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Climate-Changed Wheat: The Effect of Smaller Kernels on the Nutritional Value of Wheat

Merri C. Metcalfe [1,*], Heather E. Estrada [2] and Stephen S. Jones [1]

[1] WSU Breadlab, Department of Crop and Soil Sciences, Washington State University, Burlington, WA 98233, USA; joness@wsu.edu
[2] Department of Integrated and Agriculture Food Systems, Flathead Valley Community College, Kalispell, MT 59901, USA; hestrada@fvcc.edu
* Correspondence: merri.metcalfe@wsu.edu

Abstract: Through plant breeding and improved agronomy, the average wheat kernel size increased globally by about 40% from 1940 to 2000. Millers demand larger kernels because they contain more white flour (endosperm). Climate pressures are resulting in frequently reduced kernel size and routine rejection by the commodity system. If whole-wheat flour instead of white flour is the target, these smaller kernels have unrealized value. A total of 94% of Americans do not meet the recommended fiber intake, and inadequate fiber intake plays a role in the development of multiple chronic diseases. A total of 98% of the fiber in wheat is found in the bran. Bran content was measured in “big” ($\bar{x}$ = 0.042 g/kernel) and “small” ($\bar{x}$ = 0.023 g/kernel) kernels in nine varieties over locations and years. On average, small kernels contained 15.9% more bran than big kernels ($n = 54$, $p < 0.001$) and, thus, had higher mineral and fiber content. In the majority of cases, baking showed no difference in whole-wheat quality among flours within the same variety, regardless of kernel size, based on bread slice height and surface area. Wheat that was rejected by commercial mills as too small produced satisfactory bread. Favoring larger kernels and white flour production has unintended health consequences. Valuing smaller kernels and whole-wheat production provides an outlet for farmers dealing with increasing climate pressures and leads to an end-use product which can improve human health by increasing dietary fiber consumption.

Keywords: plant breeding; wheat breeding; fiber; nutrition; whole grain

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1. Introduction

Breeders and agronomists have been successful in developing and producing wheat lines that have larger kernels. Globally, from 1940 to 2000, the average thousand-kernel weight (TKW) increased by 2.19 g per decade with an average TKW of 31.5 g in the 1940s to an average TKW of 44.64 g in the 2000s [1]. A larger kernel size results in greater white flour yield, which is demanded by millers. Breeding for a larger seed to increase white flour yield has led breeders to reject wheats from their programs that are deemed incapable of creating sufficient white flour (i.e., smaller wheat kernels). This translates to and is expanded at the flour mills, where any remaining smaller wheat kernels are rejected. Thus, a feedback loop is created where both breeders and mills overvalue larger seed kernels in the name of producing more white flour [2–8].

This model does not work in an overheated and drying climate where smaller seed is more frequent. Smaller kernels form in response to inhibited starch deposition from heat and drought stress [9–15]. Small wheats with lower TKWs, such as those produced in response to heat and drought stresses, are rejected or docked in price by the commodity market [16]. As of May 2022, extreme heat in India is already resulting in smaller and, shriveled kernels, and wheat harvests have been reported at 400 million tons less than expected due to these devastating heatwaves [17]. Another example of this global phenomenon occurred in northwestern US in 2020 and 2021, where the TKWs of over 500 wheat samples decreased by an average of 6.7 g from previous years [18]. In the summer of 2021, Washington and Oregon each had their hottest June and July on record, and from May to September 2021, an average of 46% of the contiguous United States was in drought, with nearly 90% of eleven states across the western US experiencing varying levels of drought in July, many rated as extreme [19]. Climate pressures have been steadily increasing and the past decade (2010–2019) has been the hottest recorded to date [19]. Additionally a recent study found that the southwestern US "megadrought" is the greatest drought in 1200 years [20]. As of Spring 2022, Washington state was already reporting severe and extreme droughts in the eastern part of the state, and these droughts are predicted to cause smaller wheat kernels [21,22]. Thus, despite the fact that breeders have been selecting for larger kernel size, environmental pressures are leaving producers with a harvest that contains smaller wheat kernels. Rather than reject these kernels as is customary within the commodity wheat system, should these smaller wheat kernels instead be valued for their nutritional content and economic potential?

The authors here seek to offer an alternative to a system which favors white flour and subsequently values larger wheat kernels at all costs. If we were to realize and value our global nutritional needs, how would our food system benefit by realizing the value of and not rejecting these small wheats? This is especially relevant considering Russia's war on Ukraine. Russia and Ukraine supply up to 30% of the world's wheat, and 2022 harvests in Ukraine are sure to plummet as Ukrainian farmers were forced to flee their farms. Additionally, both Ukraine and India have now banned wheat exports, threatening the global supply [17,23]. On average, 10–15% of the wheat kernel is dietary fiber, with nearly all of this found in the bran. White flour production, which removes the bran and germ from the wheat kernel, results in the loss of 98% of the dietary fiber found in wheat [24–26]. Fiber plays an essential role in the prevention of several chronic diseases, secondary to the development of a healthy gut microbiome [27–30]. Disrupted gut microbiomes have been associated with the development of diabetes, irritable bowel syndrome, irritable bowel disease, colorectal cancer, metabolic alterations, depression, and anxiety [30–39].

The current American dietary recommendations for fiber intake are 28–34 g per day. More than 90% of women and 97% of men do not meet the recommended intake [40]. Moreover, current research further suggests that fiber recommendations should be raised to at least 50 g per day [30,37,41–43].

