2006 Progress Report: Organic Cropping Research for the Northwest

Evaluating and developing wheat varieties for organic systems

Principal Investigator:
Dr. Stephen Jones, Dept of Crop and Soil Science
Washington State University, Pullman, WA. 509-335-5462, joness@wsu.edu

Cooperators:
Blair Goates, USDA-ARS, National Small Grains Germplasm Research, Aberdeen, ID
Dr. Phillip Reeves, USDA-ARS, Grand Forks Human Nutrition Center, Grand Forks, ND
Kevin Murphy, PhD student, WSU Pullman, WA

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Abstract:
Consumer demand regarding the impacts of conventional agriculture on the environment and human health have spurred the growth of organic farming systems; however, organic agriculture is often criticized as low-yielding and unable to produce enough food to supply the world's population. Using wheat as a model crop species, we show that poorly adapted varieties are partially responsible for the lower yields often found in organic farming systems when compared with conventional farming systems (Tables 1 and 2). Our results demonstrate that the highest yielding soft white winter wheat genotypes in conventional systems are not the highest yielding genotypes in organic systems (Figures 1 and 2). This indicates that increasing yield in organic systems through breeding will require selection within organic systems. If improving quality through test weight is the primary objective of a breeding program, however, then genotypes can reliably be selected in conventional systems. With crop varieties bred in and adapted to the unique conditions inherent in organic systems, organic agriculture will be better able to realize its full potential as a high-yielding alternative to conventional agriculture. Our research continues to identify the traits most responsible for high yields and enhanced nutrition in organic systems. In our third year of field evaluations of historical and modern wheat varieties, we identified varieties that 1) yield well under organic conditions; 2) contain weed suppression and weed tolerance traits; 3) contain high levels of micronutrients and; 4) are resistant or moderately resistant to the current race(s) of stripe rust and dwarf bunt. It is our objective to select for these traits each generation in the field as we develop varieties uniquely suited to organic farming systems. In our breeding program, we work closely with farmers in an evolutionary-participatory breeding project, where the farmers will begin to develop their own varieties. These varieties will be optimally adapted to their system of farming. We are continuing to evaluate and identify advanced breeding lines that do particularly well in organic systems in an effort to release wheat varieties for organic farmers.

Objectives:
Our objectives for the 2006 year emphasized evaluating wheat varieties for traits that will optimize organic wheat production in Washington state by increasing yield and disease resistance and improving end-use quality, disease and nutritional content. These objectives include:

1. Evaluate historical wheat varieties for their ability to suppress weeds, their ability to yield well in organic fields and their ability to yield well under different tillage systems.
2. Evaluate historical varieties and advanced breeding lines for end-use quality traits and micronutrient content.
3. Evaluate historical varieties and advanced breeding lines for resistance to stripe rust and dwarf bunt.
4. Continue our farmer participatory breeding project with organic and low-input conventional farmers in the varietal development process on their own farms.
5. Evaluate advanced breeding lines and modern cultivars for yield and test weight under organic production conditions.
6. Incorporate the traits for long coleoptile and emergence from deep planting in our modern wheat varieties.

Procedures:
Objective 1: We grew 63 spring wheat varieties (56 historical and 7 modern) in a randomized, replicated split-plot field trial. Yield was taken for each variety in two types of cultivation systems (no-cultivation and rotary harrow used four times). In addition, weed biomass (g/plot of dry weight) was taken for each variety at the end of the season before harvest. This gave us an indication of weed suppression ability of the varieties. The results of this three year field trial are currently being analyzed and will be submitted for publication in 2007.

Objective 2: We evaluated historical soft white, hard red and hard white spring and winter wheat varieties for several traits important to overall quality and marketability. Baking and milling tests are performed on all wheats from the organic fields. Full evaluation of bread, cookie, cake and noodles are done at the USDA Western Wheat Quality Laboratory in Pullman, WA. In addition, we collaborated with Dr. Phil Reeves to analyze the micronutrient content of seven different minerals in each variety. Results from this study are shown in Tables 3, 4, 5 and 6 and Figures 3, 4 and 5.

Objective 3: We evaluated all of our varieties and breeding lines in the organic nurseries for resistance to stripe rust. Rust resistance was scored as a percentage of the plant leaf area infected in a plot, from visual inspection. In addition, we sent 70 lines from our advanced soft white wheat breeding nursery to Dr. Goates in Aberdeen, ID to test for resistance to dwarf bunt. Bunt is currently controlled by fungicidal seed treatments not allowed for certified organic production. Results from this experiment can be found in Table 7.

Objective 4: At Spillman Farm in Pullman, we grew out unselected, early generation populations from crosses designed specifically for our cooperating farmers. These populations were harvested in bulk and a subsample replanted on the fields of four farmer cooperators. These populations will now be pressured by both natural selection and farmer assisted selection and develop into genetically diverse landraces highly adapted to the farming systems and agroenvironments of the farmers.

Objective 5: Our advanced breeding lines and modern checks were evaluated in four locations for yield and test weight. These are randomized complete block design experiments, with four replicates for each genotype. The highest yielding breeding lines, with good quality and test weight will be advanced in each location for further evaluation next year. These lines are the most likely candidates for varietal release specifically for organic farms in the near future.

