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Uptake and Economic Value of Macro- and Micronutrient Minerals in Wheat Residue

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Abstract: Wheat (*Triticum aestivum*, L.) producers have the choice to retain or remove residue from the cropping system following grain harvest. In the U.S. Pacific Northwest and other regions, wheat residue is often sold to increase operational profitability, especially from higher-yielding systems. But there are several benefits to retaining residue, including recycling of mineral nutrients contained therein, though this is understudied. Therefore, the primary objectives of this research were to collect and analyze a large and diverse dataset on wheat residue nutrient uptake (N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu), develop tools to estimate nutrient amounts in residue, and make economic estimates of the fertilizer replacement value of those nutrients. This was accomplished by conducting replicated variety trials on five classes of wheat across many Pacific Northwest sites over two years, then collecting and analyzing data on wheat residue biomass, residue nutrient concentrations, and grain yield. The results showed that wheat residue contained a significant amount of nutrients, but was particularly concentrated in K. Production environment had the most substantial effect on residue mineral uptake amounts, due to site differences in yield and soil nutrient availability. To enable simple estimation of residue nutrient uptake across a broad range of wheat production levels, two estimation tools are presented herein. Economic analysis showed the substantial monetary value of residual nutrients. For example, in a high-yielding wheat crop (9 Mg ha^{-1}), the average fertilizer replacement value of just residue N, P, K, and S was similar to the entire fertilizer budget to grow the crop (~$211 vs. $205 ha^{-1}), not considering micronutrients in the residue or any nutrients removed through grain harvest. In making residue management decisions, wheat producers should consider the tradeoff between the immediate economic gains of residue sale and the multifaceted benefits of residue retention, including savings on future nutrient costs.

Keywords: fertilizer; nutrients; small grains; straw; residue; wheat

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1. Introduction

Wheat is grown primarily for grain as a staple food for billions of people worldwide [1,2], but residue is another product of wheat cropping systems. Wheat residue must be managed in some way, which varies across production systems, but typically involves residue removal or retention from the cropping system at various rates. When residue is removed, this is either performed by physical removal (harvest) or by burning, though burning has increasingly fallen out of favor [3,4]. Residue removal is usually performed for soil seedbed preparation of subsequent crops and/or for the economic value of residue sale. In certain wheat-producing regions, including the U.S. Pacific Northwest, wheat residue from higher-yielding systems is increasingly harvested and marketed for multiple uses, including as animal bedding, a medium for mushroom production, a component of composites and building materials, and more [5–7]. When residue is retained within the cropping system, it is either incorporated into the soil through tillage or left on the soil surface as stubble and chopped residues [8–10]. There are several demonstrated benefits to leaving residue in the system, including erosion prevention, weed suppression, water retention, increasing soil organic matter, and enhancing soil microbial activity and diversity [3,8,10–17]. The preservation and recycling of mineral nutrients contained in wheat residue is another benefit of residue retention, though this aspect of residue management seems to be understudied and underappreciated.

Significant amounts of mineral nutrients are taken up by crop plants to support growth [18]. Producers rely on the soil to supply all plant-essential minerals to some extent, then apply exogenous sources of nutrients to avoid deficiencies and to replenish nutrients removed by previously grown crops. The essential macronutrient minerals (N, P, K, Ca, Mg, S) are required in greater quantities by wheat than the micronutrient minerals (e.g., Fe, Mn, Zn, Cu, B, Mo) and thus are more likely to be applied as fertilizers to ameliorate deficiencies [19,20]. Wheat takes up most of the mineral nutrients required to support its biochemical functions by anthesis [18]. Mineral nutrients are initially concentrated in leaves and stems, then many are redistributed to grain as the plants mature [19,21]. Hocking [18] reported that more than 70% of N and P and between 15 and 50% of K, S, Mg, Cu, and Fe in grain were redistributed from shoots, while minimal amounts of Ca, Fe, and Mn were redistributed. Despite nutrient redistribution, many minerals remain in residue in relatively large quantities at physiological maturity [22]. Hocking [18] reported that more K, S, Ca, Mg, Fe, Mn, and Cu exist in wheat residue (stems, leaves, chaff, or grain heads) than in grain at maturity [18].

As described above, wheat residue can either be returned and recycled within the system, including the substantial pool of nutrients contained therein, or it can be removed in some way. Depending on the cropping system and soil chemical properties, nutrients recycled back into the system can support subsequent crop growth in the short and long term. Any application of exogenous fertilizers to replace nutrients removed from the system results in monetary expenditures by the producer, depletion of natural mineral resources, and energy consumption [23]. Despite this, there is little information within the current body of scientific literature that sheds light on the value of wheat residue as a source of mineral nutrients. Tarkalson et al. [24] published estimates wheat residue nutrient concentrations and uptake based on the average of data reported in the literature from 1986 to 2008 and some assumptions. These analyses and the data they are based on are outdated, only include N, P, and K, and are otherwise limited in experimental scope. We were unable to find any large and diverse datasets that include wheat residue analysis of both macro- and micronutrient minerals collected across multiple locations, wheat classes and varieties, and growing seasons. There are no reports that describe total residue mineral uptake or removal (i.e., the total mineral load, when multiplying mineral concentration by residue production) across the typical range of wheat production potential. Additionally, there are few reports that provide economic analysis of the nutrient replacement costs of minerals contained in residue, in terms of exogenous fertilizer application cost, should nutrients be harvested and removed from the cropping system [24,25]. Recently, Rogers et al. [26] reevaluated barley (*Hordeum vulgare* L.) nutrient uptake and fertilizer replacement value with data collected within the Pacific Northwest region and found similar N uptake, lower P uptake, and greater K uptake than previously estimated. Thus, research to update these estimates is increasingly needed to account for increased consumer demand for small-grain residue, alongside changes in crop production and fertilizer markets.

Wheat residue is an important resource that has great consumer demand, but also has multiple benefits within the cropping systems in which it is produced. One of those benefits is its fertilizer value, but the mineral nutrient content and economic value of wheat residue as a source of nutrients are presently not well quantified or understood. We hypothesized that the amount and economic value of nutrients contained in wheat residue would be of sufficient magnitude that they should be taken into consideration in long-term farm fertilizer management plans and budgets. Thus, the primary objectives of this research were (1) to collect and analyze a large and diverse dataset on wheat residue mineral uptake (N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu); (2) relate uptake of minerals in residue to grain yield using two approaches, which can be used as tools to simplify estimation of residue nutrient uptake; and (3) conduct a simplified economic analysis of nutrient (fertilizer) replacement costs, if wheat residue is harvested.