In the US, total carbohydrate intake decreased 25% from 500 g per day in 1909 to 375 g per day in 1963, while dietary fiber intake decreased at a greater rate of almost 40%. From 1963 to 1997, total carbohydrate intake increased back to 500 g per day; however, fiber intake remained as low as in 1963, suggesting a dramatically increased intake of refined carbohydrates [44]. This phenomenon has been termed the "fiber gap" and is directly linked to a low intake of dietary whole grains [37,45–47]. A low intake of dietary whole grains was named the leading dietary risk factor for death among young adults (aged 25–50) [48]. Researchers attributed three million deaths and 70 million disability-adjusted life-years to a low intake of whole grains in the diets of individuals from 195 countries between 1990 and 2017 [48].

Since fiber in wheat is found almost exclusively in the bran, a simple way to increase fiber in the kernel (and in human diets) is to decrease the endosperm in relation to its coating (the bran) and to use the whole kernel for flour. A smaller kernel size correlates to less endosperm and a higher percentage of bran. This is illustrated by the square cube law, a mathematical principle first postulated by Galileo Galilei in *Two New Sciences* where he states that 'The surface of a small solid is comparatively greater than that of a large one' [49,50]. By principles of the square cube law, small kernels ("smalls" (Figure 1), defined here as kernels which move through a standard #7 sieve when placed in commercial shaker for three minutes), contain more total grams of dietary fiber per kernel than big kernels ("bigs", defined here as kernels which do not move through a standard #7 sieve when placed in commercial shaker for three minutes). Furthermore, the total grams of dietary fiber in one kilogram of flour milled from smalls will be higher than from one kilogram of flour milled from bigs, as bigs have a higher percentage of endosperm per whole-grain kernel than smalls. This not only increases the fiber content in terms of percentage of fiber in the individual kernel, but also increases fiber content of finished products which use flour milled from wheat with less endosperm, as the increased percentage of bran is now replacing the endosperm (starch and gluten) in the wheat product.

Figure 1. Eileen "Big" with Thousand-Kernel Weight (TKW) of 42.7 g (**left**) and Eileen "Small" with TKW of 24.5 g (**right**).

Using the entire kernel is also modeling a more climate-friendly use of land and translates to a higher yield; this is because 25–30% of the farmer's harvest is not sifted off for animal feed or other low-value uses, but is instead used for direct human nourishment. The production of white flour typically removes around 25% of the kernel, which is not used in baking production [25]. Obtaining as much direct human food per acre is the best use of our limited global land base. Additionally, valuing small kernels will provide an economic outlet for farmers who are dealing with increasing drought and heat pressures and whose smaller-kernel wheat has been previously rejected by mills and sold at a lower price.

2. Materials and Methods

2.1. Percent Bran Analysis

Nine varieties of wheat grown across five locations between 2018 and 2021, for a total of eighteen unique samples, were measured using the following methods. See Table 1 for details on specific varieties, locations, and years of samples measured. Subsamples (550–600 g) of each wheat sample were sifted through a USA Standard Testing Sieve #7 (2.8 mm/0.110 in) to separate larger seeds from smaller seeds in a Ro-Tap Sound Enclosure Cabinet R-30050 (W.S. Tyler, Mentor, OH, USA) shaker for three minutes. The #7 sieve size was chosen as this is equivalent to the sieve size used by a local seed cleaning facility. This procedure was repeated with each variety until a total of 1650 g each of smalls and bigs were obtained. For most varieties, obtaining 1650 g each of smalls and bigs required at least a fifty-pound bag of seed. Some varieties which were grown in more hot and dry climates (such as those grown in Montana) contained a higher percentage of small seed to big seed per fifty-pound bag compared to other varieties and locations measured.

Table 1. Description of Samples Tested.

Variety	Location	Year Grown
Le Sourd	Mount Vernon, WA, USA (NWREC)	2019–2020
Red Russian	Mount Vernon, WA, USA (NWREC)	2019–2020
Salish Blue	Mount Vernon, WA, USA (NWREC)	2018–2019
	Mount Vernon, WA, USA (Roozen Fields)	2020–2021
Eileen	Mount Vernon, WA, USA (Viva Farms)	2020, 2021
	Chimacum, WA, USA (Finnriver Grain)	2020, 2021
Edison	Mount Vernon, WA, USA (NWREC)	2018, 2019, 2020
	Mount Vernon, WA, USA (Viva Farms)	2021
Expresso	Chimacum, WA, USA (Finnriver Grain)	2020
FVCC Wheat	Kalispell, MT, USA (FVCC Campus Farm)	2020
Ruth	Mount Vernon, WA, USA (NWREC)	2019, 2020
	Mount Vernon, WA, USA (Viva Farms)	2021
Very Blue	Mount Vernon, WA, USA (NWREC)	2020

NWREC = Northwestern Washington Research and Extension Center; FVCC = Flathead Valley Community College.

After separating by large and small kernel size, each sample was tempered to 15% moisture prior to milling. Initial moisture content of each sample was measured using the MT-CA (Brabender, Duisburg, Germany). Initial moisture content was then used to calculate the amount of water needed to bring moisture content up to 15%. Next, the calculated amount of water was added to the bulked sample and placed in a large, sealed container. The container was manually shaken 150 times to ensure the additional water was evenly dispersed throughout the grain sample. The sample was then left undisturbed for 24 h. Moisture content was measured again after tempering to ensure the desired level of 15% moisture was reached. Two samples—Eileen bigs grown in Chimacum, WA, USA in 2021 and Eileen smalls of the same location and year—had initial moisture contents of 15.26% and 14.83%, respectively; thus, they were not tempered.