Objective 6: To determine the gene action, transmission and response to selection of the gene(s) responsible for coleoptile length in wheat, we are conducting a diallel study of 7 winter wheat varieties with a range of coleoptile lengths. This year we obtained the final results from the parents and F_1 through F_4 populations. These results are currently being analyzed and will be submitted for publication in 2007. In addition, we are conducting field trials at the Dryland Research Station in Lind with populations derived from crosses of modern varieties to historical long coleoptile cultivars. These populations are subjected to pressures of deep planting and soil crusting, and natural selection determines the best emerging plants and these plants make up the population replanted the next year.

Progress Toward Objectives:

In 2006 we completed a study that identified wheat varieties with high levels of mineral nutrients. We evaluated sixty-three historical and modern wheat varieties for grain yield and mineral nutrient content of calcium, copper, iron, magnesium, manganese, phosphorus, selenium, and zinc. Our results indicated that while grain yield has increased, mineral nutrient content has decreased significantly in modern varieties for all minerals except calcium. The decrease in mineral content over time is found primarily in the soft white wheat market class, while the hard red market class has remained largely constant. This indicates that plant breeders, through selection of low ash content in soft white wheat varieties, have contributed to the decreased mineral nutrient in modern wheat cultivars. A genetically based, biological trade-off for yield / mineral content does not appear to exist and plant breeders should be able to increase mineral content in modern varieties through use of genetic variation present in historical varieties without negatively affecting yield. Our results show that modern wheat varieties require increased consumption of whole wheat bread to achieve the same percentage of the recommended dietary allowance (RDA) levels attainable by historical varieties high in mineral content. Results from this study are shown in Tables 3, 4, 5 and 6 and Figures 3, 4 and 5.

From our results suggesting that the highest yielding varieties in conventional systems are not the highest yielding varieties in organic systems (See Figures 1 and 2, Tables 1 and 2), we continued to evaluate varieties for weed competition and disease resistance (Table 7) in an effort to identify the traits most responsible for yield in organic systems. We have striven to work with farmers in the development of varieties suited to their agroecosystem. This is a long-term objective, however the first steps in this project are in place. We have identified historical wheat cultivars with excellent quality characteristics (and many more with poor quality characteristics), and included these cultivars in our crossing scheme. We are getting closer to understanding the gene action and response to selection of the gene(s) responsible for long coleoptile in wheat. In an effort to expand our research in low rainfall regions of Washington State, we successfully transitioned four acres to certified organic at the Lind Dryland Research Station.

Outputs

Publications:

Murphy, K., S. Lyon, S. Jones (2006). Low-input wheat breeding. Wheat Life, February, 2006.

Presentations and Field Days:

Murphy, K., P. Reeves, S. Jones (2006). International Plant Breeding Symposium: Breeding for Enhanced Mineral Nutrient Content in Wheat. Mexico City, Mexico.

Jones, S., S. Lyon, K. Murphy, J. Dawson (2006). Spillman Farm Field Day, Pullman, WA.

Jones, S., S. Lyon, K. Murphy, J. Dawson (2006). Lind Dryland Research Farm Field Day, Lind, WA.

Dawson, J., K. Murphy, S. Jones (2006). Proceedings of the ECO-PB Workshop: "Participatory Plant Breeding: Relevance for Organic Agriculture?" Evolutionary Participatory Wheat Breeding in Washington State (US). La Besse, France.

Murphy, K., Jones, S. (2006). Symposium on Sustainable Agriculture, Communities, and Environments in the Pacific Northwest: Participatory Wheat Breeding in the Pacific Northwest. Richland, WA.

Impact

Breeding is a long-term process and any impact is yet to be determined.

Institution/State: Dept. of Crop and Soil Sciences, Washington State University, WA

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Appendix

Table 1. Differences in yield between organic and conventional systems. Mean yield (grams/3.5m^2), number of observations (N), P-value for genotype by system interaction (G x S) with degrees of freedom (df), Spearman's rank correlation coefficient for yield (R_S Yield) measured in paired organic/conventional experiments with 35 soft white winter wheat genotypes at each of five locations. ** = significant rank correlation at P < 0.001. This table shows that the highest yielding breeding lines in organic systems are not the highest yielding lines in conventional systems and that system (organic or conventional) has a significant effect on the yield of wheat lines.

Location	***System***	***Yield***	***N***	***G x S (df)***	***R_S Yield***
1	Organic	956	140	<0.0001 (34)	-0.03
	Conventional	1530	140		
2	Organic	2028	140	0.1435 (34)	0.26
	Conventional	2400	140		
3	Organic	1058	140	0.0092 (34)	0.08
	Conventional	2668	140		
4	Organic	2105	130	0.0007 (34)	0.11
	Conventional	2068	140		
5	Organic	1850	130	<0.0001 (34)	0.79**
	Conventional	1952	140		
Mean	**Organic**	**1599**	**680**	----	----
	Conventional	**2124**	**700**		

Table 2. Differences in test weight between organic and conventional systems. Mean test weight (TW) (grams/400ml), number of observations (N), P-value for genotype by system interaction (G x S) with degrees of freedom (df), Spearman's rank correlation coefficient for test weight (R_S TW) measured in paired organic/conventional experiments with 35 soft white winter wheat genotypes at each of five locations. * = significant rank correlation at P < 0.05; ** = significant rank correlation at P < 0.001. This table shows that while significant genotype x system interactions do occur, there is no significant changes in rank for test weight. This indicates that if selection for improved test weight were the primary goal in the development of organic wheat varieties, a separate breeding program would not be necessary.