2. Materials and Methods

2.1. Experimental Sites and Design

This field research was conducted at locations across the Snake River Plain of Southern Idaho in the Pacific Northwest region of the United States. As is common in semi-arid production regions, major portions of the Snake River Plain receive 250 mm or less of average annual precipitation. This lack of water results in most crop production in Southern Idaho being supported by irrigation, though in higher-precipitation areas, there is dryland production. A diverse set of agronomic crops are produced in the region, including multiple classes of wheat. In this study, five classes of wheat (hard red spring wheat, hard white spring wheat, soft white spring wheat, hard red winter wheat, and soft white winter wheat) were selected for testing, including two to three varieties of each, at two to six locations each, over two cropping seasons (2018 and 2019), as detailed in Table 1. The Aberdeen study site was located at a University of Idaho Research and Extension Center, while all other study sites were located within commercial production wheat fields and managed in cooperation with agricultural producers. The classes of wheat were studied independently (i.e., separate experimental arrangements for each wheat class, matched across locations) in randomized complete block experimental designs with four replicates. All study sites were irrigated, except for Soda Springs, which averages about 410 mm of annual precipitation and was managed in dryland conditions. Table 2 presents soil series and measured soil chemical properties for each study site.

Table 1. Varieties and market classes of wheat tested at up to six locations over the 2018 and 2019 seasons.

Location	Hard Red Spring Wheat	Hard White Spring Wheat	Soft White Spring Wheat	Hard Red Winter Wheat	Soft White Winter Wheat
Aberdeen	X	X	X	X	X
Ashton	X	X	X		
Idaho Falls	X	X	X		
Parma	X		X	X	
Rupert	X	X	X	X	X
Soda Springs	X	X	X	X	
			Varieties Tested		
	Alum	Dayn	Seahawk	Keldin	LCS Drive
	Jefferson	UI Platnium	UI Stone	Jet	Norwest Tandem
	WB9668	WB7202	WB1035		SY Ovation

Table 2. Soil series, site elevations, and preplant soil test values for study locations in the Snake River Plain of Southern Idaho. Soil test values are averages of 2018 and 2019, representing 0 to 30 cm soil depth for P and K, and 0 to 60 cm depth for other nutrients.

Location	Soil Series/Classification	Elevation (m)	SOM ($g\ kg^{-1}$)	pH	N Supply [a] ($kg\ ha^{-1}$)	Soil Test Values P	K ($mg\ kg^{-1}$)	SO_4-S	Fertilizer Application Rate P	K ($kg\ ha^{-1}$)	S
Aberdeen	Declo loam/Coarse-loamy, superactive, mesic Xeric Haplocalcid	1342	9.0	8.1	465 (HWW) [b] 342 (SWW) 432 (HSW) 310 (SSW)	21	340	63	17 (S) [c] 24 (W)	19	120 (S) 93 (W)
Ashton	Robinlee silt loam/Coarse-silty, mixed, superactive, mesic Durinodic Haplocalcids	1603	18.5	6.2	338 (HSW) 265 (SSW)	19	188	29	0	19	11
Idaho Falls	Pancheri silt loam/Coarse-silty, mixed, superactive, frigid Xeric Haplocalcids	1434	15.0	7.7	281 (HSW) 206 (SSW)	22	184	40	15	0	20
Parma	Greenleaf-Owyhee silt loams/Fine-silty, mixed, mesic Xerollic Haplargids and Coarse-silty, mixed, mesic Xerollic Camborthids	701	20.0		408 (HWW) 390 (HSW) 315 (SSW)	19	189	16	0	0	20 (S) 20 (W)
Rupert	Portneuf silt loam/Coarse-silty, mixed, superactive, mesic Durinodic Haplocalcids	1267	12.5	7.7	424 (HSW) 303 (SSW)	25	240	38	15 (S) 25 (W)	0	34 (S) 93 (W)
Soda Springs (2018 only)	Foundem-Rexburg Complex/Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls and Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls	1760	20.6	6.5	56 (HSW) 56 (SSW)	34	409	19	17 (S) 24 (W)	19	120 (S) 93 (W)

[a] N supply ($kg\ ha^{-1}$) = inorganic N + applied fertilizer N, where inorganic N is calculated as $kg\ ha^{-1}$ as NH_4-N + NO_3-N to a depth of 60 cm. [b] HWW = hard winter wheat, SWW = soft winter wheat, HSW = hard spring wheat, SSW = soft spring wheat. [c] S = spring, W = winter.

2.2. Experimental Procedures

Soil samples were collected prior to fertilizer application and planting for measurement of soil chemical and fertility parameters. Samples were collected using a 7.6 cm bucket auger from 0 to 30 cm depths for P and 0 to 60 cm depths for pH, N, K, S. In brief, soil pH was measured potentiometrically, soil organic matter (SOM) was measured by loss on ignition, inorganic N (NO_3 and NH_4) were measured in 2M KCl, P and K were measured using the Olsen extraction, and S was measured using calcium phosphate extraction and inductively coupled optical emission spectroscopy (ICP-OES) [27].

Plot planting information was previously detailed by Marshall et al. [28,29], including planting dates. Regional planting dates range from March to May for spring wheat, with higher elevations occurring later, and winter wheat planting dates range from August to October [30]. In short, irrigated wheat was planted using a cone seeder drill at 2.5 million seeds ha^{-1} with 18 cm row spacing, whereas dryland wheat at Soda Springs was seeded at 1.7 million seeds ha^{-1} on the same row spacing. Plots at all winter wheat locations, except for Aberdeen, were planted 1.5 m wide by 4.3 m long then reduced to 3.0 m long using glyphosate herbicide or tillage for harvest. The plots in Aberdeen were planted 1.5 m wide by 4.1 m long, then reduced to 2.8 m long for harvest. Spring wheat locations were planted 1.5 m wide by 6 m long, then reduced to 4.9 m for harvest.

Fertilizer management was also previously described by Marshall et al. [28,29] and pertinent details are reported in Table 2. Briefly, fertilizer applications were coordinated with producers and were based on a "N supply" concept that involves consideration of soil inorganic N and historical yield goals by wheat class. Hard wheats target higher grain protein (i.e., N) levels and soft wheats target lower protein. The N supply ($kg\ ha^{-1}$) = inorganic N + applied fertilizer N, where inorganic N is the measured soil NH_4-N + NO_3-N to a depth of 60 cm. Fertilizer applications were made preplant, with N supply targets for soft white winter wheat = 35 kg N metric ton^{-1} of expected yield and hard wheats = 42 kg N per metric ton^{-1}, and 18 kg N ha^{-1} were applied near anthesis (included in N supply) in hard wheats to ensure target grain protein concentration was achieved. Application rates of other, non-N nutrients are detailed in Table 2.

At irrigated study sites, water was applied to the crop by manually operated sprinkler lines (hand-lines or wheel-lines) that are commonly used in production settings in the region. Irrigation water is available for use from mid-April to October and the rate of irrigation, including precipitation, was estimated to fully replace crop evapotranspiration based on estimates generated by local weather station networks (Agrimet). Thus, irrigation amounts were the same for winter and spring wheat at each study site and crop water stress was assumed to not occur. Weather data for the study sites were obtained from the Agrimet network as well. Table 3 provides mean daily air temperature ranges, precipitation, and irrigation calculated from crop evapotranspiration for each experimental site, broken out by winter and spring seasons and averaged across years.

Table 3. Two-year average environmental information for the study sites within the Snake River Plain of Southern Idaho.

