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IMPROVEMENT OF WHEAT QUALITY AND YIELD

by

V. A. Johnson

Food quality can be defined in various ways. I shall be concerned with wheat quality mainly as it relates to the nutritional value of the protein. Enrichment, fortification, or supplementation are sometimes employed to enhance nutritional quality but these are difficult in most countries where the need is greatest.

World Food Supply

After 1800 years of relative stability there is now occurring an alarming increase in population which by the year 2000 is expected to reach 7 billion people. This is especially alarming in the face of already existing food shortages with a current world population of less than ½ of 7 billion people. The population problem is made more serious by the fact that the largest increases are occurring in the under-developed countries where inadequate food supply already is a serious problem.

The underlying reason for the increase in these countries is well understood. With introduction of modern medicine and health measures, death rate has been reduced substantially with no commensurate reduction in birth rate. Result: population explosion! An inevitable consequence of this trend is that the population of the developed countries constitutes an ever smaller portion of the world's total population.

The land area of the world most suited for food production already is largely utilized. Increases in food production, therefore, must come from increases in yields. All of us are acquainted with the recent "green revolution"

and the activities of Nobel Prize winner Norman Borlaug in bringing about the spectacular increases in wheat production in parts of Asia. He has warned that the contribution of the green revolution in alleviating hunger in India and Pakistan is only temporary unless some reasonable control of population in those countries is achieved. It is a historical fact that population increases follow in the wake of improved food supplies. Unless checked, famines even more serious than those of the past, most surely will occur.

Where does the wheat breeder fit into this fight against hunger? In my opinion his role is a key one. One-third of the world's people rely on wheat as their main food staple. Wheat is the most widely adapted of all the cereals. It is an efficient producer of protein. Do you know that wheat will produce more protein and more of every essential amino acid from an acre of land than can be produced by livestock grown on that acre? And most of ud don't even think of wheat as a protein food. Meat-eating is a luxury that few countries can afford! I am convinced that wheat and the other cereal grains will continue to be the most important category of world food in the foreseeable future. Any improvement in their quality and productivity would have global significance.

Productivity of Wheat

Substantial advances in wheat productivity have been achieved in the last two decades. They have resulted from improvements in varieties and in wheat production practices. The green revolution probably has been the most widely publicized. With a combination of short, lodging-resistant varieties, irrigation water, and heavy increments of fertilizer wheat yields in India and Pakistan were more than doubled. The same factors led to Mexico becoming self-sufficient in wheat in the last decade in contrast to its historical

position as a wheat deficient country. In fact, advances in wheat yields were recorded in all wheat producing countries and regions in 1970 (Table 1).

World record yields in excess of 200 bushels per acre have been recorded for Gaines wheat in the Pacific Northwest. Less spectacular but steady increases also have been achieved elsewhere in the U.S.A. In the hard red winter wheat region of which Texas is a part, there have been vigorous wheat breeding programs from which many increasingly productive improved varieties have come. In 1963, the variety Scout was released by the Nebraska Experiment Station. Regional records indicate that Scout was 10% more productive than Comanche (Table 2). Centurk, another Nebraska variety released in 1971 has been 10% more productive than Scout in regional trials.

The objectives of most wheat breeding programs with respect to yield are two-fold. The first is to increase yield by accumulation of yield genes in adapted varieties or by protecting varieties against yield-depressing hazards through incorporation of various resistance genes. Continuing increase in productivity are basic to all other considerations, nutritional and otherwise. To achieve quality improvements in wheat at the sacrifice of productivity is unthinkable.

The second is to improve the yield stability of varieties. Most of the vast wheat acreage of the United States and world is non-irrigated. The wheat is subjected to wide variations in precipitation, temperature, soil fertility and other environmental factors, and frequently must produce a crop under extreme stress. Some varieties can withstand such stress better than others. A successful variety in the central plains of the United States must perform well, relative to other varieties, in poor as well as good growing conditions. The Scout variety is such a variety (Figure 1) and currently occupies the largest acreage of any wheat variety in the United States.