Location	***System***	***TW***	***N***	***G x S (df)***	***R_S TW***
1	Organic	422	140	0.0004 (34)	0.60*
	Conventional	441	140		
2	Organic	425	140	0.264 (34)	0.75**
	Conventional	427	140		
3	Organic	424	140	<0.0001 (34)	0.56*
	Conventional	435	140		
4	Organic	425	130	0.0007 (34)	0.85**
	Conventional	422	140		
5	Organic	428	130	<0.0001 (34)	0.61*
	Conventional	420	140		
Mean	**Organic**	**425**	**680**	**----**	**----**
	Conventional	**429**	**700**		

Table 3. Mineral content in historical and modern wheat varieties. Mineral content is given in mg/kg dry weight ± standard error for all minerals except Se, which is given in ug/kg. *, **, ***: P < 0.05, 0.01 and 0.0001, respectively. Ns = not significant. The 95% confidence interval for the grain yield/mineral content correlation is shown in parentheses. This table shows that historical wheat varieties are generally higher in mineral content (not significant for Ca) than modern wheat varieties. It also shows negative yield/mineral content correlations for all minerals except Fe and Se.

Mineral	**Mineral Content**			***Grain Yield/Mineral Correlation***
	Historical (1842-1965)	**Modern (2003)**	**% Change**	
Ca	421.58 ± 10.90	398.49 ± 16.12	- 6	-0.43 (-0.49, -0.32) *
Cu	4.76 ± 0.13	4.10 ± 0.23	- 16 ***	-0.46 (-0.51, -0.34) *
Fe	35.73 ± 1.00	32.31 ± 1.75	- 11 **	0.01 (-0.09, +0.11) ns
Mg	1402.62 ± 21.01	1307.6 ± 25.63	- 7 ***	-0.36 (-0.43, -0.25) *
Mn	49.98 ± 1.22	46.75 ± 3.14	- 7 *	-0.38 (-0.45, -0.27) *
P	3797.08 ± 55.65	3492.7 ± 119.25	- 9 ***	-0.25 (-0.34, -0.14) *
Se	16.17 ± 1.74	10.75 ± 2.73	- 50 *	-0.08 (-0.18, +0.03) ns
Zn	33.85 ± 0.92	27.18 ± 1.88	- 25 ***	-0.60 (-0.61 ,-0.45) *

Table 4. Variety name, market class (M.C.), place of origin, release date or year variety was introduced to the Pacific Northwest, USA (year), grain yield (kg/ha), Ca content (mg/kg) and Cu content (mg/kg) of all spring wheat varieties used in this study. Varieties in bold were designated as 'modern' for this study; all other varieties designated 'historical'. SW = Soft White, SR = Soft Red, HR = Hard Red, HW = Hard White. All values are ± s.e.m. This table (along with Table 5) will be valuable to breeders interested in selecting for high mineral content of specific nutrients while keeping yield potential as high as possible in the parents of potential crosses.

Variety	*M.C.*	*Origin*	*Year*	*Grain Yield*	*Ca*	*Cu*
Allen	SW	WA, USA	1900	1448±187	374±9	4.9±0.2
Alpowa	**SW**	**WA, USA**	**1994**	**1779±156**	**372±11**	**3.8±0.1**
Awned Onas	SW	CA, USA	1950	860±277	458±22	4.3±0.3
Baart 46	SW	CA, USA	1948	971±161	375±21	4.8±0.3
Beaver	SW	WA, USA	1965	1555±227	361±8	3.7±0.3
Big Club	SW	Chile	1870	759±247	494±17	4.3±0.3
Bluechaff Club	SW	OR, USA	1894	533±139	488±42	5.7±0.4
Bunyip	SW	Australia	1914	826±102	422±13	4.9±0.2
Cadet	HR	ND, USA	1946	1648±185	341±7	5.1±0.1
Canadian Red	HW	CA, USA	1919	1615±163	371±6	4.2±0.1
Canus	HR	Canada	1934	1934±321	471±5	4.3±0.1
Ceres	HR	ND, USA	1926	1033±111	453±21	5.1±0.4
Comet	HR	MT, USA	1940	1288±244	413±11	4.3±0.2
Currawa	SW	Australia	1916	1332±261	313±20	3.8±0.1
Dicklow	SW	ID, USA	1912	819±192	506±33	5.2±0.5
Federation	SW	Australia	1914	842±216	512±26	5.0±0.3
Federation 67	SW	ID, USA	1967	1057±210	440±7	4.6±0.1
Flomar	HW	WA, USA	1933	1360±138	414±11	3.9±0.1
Galgalos	SW	Russia	1903	1449±84	339±9	4.2±0.1
Gypsum	SW	CO, USA	1912	762±164	429±3	5.2±0.1
Hard Federation	HW	Australia	1915	1214±280	358±21	4.9±0.1
Henry	HR	WI, USA	1944	1106±181	366±13	4.7±0.2
Hope	HR	SD, USA	1927	1516±148	349±12	4.3±0.1
Hybrid 123	SR	WA, USA	1907	406±71	515±22	4.5±0.3
Hybrid 143	SW	WA, USA	1907	542±104	519±40	4.7±0.3
Hybrid 63	SW	WA, USA	1907	338±24	467±16	5.0±0.2
Hyper	SW	WA, USA	1929	1491±110	474±40	5.5±0.4
Idaed	SW	CA, USA	1938	1489±282	345±11	4.4±0.1
Idaed 59	SW	ID, USA	1962	1452±232	479±2	5.5±0.1
Indian	SW	UT, USA	1917	1266±165	370±14	5.2±0.2
Komar	HR	ND, USA	1930	1106±249	471±15	4.4±0.2
Ladoga	HR	Russia	1888	1401±100	385±11	4.4±0.1
Lemhi	SW	ID, USA	1939	618±270	560±36	7.2±0.6
Lemhi 66	SW	ID, USA	1966	980±314	531±31	6.4±0.5
Little Club	SW	OR, USA	1914	449±109	568±33	5.3±0.1
Mackey	SW	ID, USA	1906	1029±175	483±11	5.8±0.2
Marquis	HR	OT, Canada	1911	1199±136	380±12	3.9±0.1