	Winter Season		Spring Season		Winter and Spring
Study Site	**Mean Daily Air Temperature Range (C)**	**Precipitation (mm)**	**Mean Daily Air Temperature Range (C)**	**Precipitation (mm)**	**Irrigation (mm)**
Aberdeen	−36.8 to 25.5	163	2.9 to 25.2	50	555
Ashton	−20.5 to 22.6	412	1.4 to 22.6	151	426
Idaho Falls	−17.3 to 26.9	354	3.3 to 26.9	167	405
Parma	−8.2 to 28.8	224	4.4 to 28.8	64	598
Rupert	−12.8 to 25.1	221	2.7 to 25.1	73	554
Soda Springs	−18.6 to 24.7	263	0.6 to 24.7	104	0

At physiological maturity, whole wheat plants were hand-sampled by clipping just above the soil surface from the second row of each plot from a 0.1 m^2 area along a single row [26]. The samples were oven-dried at 55 °C until weight loss ceased, then total dry weight was recorded. Dry plants were threshed by hand to separate grain from residue (i.e., all remaining plant components, including grain head). The dry weight of grain was recorded. Residue weight was determined by taking the difference between total sample weight and grain weight. Grain yield was calculated by dividing grain weight by the sampling area. The harvest index (HI) was calculated by dividing grain weight by total aboveground biomass weight (including grain).

Dry residue samples were subsequently ground to pass through a 1 mm sieve using a Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA) and used for chemical analyses. Total C and N concentrations were measured by combustion analysis based on the Dumas method (Variomax CN, Elementar Americas, Ronkonkoma, NY, USA). Other mineral concentrations (P, K, Mg, Ca, S, Mn, Fe, Zn, Cu) were measured by extracting and digesting tissue samples with nitric acid, followed by analysis via inductively coupled plasma optical emission spectroscopy (ICP-OES) (SPECTROBLUE ICP, SPECTRO Analytical Instruments GmbH, Kleve, Germany). Mineral concentrations were extrapolated to total crop residue mineral uptake values by multiplying them by associated residue production values at the individual plot level.

2.3. Fertilizer Replacement Value of Nutrients in Wheat Residue

The economic analysis relates to the decision wheat producers make between leaving wheat residue in the field after the grain has been harvested or baling and selling the residue. While selling wheat residue can provide some additional revenue to the operation, removing the residue also removes mineral nutrients, which have monetary value. There are additional economic considerations to residue management, such as erosion control, but the potential revenue and cost impacts are more difficult to quantify and are beyond the scope of this study. Thus, this economic analysis was simplified to focus just on the fertilizer replacement value (US $) of nutrients removed through residue harvest, similar to previous studies [24,25,31].

The methods used in making these calculations follow an expanded approach relative to previous studies that were more limited in scope, including Battaglia et al. [31], Reiter et al. [25], and Tarkalson et al. [24]. The calculations include sequential estimation of the nutrient uptake of wheat residue across a range of grain yield levels and the values of those nutrients in terms of fertilizer replacement costs. In this final step, nutrient uptake amounts (kg ha^{-1}) are multiplied by nutrient prices (US $ kg^{-1}) to obtain fertilizer replacement costs (US $ ha^{-1}) of nutrients contained in the residue. Residue harvest and subsequent fertilizer application costs were not accounted for, so this is an estimate of only the direct fertilizer purchase costs. The specific nutrients for which these calculations were made include N, P, K, and S. Other secondary macro- and micronutrients were not included in this analysis because they are less commonly applied as fertilizers, although they also can become depleted in soil with sequential crop harvests and eventually will need replacement.

Residue nutrient uptake values were obtained using the grain yield (Mg ha^{-1}) vs. residue nutrient uptake (kg ha^{-1}) relationships presented among the results of this paper. Four yield levels were chosen for economic analysis to represent a range from low to very high yields: 3, 6, 9, 12 Mg ha^{-1}. While a wheat yield of 12 Mg ha^{-1} is higher than yields typically observed in production fields in the study region and elsewhere, wheat yields this high are documented and provide an upper bound based on observed yields from field trial data. The residue nutrient uptake values were multiplied by prices that reflect low, average, and high prices based on historical price data for 2001 to 2019 found in irrigated potato enterprise budgets from the University of Idaho [32]. The potato budgets were used since they included all nutrients including S, which was not accounted for in the wheat enterprise budgets.

2.4. Statistical Analysis

Statistical analyses were implemented using the Statistical Analysis System (SAS) 9.4 software package (SAS Institute Inc., Cary, NC, USA) and SigmaPlot 15.0 software (Systat, Inpixon, Palto Alto, CA, USA). Due to the independence of the different market classes of wheat in the field experiments, statistical analyses were conducted separately for each or collectively (pooled), but wheat classes were not statistically compared to each other. Statistical results are not presented for the minerals Fe and Cu, as there appeared to be analytical error or unknown sources of contamination that affected their chemical analysis, creating unexpected values and non-normal distributions.

For each class of wheat, analysis of variance (ANOVA) was performed using the MIXED procedure in SAS for grain yield, residue production, HI, and mineral nutrient uptake in residue. The data were checked to ensure they satisfied the assumptions of normality and equal variances. This was performed using Q-Q Plots, histograms, and plots of residuals. Wheat variety, production location, and the interaction of variety and location were considered fixed effects in the statistical model. Year (season) and the interaction of block and year were considered random effects. Pairwise mean comparisons were made using Tukey's method. Treatment effects were considered significant based on a threshold of $p < 0.05$.

The MEANS procedure in SAS was used to calculate means and coefficient of variation (CV) values for grain yield, residue production, HI, and mineral nutrient uptake of residue. Because production location was nearly always a significant treatment factor and wheat variety was significant less often, means and CVs were presented by location and overall (across all locations) for each market class of wheat, but not by wheat variety. The MEANS procedure was also used to calculate quartiles [Q1, Q2 (median), and Q3] for mineral concentrations in residue (mg or g kg^{-1}). Summary statistics were calculated based on the entire dataset, pooled across all locations, market classes and varieties of wheat, and years of the study.

SigmaPlot 15.0 (Systat, Inpixon, Palto Alto, CA, USA) was used to generate plots and implement regression analyses on the relationships between grain yield (dependent variable) and mineral uptake of residue (independent variable). The data were pooled across all locations, market classes and varieties of wheat, and years of the study. In the regression analyses, a first-order linear regression model was used (y = mx + b; where m = slope and b = intercept). Although there would be a minimal baseline of residue production and mineral uptake even when grain yield is zero, the data were constrained to pass through the origin (b = 0) to help control for inherent variation in this kind of dataset. Root mean square error (RMSE), 95% confidence intervals, adjusted r^2 (Adj r^2), and *p*-values were computed by SigmaPlot.

3. Results

Grain yield, residue production, and HI were measured across all study sites and other treatments. These data are presented in Table 4 for hard red spring wheat, as an example for one wheat class. Supplementary Tables S1–S4 are similar tables, presenting data for the other classes of wheat that were studied. Across production sites, spring wheat yields generally ranged from averages of about 5 to 8 Mg ha^{-1}, with the lowest yields observed in dryland conditions and the highest yields under irrigation. In winter wheat, average yield ranged higher, up to 9 or 10 Mg ha^{-1}. Individual observations ranged beyond the averages. There were statistical differences in yield among production locations for all wheat classes, except soft white winter wheat, which only had two test locations. Statistical differences in yield among varieties of each wheat class were less common. When considering all treatment factors included in the studies, the percent CV for grain yield ranged from 16 to 42% across all classes of wheat. There was less variation in the HI. Across all wheat classes, the average HI had a narrow range of 0.47 to 0.51, with CVs of 8 to 12%. This meant that the amount of residue produced was generally closely matched to the amount of grain produced, although observation of statistical differences in HI among locations and wheat varieties was common.