Next, for each variety and location, a 510–520 g sample of bigs was milled through a Quadrumat Junior (Brabender, Germany) miniature roller mill with the feeder open halfway. Once all seed had moved past the feeder, the mill was left running for an additional 60 s. After 60 s had passed, the mill was turned off. Next, a small nylon brush was used to move any flour that remained in the area past the rollers into the sifter. The mill was then run for an additional 60 s. Next, the drawer containing the sifted white flour was removed and the flour in this drawer was weighed using a KL1001—Precision Balance (Veritas, Beijing, China). This weight was used in the calculation as "weight of white flour from roller mill". The flour portion which presumably contained more bran and germ was transferred into a Bran Duster (Brabender, Germany). The flour that remained in the sieve of the roller mill was also transferred into the bran duster for further partitioning. It was observed, in preliminary experiments, that a small pile (about 1 g) of flour was expelled from the roller mill from the opening of the plates (where the brush was placed). This small pile was also added to the bran duster. Once all partitions had moved past the auger of the bran duster, the duster was left running for an additional 60 s. After the bran duster was turned off, the left side door of the bran duster was opened, and a small one-inch paint brush was used to brush off the bran that remained in the sifter into the leftmost drawer which contained the dusted bran. The contents of the bran drawer were then weighed. Next, the top door of the duster was opened, and a two-inch paint brush was used to brush off any excess white flour from around the sieve. The white flour drawer was removed and the flour in this drawer weighed using a KL1001—Precision Balance (Veritas, China). This weight was used in the calculation as "weight of white flour from bran duster". Next, the sieve was removed and any remaining bran in the sieve was weighed. This weight was added to the weight of the contents of the bran drawer and the total weight was used in the calculation as "total bran weight". This procedure was repeated two more times with the bigs of each variety and location—cleaning the mill and bran duster between each sample preparation. The same procedure was then repeated three times with the smalls of each variety and location—again, cleaning the mill and bran duster thoroughly between each sample preparation. The estimated percent bran of small and big seeds was calculated by dividing "total bran weight" by "total bran weight + weight of white flour from bran duster + weight of white flour from roller mill" multiplied by 100 (e.g., [109.6 g/(109.6 + 26.6 g + 374.1)] = 21.5% bran in first rep from Red Russian harvested in 2020). The percent increase bran was calculated using the formula, [(Large bran−small bran)/large bran] × 100 (e.g., [(27.91−24.09)/24.09] × 100 = 15.9%).

2.2. Percent Ash

Ash content was measured for each variety and repeated three times for both large and small kernel size samples for each variety and location. Ash content was measured using AACC Approved Method 08-01.01, "Ash—Basic Method" (AACC Approved Methods of Analysis 1999). Ash content was measured using a Thermolyne Muffle Furnace (Thermo Scientific, Waltham, MA, USA). Flour samples for percent ash analysis were taken from flour milled as described in "Percent Bran Analysis" after having been recombined in a metal bowl and stirred 100 times with a large spoon to ensure all particles were evenly dispersed.

2.3. Thousand-Kernel Weight

Thousand-kernel weight was measured after tempering to 15% moisture and prior to milling, as described in the "Percent Bran Analysis". A C1 Seed Counter (Elmor, Schwyz, Switzerland), with speed and size set at the number "3" setting, was used to count 100 seeds of each variety with large- and small-sized kernels measured separately. Next, these 100 seeds were weighed on a KL1001—Precision Balance (Veritas, China) with weight multiplied by 10 to estimate TKW. Each sample was measured three times.

2.4. Test Baking

Baking functionality was determined by baking pup loaves using flour milled from only smalls in addition to loaves using flour milled from only bigs of each sample. Baking was carried out after all prior tests had been completed, using the flour milled during percent bran analysis, which had been recombined when measuring percent ash. The baking formula for the "Approachable Loaf", created by professional baker Jeff Yankellow [51,52], was used, with 500 g as the total loaf volume for each flour sample. Dough was scaled out to 140 g per loaf. Bulk fermentation and folding time remained the same as original formula. Proofing time was decreased to 25 min at 72 °F to adjust for smaller pup loaf size. Loaves were baked in a One39-E Electric Mini Rotating Oven (Revent, Upplands Väsby, Sweden) and steamed at 5 min. The oven was preheated to 400 °F and turned down to 375 °F when loaves were placed in the oven. Baking time was decreased to 22 min from the 45 min used in original "Approachable Loaf" formula to adjust for smaller pup loaf size. Three pup loaves of each sample were baked along with an additional two control loaves per pan. Control loaves were baked using a single lot of Skagit 1109 flour. Skagit 1109 is a landrace released by WSU Breadlab in September 2016 and is widely accepted by millers and bakers nationally and globally. Note that each pup loaf pan had slots for eight loaves. Each pan contained three loaves using flour from small kernel sizes and three loaves using flour from large kernel sizes of the same variety, location, and year grown, along with two control loaves. Loaves were randomly placed in the pup loaf pan. Baking functionality of small seeds was also tested using 20–30-pound samples of small wheats that were rejected to be sold as animal feed by three separate commercial flour mills. These seeds were milled on a Mockmill 200 (Mockmill, Groß-Umstadt, Germany). Again, the "Approachable Loaf" formula was used; however, these loaves were baked as full-size loaves scaled out to 900 g of dough each. Bulk fermentation, folds, proofing, and baking time were not changed from the original "Approachable Loaf" formula. Again, loaves baked with Skagit 1109 flour were used as controls. Three full-size loaves from each commercial flour mill reject sample were baked in one pan, along with one control loaf for each pan.

Both pup loaves and full-size loaves were evaluated using the same methods. Loaf slice height was evaluated using a caliper set to the mm setting and loaf slice surface area was measured using the Leafscan app with the reference length set at 8 cm for the pup loaf slices and 15 cm for the full-size loaf slices [53]. Loaf slice height was measured at the tallest cross section of each loaf. Each measurement was taken twice with the average of the two measurements used in statistical analysis. Photos were taken of all loaves.

