Table A3: Median micronutrient removal (in grain) (lbs per 100 bushels of grain produced) and grain yield (bushels per acre) estimated across Western Canadian prairies in 2020, 2021, and 2022 growing seasons. Bolded values are the mean grain yields and median nutrient removal from 2020-2022. Numbers in parentheses represent the first quartile (Q1) and third quartile (Q3) in the data set (i.e., arranging the data set in increasing order, 25% of the data are below Q1, the median splits the data set in half, and 25% of the data are above Q3).

Crop **(x̄)** (Current yield range)	**Boron (B)**	**Copper (Cu)**	**Zinc (Zn)**
	---------------lbs per bushel × 10^{-2} of grain produced--------------		
Barley **(80)** (10-125), *n=201*	**0.007** (0.004-0.009)	**0.023** (0.019-0.029)	**0.126** (0.106-0.152)
Corn **(150)** (90-191), *n=59*	**0.013** (0.012-0.015)	**0.008** (0.007-0.012)	**0.083** (0.074-0.089)
Durum **(48)** (10-80), *n=59*	**0.009** (0.007-0.010)	**0.035** (0.031-0.048)	**0.168** (0.134-0.189)
Oat **(118)** (25-180), *n=166*	**0.004** (0.003-0.006)	**0.017** (0.013-0.022)	**0.076** (0.066-0.097)
Wheat **(62)** (15-120), *n=310*	**0.006** (0.004-0.007)	**0.026** (0.022-0.033)	**0.167** (0.143-0.191)
W. Wheat (**46**) (40-110), *n=11*	**0.012** (0.008-0.055)	**0.038** (0.025-0.044)	**0.141** (0.126-0.163)
Canola **(43)** (7-90), *n=373*	**0.053** (0.048-0.058)	**0.016** (0.014-0.024)	**0.161** (0.139-0.184)
Flax **(30)** (8-70), *n=89*	**0.078** (0.049-0.093)	**0.052** (0.029-0.061)	**0.198** (0.174-0.228)
Mustard (**18**) (8-23), *n=15*	**0.050** (0.045-0.051)	**0.025** (0.024-0.028)	**0.207** (0.169-0.219)
Soybean **(40)** (11-64), *n=96*	**0.148** (0.069-0.174)	**0.060** (0.040-0.075)	**0.196** (0.176-0.220)
Chickpea **(30)** (12-60), *n=38*	**0.047** (0.046-0.052)	**0.047** (0.040-0.055)	**0.177** (0.166-0.198)
Dry bean **(39)** (18-58), *n=61*	**0.064** (0.057-0.071)	**0.045** (0.040-0.049)	**0.153** (0.143-0.166)
Faba bean **(50)** (25-72), *n=37*	**0.058** (0.055-0.064)	**0.065** (0.050-0.072)	**0.255** (0.227-0.298)
Lentil **(26)** (12-51), *n=106*	**0.042** (0.037-0.046)	**0.050** (0.044-0.055)	**0.202** (0.171-0.233)
Pea **(50)** (8-100), *n=170*	**0.046** (0.040-0.052)	**0.036** (0.031-0.042)	**0.174** (0.150-0.201)

Table A4: Grain yield (bushels per acre) and 75th quantile values for nutrient removal (in grain) (lbs per bushel of grain produced) across Western Canadian prairies (2020-2022). The 75th percentile values were used as the nutrient coefficients in the removal calculators.

Crop (**x̄**) (range)	**Nitrogen (N)**	**Phosphorus (P_2O_5)**	**Potassium (K_2O)**	**Sulphur (S)**	**Boron (B)**	**Copper (Cu)**	**Zinc (Zn)**
	lbs nutrient per bushel grain produced				**lbs nutrient per 100 bu grain produced**		
Barley **(79)** (49-105)	**0.89**	**0.39**	**0.28**	**0.07**	**0.009**	**0.029**	**0.152**
Corn **(150)** (111-181)	**0.80**	**0.38**	**0.25**	**0.06**	**0.015**	**0.012**	**0.089**
Durum **(50)** (29-72)	**1.81**	**0.53**	**0.34**	**0.12**	**0.010**	**0.048**	**0.189**
Oats **(113)** (69-157)	**0.71**	**0.27**	**0.18**	**0.06**	**0.0.006**	**0.022**	**0.097**
Wheat **(62)** (41-83)	**1.46**	**0.53**	**0.27**	**0.10**	**0.007**	**0.033**	**0.191**
W. Wheat (**53**) (42-83)	**1.97**	**0.59**	**0.74**	**0.12**	**0.055**	**0.044**	**0.163**
Canola **(43)** (31-55)	**1.87**	**0.78**	**0.38**	**0.22**	**0.058**	**0.024**	**0.184**
Flax **(30)** (19-43)	**2.14**	**0.70**	**0.47**	**0.14**	**0.093**	**0.061**	**0.228**
Mustard (**17**) (12-22)	**2.46**	**0.83**	**0.48**	**0.64**	**0.051**	**0.028**	**0.219**
Soybeans **(40)** (27-53)	**3.10**	**0.87**	**1.15**	**0.20**	**0.174**	**0.075**	**0.220**
Chickpeas **(32)** (18-45)	**2.62**	**0.54**	**0.81**	**0.12**	**0.052**	**0.055**	**0.198**
Dry bean **(42)** (36-51)	**2.13**	**0.66**	**1.00**	**0.12**	**0.071**	**0.049**	**0.166**
Faba bean **(50)** (31-67)	**3.07**	**0.74**	**0.94**	**0.13**	**0.064**	**0.072**	**0.298**
Lentil **(28)** (19-39)	**2.69**	**0.62**	**0.71**	**0.13**	**0.046**	**0.055**	**0.233**
Pea **(50)** (29-73)	**1.94**	**0.51**	**0.64**	**0.11**	**0.052**	**0.042**	**0.201**