Average wheat yields in the United States have doubled since 1900. In the hard red winter wheat region in which more than one-half of all U. S. wheat is produced, high yields have been accompanied by measureably lower protein content of the grain (Table 3). This is especially evident in the high plains where nitrogen fertilization of wheat has not been a profitable practice. Continued cropping without fertilizer use has slowly mined the soil of its nitrogen content. In Kansas, Nebraska, and Oklahoma increased yields in the 1967-1969 period resulted in measureably lower protein content of the wheat. Further decreases in wheat protein have been recorded in these states and Colorado since 1969.

The point has been reached in wheat improvement where major attention must be focused on its nutritional value in addition to productivity. Thus far, the preoccupation of breeders has been with increasing yields. This has been reasonable since successful new wheat varieties must be productive to be accepted by farmers.

Nutritional Improvement

Ordinary wheat produces grain comprised of approximately 12% protein. Environment exerts strong influence on the level of protein. It can cause the level to be as low as 7% or as high as 20%. Nitrogen availability of the soil on which the wheat is produced is a major environmental component. Environment also can exert strong influence on the physical properties of wheat flow that affect its acceptability in modern bread-making processes.

Wheat and other cereals are an important source of protein for much of the world. You are aware that the nutritional value of cereal protein is lower than that of meat and animal products. But, it is not as low as we are led to believe by some food faddists.

Protein value is tied to the amino acid composition of the protein and its biological availability. Meat and animal products possess protein comprised of essential amino acids in approximately the ratio required by the human body. Wheat and other cereals produce protein with the same amino acids but their ratio to one another is different from the requirements of man. Consequently, wheat protein is not utilized by man so fully as animal protein. The degree to which it is utilized is largely determined by the essential amino acid which is in the shortest supply.

In the case of wheat and other cereals this amino acid is lysine (Table 4). Note that wheat protein possesses less than one-half the lysine necessary for it to be in balance with the other essential amino acids according to man's requirements. Thus, efforts to improve the nutritional value of wheat protein must begin with lysine, not because it is more important than the other amino acids, but because it is in the shortest supply.

The University of Nebraska in cooperation with the Agricultural Research Service, U. S. Department of Agriculture, and Agency for International Development, U. S. Department of State, has engaged in wheat protein research for several years. The research encompasses investigation of protein content as well as protein composition. The objective of our research effort is to improve the nutritional value of wheat by 1) increasing its protein content, 2) improving the ratio of amino acids in the protein, or 3) both.

The nutritional improvement of wheat may not be entirely compatible with accepted standards of bread wheat quality. The non-endosperm proteins are richest in lysine (over 4%) whereas endosperm proteins are relatively poor in lysine (around 2%). Non-endosperm proteins are largely eliminated from wheat flour in the milling process. Increases in the lysine content of the non-endosperm proteins then would contribute little to increased lysine content of high grade wheat flour.

Further incompatibility of nutritional improvement with baking quality may exist in the endosperm proteins themselves. These can be divided into gluten proteins and water- and salt-soluble proteins. The water-salt-soluble proteins are high in lysine (over 4%) whereas the gluten proteins are very low (less than 2%). The ratio of water-soluble to gluten protein varies. Low protein wheats usually have a higher percentage of water-soluble protein. This accounts for the tendency of low protein wheats to have a higher percentage of lysine. Also, wheats that are high in the water-salt-soluble endosperm proteins tend to have soft texture and poor bread wheat milling and baking properties.

It is important that the difference between nutritional quality and baking quality by western standards be understood and appreciated. In those parts of the world where the whole grain of wheat is utilized for food the site of the lysine rich protein in the wheat kernel would be of little consequence. Increases in the quantity of any of the proteins or increases in their lysine content would significantly enhance the nutritional value of the wheat. The greatest nutritional enhancement would derive from simultaneous increases in both.

Assume that a person consumes 400g of whole wheat daily (Table 5). We see that a 3% increase in actual protein content would result in the same increase in the amount of lysine consumed as a 0.9% increase in lysine content itself. Simultaneous increase of both protein and lysine would provide the largest enhancement of nutritional value.

