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Addressing the challenges of new decentralized flour mills in alternative agriculture and food systems: a study on grain aging prior to whole wheat milling

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ABSTRACT

Entrepreneurship in grain infrastructure has emerged in the development of new wheat supply chains from farm to market to support alternative agriculture and food systems. This includes the establishment of flour mills with the ability to preserve the identity of small batches of flour, mediate flour quality and safety, and retain processing and value within rural communities. Yet new decentralized flour mills may lack adequate space and environmental controls and refrain from pesticide treatments necessary for long-term grain storage and aging prior to milling. The relationship between grain aging and whole wheat bread baking quality under informal storage conditions was evaluated using factor and multiple regression analyses. The results indicated that aging correlates positively with whole wheat bread baking quality over 1 year of storage. Growing location, growing year and their interaction, however, were better predictors of quality. These results suggest when storage space and environmental controls are limited, blending grain by growing location could be a more effective and practical method to improve quality than grain aging or blending by growing year, which both necessitate long-term storage. Blending by location may strain definitions of regional or local in some alternative systems.

KEYWORDS

Triticum aestivum L.; rheology; wheat quality; differentiated wheat; sustainability

Introduction

Farms, mills, and food producers, such as bakeries, with the aim to differentiate wheat (*Triticum aestivum* L.) systems and products from US and industry standards necessitate identity preservation of grain and flour. Differentiation includes both real and perceived physical and invisible attributes of the product that make it unique when compared to standardized commodities (Magnan 2011; Titus and Dooley 1996). For wheat, differentiation can include variety, nutritional content, flavor or freshness, as well as characteristics otherwise easily obscured such as economic, social, and environmental impacts of production. Differentiation is often a characteristic of

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alternative food systems reflecting differences both on-farm, such as sustainable agronomic practices, and during processing, such as maintaining nutritional characteristics, as compared to dominant industrial standards.

Identity is often preserved through direct-to-consumer markets where the farmer is both producer and seller. "Intermediate," "midscale," or "local" value chains add processing and distribution steps and can increase supply by networking together small and midsized farms (Stevenson et al. 2011) and also increase consumer access by utilizing larger retail outlets such as grocery stores (Bogomolova et al. 2018). However, these value chains often necessitate coordination with new actors and creation of new infrastructure along the supply chain for processing and distribution (Kirschenmann 1995; Stevenson et al. 2011). For wheat products, supply chains span farm production, grain handling and storage, milling, and production by bakers or chefs into an end product that preserves the unique traits introduced at each level, which then requires distribution. Milling is a critical step to transform grain into flour while also mediating quality and safety of the final product. Alternative wheat systems could benefit from mature supply chains that include appropriate milling partners with the ability to support high quality and consistent flour supplies.

The dominant US flour milling industry operates under massive economies of scale with high daily production capacity (greater than an average 454 mt of flour per day per mill) (Kim et al. 2001). In the US, 169-wheat flour milling operations, excluding durum wheat, were reported in 2016 (Grain & Milling Annual Report 2016). Of the total US milling operations, 70 (41%) are multi-facility operations with an average daily capacity of over 454 mt, which classifies them as large operations by production; 73 (43%) operate at a midsized daily capacity of between an average of 45.4 mt and 454 mt; and 26 (15%) are small mills with an average capacity of less than 45.4 mt per day, the smallest category considered (Grain & Milling Annual Report 2016). Based upon total average daily capacity of the industry, rather than number of mills, the majority of US flour is produced by large milling operations; for example, Ardent Mills, the largest milling operation in the US, has a daily capacity across all of its facilities of over 21,800 mt of flour (Grain & Milling Annual Report 2016). The 20 largest US milling operations, 19 with an average daily capacity of over 454 mt, produced 94.7% of US wheat flour as reported in 2016 (Grain & Milling Annual Report 2016).