Table 4. Selected ANOVA results for **hard red spring wheat**, including data and statistics on grain yield, residue production, harvest index, residue carbon contents, and residue uptake values of 10 mineral nutrients. No statistical results were generated for Fe and Cu due to analytical issues.

Treatments	Grain Yield (Mg ha^{-1})	(%CV)	Residue Prod. (Mg ha^{-1})	(%CV)	Harvest Index (Mg Mg^{-1})	(%CV)	Residue C (Mg ha^{-1})	(%CV)	Residue N (kg ha^{-1})	(%CV)	Residue P (kg ha^{-1})	(%CV)	Residue K (kg ha^{-1})	(%CV)
Location														
Aberdeen	6.84 a	19	8.14 a	20	0.46	11	3.23 a	20	62.8 a	33	3.02 ab	44	295 a	25
Ashton	5.48 b	28	5.77 b	23	0.48	9	2.40 b	24	36.7 b	43	1.89 c	47	196 b	26
Idaho Falls	7.73 a	18	7.94 a	19	0.49	4	3.29 a	19	35.6 b	28	2.27 bc	38	204 b	24
Parma	7.21 a	19	8.42 a	20	0.46	9	3.45 a	21	32.3 b	38	3.21 a	41	195 b	24
Rupert	7.21 a	15	8.45 a	16	0.46	6	3.41 a	16	55.6 a	32	2.66 ab	52	284 a	19
Soda Springs	5.08 b	41	5.23 b	33	0.48	11	2.28 b	32	28.2 b	42	1.72 c	50	115 c	44
OVERALL	6.57	27	7.30	28	0.47	9	3.00	26	42.1	47	2.41	50	215	38
p-values														
Location (L)	<0.0001		<0.0001		0.0014		<0.0001		<0.0001		<0.0001		<0.0001	
Variety (V)	0.8390		0.0012		0.0002		0.0002		<0.0001		<0.0001		0.2171	
LxV	0.5535		0.6857		0.0902		0.6790		0.0090		0.0017		0.2775	

Treatments	Residue Ca (kg ha^{-1})	(%CV)	Residue Mg (kg ha^{-1})	(%CV)	Residue S (kg ha^{-1})	(%CV)	Residue Fe (g ha^{-1})	(%CV)	Residue Zn (g ha^{-1})	(%CV)	Residue Mn (g ha^{-1})	(%CV)	Residue Cu (g ha^{-1})	(%CV)
Location														
Aberdeen	34.0 a	21	9.22 b	24	16.0 a	22	40.4	219	60.6 b	36	212 a	28	6.43	120
Ashton	22.4 cd	31	3.78 d	34	12.3 b	24	133	78	23.0 c	27	247 a	66	6.57	66
Idaho Falls	28.0 b	20	7.30 c	22	14.6 ab	18	140	109	153 a	68	101 b	23	3.90	163
Parma	25.8 bc	25	6.14 c	31	6.79 c	26	18.1	212	36.5 bc	77	112 b	49	2.78	145
Rupert	34.6 a	18	11.4 a	23	15.6 a	26	134	209	51.8 bc	50	218 a	35	5.06	128
Soda Springs	19.7 d	49	6.16 c	48	6.81 c	44	275	58	58.5 bc	67	215 a	77	2.98	126
OVERALL	27.5	33	7.37	44	12.2	40	127	139	63.1	103	185	65	4.78	123
p-values														
L	<0.0001		<0.0001		<0.0001		-		<0.0001		<0.0001		-	
V	0.2363		0.0003		0.0067		-		0.0496		0.4114		-	
LxV	0.6084		0.5342		0.0157		-		0.8848		0.8081		-	

Values within a column followed by same lowercase letter are not statistically different.

Figure 1 graphically illustrates the relationships of grain yield with residue production and HI. This analysis was performed by integrating data from all wheat classes together, since the classes were studied in separate experimental designs. The associated regression results are given mathematically in Table 5. This analysis was performed to enable simple estimation of wheat residue production from grain yield, since yield is the most widely measured and reported metric for wheat production. The regression results indicate that residue production of about 0.92 Mg ha^{-1} would be expected even when grain yield is zero. The results further indicate that for each 1.0 Mg ha^{-1} increase in yield, residue production will increase by about 0.92 Mg ha^{-1}. Correspondingly, the slope for the relationship between grain yield and HI was slightly positive (significantly different and greater than zero), further indicating that the amount of grain produced relative to residue increases somewhat with increasing yield. For example, using the equation presented in Table 5, HI values of approximately 0.47, 0.48, 0.50, and 0.51 would be expected at yields of 3.0, 6.0, 9.0, and 12 Mg ha^{-1}, respectively.

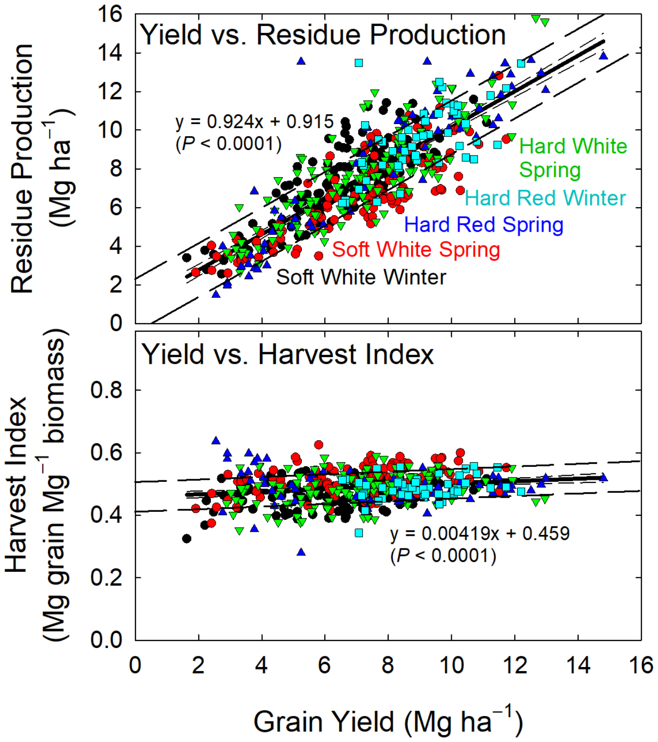

Figure 1. Relationships of grain yield with residue production and harvest index for data collected in Southern Idaho in the 2018 and 2019 growing seasons. The differently colored symbols represent different classes of wheat, as indicated by the color of the wheat class labels. Solid lines in the graphs are regression results (Table 5), short-dashed lines are 95% confidence intervals, and long-dashed lines are the root mean square error (RMSE).