Protein Quantity

The quantity of protein in the grain or wheat can be significantly increased by breeding. Further, the protein increase appears to be compatible with accepted standards of bread quality. Substantial genetic differences in

grain protein content of wheat have been identified. The "Frondoso"-derived "Atlas 66" and "Atlas 50" bred in North Carolina, produce grain with significantly higher protein content than other varieties. We have utilized Atlas 66 in our protein breeding program at the University of Nebraska.

The protein content of Atlas 66 is significantly higher than that of the hard red winter wheat variety "Wichita" (Figure 2). Incomplete dominance of high protein is indicated by a F_2 population that is intermediate to the parents. Environmental influence on grain protein content is large. Thus, the heritability of protein is not as high as some other economic traits in wheat although we have computed heritability estimates as high as 0.8 in some experiments.

A gene from Atlas 66 with major effect on protein appears to be genetically linked with leaf rust resistance (Table 6). Note the high protein of the resistant rows compared with that of susceptible rows. We postulate that at least one additional gene for protein with major effect is functioning in our material. This is indicated by recovery of both leaf rust resistant and leaf rust susceptible lines with intermediate levels of protein. We are using chromosome substitutions to identify the chromosomes of Atlas 66 that carry the genes for high protein.

We have transferred the high protein trait from Atlas 66 to experimental lines of hard winter wheat (Table 6). You will note that Atlas 66 x Comanche lines intermediate to Warrior and Scout in yield were much higher than these varieties in grain protein content. Data from Nebraska and Kansas indicate that the high protein trait can be combined with acceptable bread wheat milling and baking quality.

Comparisons of nitrogen relations in high and low protein winter wheats have provided indirect evidence that high grain protein results from more complete translocation of nitrogen from the plant to its grain. We have been

unable to demonstrate differential nitrogen uptake as a basis for high grain protein in our Atlas-derived lines. The plant nitrogen content of a high protein line, NB60306, and Scout was not different at any time during the spring growing season (Figure 3). However, the grain nitrogen content of NB60306 was higher than Scout at all stages of kernel development.

Warrior, a low protein winter wheat and high protein NB60305 were compared (Figure 4). The foliage nitrogen content of Warrior was significantly higher than NB60305 at all stages of spring growth. Even so, the grain of NB60305 possessed significantly more nitrogen than Warrior throughout the kernel development period. In no case have we found the high grain protein of Atlas 66-derived lines to be associated with higher plant nitrogen concentrations.

Phenotypic expression of the high protein trait from Atlas 66 has been reasonably stable in Nebraska tests. We reasoned that this would be so since nitrogen translocation rather than nitrogen uptake by the plants is involved. In 1968, one of our high protein lines was compared with the Lancer variety at six levels of N-fertilizer treatment at four sites in Western Nebraska where soil fertility is low (Table 7). The protein superiority of NB65307 over Lancer was consistently expressed at all soil fertility and grain protein levels.

An International Winter Wheat Performance Nursery was organized in 1968 in which representative winter wheat varieties from many countries were evaluated. We included three high protein wheats in this nursery. The nursery is grown in most of the winter wheat producing countries of the world. Performance data were obtained from 21 sites in 14 countries in 1969. As in the Nebraska tests there was excellent expression of the high protein trait at all reporting sites (Table 8).

Protein Composition

Do significant differences in amount of lysine occur in wheat protein? This is a key question since lysine is the most deficient among the essential amino acids in wheat protein. The World Collection of Wheats, comprised of 17,000 varieties, is being searched in our Laboratory. To date 7,000 have been analyzed for protein and lysine content. The majority were in the 10 to 16% protein classes with a few below 8% and above 19%. We believe most of this variation to be non-genetic, i.e. environmentally induced. We have reason to think that the genetic component of total protein variation measured in the World Collection is from 4 to 5 percentage points.

The frequency distribution for lysine showed a range from less than 2 to above 4% where lysine is expressed as a percent of protein. The mean lysine value for 7,000 wheats was approximately 3%. Only 4 wheats had values higher than 4%.