This large scale of operation allows efficiencies in transportation and production; however, the high capital investment and consolidation of smaller mills create oligopolistic control of the market (Kim et al. 2001). The consolidation of small wheat mills began with the introduction of merchant mills and industrialized roller mills during the mid-19th century (Storck and Teague 1952). In 1840, 23,661 small toll mills were reported; by 1860, 15,781 remained (Storck and Teague 1952). By the 21st century, these small mills were rare: 125 small mills were in operation in 1973, 34 in 1998 (Kim et al. 2001), and 26 in 2016 (Grain & Milling Annual Report 2016). The top three largest milling operations, Ardent Mills, ADM Milling Co, and Grain Craft, held 61% of the total US wheat flour production capacity (78,025,697 kg) in 2016 (Grain & Milling Annual Report 2016). Adding Miller Milling Co, the fourth largest operation, the four-firm concentration ratio for the industry is 67% (compiled from data in the Grain & Milling Annual Report 2016). This high concentration in the wheat flour milling industry allows for oligopolistic control of the characteristics of grain purchased and flour produced and sold on the US wheat market.

Because of its purchasing power and storage capacity within milling facilities and in conjunction with grain elevators, often owned by the same firm (Wilson 1995), the large milling industry can manage large supplies of grain and flour. Grain storage has consolidated similarly, although at lesser magnitude, to the milling industry (e.g., Reynolds 2009; Titus and Dooley 1996; Wilson and Dahl 2014). The consolidation of mills and storage facilities has meant a loss of infrastructure and intact supply chains for regional and smaller scale agricultural and food systems; however, the bulking function of large grain storage and milling facilities makes them difficult partners to achieve small and medium-sized batches of identity preserved differentiated flour. Milling operations decentralized from industry standards and decision-making and with smaller batch size requirements may be more suitable partners in alternative wheat supply chains.

Establishment and operation of new small and midsized mills does not come without challenges. One challenge previously identified is consistent high quality flour production (Hills, Goldberger, and Jones 2013). It is generally accepted that grain aging, or storage of grain for 2 to 3 months prior to milling, or blending the new harvest with the previous season's grain at a rate of 5% to 15% is the best practice to achieve consistent quality flour (Posner and Deyoe 1986; Wang and Flores 1999). Long term managed storage and adequate supplies are both necessary to follow this practice. For new small and midsized mills, adequate farm supply of grain to meet demand and limited storage space and environmental controls can challenge long-term storage. Mills supporting alternative systems may also choose to abstain from structural fumigation or residual pesticide use, which can also limit storage capability if proper alternatives are not put into practice.

Aging of new harvest grain was therefore investigated here as one example of research needed to elucidate large industrial processes for new small and midsized milling operations seeking to form new supply chains in support of alternative agriculture and food systems. Specifically, quality was evaluated for whole wheat bread flour, a differentiated product making up only 5.2% of total flour milled in the US in 2016 (USDA NASS 2017), and for emerging decentralized flour mills.

Grain aging and wheat quality

Storage conditions, particularly temperature and relative humidity; grain condition including starting temperature, moisture content, presence of broken kernels, weed seeds, and immature kernels; processing, such as fumigation, residual pesticide application, drying, and tempering; and the presence of insects or microorganisms influence the effect grain storage will have on quality (Fourar-Belaifa, Fleurat-Lessard, and Bouznad 2011; Nithya et al. 2011; Tipples 1995). Wheat class and variety also can influence the effect of storage (Tipples 1995; Wang and Flores 1999). Under optimal storage conditions oxidative and enzymatic activities of the living seed lead to changes in protein structure, fat, and starch in the grain (Tipples 1995), in addition to changes in milling characteristics, such as particle size (Ephrat and Sinmena 1976), thereby affecting quality. The type of storage available, as well as the time in storage, will impact the quality of wheat grain: Suboptimal storage conditions will be detrimental to quality over time leading to deterioration of the seed competing with any potential benefits from grain aging. Best storage practices include: a grain moisture content of 12% to 13% or less for wheat; grain clean of broken kernels and foreign material; grain temperature controlled to 6.7°C to 9.5°C of the environmental average monthly temperate to a maximum of 10°C to 15.5°C; aeration of grain adjusted to seasonal changes; and integrated pest management including application of insecticide when necessary (McKenzie and Van Fossen 2002; Tipples 1995). Grain aging to improve quality first necessitates controlled storage conditions, primarily temperature and moisture, and sound grain (Wrigley, Gras, and Bason 1994).