New Zealand	SW	France	1890	726±59	387±15	5.7±0.2
Onas	SW	Australia	1918	1043±268	392±5	5.0±0.3
Oregon Zimmerman	SW	OR, USA	1921	1071±178	365±10	5.5±0.2
Pacific Bluestem	SW	Australia	1882	569±141	440±33	5.2±0.4
Penawawa	**SW**	**WA, USA**	**1985**	**1282±285**	**454±12**	**3.8±0.1**
Pilcraw	SW	CA, USA	1917	331±93	433±16	5.4±0.4
Red Bobs	HR	SA, Canada	1918	1387±158	298±11	3.5±0.1
Red Fife	SR	Galacia	1842	352±86	398±12	4.5±0.1
Reliance	HR	MT, USA	1926	1472±162	387±5	3.6±0.1
Reward	HR	ON, Canada	1917	1207±130	371±20	4.7±0.2
Rink	SW	OR, USA	1909	1357±143	398±7	5.2±0.1
Rival	HR	ND, USA	1939	1007±70	401±25	5.3±0.2
Ruby	HR	ON, Canada	1917	1637±262	338±19	3.8±0.1
Scarlet	**HR**	**WA, USA**	**1999**	**1619±244**	**387±10**	**4.0±0.1**
Sea Island	HR	CO, USA	1890	1096±117	490±16	4.2±0.1
Sonora	SW	Mexico	1907	1473±160	442±28	4.6±0.2
Spinkota	HR	SD, USA	1944	2033±101	288±35	3.4±0.2
Supreme	HR	SA, Canada	1922	1200±137	346±14	3.8±0.1
Surprise	SW	VT, USA	1870	578±124	478±43	5.6±0.4
Thatcher	HR	MN, USA	1934	1440±150	396±10	4.4±0.1
Wakanz	**SW**	**WA, USA**	**1987**	**1802±263**	**428±8**	**4.1±0.1**
Wawawai	**SW**	**WA, USA**	**1994**	**2212±222**	**339±3**	**4.2±0.1**
Westbred Express	**HR**	**WA, USA**	**1991**	**1732±160**	**414±13**	**4.9±0.5**
White Federation	SW	Australia	1916	944±213	454±17	4.2±0.3
White Marquis	HW	MN, USA	1923	1678±175	441±18	4.3±0.1
Zak	**SW**	**WA, USA**	**2000**	**1928±224**	**395±8**	**3.9±0.1**

Table 5. Fe, Mg, Mn, P, Se and Zn content levels for each variety. Results are in mg/kg, except for Se (µg /kg). Varieties in bold were designated as 'modern' for this study; all other varieties designated 'historical'. All values are ± s.e.m.