Table 5. Linear regression results describing relationships of wheat grain yield with residue production and harvest index as graphically shown in Figure 1.

Independent Variable	Dependent Variable	m [a]	b	Adj r^2	RMSE	*p*-Value
Grain Yield (Mg ha^{-1})	Residue (Mg ha^{-1})	0.924	0.915	0.70	1.39	<0.0001
Grain Yield (Mg ha^{-1})	Harvest Index (Mg Mg^{-1})	0.00419	0.459	0.0370	0.0474	<0.0001

[a] In the linear regression equation (y = mx + b), m = slope and b = intercept. Measures of error and fit are also given, including adjusted r^2 (Adj r^2) and root mean square error (RMSE), as determined in SigmaPlot.

In addition to yield and production information, Table 4 and Supplementary Tables S1–S4 also present data on residue C and 10 mineral nutrients (N, P, K, Ca, Mg, S, Fe, Zn, Mn, Cu) in terms of total uptake (kg ha^{-1} or g ha^{-1}) individually for the five classes of wheat. There were statistical differences among production environments (locations) in residue C and mineral uptake for nearly every mineral in each class of wheat. Observation of statistical differences among wheat varieties in C and mineral uptake for each wheat market class was also common, but less so. For the macronutrient minerals for each class of wheat, the CV across the datasets ranged from approximately 35 to 65%. Variability was greater for the micronutrient minerals. High levels of experimental or analytical error prevented generation of statistical results for Fe and Cu uptake in residue. Table 6 presents residue mineral nutrient concentrations (g or mg kg^{-1}), pooled across all locations, market classes and varieties of wheat, and years of the study. The data are presented in terms of quartiles [first, second (median), and third] to give an indication of variation. The concentration values can be used as benchmarks for extrapolation of low, average, and high mineral densities in wheat residue.

Table 6. Concentrations of carbon and mineral nutrients in wheat residue, summarized by quartiles for data collected in Southern Idaho in the 2018 and 2019 growing seasons. No statistical results were generated for Fe and Cu due to analytical issues.

Nutrient(s)	Unit	Q1 [a]	Median	Q3
		Concentration in Residue		
C	g kg^{-1}	401	409	420
N	g kg^{-1}	3.87	5.10	6.80
P	g kg^{-1}	0.210	0.310	0.469
K	g kg^{-1}	21.8	26.9	32.6
Ca	g kg^{-1}	3.07	3.60	4.22
Mg	g kg^{-1}	0.780	1.05	1.32
S	g kg^{-1}	1.23	1.62	1.96
Fe	mg kg^{-1}	- [b]	-	-
Zn	mg kg^{-1}	3.50	6.46	13.7
Mn	mg kg^{-1}	13.7	23.6	36.8
Cu	mg kg^{-1}	-	-	-

[a] Q1 = first quartile, Median = second quartile, Q3 = third quartile. [b] Dashes are included to indicate missing values, because no statistical results were generated for Fe and Cu due to analytical issues.

Using a stepwise approach, residue production values (determined via grain yield information, using the regression equation in Table 5) can be multiplied by the nutrient concentrations presented in Table 6 to obtain estimates of mineral uptake in residue. Estimation of total residue K uptake will be used here as an example. As an example, if grain yield was measured to be 9.0 Mg ha^{-1}, then residue production would likewise be estimated to be about 9.0 Mg ha^{-1} (9000 kg ha^{-1}) using either of the functions presented in Table 5. If residue K concentration was assumed to be near the average in this study at 26.9 g kg^{-1} (Table 6), then total K uptake could be calculated as follows:

$$\frac{9000\ \text{kg}\ straw}{\text{ha}} \times \frac{26.9\ \text{g}\ K}{\text{kg}\ straw} \times \frac{1\ \text{kg}\ K}{1000\ \text{g}\ K} = \frac{242\ \text{kg}\ K}{\text{ha}}$$

This stepwise approach gives the flexibility to alter the calculation inputs (i.e., residue production and nutrient concentrations) based on direct user measurements or assumptions of local conditions.

Residue nutrient uptake values were also determined based on grain yield using a more direct, but less flexible single-step approach. The raw data, results of linear regression analyses of the data, plus associated measures of data confidence and variability, are graphically shown in Figure 2. Table 7 gives the mathematical results of the linear regression analyses, including regression coefficients and metrics of model fit and error (adjusted r^2 and RMSE). All regression equations were constrained to pass through the origin (y-intercept or b = 0). This step introduced some error by not accounting for residue that would be produced even when grain yield was zero but was needed to control or counteract variability in the data for some nutrients. The linear functions and error terms presented in Table 7 can be used to estimate residue mineral uptake and potential removal/harvest amounts using only grain yield information. Again, estimation of total residue K uptake will be used as an example. Making the same yield assumption as in the previous example (9 Mg ha^{-1}) and using the equation coefficients for K (m = 28.4 kg ha^{-1}, b = 0 kg ha^{-1}) given in Table 7, residue K uptake can be estimated as follows:

$$(28.4 \times 9.0) + 0 = \frac{256 \text{ kg } K}{\text{ha}}$$

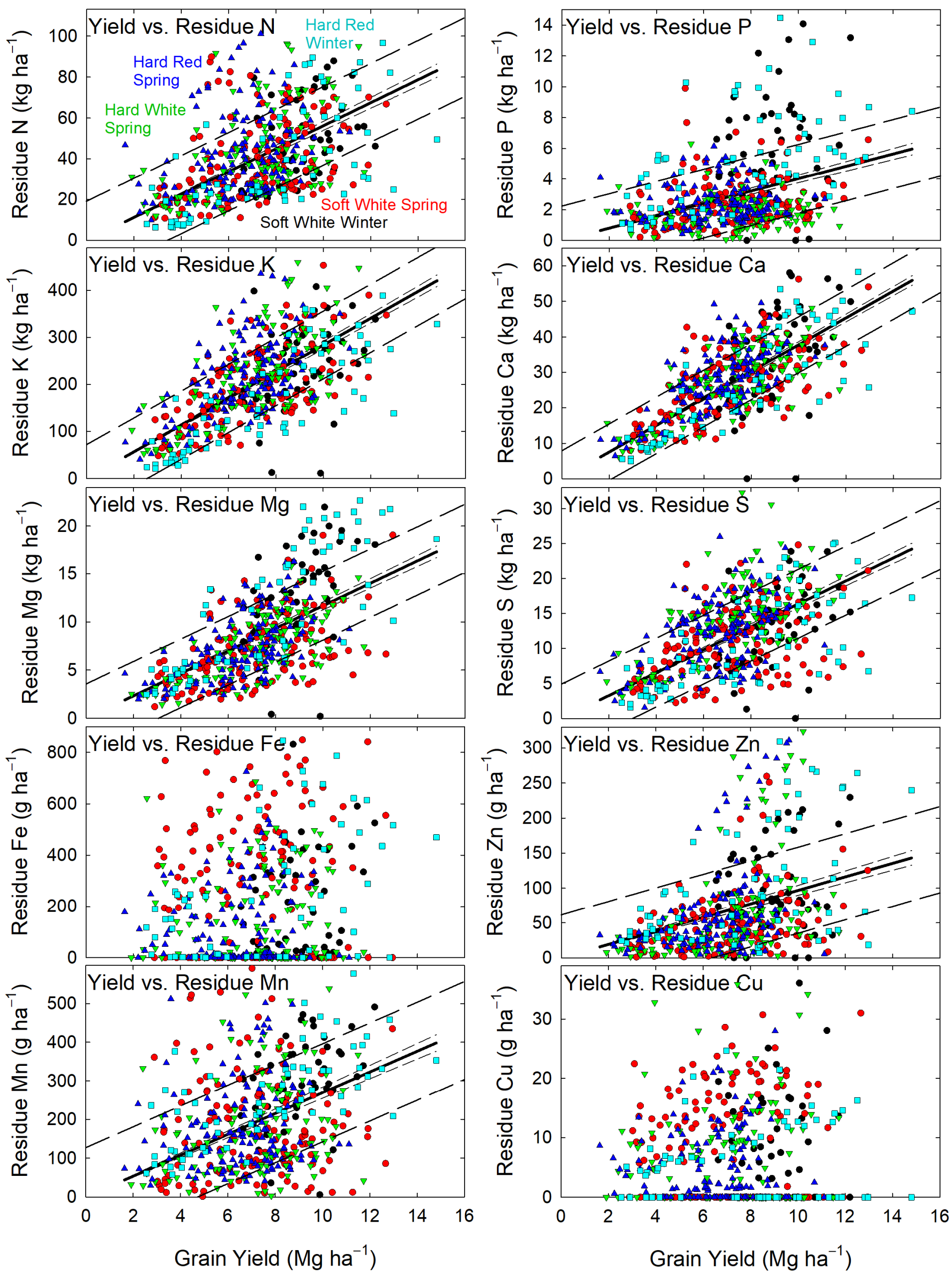

Figure 2. Uptake of 10 mineral nutrients in wheat residue as a function of grain yield for data collected in Southern Idaho in the 2018 and 2019 growing seasons. The differently colored symbols represent different classes of wheat, as indicated by the color of the wheat class labels. The solid lines are regression results, the short-dashed lines are 95% confidence intervals, and the long-dashed lines are the regression results plus and minus the root mean square error (RMSE) (Table 7). No statistical results were generated for Fe and Cu due to analytical issues.

Table 7. Linear regression results describing relationships between wheat grain yield and mineral nutrient uptake in residue as graphically shown in Figure 2. Each analysis was constrained to pass through the origin (b = 0). No results were generated for Fe and Cu due to analytical issues.

Independent Variable	Dependent Variable	m [a]	b	Adj r^2	RMSE
Grain Yield (Mg ha^{-1})	Residue N (kg ha^{-1})	5.62	0	0.83	19.2
Grain Yield (Mg ha^{-1})	Residue P (kg ha^{-1})	0.403	0	0.65	2.24
Grain Yield (Mg ha^{-1})	Residue K (kg ha^{-1})	28.4	0	0.90	72.2
Grain Yield (Mg ha^{-1})	Residue Ca (kg ha^{-1})	3.78	0	0.93	7.94
Grain Yield (Mg ha^{-1})	Residue Mg (kg ha^{-1})	1.17	0	0.86	3.56
Grain Yield (Mg ha^{-1})	Residue S (kg ha^{-1})	1.64	0	0.86	4.92
Grain Yield (Mg ha^{-1})	Residue Fe (g ha^{-1})	-	-	-	-
Grain Yield (Mg ha^{-1})	Residue Zn (g ha^{-1})	9.68	0	0.59	61.6
Grain Yield (Mg ha^{-1})	Residue Mn (g ha^{-1})	26.9	0	0.72	127
Grain Yield (Mg ha^{-1})	Residue Cu (g ha^{-1})	-	-	-	-

[a] In the linear regression equation (y = mx + b), m = slope and b = intercept. Measures of error and fit are also given, including adjusted r^2 (Adj r^2) and root mean square error (RMSE), as determined in SigmaPlot.

This result is 19 kg K ha^{-1} or about 8% higher than the estimate using the stepwise approach. The difference between estimates would vary depending on the nutrient being considered and grain yield. But because the regressions were constrained to pass through the origin, nutrient uptake estimates using this method will generally be higher compared to the stepwise approach (except at the lowest grain yield levels).

Economic analysis of residue mineral replacement costs, should residue be harvested and removed from the field, was conducted based on historical market fertilizer prices and the residue nutrient uptake values determined using the stepwise approach outlined in this study (Tables 8 and 9). This was performed for four nutrients (N, P, K, and S) at four discrete benchmark grain yield points (3, 6, 9, 12 Mg ha^{-1}). Table 8 presents the residue nutrient uptake values associated with the four yield benchmarks, as well as ranges in fertilizer (nutrient) prices (low, average, and high) based on historical prices from 2001 to 2019 from University of Idaho enterprise budgets (University of Idaho, 2019). There were substantial differences in the amount of each nutrient contained in wheat residue, with K uptake being the greatest by a wide margin, followed by N, S, and P. Regarding fertilizer (nutrient) prices, the highest average price was that for N, followed by K, S, and P. Notably, K prices had the largest price range or difference between historically high and low prices, with historically high K prices being similar to N (87% of N), and historically average and low K prices being incrementally lower than N (63% and 41% of N, respectively). Table 9 presents residue nutrient replacement costs (residue nutrient uptake values multiplied by nutrient prices). The bold values in the table represent costs calculated at historical average prices, while the ranges given below the averages in parentheses represent costs at low-to-high historical prices. Since the uptake of K in residue was the greatest by a wide margin and historical K fertilizer prices ranged from 41 to 87% of N prices, the K nutrient replacement costs were the highest among nutrients. At average K fertilizer prices, K represented about 74% of the total. Nitrogen replacement costs were the second-most significant at about 23% of the total cost, followed by relatively minor P and S costs.

Table 8. Wheat residue nutrient uptake values corresponding to a range of discrete grain yields (top). Also, market fertilizer prices for individual mineral nutrients (bottom), should fertilizer need to be applied to replace nutrients removed through residue harvest.

Grain Yield (Mg ha^{-1})	Residue Nutrient Uptake [a] N	P	K	S
	(kg ha^{-1})			
3	18.8	1.14	99.2	5.97
6	32.9	2.00	173	10.5
9	47.1	2.86	248	15.0
12	61.2	3.72	323	19.4

Table 8. *Cont.*

Cost Category	Fertilizer Nutrient Prices [b] (US $ kg^{-1}) N	P	K	S
Low	0.66	0.18	0.27	0.26
Average	1.00	0.36	0.63	0.40
High	1.50	0.55	1.30	0.55

[a] Residue nutrient uptake values were calculated using the stepwise approach outlined herein. [b] Fertilizer nutrient price ranges are based on historical prices in University of Idaho Enterprise Budgets for potatoes from 2001 to 2019. P_2O_5 and K_2O prices were converted to P and K values based on conversion factors of 0.4365 and 0.8301, respectively.