Research suggests grain aging improves bread-making quality as observed as increased bread loaf volume, water absorption, disulfide to thiol group ratio, glutenin to gliadin ratio, gas retention, falling number, white flour extraction rate, and flour particle size (reviewed by Wang and Flores 1999). Whereas protein content did not change in most studies (ct. Kibar 2015 where a decrease in crude protein with increased storage time was observed), increases in soluble protein at elevated temperature (Wilkes and Copeland 2008), decreases (Strelec et al. 2010) or increases (Mezei, Sipos, and Győri 2007) in wet gluten, and increases in protein disulfide groups and decreases in thiol groups (Rao, Vakil, and Sreenivasan 1978) have been reported. However, not all studies are in agreement for all trends in quality changes due to storage conditions used (Gonzalez-Torralba et al. 2013), methods of evaluation, and whether seed deterioration occurred warranting continued research. For example, Ephrat and Sinmena (1976) found a decrease in quality based on Zeleny sedimentation value 2 to 3 months post-harvest while Muir, Wallace, and Bushnuk (1973) found a decrease at 8-, 24-, and 41-weeks, and Lukow, White, and Sinha (1995) found a decrease after 180 days. Mezei, Sipos, and Győri (2007) found a decrease in dough strength by 20% to

40% over 129 days at 10°C to 13°C as measured by Alveograph W, while González-Torralba et al. (2013) found an increase in W over 240 days at the specific storage conditions of 30°C and 75% rh and no statistical change at other conditions evaluated (15°C and 55% rh, 15°C and 75% rh, and 30°C and 55% rh). Additionally, quality analyses using bake tests and Farinograph and Alveograph methods to determine the effect of aging have been based on the performance of white flour only.

Aging has also been evaluated for the efficient and maximum production of high-extraction white flour. Posner and Deyoe (1986) determined 14 weeks as the point at which maximum benefits of grain aging are achieved considering the monetary gains of improved flour quality and the cost of storage. This recommendation was based upon the monetary value of milling products obtained on a five-break roller mill with white flour streams of lowest ash content receiving the highest price point. The advice of Posner and Deyoe (1986) is similar to the accepted 2 to 3 months storage practice (Wang and Flores 1999). The recommendation of Posner and Deyoe (1986) did not consider changes in dough and baking characteristics, only the rate of white flour production on a roller mill system. Consideration of whole wheat flour with quality characteristics different from white flour milling criteria, such as extraction rate and ash content, is valid.

Research aim

The aim of the study was to evaluate the relationship between whole wheat bread baking quality and grain aging, measured as time in storage. Additionally, because growing environment is a known contributor to wheat quality (Halverson and Zeleny 1988), growing location, growing year, and the interaction between the two, were included as additional explanatory variables in the analysis. Ambient temperature and relative humidity under controlled building conditions were used, rather than a model of a formal, managed grain elevator or silo, or under refrigeration or freezing, mimicking an informal storage mechanism that may be used by new small and midsized mills and in-bakery mills. The study contributes technical knowledge to the field by addressing grain storage for milling operations that aim to support alternative wheat systems using laboratory equipment not available to producers and end-users at this scale. As milling is a key component of wheat supply chains, acting as buyer, processor, and seller, while connecting farmer to consumer, this focus is a valuable contribution to new wheat supply chains aiming to produce safe, consistent supplies of differentiated high-quality flour in alternative agriculture and food systems.

Materials and methods

Experimental design

The variety 'Edison,' a hard white spring wheat bred by Merrill Lewis and selected at The Bread Lab, Washington State University (WSU), Mount Vernon for its agronomic and whole wheat bread baking attributes specifically for the emerging regional grain economy in western WA was utilized for this study. Edison is popular among growers and bakers in western WA and OR and was used for its relevance to this region.