2.5. Protein Content Analysis

Protein content, along with moisture content, was determined using an Inframatic Flour Analyzer (Perten Instruments, Hamburg, Germany). Flour was spooned into the analyzer and compressed into the view window using the designated plunger. A sample of bigs and smalls from each variety was run once using the "Whole Grain" setting. One replication was completed for each sample. After determining protein and moisture for each sample, all samples were adjusted to 15% moisture. This adjusted value was used in the statistical analysis.

2.6. Statistical Analysis

The obtained data were analyzed with IBM SPSS Statistics for Windows, version 28.0. Descriptive statistics including mean values, standard deviation, standard error of the mean, and range of bran per 100 g, TKW, percent ash, and percent protein were run for both total bigs and smalls, as well as split by variety, location, and year grown. Independent samples *t*-tests were run for total bran per 100 g, TKW, percent ash, and protein, and split by variety, location, and year to determine significance of the differences between bigs and smalls. Effect size was measured using Cohen's d. Descriptive statistics including mean values, standard deviation, standard error of the mean, and ranges were run for bread loaf slice height and bread loaf slice surface area of control pup loaves and of all full-size loaf test bakes. Analyses of variance between independent variables (bran per 100 g, TKW, and percent ash) and categorical variables (variety, location, and year grown) were run to check for interaction effects.

3. Results

3.1. Percent Bran, TKW, and Ash (%) Analysis

Table 2 summarizes the mean values, standard deviations, and standard errors of the mean for bran per 100 g, TKW, ash, bread slice height, and bread slice surface area, split by variety, year, and location. Table 3 summarizes the mean values, standard deviations, and standard errors of the mean for bran per 100 g, TKW, ash, bread slice height, and bread slice surface area for all the samples. The differences in bran per 100 g between the bigs and smalls of each variety, split by year and location, were significant at $p = 0.025$ or less. On average, smalls contained 15.9% more bran than bigs. The differences in TKW between the bigs and smalls of each variety, split by year and location, were significant at $p = 0.015$ or less. The differences in percent ash between the bigs and smalls of each variety, split by year and location, were significant at $p = 0.026$ or less. The standard errors of the mean ranged from 0.12 to 1.01 for bran per 100 g versus kernel size, 0.01 to 2.06 for TKW versus kernel size, and 0–0.05 for ash versus kernel size. The effect size (Cohen's d) ranged from 2.26–26.86 for bran per 100 g, 6.43–31.08 for TKW, and 3.35–26.13 for ash for each variety, split by year and location, suggesting a very strong relationship between kernel size and percent bran, TKW, and ash. Three-way ANOVAs were run and no interaction effects were detected (data not shown).

Table 2. Bran/100 g, TKW, percent ash, test-bake pup loaf slice height, and test-bake pup loaf slice surface area differed between large- and small-sized kernels, split by variety, year grown, and location grown.