Variety	***Fe***	***Mg***	***Mn***	***P***	***Se***	***Zn***
Allen	42.0±2.0	1582±46	52±3.6	4323±92	20±3.5	37±2.9
Alpowa	**31.0±1.3**	**1303±19**	**39±3.1**	**3391±55**	**11±2.5**	**24±1.2**
Awned Onas	31.1±1.5	1415±46	50±2.7	3383±103	25±7.4	31±2.7
Baart 46	37.5±2.0	1489±63	47±3.4	3943±167	22±7.3	32±3.1
Beaver	29.6±1.2	1349±34	47±3.1	3549±101	20±5.6	30±1.8
Big Club	37.9±2.4	1518±46	52±2.9	4306±142	25±6.5	37±2.9
Bluechaff Club	35.5±1.7	1552±90	48±6.2	4329±238	17±4.3	40±6.1
Bunyip	40.7±4.6	1524±24	62±5.1	3895±33	19±3.7	35±2.2
Cadet	34.1±0.8	1531±33	55±5.2	4026±121	15±4.5	37±2.2
Canadian Red	36.4±3.4	1280±28	50±1.5	3421±67	13±3.4	33±0.8
Canus	36.5±0.7	1358±16	51±3.0	3804±44	15±4.0	34±1.1
Ceres	28.8±0.7	1430±30	60±2.9	3989±103	20±6.8	33±2.4
Comet	36.1±1.8	1366±6	54±4.0	3738±30	13±3.1	35±2.0
Currawa	32.3±2.8	1168±42	40±1.1	3092±139	17±4.5	23±0.6
Dicklow	32.5±1.0	1384±50	48±3.5	3628±179	23±5.9	38±5.3
Federation	35.0±2.3	1574±93	58±3.9	3685±132	15±4.4	37±3.3
Federation 67	33.2±2.5	1394±31	51±1.8	3351±149	16±4.0	32±1.5
Flomar	34.6±3.5	1355±29	49±1.8	3613±82	14±4.1	32±0.5
Galgalos	36.7±3.2	1351±20	47±1.6	3681±75	19±3.7	33±1.0
Gypsum	39.2±3.0	1386±22	48±2.5	3864±48	22±7.5	37±2.0
Hard Federation	35.8±3.7	1462±44	56±2.0	3725±172	12±4.4	36±0.7
Henry	31.9±2.3	1353±46	44±2.3	3840±139	12±2.8	36±1.1
Hope	32.7±0.5	1351±14	51±2.0	3588±18	11±3.5	34±1.2
Hybrid 123	34.9±2.5	1279±13	47±5.3	3780±49	19±6.2	31±0.8
Hybrid 143	35.8±2.9	1547±33	58±6.1	4107±91	18±5.6	32±1.1
Hybrid 63	31.9±2.7	1456±28	42±2.4	3684±86	20±7.0	33±1.2
Hyper	35.7±3.9	1428±73	53±0.9	3897±200	12±4.1	32±0.4
Idaed	34.7±2.5	1238±35	52±2.5	3516±133	11±3.6	30±1.1
Idaed 59	52.2±0.2	1723±16	57±0.4	4738±43	15±4.6	36±0.3
Indian	42.8±3.0	1536±63	56±1.3	4236±229	15±4.9	34±0.4
Komar	30.3±1.6	1386±50	48±2.8	3806±89	14±5.1	35±2.8
Lagoda	38.4±1.0	1368±22	49±4.1	3935±67	15±4.3	35±2.5
Lemhi	40.0±1.0	1627±88	55±5.0	4039±266	14±5.1	43±5.7
Lemhi 66	43.6±1.4	1572±68	55±3.9	3800±179	23±8.2	41±5.0
Little Club	50.4±7.3	1550±30	51±3.3	3883±101	15±5.0	35±3.0
Mackey	45.6±2.1	1468±16	50±1.6	4125±30	30±11.0	39±0.7
Marquis	28.7±0.8	1271±24	44±3.6	3748±80	10±2.9	33±1.2
New Zealand	43.6±2.8	1457±39	49±3.3	4184±130	11±3.0	39±2.7
Onas	33.7±1.8	1372±33	55±5.9	3625±109	5±1.2	32±2.5
Oregon Zimmerman	32.5±0.9	1446±19	47±2.8	3995±34	12±4.0	39±3.0
Pacific Bluestem	36.3±0.3	1488±36	52±3.2	3958±86	16±4.3	39±2.9
Penawawa	**29.1±1.4**	**1348±42**	**46±3.4**	**3601±180**	**4±0.2**	**28±2.3**

Pilcraw	34.9±1.6	1436±48	47±2.0	3709±88	20±7.0	34±2.8
Red Bobs	31.4±0.6	1145±34	43±3.5	3206±71	13±4.3	30±1.3
Red Fife	35.5±2.5	1435±14	50±3.6	4041±70	11±3.0	34±2.0
Reliance	31.4±0.4	1177±10	39±2.0	3315±24	14±4.7	26±0.4
Reward	35.8±1.4	1271±32	52±2.0	3895±103	13±3.1	36±0.9
Rink	33.0±1.4	1371±23	43±2.6	3688±122	17±5.8	26±1.6
Rival	32.4±2.3	1426±55	51±1.4	3868±167	19±5.2	38±0.7
Ruby	33.5±1.9	1161±20	39±1.1	3243±88	14±3.4	29±1.2
Scarlet	**34.0±1.2**	**1295±18**	**46±1.7**	**3527±116**	**12±2.4**	**28±1.7**
Sea Island	29.7±2.0	1237±32	47±2.6	3532±89	16±4.4	28±1.0
Sonora	36.9±2.0	1394±36	49±1.3	3884±121	15±4.0	31±0.8
Spinkota	40.5±3.1	1277±57	45±1.1	3437±142	21±6.3	29±0.7
Supreme	33.8±0.9	1275±50	49±3.8	3593±116	9±1.7	34±2.1
Surprise	33.1±0.8	1302±64	45±4.3	3490±181	19±5.6	32±4.5
Thatcher	27.1±0.2	1301±40	47±3.5	3789±108	12±3.1	28±2.0
Wakanz	**31.6±1.7**	**1286±35**	**46±4.1**	**3445±174**	**2±0.1**	**26±2.1**
Wawawai	**30.6±2.2**	**1328±20**	**47±2.4**	**3584±88**	**2±0.2**	**29±2.0**
Westbred Express	**33.8±1.1**	**1336±10**	**51±1.5**	**3545±82**	**13±2.4**	**27±1.9**
White Federation	33.9±2.0	1408±45	53±3.5	3431±81	10±2.6	33±1.6
White Marquis	30.9±1.4	1314±25	49±0.7	4052±108	19±5.8	33±0.4
Zak	**36.1±2.2**	**1257±12**	**52±3.8**	**3356±115**	**16±3.9**	**27±2.0**

Table 6. Correlation between minerals in spring wheat varieties grown in Pullman, WA in 2004 and 2005. All correlations except Fe-Cu are significant at P < 0.05. The numbers in parentheses represent 95% CI. Shaded areas show the pattern of significant negative correlations between minerals. This table suggests that certain minerals (Ca, Cu, Mg, Mn, P and Zn) may be selected for simultaneously due to significant positive correlations. Se and Fe are highly correlated to each other, suggesting selection for these two minerals in tandem will be effective.