Edison was grown under conventional dryland management at two locations over two years resulting in four year by location samples of grain. In 2014 and 2015 Edison was grown at the experimental research fields at the Northwest Washington Research and Extension Center (NWREC) at WSU, Mount Vernon, WA and under commercial production on-farm in Junction City, OR in collaboration with farmers Sue and Tom Hunton. Mount Vernon, WA is located in the Skagit Valley west of the Cascade Mountain range. Junction City, OR is located in the Willamette Valley, east of the Oregon Coast Range and west of the Cascade Mountain range. The Skagit Valley is classified as maritime with a cool and wet climate. Annual temperatures in Mount Vernon range from an average minimum of 7.5°C to an average maximum of 23.2°C (WRCC 2016). Average annual precipitation is 822 mm with 114 mm falling between June and August (WRCC 2016). The Willamette Valley experiences hotter and lower precipitation growing seasons, although with available moisture the majority of the year and still moderate temperatures (WRCC 2016). Junction City receives approximately 1142 mm average annual precipitation, 63 mm falling between June and August, and annual temperatures ranging from an average minimum of 0.9°C to an average maximum of 27.9°C (WRCC 2016).

Each year following harvest grain from each location was cleaned using a Carter-Day Dockage Tester (Carter Day International, Inc.) and stored in Kraft ¼ barrel paper storage bags (Uline S-11540) under temperature and relative humidity controlled in an office – laboratory setting. Temperature and relative humidity data were collected using an EasyLog (EL-USB-2-LCD) (Lascar Electronics, Inc.) data logger for the course of the grain storage period. Days in storage were used as a measurement of grain aging.

Data collection

For bread, strong doughs resulting from the quantity and molecular structure of glutenin and gliadin proteins are necessary for dough handling, gas-retention, and risen baked loaves with good crumb and texture (Pomeranz 1988). Production of bread wheat end products is primarily assessed by protein content and strength (Mailhot and Patton 1988). Rheological characteristics were used here as indicators of dough strength. Water absorption, related to protein content and strength, is also important in bread quality as it determines the amount of water the dough can retain for a full loaf (Pomeranz 1988). Enzyme activity, specifically α-amylase, in the grain, along with the presence of damaged starch after milling, influences the availability of starch in the dough for fermentation; excess α-amylase can lead to slack doughs and sticky crumbs in the final product (Kruger and Reed 1988). Therefore, protein content and strength, water absorption, moisture content, and falling number were used as indicators of the effect of grain aging on bread baking quality.

Quality data were collected once a week for the first six weeks, once per month for the following eight months, and once every six weeks for an additional three months, for a total data set covering one year of storage for each year by location sample. Immediately prior to conducting quality analyses, a 1300 g sample of the stored grain was hammer milled with a laboratory mill fit with a 0.5 mm screen (LM 3100, Perten Instruments, Hägersten, Sweden). Flour was homogenized by stirring and shaking prior to measurement and stored in a sealed 4 L polypropylene food storage container throughout data collection. Flour protein and moisture content, falling number, and rheological characteristics were measured on the whole wheat hammer-milled flour. Percent flour protein and moisture content were determined using an infrared reflectance spectrometer on whole wheat flour wet basis (Inframatic 8600 Flour Analyzer, Perten Instruments) in duplicate. Falling number was determined in triplicate with an automatic falling number system (FN 1500, Perten Instruments) corrected to a 14.0% moisture basis, according to AACC method 56–81.03 (AACC International 1999). Falling number is an indicator of α-amylase activity as measured by the resistance of a heated (100°C) flour sample mixed with water to a dropping stir bar (Kruger and Reed 1988).

Rheological characteristics of development time, stability time, and water absorption were assessed using Farinograph assays (Brabender Farinograph-AT, Duisburg, Germany) under the constant flour weight basis in a 300 g bowl according to a modified AACC Method 54–21.02 (AACC International 2011) to use whole wheat flour, in triplicate. Development time is the duration of time from water added to the flour sample to the start of the decline of the torque peak; stability time is the duration the peak of the upper torque line remains above the consistency line; and water absorption is the percent water added to achieve a consistency within the range of 480 to 520 Farinograph Units (FU).

Statistical analysis

All statistical analyses were conducted using R (R Core Team 2017). Principal Component Analysis (PCA) was conducted using "stats" (R Core Team 2017) as a preliminary exploratory tool to assess and visualize the complete dataset and the relationship between the explanatory variable, days in storage, and the response variables (protein content, moisture content, falling number, development time, stability time, and water absorption). "ggbiplot" (Vu 2011) was used to visualize the principal components. A correlation matrix, using "Hmisc" (Harrell 2017), with Pearson's correlation coefficients was used to quantify and statistically evaluate the relationship between response variables.