Variety, Year, and Location			**Bran per 100 g**	**TKW (g)**	**Ash (%)**	**Slice Height (mm)**	**Slice Surface Area (cm^2)**
Le Sourd	2020 MV	Bigs	23.92 ± 0.56 (0.32) ***	39.23 ± 0.84 (0.48) ***	1.62 ± 0.03 (0.02) **	52.59 ± 0.49 (0.28) ns	28.46 ± 0.36 (0.21) ns
		Smalls	27.26 ± 0.32 (0.19)	24.04 ± 0.02 (0.01)	1.75 ± 0.01 (0.00)	51.57 ± 1.45 (0.83)	28.15 ± 1.02 (0.59)
Red Russian	2020 MV	Bigs	22.92 ± 1.30 (0.75) **	41.23 ± 1.87 (1.08) ***	1.67 ± 0.07 (0.04) **	54.90 ± 1.52 (0.88) *	31.45 ± 1.31 (0.76) ns
		Smalls	27.75 ± 1.05 (0.61)	21.77 ± 0.86 (0.50)	1.99 ± 0.01 (0.01)	51.50 ± 0.97 (0.56)	29.74 ± 0.92 (0.53)
Eileen	2020 MV	Bigs	25.31 ± 0.21 (0.12) **	42.74 ± 0.89 (0.52) ***	1.75 ± 0.00 (0.00) ***	50.53 ± 0.72 (0.42) ns	26.04 ± 0.83 (0.48) ns
		Smalls	29.02 ± 1.09 (0.63)	24.54 ± 0.28 (0.16)	1.93 ± 0.04 (0.02)	49.78 ± 0.47 (0.27)	25.86 ± 0.87 (0.50)
	2021 BL	Bigs	25.01 ± 0.39 (0.23) **	44.75 ± 1.10 (0.64) ***	1.76 ± 0.04 (0.02) **	53.04 ± 0.97 (0.56) *	29.57 ± 1.99 (1.15) ns
		Smalls	27.58 ± 0.53 (0.31)	23.26 ± 0.34 (0.19)	1.93 ± 0.04 (0.02)	50.95 ± 0.93 (0.54)	28.04 ± 1.40 (0.81)
	2020 CM	Bigs	29.57 ± 0.63 (0.36) ***	40.79 ± 1.61 (0.93) ***	1.75 ± 0.09 (0.05) *	51.02 ± 0.98 (0.57) *	27.09 ± 0.67 (0.39) ns
		Smalls	34.26 ± 0.88 (0.51)	20.99 ± 0.80 (0.46)	2.00 ± 0.01 (0.00)	48.99 ± 1.11 (0.64)	26.65 ± 0.98 (0.56)
	2021 CM	Bigs	24.83 ± 1.11 (0.64) **	44.66 ± 0.73 (0.42) ***	1.50 ± 0.02 (0.01) ***	52.68 ± 0.95 (0.55) **	29.94 ± 1.38 (0.80) ns
		Smalls	28.81 ± 0.22 (0.13)	20.98 ± 0.79 (0.46)	1.75 ± 0.02 (0.01)	49.69 ± 0.19 (0.11)	27.60 ± 0.68 (0.39)
Edison	2018 MV	Bigs	21.61 ± 0.61 (0.35) **	46.60 ± 1.03 (0.60) ***	1.65 ± 0.00 (0.00) **	53.84 ± 1.69 (0.98) **	29.88 ± 1.15 (0.66) *
		Smalls	24.28 ± 0.59 (0.34)	26.20 ± 0.51 (0.29)	1.75 ± 0.04 (0.02)	49.35 ± 0.79 (0.46)	26.59 ± 0.13 (0.08)
	2019 MV	Bigs	22.05 ± 0.36 (0.21) ***	43.48 ± 2.23 (1.29) ***	1.35 ± 0.01 (0.00) ***	52.31 ± 1.86 (1.07) ns	28.19 ± 1.58 (0.91) ns
		Smalls	26.94 ± 0.20 (0.12)	22.60 ± 0.89 (0.51)	1.46 ± 0.00 (0.00)	50.40 ± 0.46 (0.26)	28.14 ± 0.80 (0.46)
	2020 MV	Bigs	22.65 ± 0.59 (0.34) ***	47.10 ± 3.16 (1.82) **	1.39 ± 0.04 (0.02) ***	53.04 ± 2.13 (1.23) ns	30.08 ± 0.86 (0.50) *
		Smalls	26.31 ± 0.58 (0.34)	20.70 ± 0.23 (0.13)	1.70 ± 0.02 (0.01)	50.49 ± 2.32 (1.34)	26.51 ± 1.77 (1.02)
	2021 BL	Bigs	22.55 ± 0.73 (0.42) **	41.51 ± 1.20 (0.69) ***	1.73 ± 0.06 (0.00) ***	52.88 ± 2.08 (1.20) ns	28.70 ± 0.79 (0.46) ns
		Smalls	25.45 ± 0.56 (0.32)	22.53 ± 0.71 (0.41)	1.94 ± 0.04 (0.02)	52.06 ± 1.45 (0.84)	27.72 ± 0.63 (0.36)
Ruth	2019 MV	Bigs	23.85 ± 0.62 (0.36) **	45.13 ± 1.01 (0.58) ***	1.54 ± 0.06 (0.04) **	52.09 ± 0.38 (0.22) ns	28.22 ± 0.41 (0.24) ns
		Smalls	26.96 ± 0.77 (0.44)	23.48 ± 0.41 (0.24)	1.70 ± 0.03 (0.02)	50.88 ± 1.03 (0.59)	27.42 ± 1.11 (0.64)
	2020 MV	Bigs	21.89 ± 0.28 (0.16) ***	44.48 ± 0.66 (0.38) ***	1.49 ± 0.02 (0.01) ***	53.56 ± 0.94 (0.54) ns	29.16 ± 1.71 (0.99) ns
		Smalls	28.60 ± 0.21 (0.12)	22.08 ± 0.23 (0.13)	1.74 ± 0.02 (0.01)	51.35 ± 2.02 (1.17)	28.42 ± 1.61 (0.93)
	2021 BL	Bigs	21.85 ± 0.66 (0.38) ***	45.13 ± 1.01 (0.58) ***	1.49 ± 0.02 (0.01) ***	55.18 ± 1.18 (0.68) *	29.68 ± 1.69 (0.97) ns
		Smalls	25.32 ± 0.30 (0.18)	24.08 ± 0.70 (0.41)	1.73 ± 0.02 (0.01)	53.05 ± 1.12 (0.64)	28.49 ± 0.40 (0.23)
Very Blue	2020 MV	Bigs	24.86 ± 0.54 (0.31) **	43.87 ± 1.26 (0.73) ***	1.54 ± 0.04 (0.02) ***	53.13 ± 1.52 (0.88) *	29.05 ± 0.54 (0.31) ns
		Smalls	27.23 ± 0.21 (0.12)	22.30 ± 0.95 (0.55)	1.76 ± 0.02 (0.01)	50.40 ± 0.95 (0.55)	27.83 ± 1.10 (0.64)

Table 2. *Cont.*

Variety, Year, and Location			Bran per 100 g	TKW (g)	Ash (%)	Slice Height (mm)	Slice Surface Area (cm^2)
FVCC Wheat	2020 KL	Bigs	23.37 ± 0.56 (0.32) *	29.55 ± 0.85 (0.49) ***	1.93 ± 0.02 (0.01) **	50.40 ± 0.95 (0.55) ns	27.15 ± 1.12 (0.65) ns
		Smalls	24.85 ± 0.73 (0.42)	19.35 ± 0.54 (0.31)	2.05 ± 0.02 (0.01)	50.14 ± 0.95 (0.14)	26.49 ± 1.03 (0.59)
Salish Blue	2019 MV	Bigs	27.73 ± 0.53 (0.30) **	31.75 ± 3.56 (2.06) **	1.96 ± 0.02 (0.01) ***	51.61 ± 1.01 (0.58) ***	27.06 ± 0.86 (0.50) **
		Smalls	33.92 ± 1.72 (1.01)	21.49 ± 0.99 (0.57)	2.16 ± 0.04 (0.02)	46.52 ± 0.68 (0.39)	24.33 ± 0.17 (0.10)
	2021 MV2	Bigs	25.12 ± 0.36 (0.21) ***	41.52 ± 0.88 (0.51) **	1.69 ± 0.00 (0.00) ^{E}	53.57 ± 0.95 (0.55) **	29.72 ± 0.88 (0.51) **
		Smalls	29.03 ± 0.36 (0.21)	25.43 ± 3.43 (1.98)	1.82 ± 0.00 (0.00)	50.39 ± 0.96 (0.55)	26.97 ± 0.79 (0.45)
Expresso	2020 CM	Bigs	24.53 ± 0.79 (0.45) ***	37.17 ± 0.31 (0.18) ***	1.59 ± 0.04 (0.02) ***	53.49 ± 1.02 (0.59) ns	29.79 ± 0.74 (0.43) **
		Smalls	28.82 ± 0.40 (0.23)	20.96 ± 0.96 (0.55)	1.68 ± 0.01 (0.00)	52.00 ± 1.30 (0.75)	26.82 ± 0.25 (0.15)