Mineral	*Ca*	*Cu*	*Fe*	*Mg*	*Mn*	*P*	*Se*
Cu	0.56 (0.48, 0.62)	----					
Fe	-0.12 (-0.22, -0.02)	-0.04 (-0.14, 0.06)	----				
Mg	0.61 (0.55, 0.67)	0.72 (0.67, 0.77)	-0.11 (-0.21, -0.01)	----			
Mn	0.38 (0.28, 0.46)	0.43 (0.34, 0.51)	-0.25 (-0.34, -0.15)	0.57 (0.49, 0.63)	----		
P	0.51 (0.43, 0.58)	0.61 (0.54, 0.67)	-0.23 (-0.32, -0.13)	0.84 (0.81, 0.87)	0.52 (0.44, 0.59)	----	
Se	-0.20 (-0.29, -0.10)	-0.15 (-0.25, -0.15)	0.89 (0.86, 0.91)	-0.28 (-0.37, -0.18)	-0.13 (-0.23, -0.03)	-0.39 (-0.48, -0.30)	----
Zn	0.36 (0.27, 0.45)	0.61 (0.54, 0.67)	0.13 (0.03, 0.23)	0.56 (0.48, 0.62)	0.70 (0.64, 0.74)	0.51 (0.43, 0.58)	0.22 (0.12, 0.31)

Table 7. Percent resistance to dwarf bunt of 75 F_5 breeding lines and a check cultivar (Cheyenne). This table will help us identify breeding lines with high levels of resistance to dwarf and common bunt. Susceptible lines can be dropped from the organic breeding program at this point, or used as parents with bunt resistant varieties for future selection.

Breeding line	% Bunt Rep 1	% Bunt Rep 2
5K020001-2	4	3p
5K020006-3	2	20p
5K020007-1	0p	0v
5K020023-2	1	0
5K020023-3	1	3
5K020023-4	2	0v
5K020023-5	1	4p
5K020023-6	6	3
5K020023-7	6	4
5K020037	20	40
5K020042-2	25	0v
5K020042-3	0v	70p
5K020042-5	20v	n
Cheyenne	50	50
5K020042-9	25p	30v
5K020072-1	4p	0v
5K020072-2	60	30v
5K020072-3	30v	0v
5K020072-4	2p	0v
5K020072-6	0p	0p
5K020072-7	0p	0v
5K020072-8	0v	0v
5K020072-10	20p	20p
5K020082-1	0p	40p
5K020082-2	0p	60p
5K020082-3	15p	50p
5K020082-6	5	10p
5K020082-8	40	50p
5K020082-9	40	10v
5K020082-10	60	60
5K020082-11	0v	50
5K020095-1	30	65
5K020095-2	30v	65
Cheyenne	50p	n
5K020095-3	30p	0v
5K020095-4	30p	20p
5K020095-5	35p	70
5K020095-6	30p	25p
5K020095-7	50	20
5K020095-8	9	60
5K020095-9	15	75

5K020095-10	7v	8p
5K020095-11	30p	0v
5K020095-14	40	40
5K020100-1	40p	0v
5K020100-2	70	60
5K020100-3	60	65
5K020100-4	25	50f
5K020100-5	40	30f
5K020106-2	65	20p
5K020106-4	30p	5v
5K020106-5	50	20
5K020106-8	60	30p
Cheyenne	0v	70
5K020106-9	n	50p
5K020106-10	40v	60p
5K020106-12	75v	40p
5K020108-1	40	60
5K020108-2	50	75
5K020117-1	4p	65
5K020117-3	15p	10
5K020117-4	20p	9p
5K020117-5	20	50
5K020118-2	40	60
5K020121-2	4v	15p
5K020122-1	4	50
5K020122-5	0v	15v
5K020122-6	25	40
5K020122-7	20	7
5K020122-8	35	9p
5K020128-1	30	10
5K020138-1	4	15p
5K020138-3	40	20
Cheyenne	85	30
5K020144-2	1p	30
5K020144-4	30p	35
5K020149-1	30p	60p
5K020151-1	60p	20v
5K020198	30	10

Figure 1. Yield (Fig. 1A) and test weight (Fig. 1B) in organic vs conventional wheat nurseries. The striped bars denote the organic nurseries and the shaded bars denote the conventional nurseries. † = significant genotype x system interactions at $P < 0.001$. * = significant difference between organic and conventional nurseries (* = $P < 0.05$; *** = $P < 0.0001$). Results are nursery means ± s.e.m. This figure shows that while conventional systems significantly outyielded organic systems at two of the five locations, there were significant genotype x system interactions at four of the five locations. This indicates that organic farmers are growing wheat varieties that are poorly adapted to organic farming systems.