Pearson's correlation matrix and PCA indicated the response variables were correlated amongst themselves indicating dimensionality of the response space less than six. Following determination of this dependency of response variables, maximum-likelihood factor analysis using varimax rotation was used to produce independent factors. "stats" and "nFactors" (Raiche 2010) were used. "Eigen value of greater than one" and leveling off of the scree plot were used to evaluate the number of factors to retain. To test the null hypothesis, grain aging is not correlated with quality, multiple linear regression analyses were used to predict Thompson's regression scores for each factor based upon the explanatory variables days in storage, growing location, growing year, and the interaction between growing location and year.

Results

In the first year of grain storage conditions ranged from 19.5°C to 25°C, with relative humidity ranging from 15.5% to 63%. In the second year of storage, conditions ranged from 15.5°C to 29.5°C with relative humidity ranging from 21% to 65%. Moisture content of the seed throughout the duration of both years of the study remained between 11.8% and 14.5%. Means, standard deviations, and coefficients of variation for each response variable by growing location and year are presented in Table 1.

PCA revealed seven principal components contributed to the variation in the complete dataset – each response variable, as well as days in storage – for all year by location samples. The first two components resulted in Eigenvalues greater than one and captured 78.2% of the variation in the data (Figure 1). The first component captured 60.4% of the total variation with an Eigenvalue of 4.22 and based upon the loading scores was largely composed of development time (41.8), stability time (45.1), water absorption (42.3), protein content (43.3), and falling number (37.2). Harvested samples of grain clustered in distinct groups along the first principal component by growing location and to a lesser extent year and growing location by year. Principal component 2 captured 17.8% of the total variation with an Eigenvalue of 1.25 and based upon the loading scores was composed of days in storage (72.9) and moisture content (48.3). Variation along this second vector varied positively according to days in storage and inversely with moisture content.

Table 1. Means, standard deviations (SD), and coefficients of variation (CV%) for each quality indicator for growing year by location samples.

	Protein content (%)			Moisture content (%)			Falling number (min)		
	Mean	SD	CV%	Mean	SD	CV%	Mean	SD	CV%
Mount Vernon 2014	11.93	0.23	1.97	12.99	0.78	6.01	350.84	21.58	6.15
Mount Vernon 2015	10.94	0.22	2.03	13.23	0.53	4.02	375.78	25.97	6.91
Junction City 2014	13.00	0.19	1.43	12.97	0.73	5.65	384.13	24.65	6.42
Junction City 2015	13.16	0.10	0.80	12.71	0.42	3.29	418.00	25.00	5.98
	Development time (min)			Stability time (min)			Water absorption (%)		
	Mean	SD	CV%	Mean	SD	CV%	Mean	SD	CV%
Mount Vernon 2014	4.08	0.31	7.58	6.87	0.98	14.34	69.55	1.20	1.73
Mount Vernon 2015	4.74	0.21	4.48	7.58	0.58	7.66	66.89	0.67	1.01
Junction City 2014	6.03	0.39	6.42	11.92	0.86	7.24	71.03	0.95	1.34
Junction City 2015	5.97	0.34	5.54	12.83	0.75	5.81	71.30	0.65	0.91

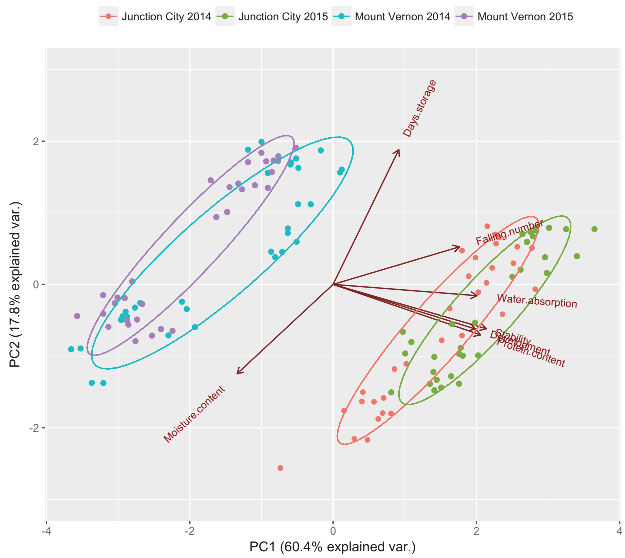

Figure 1. Grain aging exploratory analysis using principal component analysis. All six response variables and the explanatory variable, days in storage, were used in the analysis. The first two principal components, contributing 78.2% of the variance in the dataset and with Eigen values greater than 1, are presented. Ellipses for each growing location by year environment are 68% confidence intervals.