Mean ± standard deviation (s.e.m.), $n = 3$; * $p < 0.05$, ** $p \leq 0.01$, *** $p < 0.001$; ns = non-significant at $p > 0.05$; E = cannot be computed, no variation between three samples of small kernel size and no variation between three samples of large kernel size; MV = Mount Vernon, Washington; MV2 = Different farm in Mount Vernon, Washington; BL = Burlington, Washington; CM = Chimacum, Washington; and KL = Kalispell, Montana.

Table 3. Bran/100 g, TKW, percent ash, test-bake pup loaf slice height, and test-bake pup loaf slice surface area between large- and small-sized kernels of all samples tested.

Seed Kernel Size	Bran per 100 g	TKW (g)	Ash (%)	Slice Height (mm)	Slice Surface Area (cm^2)
Bigs	24.09 ± 2.12 (0.29) ***	41.71 ± 4.85 (0.66) ***	1.63 ± 0.17 (0.02) ***	52.66 ± 1.74 (0.23) ***	28.69 ± 1.65 (0.22) ***
Smalls	27.91 ± 2.69 (0.37)	22.60 ± 1.95 (0.27)	1.82 ± 0.17 (0.02)	50.47 ± 1.75 (0.23)	27.27 ± 1.44 (0.19)
Effect size (Cohen's d)	1.576	5.166	1.154	1.322	1.549

Mean ± standard deviation (s.e.m.), $n = 54$; *** $p < 0.001$.

3.2. Pup Loaf Test-Bake Analysis

To test the functionality of bigs versus smalls of all the varieties measured, pup loaf test bakes were conducted. We observed slightly higher loaf volume with larger kernels (See Figure 2, slices 3–6). Less variation was seen when *t*-tests were run on samples split by variety, year, and location. As shown in Table 2, independent samples *t*-tests between the pup loaf bread slice heights of loaves baked with flour from small versus large kernels, split by variety, year, and location, were found to be non-significant for nine out of eighteen tests. Independent samples *t*-tests between the pup loaf bread slice surface area of the same set of loaves was found to be non-significant for thirteen out of eighteen tests, suggesting that in many instances, kernel size does not significantly impact bread baking qualities. The descriptive statistics (mean values and ranges) of the bread slice height and bread slice surface area of the control loaves are shown in Table 4.

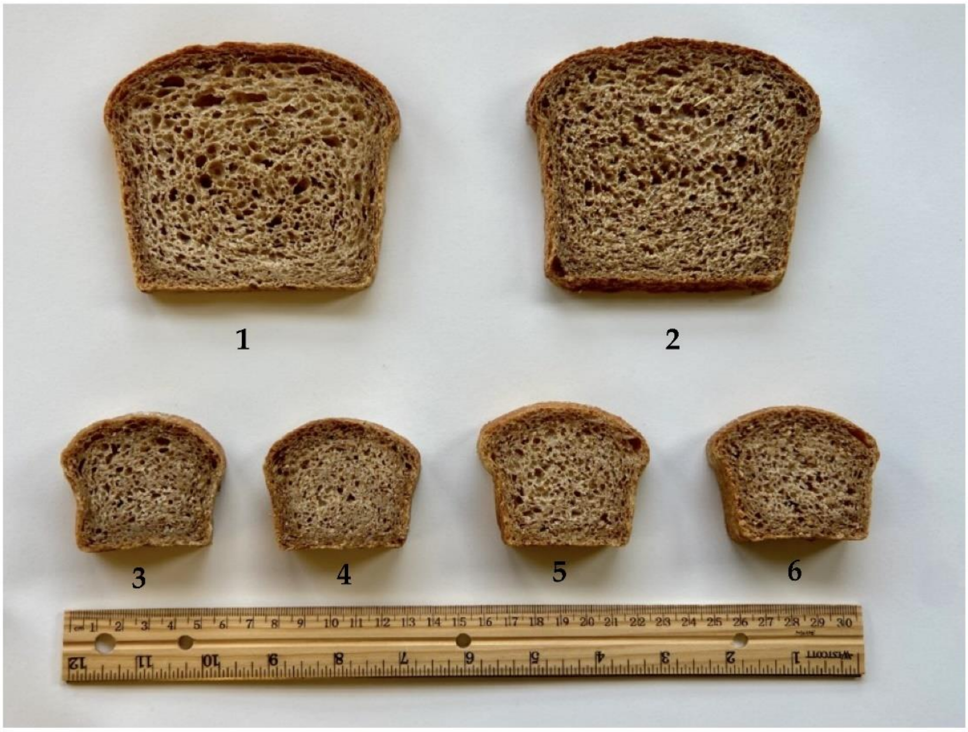

Figure 2. Pup and full-size Approachable Loaf test bakes. Skagit 1109 full-size control loaf (left, **1**) versus rejected small Rouge de Bordeaux wheat from commercial mill (right, **2**); 2020 Le Sourd bigs (**3**); 2020 Le Sourd smalls (**4**); 2020 Red Russian bigs (**5**); and 2020 Red Russian smalls (**6**).