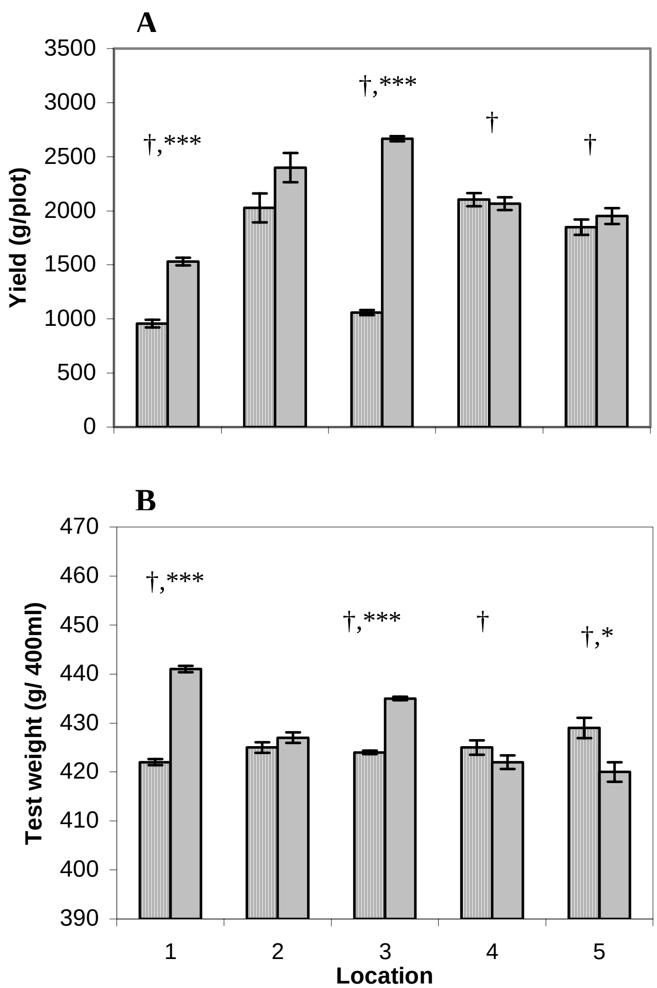

Figure 2. Genotypic change in rank between organic and conventional wheat nurseries. The top five ranking genotypes for yield in both organic and conventional systems were compared at each location. Genotypes are ranked from one = highest yield to 35 = lowest yield. This figure shows that the highest yielding varieties in organic systems are generally not the highest yielding varieties in conventional systems.

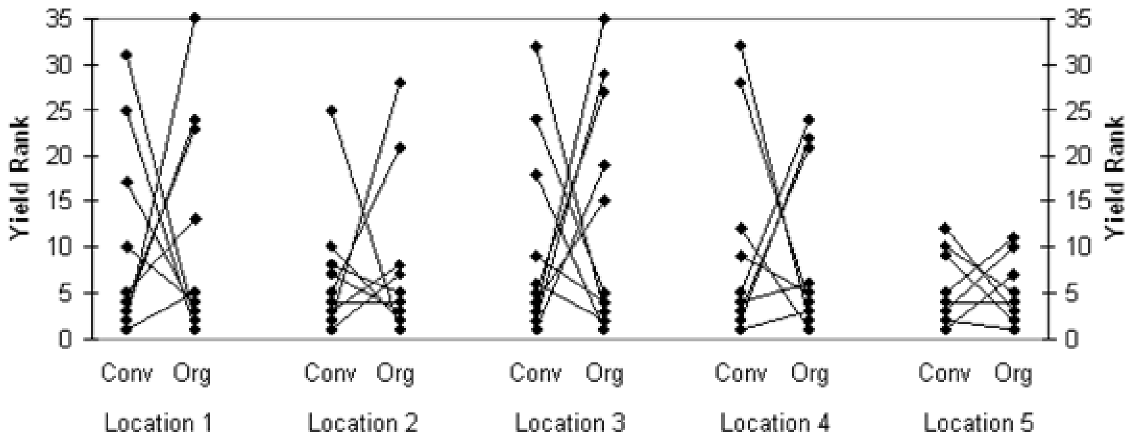

Figure 3. Regressions of wheat seed mineral nutrient content on the date of variety release for soft white spring wheat (open triangle, light solid line) and hard red spring wheat (closed diamond, dark solid line). Regression line is the best-fit simple linear regression model. This figure shows that soft white wheat varieties are responsible for the decline in mineral nutrient content, while hard red wheat varieties have remained relatively constant over the past 120 years.