Pearson's correlation matrix (Table 2) confirmed significant correlations between response variables. All correlations were positive, with the exception of those with moisture content, and were statistically significant ($p < .005$). The strongest correlations were between development and stability time, water absorption and protein content, protein content and stability time, protein content and development time, water absorption and stability time, and stability time and falling number. Due to these strong correlations between

Table 2. Pearson's correlation coefficients between response variables (n = 127, $p < .005$).

	Development time	Stability time	Water absorption	Protein content	Moisture content	Falling number
Development time	1	0.92	0.62	0.74	−0.28	0.65
Stability time	0.92	1	0.73	0.85	−0.32	0.71
Water absorption	0.62	0.73	1	0.92	−0.62	0.43
Protein content	0.74	0.85	0.92	1	−0.38	0.51
Moisture content	−0.28	−0.32	−0.62	−0.38	1	−0.38
Falling number	0.65	0.71	0.43	0.51	−0.38	1

variables factor analysis was used to reduce the response variables to independent factors.

Factor analysis suggested a reduction of the six response variables to two independent factors. Factor 1 explained 45% of the variation among the response variables with an Eigenvalue of 4.10 (Table 3). Based upon the factor loadings, development time, stability time, falling number, and protein content were the major contributors (>0.60) for Factor 1. Factor 2, with an Eigenvalue approaching one, explained an additional 33% of variation, with water absorption, protein content, and moisture content contributing the largest loadings (>0.60) (Table 3). Moisture content had an inverse relationship with protein content and water absorption. Variables contributing to each factor in the analysis were supported by the PCA. A scree plot supported between two and four factors based upon the slope of the plot; however, factors three and four had Eigenvalues of only 0.65 and 0.24, respectively. Additionally, with only six response variables, a greater number of factors reduces the summarizing function of the analysis and the degree of independence that is maintained. Therefore, two factors were chosen capturing 78% of the variation in the data.

Multiple regression analysis of scores from Factor 1 with the explanatory variables days in storage, growing location, growing year, and the interaction

Table 3. Factor loadings for each response variable given two factors. SS (sum of squared) loadings, proportion variation for each factor, and cumulative variation for both factors are presented. Loadings bolded are considered the major contributors of that factor.

	Factor 1	Factor 2
Development time	**0.88**	
Stability time	**0.93**	0.37
Falling number	**0.71**	
Water absorption	0.43	**0.90**
Protein content	**0.63**	**0.72**
Moisture content		**−0.64**
SS loadings	2.73	1.97
Proportion variation	0.45	0.33
Cumulative variation	0.45	0.78
Eigenvalue	4.10	0.93

between growing location and year were highly correlated and significant ($R^2 = 0.905$, $p < .0001$) (Table 4). For days in storage, the primary explanatory variable under consideration, the relationship with Factor 1 was positive ($B = 0.001$, $p < .0001$) given growing location, growing year, and the interaction between growing location and year. The predictive ability of the remaining explanatory variables was also significant and of higher magnitude than days in storage considering the interpretation of the units for each coefficient.

Multiple regression analysis of scores from Factor 2 with days in storage, growing location, growing year, and the interaction between growing location and year were also correlated and significant ($R^2 = 0.729$, $p < .0001$) (Table 4); however, the model fit is lower than the regression model for Factor 1 with a greater proportion of unexplained variation. Days in storage were positively correlated with Factor 2 ($B = 0.002$, $p = .0002$) given growing location, growing year, and the interaction between growing location and year. The estimates for growing location and year were not significant; however, the interaction between these two variables was and its predictive capability for Factor 2 was of a larger magnitude than days in storage, again considering the units for each variable. Days in storage and quality were non-linearly correlated in Factor 2. Modeling of this relationship, rather than testing the correlation of storage and quality as in this study, requires further statistical analysis.