3.3. Protein Content Analysis

Table 5 summarizes the means, standard deviations, and standard errors of the mean for protein adjusted to 15% moisture for all bigs and smalls. The protein of smalls was significantly higher than that of bigs at $p = 0.004$ using an independent samples *t*-test.

3.4. Full-Size Loaf Test-Bake Analysis

To test the theory that small kernels can make good whole-wheat bread in a commercial way, full-size loaves were baked using four samples of small wheats rejected by local mills. This portion of the experiment was not comparing big and small kernels; rather, it was testing the performance of flour made from small kernels with that of flour made from a commercially accepted wheat. Table 6 summarizes the descriptive statistics of the full-size test bakes. The average bread slice loaf height of all mill-reject test bakes was 100.43 ± 4.16 mm ($n = 12$) compared to an average bread slice loaf height of 99.48 ± 1.93 mm in the control loaves ($n = 4$). The mill-reject test-bake bread slice heights ranged from 92.31 to 106.32 mm and the control bread slice heights ranged from 97.63 to 102.19 mm. The mill-reject test-bake bread slice surface areas ranged from 94.14 to 107.78 cm^2 and the control bread slice surface areas ranged from 99.20 to 107.37 cm^2. Figure 2 shows a comparison of a slice of one of the control loaves (#1) and reject Rouge de Bordeaux wheat test loaf (#2). We find both loaves to be visually appealing with a nearly identical crumb.

Table 4. Test-bake pup loaf slice height, and test-bake pup loaf surface area from Skagit 1109 flour as a control.

	Mean ± SD	**Range**
Skagit 1109 Control Bread Slice Height (mm)	55.94 ± 1.54 (0.26)	52.51–58.90
Skagit 1109 Control Bread Slice Surface Area (cm^2)	31.57 ± 1.42(0.24)	29.12–36.09

Mean ± standard deviation (s.e.m.); n = 36.

Table 5. Protein adjusted to 15% moisture between large- and small-sized kernels of all samples tested.

Seed Kernel Size	**Protein (%)**	**Range**
Bigs	9.56 ± 1.28 (0.30) **	7.12–11.86
Smalls	10.78 ± 1.29 (0.30)	8.86–13.35
Effect size (Cohen's d)	0.946	

Mean ± standard deviation (s.e.m.), n = 18; ** p = 0.004.

Table 6. Full-size test bakes with mill rejects from three mills against Skagit 1109 flour as a control.

	Mean ± SD	**Range**
Mill-Reject Bread Slice Height (mm)	100.43 ± 4.16 (1.20)	92.31–106.32
Mill-Reject Bread Slice Surface Area (cm^2)	103.61 ± 6.22 (1.80)	94.14–107.78
Skagit 1109 Control Bread Slice Height (mm)	99.48 ± 1.93 (0.97)	97.63–102.19
Skagit 1109 Control Bread Slice Surface Area (cm^2)	103.48 ± 3.58 (1.79)	99.20–107.37

Mean ± standard deviation (s.e.m.), n = 12 for bakes made with mill rejects from three mills and n = 4 for bakes made with Skagit 1109 flour as control.

4. Discussion

In this study, nine varieties of wheat grown between 2018 and 2021 among five locations across the US states of Washington and Montana, for a total of eighteen samples, were used to compare the percent bran, TKW, percent ash, and baking quality of large and small kernel size within each variety. The data herein provide evidence that small-sized wheat kernels have commercial and nutritional value. The rejection of small kernels is a lost economic opportunity. When these small kernels are rejected at a mill, the price paid for them is greatly diminished as the wheat becomes a secondary product. Rejecting small kernels also results in lost potential for increased nutrient capture. Smalls among every variety and location contain more bran and more ash (Tables 2 and 3); this equates to more dietary fiber, minerals, and vitamins and, thus, more nutrient-dense bread for direct human nourishment [54–56]. Increased minerals and vitamins of note in the bran include iron, calcium, thiamin, riboflavin, niacin, B6, and folate [57]. On average, smalls contained 15.9% more bran than bigs. According to USDA data describing the average chemical composition of wheat bran per 100 g, using smalls instead of bigs to produce flour would equate to an increase of 6.7 g of fiber (42.8 g to 49.6 g), 1.7 mg iron (10.6 mg to 12.3 mg), 11.5 mg calcium (73 mg to 84.5 mg), 1.16 mg Zn (7.3 mg to 8.5 mg), 0.1 mg thiamine (0.5 mg to 0.6 mg), 0.1 mg riboflavin (0.6 mg to 0.7 mg), 2.2 mg niacin (13.6 mg to 15.8 mg), 0.2 mg B6 (1.3 mg to 1.5 mg), and 12.6 ug folate (79 ug to 94.6 ug) per 100 g of kernels milled [57].

An average increase of 6.7 g fiber per 100 g of all smalls (Table 3) is notable given the global fiber intake gap. The increases in iron, calcium, folate, and other B vitamins are also worth noting in relation to the FDA requirements for flour labeled as enriched, which include the fortification of at least 2.9 mg thiamin, 1.8 mg riboflavin, 24 mg niacin, 0.7 mg folic acid, and 20 mg iron per pound of flour (454 g) [58]. Interestingly, fiber is not supplemented into flour labeled as enriched, highlighting the devaluation of this nutrient [58].

The irony of doing this would be powerful, further emphasizing the importance of a shift towards whole-grain uses.

Franz Bread, a popular commercial brand, has 0 g fiber in one slice (30 g) of their *Franz Big White Premium Bread* and 2 g fiber in one slice (43 g) of their *Franz 100% Whole-Wheat Sandwich Bread* [59,60]. Whole-wheat sandwich bread made from flour of the bigs in this study with the least bran (Edison) would be 2.1 g per slice (40 g) and from the smalls with the greatest amount of bran (Eileen) would be 3.4 g fiber in a single slice (40 g).