Lysine expressed as percent of protein is negatively correlated with protein (Figure 5). The coefficient for 7,000 wheats was -0.63. In contrast, lysine expressed as percent of dry grain weight is positively correlated with protein (Figure 6). This would be anticipated since lysine is a constituent of protein. The correlation coefficient is 0.83. The shaded areas in Figures 5 and 6 indicate the range of dispersal of actual values about the regression lines.

Only 40% of the variation in lysine/protein is attributable to variation in protein. Seventy-five percent of the variation in lysine/dry grain weight is attributable to variation in protein. Thus, in our effort to identify genetically high lysine wheats, we are confronted with the problem of the influence of protein level on the values obtained. This is particularly critical

because of the strong influence of environment and grain yield on protein level. Lysine values, unadjusted for protein variation, could be artifacts from a genetic standpoint.

We favor the use of lysine expressed as percent of protein in our work because it is less affected by uncontrollable protein variations. In fact, we now utilize the regression of lysine/protein on protein to adjust lysine values to a common protein level. When we adjusted the lysine values of 7,000 World Collection wheats to 13.5% protein, only 125 had adjusted values higher than 3.5% and, of this number, only six were higher than 3.8%.

Growouts of World Collection wheats with the highest lysine values were made to determine the reliability of the initial values obtained as an indication of genetic differences in lysine. Our results indicate a large effect of production environment on lysine content. Few of the high lysine wheats based on the initial analysis remained high in lysine when grown in different sites in the United States.

The high lysine values persisted in a few wheats. One of the more promising of these is a variety from India, P.I.176217. It appears to possess higher-than-normal values for both protein and lysine. Its lysine advantage over normal varieties is approximately 0.5 percentage point. We believe this to be sufficiently large to be useful for breeding purposes and the variety has been utilized extensively in new crosses.

We have been concerned with the effect of the high protein trait from Atlas 66 on amino acid composition of the protein. Analysis of the World Collection indicated a decrease in lysine level associated with higher protein. Since normal wheat is deficient in lysine, further decrease in that amino acid could be serious. Analyses of a number of our high protein Atlas-derived lines

were made for lysine, methionine, and threonine (Table 9). Note that some of the lines were equal to or higher than their low protein parent in content of these three essential amino acids. Others were lower than their low protein parent. It is clear from these data that high protein lines can be selected that are comparable to lower protein varieties in their composition of essential amino acids.

The potential effectiveness of breeding for high protein as a means of increasing the nutritional value of wheat is evident from Table 10 in which lysine, methionine, and threonine in high protein lines are expressed as percentage increase per unit weight of grain over the low protein parent. Twenty-two percent more protein in Atlas 66 x Comanche 2509 resulted in 30.1% more lysine, 33.4% more methionine, and 14.2% more threonine than was contained in an equal weight of grain of the Comanche parent. It would seem from these data that significant advances in the nutritional value of wheat can be achieved by increasing its protein content.

The comparative contributions of high protein and high lysine toward increased amounts of essential amino acids in wheat are shown in Table 11. More of every amino acid per unit weight of grain is provided by wheat with 17.2% protein than high lysine wheat with only 8.3% protein. Clearly, selection of high lysine at the expense of protein content would not be warranted on the basis of these data.

Much has been heard about opaque-2 maize which is high in lysine and tryptophan and powsesses excellent nutritional value. We compared the amount of each essential amino acid per unit weight of grain provided by opaque-2 maize with 10.0% protein and high protein wheat with 17.2% protein (Table 12). As much lysine and more of every other essential amino acid is provided by the high protein wheat.

How good nutritionally are high protein wheats? Our in-vitro laboratory analyses indicate that they should be distinctly superior to ordinary wheat. The final answer will come only from feeding trials which ultimately must involve people as subjects. We have completed preliminary plans for establishment of a small animal laboratory in the Department of Foods and Nutrition of the University of Nebraska in which the mouse will be the test animal. We hope to establish the degree to which the in-vitro laboratory tests reflect nutritional value based on the mouse tests.

Table 1. World Wheat Production (bu/a)

	1964-68	1970
USA	26.6	31.2
Nebraska	27.7	38.0
USSR	14.3	16.4
East Europe	33.5	35.3
West Europe	36.8	38.1
Mexico	34.5	41.6 (1969)
India	13.3	18.6
Pakistan	12.8	17.5

Table 2. Winter Wheat Variety Performance Southern Regional Performance Nursery, 1968-1970.