Table 9. Estimates of fertilizer replacement cost for selected macronutrients (N, P, K, S) contained in wheat residue for a range of grain yields. The bolded, primary values were calculated using the residue nutrient uptake values and average fertilizer prices given in Table 8. The ranges given below the primary values (in parentheses) are based on historical low and high fertilizer prices given in Table 8.

Grain Yield (Mg ha^{-1})	Residue Nutrient Replacement Costs (US $ ha^{-1}) N	P	K	S	Total
3	**18.80**	**0.41**	**62.48**	**2.9**	**84.09**
	(12.41, 28.21)	(0.21, 0.63)	(26.78, 128.93)	(1.55, 3.29)	(40.95, 161.05)
6	**32.94**	**0.72**	**109.46**	**4.19**	**147.31**
	(21.74, 49.41)	(0.36, 1.10)	(46.91, 225.87)	(2.72, 5.75)	(71.73, 282.14)
9	**47.08**	**1.03**	**156.44**	**5.98**	**210.53**
	(31.07, 70.62)	(0.52, 1.57)	(67.04, 322.81)	(3.89, 8.22)	(102.52, 403.22)
12	**61.22**	**1.34**	**203.41**	**7.78**	**273.75**
	(40.40, 91.82)	(0.67, 2.05)	(87.18, 419.74)	(5.06, 10.69)	(133.31, 524.31)

4. Discussion

4.1. Nutrient, Economic, Operational, and Other Considerations for Wheat Residue Harvest or Retention

Wheat producers face the choice to retain or remove residue following harvest, especially in higher-yielding systems that produce a substantial amount of biomass. Although residue harvest is common in certain regions, there are multiple demonstrated benefits to retaining residue in the cropping system. Residue is quite effective at stabilizing the soil and preventing erosion, which is one of the largest motivations for keeping it in place [11,16]. Residue on the soil surface can reduce weed pressure [12] and improve soil water retention [14,17]. Retaining residue also contributes to increasing or maintaining soil organic matter, though it is not as strong a contributor as root biomass [3,13,15]. Residue retention can have positive impacts on soil microbial activity and diversity, improving soil health and function [8,10]. And as addressed in the current research, returning residue to the system also recycles a portion of mineral nutrients that were assimilated by the wheat plant to support the growth of subsequent crops in the system.

The results of this research highlight that wheat residue is a significant repository of nutrients that have great fertilizer and economic value (Figure 2; Table 9). As observable in the data, K accumulates to particularly high levels in wheat residue, but contains substantial amounts of other nutrients too (Table 6; Figure 2). In a high-yielding crop that produces 9 Mg grain ha^{-1}, for example, the residue can contain approximately 248 kg K ha^{-1}, 47 kg N ha^{-1}, 3 kg P ha^{-1}, and 15 kg S ha^{-1}, plus other nutrients (Table 8). If the residue is harvested containing these nutrients, Table 9 summarizes the fertilizer nutrient replacement costs. At a yield level of 9 Mg ha^{-1} and an average fertilizer price (Table 8), replacing the K in residue alone through exogenous fertilizer application would cost an estimated $156 ha^{-1} (Table 9). The total nutrient replacement costs for all four nutrients contained in residue that were considered would be $211 ha^{-1} (Table 9). For comparison, the amount that a producer may budget for N, P, and K (not including fertilizer application costs) to produce an irrigated wheat crop (including grain, plus residue production) is about \$205 ha^{-1} [32]. It is important to note, however, that the relative distribution of N, P, and K that farmers typically apply to produce wheat [32] is substantially different than the relative amounts of these nutrients contained in residue. Depending on soil nutrient levels, fertilizer application rates are usually the highest for N, followed by P and K. The results of this study highlight the substantial soil K mining that can occur when wheat residue is harvested and the subsequently high K fertilizer application costs that can be expected to replace that K in the short or long term.

In the conditions of this study, plant K uptake was supported by high native concentrations of K in the soils of Southern Idaho, which have been decreasing since the introduction of large-scale commercial agriculture to the region [33]. Soil K reduction is exacerbated in cropping systems when there is total removal of biomass. In common crop rotations in Southern Idaho, harvest of all crop biomass occurs from most crops, including alfalfa (*Medicago sativa*, L.), silage corn (*Zea mays*, L.), wheat, and barley. These crops are widely grown and harvested for forage, grain, and residue in the region, especially near major dairy production areas, and create a major export of K and other mineral nutrients from agricultural soils. It is well established that small-grain nutrient uptake levels strongly depend on the environment in which they are grown, with some nutrients varying more across environments than others [26,34]. Thus, the best estimates of small-grain nutrient uptake will be made using region-specific research. However, as described in the Introduction, there have been few studies reported on this topic, none of them recent, and all have had limited experimental scope. Tarkalson et al. [24] summarized and analyzed data from these studies (ranging in publication date from 16 to 38 years ago) on the nutrient concentration, uptake, and fertilizer replacement value of N, P, and K in wheat residue.

There are several differences in the results presented by Tarkalson et al. [24] compared to the current study results. In their analysis, Tarkalson et al. [24] presented residue nutrient data at a single grain yield value of 6 Mg ha^{-1}, with an assumed harvest index value of 0.45. At that same grain yield level, the average harvest index found in the current study was 0.48 (Table 5), suggesting that progress has been made over time in improving the harvest index and shifts may have occurred in plant nutrient distribution. The average residue concentrations of N, P, and K observed in the current study (Table 6) were −37, −74, and 161% different, respectively, than the values reported by Tarkalson et al. [24]. These differences likely primarily reflect regional differences in cultural management practices, soil nutrient availability, and differences in nutrient utilization traits among regional wheat varieties. Similarly, assuming the same yield level of 6 Mg ha^{-1}, the average residue nutrient uptakes of N, P, and K observed in the current study (Tables 5 and 6) were −44, −77, and 130% different, respectively, than those reported by Tarkalson et al. [24]. As would be expected with shifting economic conditions, the fertilizer nutrient prices used by Tarkalson et al. [24] to make economic estimates, which were low and high price averages reported by USDA from 2000 to 2008, also differed from the more recent nutrient prices used in the current study. The historic low N, P, and K prices used in the current study (Table 8) were 38, −25, and 8% different than the older values used by Tarkalson et al. [24], while the high N, P, and K prices were 9, −36, and 51% different, respectively. A key takeaway from these comparisons is that actual wheat residue K concentration and uptake in Southern Idaho are considerably higher than previously thought or estimated, and that fertilizer K prices have significantly increased over time. These findings put a greater spotlight on the potentially unfavorable long-term economic tradeoff that many regional farmers are making in harvesting and selling wheat residue.