Discussion

In the present study, six parameters were used as indicators of quality for the production of consistent high quality whole wheat bread flour for new small and midsized mills and in-bakery mills seeking to preserve differentiated wheat products. These six parameters – protein content, moisture content, falling number, development time, stability time, and water absorption – were used to evaluate the relationship between grain aging and whole wheat

Table 4. Results of the multiple regression analyses of Factors 1 and 2 with the explanatory variables serving as predictors. Explanatory variables included in the model are: days in storage, growing location, growing year, and the year by location interaction term.

	Factor 1[a]		Factor 2[b]	
Predictor	*B*	*SE*	*B*	*SE*
Intercept	0.502***	0.066	0.235*	0.111
Growing location (Mount Vernon)	−2.013***	0.079	0.132ns	0.133
Growing year (2015)	0.401***	0.079	−0.054ns	0.133
Days in storage	0.001***	0.0003	0.002**	0.0004
Growing location x year (Mount Vernon 2015)	0.670***	0.111	−1.943***	0.187

Note: *B* is the unstandardized coefficient; *SE* is the standard error.
[a] Factor 1: $R^2 = 0.905$, $F(4,122) = 289.6$, $p < .0001$
[b] Factor 2: $R^2 = 0.729$, $F(4,122) = 82.09$, $p < .0001$
* $p < .05$, ** $p < .001$, *** $p < .0001$, ns is non-significant at $p > .05$

bread baking quality. As the genetic component of the study was held constant with the use of one variety, days in storage, growing location, and growing year, and the interaction between location and year were the *a priori* explanatory variables for the study.

That the six measured response variables were not independent was not unexpected. Development time, stability time, and water absorption are indicative of the mixing behavior of a dough, influenced by protein content and structure, among other factors. Protein content and dough mixing behavior are expected to co-vary. Protein content is a measurement of the organic nitrogen content in the grain (Mailhot and Patton 1988) and depends upon the environmental conditions and field management of the crop (Halverson and Zeleny 1988); genotype is less influential on protein content than environmental conditions and field management. Dough strength is influenced by the specific molecular structure of the glutenin and gliadin proteins, which is under genetic control and held constant here, with little or no impact due to environment and management (Wrigley and Bietz 1988). The correlation suggests changes in mixing behavior due to protein content or changes in protein structure during storage (e.g., Gonzalez-Torralba et al. 2013; Rao, Vakil, and Sreenivasan 1978). Falling number has previously been correlated with changes in rheological tests, specifically development time and mechanical tolerance index, as well as water absorption (Kruger and Reed 1988; cf. Kibar 2015), confirming results reported here. However, this relationship is not necessarily causative. That protein content, development time, stability time, and falling number were included into a single independent factor, Factor 1, representing overall bread baking quality is appropriate and meaningful.

Water absorption, moisture content, and protein content were the major variables contributing to Factor 2. Protein content and water absorption are known direct correlates: 1 kg of dry protein absorbs 1 to 3 kg of water (Bloksma and Bushuk 1988). That protein content was considered a component of both Factor 1 and 2 is not redundant. As discussed, the variation in Factor 1 contributed by protein content can be understood as the proportion of protein content that co-varies with development time and stability time. In Factor 2, the variation in protein content could be understood as that varying with changes in moisture content of the grain; protein measurements were taken in the sample's stored state following milling rather than on a constant moisture basis (for example, Delwiche 1995). In Factor 2 the proportion of variation in protein content as related to moisture content is therefore not a real change in protein content, only as relative to changing moisture content. Future analysis could benefit from testing the daily storage conditions, rather than days treated as invariable, against the response variables or by including moisture as an *a priori* explanatory variable in the regression analysis. This hypothesis is supported by the

PCA and previous studies. Factor 2 could then be understood to reflect changes in quality due to changing environmental factors such as temperature and relative humidity that varied throughout the storage period, rather than storage time *per se*.