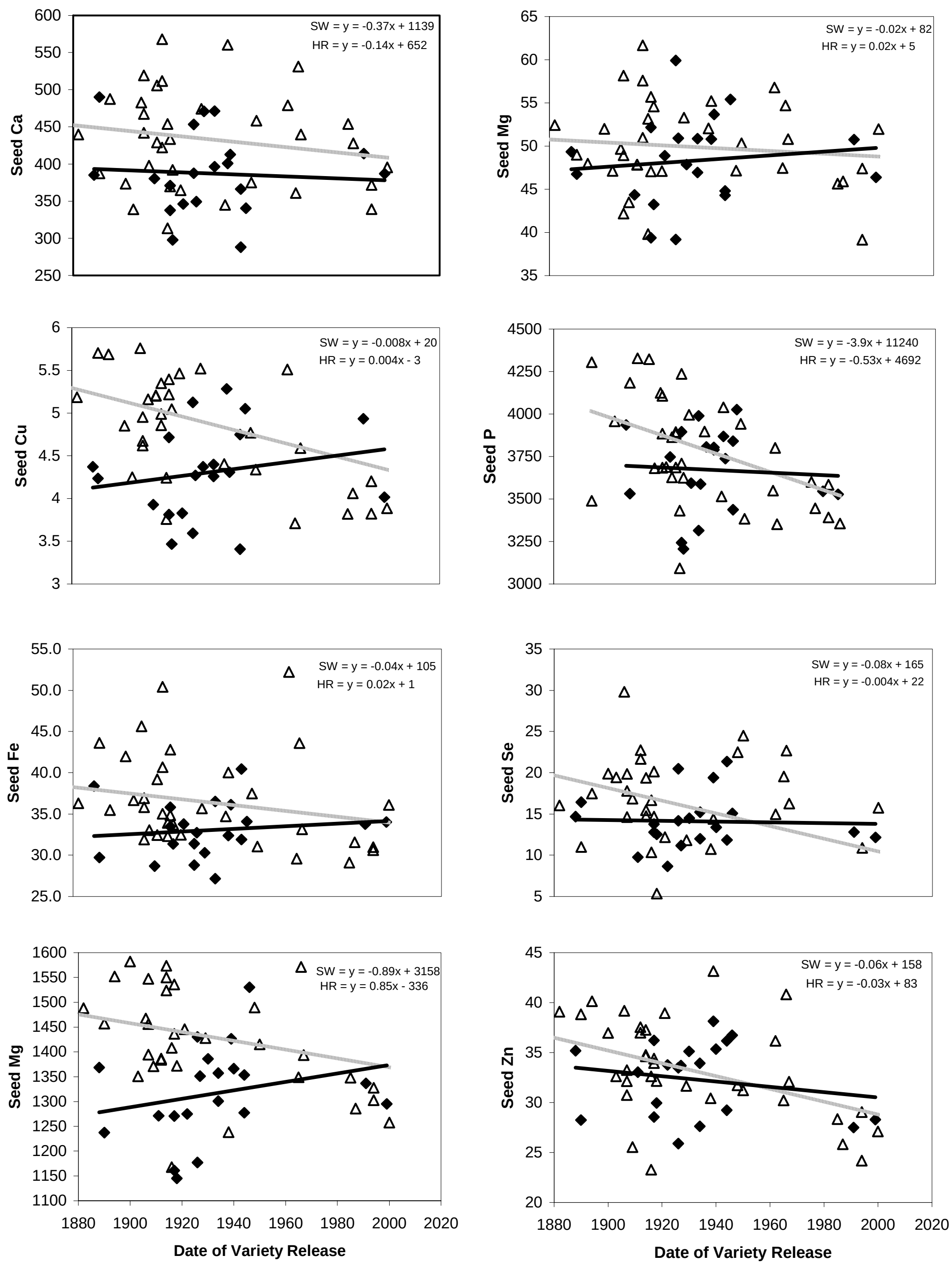

Figure 4. Estimated number of slices of bread required to meet the Recommended Dietary Allowance (RDA) levels for Zn, Cu, Mg, and P, with flour from both modern varieties (denoted 'Top 7 Modern') and historical varieties with high levels of nutrient content (denoted 'Top 7 Historical').

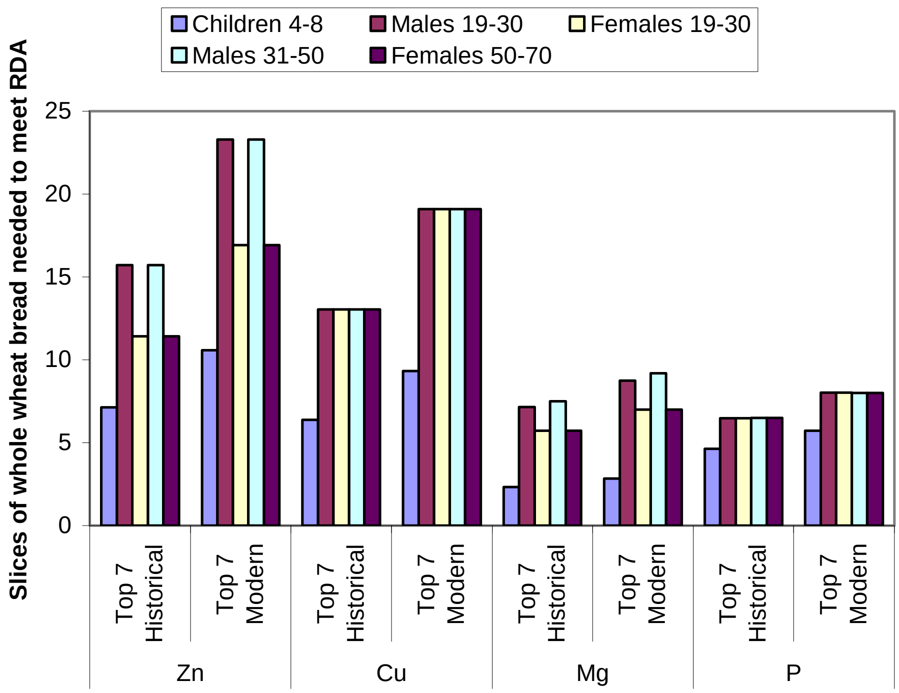

Figure 5. Estimated number of slices of bread required to meet the Recommended Dietary Allowance (RDA) or Adequate Intake (AI) levels with flour from both modern varieties (denoted 'Top 7 Modern') and historical varieties with high levels of nutrient content (denoted 'Top 7 Historical'). RDA was used for Fe, and Se. AI was used for Ca and Mn.