The highest percent bran of any variety was seen in Eileen grown in 2020 in Chimacum, WA, USA, with smalls measured at an average of 34.3 ± 0.44% bran and bigs measured at an average of 29.57 ± 0.44% bran (Table 2). The second-highest percent bran was seen in Salish Blue grown in 2019 in Mount Vernon, WA, USA, with smalls measured at an average of 33.92 ± 0.21% bran and bigs measured at an average of 27.73 ± 0.74% bran (Table 2). Salish Blue samples were highly diverse "field blends" as opposed to pure Salish Blue, as they contained a mix of pure Salish Blue seed and a mix of hard red winter and other wheat. After sifting, it was noticeable that the bigs sample contained more of the hard red winter wheat and the smalls sample contained a higher amount of pure Salish Blue, which probably also explains the variation in baking performance seen in this line.

Protein content was higher in the smalls of each variety and location when adjusted to 15% moisture (Table 5). This is likely related to the higher amount of bran in the smalls and the proteins formed in the aleurone during grain development. These proteins, by contrast to the glutenins and gliadins (found in the endosperm), include small amounts of every essential amino acid and some non-essential amino acids, all of which contribute to a more nutrient dense food product. Given that the proteins in the bran have been shown to be related to defense functions and oxidative stress [54], future research may explore the effect that climate stress, such as increased heat and drought, has on the beneficial protein content of the wheat bran, which is often overlooked. Bakers have developed a preference for high-protein flours, specifically higher glutenins and gliadins in the endosperm, which are needed for gluten development in bread [56].

Increased fiber intake along with increased intake of whole grains has been repeatedly linked to a decrease in chronic disease [32,37,41,44,48,61]. Researchers analyzed data from 185 prospective studies and 58 clinical trials, amounting to a total of 4635 participants, and found a 15–30% decrease in colorectal cancer, type 2 diabetes, and cardiovascular-related mortality, along with decreased incidence of coronary artery disease, stroke, and mortality in high fiber consumers compared to low fiber consumers [62]. Better health outcomes were associated with a daily fiber intake of 25 to 29 g; however, dose–response curves suggested even greater benefit with an even higher intake [62]. Another meta-analysis published in 2016 examining chronic disease risk and mortality associated with whole-grain consumption had similar findings. They included 45 studies and found an intake of 210–225 g per day of whole grains to be associated with decreased risk of all-cause mortality and cardiovascular disease [32].

Baking with smaller wheat kernels is possible with very slight decreases in baking functionality (Tables 3, 4 and 6). We saw slightly higher loaf volumes with larger kernels (Table 3). This is to be expected and represents an average increase in bread slice height of only about 2.2 mm or 4%, which would equate to about 4 mm less height in a typical grocery-store-style loaf of bread. This variation is acceptable as it is similar to that observed in typical commercial bread production (personal comm. King Arthur Baking Co., Norwich, VT, USA, 2022). The flavor and taste acceptance of whole-grain bread samples was outside the scope of this study; however, this has been extensively studied, and positive acceptance of whole-grain products has been found to be related to education regarding health benefits, availability, and price [63–66]. Moreover, some people even prefer it [67]. We have found it to just taste better [68,69]. In an informal blind taste test among five lab members and one professional baker, small differences in taste between the loaves made with bigs and smalls were detected, but none of the loaves were rated as unacceptable (results not shown). All loaves were seen as "good bread" with no off flavors.

Given the implications of our changing climate and the struggles for growers resulting from climate change, valuing small wheats will make a profound impact on current food system challenges. Valuing small wheats provides a use for a product that is currently sold off as a low-value useable "waste". They reject small kernels because they do not mill as efficiently as large kernels [4]. This rejected wheat is commonly used as hog feed and the argument is that "it is not wasted; it is going to animal feed". However, this wheat was not designed for this use. It was designed for direct human nourishment. Using hog feed as an example, blended and supplemented feed for hogs will add weight gain of consumable meat at a range that declines, as they grow to less than 30% [70]. If wheat sold into the animal feed chain was made into bread, this would produce 100% human food as opposed to food produced at a 30% efficiency. Wheat is developed from the beginning as a crop that would be turned into either white or whole-wheat flour. The agronomics, the cultural practices, and the genetics were all geared towards the crop going to direct human consumption—to develop a feed crop for hogs is something entirely different.

Human consumption and direct human nourishment is more climate friendly than using wheat as animal feed, even when something that is more efficient than hogs such as poultry is considered. In their study on healthy and sustainable diets for the planet, Macdiarmid et al. [71] categorized bread as a Low Greenhouse Gas Emission (<1.0 kg CO_2 e/kg edible weight) food group, chicken as a Medium Greenhouse Gas Emission (1.0–4.0 CO_2 e/kg edible weight) food group, and pork as a High Greenhouse Gas Emission (>4.0 kg CO_2 e/kg edible weight) food group.

Given the increasing heat and drought pressures secondary to climate change and the effects of these pressures on wheat kernel size in the field, as discussed in the introduction, we are likely to see increased amounts of small kernels in farmers' harvests in the coming years. Learning to value smaller wheats is a proactive solution that not only has climate efficiency benefits, but also has human nutrition benefits in terms of fiber and micronutrients.

The utility of wheat commercially rejected as animal feed was shown in our test bakes (Figure 2). We have shown that these breads are also more nutritious, and thus, could provide a higher-value use for wheat that was once destined to be rejected and devalued.

If wheat is destined for whole-wheat uses—which, as argued herein, is better for both human health and for the planet—it will improve the health of consumers, while simultaneously providing value to a farmer's wheat crop and a miller's rejects. The frequency of small kernels in wheat is already increasing in a changing and warming climate. How we choose to deal with them can either harm or help us and the planet.

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