Although individual response variables were not evaluated statistically, comparison of variable trends with previous studies both support and conflict with the trends observed here. Kibar (2015) found a decrease in protein content, fluctuation in moisture content by season, and an increase in falling number over 120 days storage in wheat silos. After 15 months of storage in cotton bags in an unheated barn, Lukow, White, and Sinha (1995) observed a change in seed moisture with relative humidity, constant protein content, increased falling number, increased stability time for one of the two varieties evaluated, and constant development time. Over 270 days of storage in glass desiccators placed in growth chambers set to multiple temperature and relative humidity regimes, Gonzalez-Torralba et al. (2013) observed increased falling number, decreased Alveograph W (dough strength), and increased glutenin and gliadin content. Again, the body of work and this current study confirm the effect of grain aging is influenced by experimental design. However, analyzing the variables as reduced independent factors of quality support earlier research and accumulated knowledge that overall suggests safe storage improves the bread baking quality of newly harvested wheat (reviewed by Wang and Flores 1999), but that results are unimpressive (Shellenberger 1939) and dependent upon environmental conditions, such as temperature, relative humidity, and presence of pests (Fourar-Belaifa, Fleurat-Lessard, and Bouznad 2011; Gonzalez-Torralba et al. 2013).

The study showed a significant correlation between grain aging, measured as time in storage, and whole wheat quality given growing location, growing year, and the interaction between growing location and year as determined by reduction of the data to two independent factors. For both factors, under a simple storage system of paper storage sacks held in a temperature controlled building, quality increased with increased time in storage. However, given the number of days required to improve quality to the degree of utilizing explanatory variables of growing location, year, and their interaction, there is not strong evidence from the current study that grain aging should be prioritized over or before these other methods of quality improvement. Growing location, growing year, and the specific location and year combination, were better predictors of wheat quality, than was days in storage for Factor 1. For Factor 2, the growing location and year combination was a better predictor than days in storage, which may represent the moisture content of the seed at harvest. These results suggest the starting quality of a sample following harvest contributes to quality more than that gained during grain aging. Factor 2 also suggests that seasonal changes in temperature and relative humidity throughout storage impact quality by influencing the moisture content of the grain. For new small and midsized mills and in-bakery mills without infrastructure for long-term storage or the environmental controls to prevent seed deterioration, the potential benefit for storing grain long term is not large enough to risk detrimental effects of grain aging.

Acquiring the ability to source grain from multiple locations with variation in environment, such as precipitation or lack of, or management, such as fertilization treatment (Halverson and Zeleny 1988), could assist in the improvement of wheat quality at a magnitude greater than will aging. For example, blending grain sourced from Junction City, OR could improve the quality of Mount Vernon, WA sourced wheat, per the parameters evaluated here, with a greater impact than grain aging at the recommended 2 to 3 months. Blending across locations could pose a challenge to wheat supply chains aiming to differentiate through place-based agriculture and food production with strictly defined parameters of regional or local. However, blending by location to meet end-user preferences can improve consistency in quality and decrease risk along the supply chain that results from inclement weather and failed crops, leading to low quality and supply. Monitoring and management of moisture content of the grain post harvest can also assist in quality consistency. Blending by year is also supported by this study, again a known variable of wheat quality, but requires long-term storage.

Understanding the relationship between storage of wheat grain and quality is necessary for new millers to evaluate whether aging is necessary for their scale of operation. Changes expected with storage can then be utilized, corrected, or communicated to consumers. As new infrastructure and alternative wheat value chains mature, the addition of economic analyses can assist in decision making for appropriate infrastructure and management practices based upon the expected return on investment. Time in storage, environmental conditions, size of stored bulk samples (Fourar-Belaifa, Fleurat-Lessard, and Bouznad 2011), pest control, and food safety need to be taken into consideration and would expand upon the results here. For whole wheat flour, mill type and resulting particle size (Doblado-Maldonado et al. 2012) could also be considered. A benefit-risk analysis of foregoing enrichment of white flour is also an area of investigation as observation suggests many alternative mills and bakeries sell unenriched refined wheat products.

Transformations in agriculture and food systems as envisioned by sustainable and alternative food movements in part depend upon the success and sustainability of new supply chains that preserve the identity, process, and equitably distribute these products to consumer bases (Kirschenmann et al. 2008; Stevenson et al. 2011; Stevenson and Pirog 2008). Continued research to identify and support new and diverse actors along these chains, including underlying social, environmental, and economic aims and challenges, will contribute to this effort (Stevenson and Pirog 2008; Swisher, Ruiz-Menjivar, and Koenig 2018).

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