The economic analysis presented herein was simplified and focused on wheat residue nutrient uptake values and their associated replacement costs, and there are assumptions and other economic considerations that are important to discuss. The economic estimates are based on a mass balance approach that indicates the value of nutrients should they leave the system through residue harvest and thus are no longer available for plant uptake or soil nutrient cycling. If producers choose to return residue and the associated nutrient to the system, then there are complex chemical, physical, and biological factors that would affect the cycling and ultimate plant availability of the nutrients. Those factors were beyond the scope of this study. The economic analysis also does not consider any potential additional N requirement to prevent yield loss of subsequent crops when high C:N wheat residues are returned to the system. This issue is discussed in greater detail in the following subsection. Another important consideration, as discussed above, is that retention of wheat residue in the cropping system has non-nutrient economic benefits and ecosystem services that are difficult to quantify, but likewise affect cropping system sustainability. These include erosion control, preservation of soil moisture, maintenance of soil organic matter, and others. Finally, while the economic analysis included only the macronutrients N, P, K, and S, due to the large plant demand and common limitation of these nutrients in agricultural soils, other macro- and micronutrients (e.g., Mg, Zn, etc.) can also be limiting to crops and require replacement if persistently harvested through residue. Although the amount of secondary macro- and micronutrients that may need to be applied when they are limiting is relatively small, when they do need to be applied, the fertilizer prices can be high enough to substantially reduce farm profitability.

4.2. Management of Retained Wheat Residue

When wheat residue is retained in the cropping system, especially in higher-yielding systems, it must be managed in some way, so it does not become an obstacle to planting of subsequent crops. Wheat residue can be finely chopped and evenly distributed across the field with the harvesting combine. Even distribution and fine particle size can immediately reduce the physical impediment to planting later, and this can also accelerate the residue decomposition process [35–38]. Taking this approach may depend on the size of the residue load and the timing of subsequent crop production. When residue loads are very high and/or cropping intensity is high (i.e., rapid turnaround for planting another crop), harvesting a portion of the residue, in conjunction with finely chopping and evenly distributing the retained residue, may be an optimal tradeoff. In tilled systems, surface residue reduction can be accomplished by incorporating it into the soil, which moves a portion of the residue below the surface and can also accelerate decomposition [10,36,39].

When wheat residue is retained, effects on soil N dynamics must also be considered because of interactions between residue biodegradation and soil N bioavailability [38]. When high C:N crop residues, like wheat residue, are left in agronomic systems, additional application of N fertilizer may be needed to prevent N deficiencies and yield loss in subsequent crops. This is reflected in fertilizer recommendations in the study region that recommend supplemental N based on remaining small-grain residue [13,38,39]. Implementing crop rotations that include legumes, which can symbiotically fix their own N, especially when soil N is limited, can help to naturally ameliorate this issue [40]. Consistent return of crop residues to the system can also shape and stimulate soil microbial communities, enabling more effective decomposition of residues and mineralization of nutrients contained within [41]. Additionally, nutrients supplied in residue are not as readily available as those applied as inorganic fertilizer and thus a long-term approach of nutrient management from residues is needed. In deciding when and how much wheat residue to retain in a cropping system, the potential additional residue management and N fertilizer costs should be weighed by producers against long-term fertilizer savings for all nutrients contained in the residue and other ecosystem services that residue provides.

4.3. Use of the Residual Nutrient Estimation Tools Developed through This Research

There was great diversity in the sources from which the current wheat residue mineral nutrient dataset was derived (i.e., several different wheat production environments and seasons, wheat classes and varieties) and the dataset is broad in scope (i.e., the data span most of the typical range of wheat yields observed in the field). As a result, we expect that the residue nutrient uptake estimations derived from the dataset (Tables 5–7;

Figures 1 and 2) will be more widely applicable and useful to wheat producers, researchers, and policymakers than any analysis or report previously published for wheat on this topic [24,25,42]. Estimates can be made using no more than grain yield information and the nutrient concentrations presented herein. Grain yield is commonly measured by wheat producers and aggregate grain yield information (i.e., county or statewide) is also widely available through USDA databases and other sources [43]. For wheat producers, having an estimate of the amount of nutrients contained in residue can aid in making more informed residue management decisions.

Despite the diversity represented in this dataset, those estimating residue nutrient uptake using the tools presented herein should consider how representative the data may be of their specific production conditions. The region in which this dataset was generated, Southern Idaho, is among the most productive regions for small grains in the U.S., largely due to fertile soils, availability of elite germplasm, and widespread irrigation [44]. The variability within the current dataset (characterized by R^2, RMSE, CV, and quartiles) arose from differences in crop nutrient uptake and partitioning among different wheat varieties of several market classes grown in different production environments and seasons. If a user of the data had substantially different wheat germplasm and/or production conditions (e.g., inherently low or high soil nutrient levels, high exogenous fertilizer application rates, history of manure applications, marginal soils, or unimproved germplasm) than represented by the current study, the residue nutrient uptake estimates may not be closely representative. Use of the stepwise approach is recommended in these cases. Direct measurements or educated estimates of input parameters should be used in making more reasonable projections. For example, Dai et al. [45] measured the HI and straw production of wheat produced at multiple, climactically diverse locations across the U.S and reported HI values ranging from 0.33 to 0.61 (compared to averages of 0.47 to 0.51 across wheat classes in this study). This represents large differences in relative amounts of grain and residue production across U.S. wheat systems, which would impact nutrient partitioning between these pools. And, as discussed above, nutrient uptake values can vary considerably across environments.

5. Conclusions

Through this research, data and estimation tools were developed describing relationships between wheat grain yield and uptake values of 10 mineral nutrients in residue. These can be used to estimate crop removals of mineral nutrients from soil, allowing more informed agronomic and economic residue management decisions to be made in wheat-based cropping systems. The primary limitation of this research is that residue nutrient uptake is affected by system-specific soil nutrient availability and wheat germplasm traits. Despite the diversity represented in the dataset, those who estimate residue nutrient uptake using the tools presented herein should consider how representative the data may be of their specific production conditions and make reasonable adjustments to the input parameters. Our analysis indicated that the economic value of four key nutrients (N, P, K, and S) contained in residue, in terms of fertilizer replacement cost, was approximately equivalent to the entire nutrient management budget to grow a wheat crop (not considering residual micronutrients or any nutrients taken up by grain). This cost will likely far exceed the revenues obtained from residue sale on its own, and residue harvest and subsequent fertilizer application costs were not considered in the analysis. Notably, the estimates of residue K uptake and fertilizer replacement cost for the study region of Southern Idaho far exceeded previous estimates. Other economic considerations are discussed herein. Persistent removal of nutrients from cropping systems through residue harvest will affect soil nutrient availability in the short and long term, and the magnitude and timeframe of these changes will depend on the cropping system and soil. The tradeoff between the immediate gains of residue sale and future nutrient costs should be carefully considered. Importantly, residue retention has other economic and ecological benefits in cropping systems that are more difficult to quantify, but likewise affect long-term system sustainability, such as erosion control, maintenance of organic matter, preservation of soil moisture, and others. In any policy decisions regarding farm residue management, policymakers should consider the multifaceted benefits of wheat residue retention, including preservation of soil nutrients. Potential future research could include studies on the fate of nutrients in wheat residue that are returned to the cropping system, including quantifying the timeframe for nutrient turnover/mineralization and any nutrient loss.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14081795/s1, Table S1: Select ANOVA results for Hard White Spring Wheat; Table S2: Select ANOVA results for Soft White Spring Wheat; Table S3: Select ANOVA results for Hard Red Winter Wheat; Table S4: Select ANOVA results for Soft White Winter Wheat.

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