Variety	Year released	1968 bu/a	1969 bu/a	1970 bu/a	Increase %
Centurk	1971	45.3	48.1	45.0	10% over Scout
Scout	1963	39.1	43.9	43.3	10% over Comanche
Comanche	1942	36.8	38.5	39.6	14% over Kharkof
Kharkof	Russian Introduction, 1900	32.8	33.5	34.2	

Table 3. Wheat Yield and Protein Trends - HRWW Region.

State	Av. Yield (bu/a)			Av. Protein (%)		
	1967	1968	1969	1967	1968	1969
Nebraska	26.5	32.0	31.5	11.9	11.3	11.2
Kansas	20.0	25.0	31.5	12.9	11.7	10.9
Colorado	19.5	20.0	21.0	11.7	11.6	11.8
Oklahoma	17.0	23.0	28.0	12.9	11.5	10.9

Table 4. Deviation of Essential Amino Acids in Wheat Proteins from Requirements of Man, FAO-1957.

Amino Acid	% Deviation from Requirement
Lysine	-55.0
Methionine[1/]	-12.5
Isoleucine	-16.7
Leucine	+30.4
Tyrosine	+ 9.7
Phenylalanine	+40.4
Threonine	- 3.4
Valine	+ 4.5

[1/] Adjusted provisional amino acid pattern, WHO 1965.

Table 5. Effect of various levels of protein and lysine on amount of lysine in wheat grain.

400 g. whole wheat

with

10% protein; 3.1% lysine

Provides 40 g. protein; 1.2 g. lysine

13% protein; 3.1% lysine

Provides 52 g. protein; 1.6 g. lysine

10% protein; 4.0% lysine

Provides 40 g. protein; 1.6 g. lysine

13% protein; 4.0% lysine

Provides 52 g. protein; 2.1 g. lysine

Table 6. Grain protein frequency distribution of F_6 rows of Atlas 66 x Wichita homozygous for reaction to leaf rust at Lincoln, Nebraska.

Population	% Grain protein (Class centers)									
	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Number of rows									
Wichita (Susc.)		3	10	1						
Susc. F_6 rows	1	3	12	61	121	60	30	8	2	
Res. F_6 rows					8	18	35	89	75	29
Atlas 66 (Res.)										

Table 7. Effect of nitrogen fertilization on the grain protein content of the high protein line NB65307 and Lancer grown at four Nebraska outstate testing sites in 1968.

Nitrogen application (rate and time) lb/a	Lancer %	NB65307 %
none	8.2	9.8
20 S[1/]	8.9	10.6
40 F	9.8	11.4
40 S	10.6	12.1
60 S	11.5	13.0
80 S	12.3	13.8

[1/] S = spring; F = fall application

Table 8. Mean grain yield and protein content of seven varieties grown in the International Winter Wheat Performance Nursery in 1969.

Variety	Mean yield bu/a	Mean protein content % (dry wt. basis)
No. reporting sites:	16	18
Lancer	54.9	14.0
Triumph 64	53.4	14.7
NB67730 (high protein)	52.2	16.4
Atlas 66 (high protein)	50.1	17.5
Purdue 28-2-1 (high protein)	49.4	16.6
Winalta	48.3	13.8
Gaines	46.1	13.0

Table 9. Protein, lysine, methionine, and threonine content of high protein Nebraska lines in comparison with the parent varieties.

Variety		Protein content[1/]	Lysine % protein	Methionine % protein	Threonine % protein
Comanche		15.0	3.2	1.7	3.5
Atlas 66		18.0	3.3	1.1	3.4
Atl 66-Cmn	2509	18.3	3.5	1.8	3.3
	2500	18.3	3.2	1.7	3.2
	2499	18.2	3.3	1.7	3.1
	2504	17.9	3.4	1.1	3.7
	2507	17.7	3.7	1.7	2.6
	2510	16.5	3.4	1.7	3.2

[1/] Dry weight basis.

Table 10. Percentage increase in protein, lysine, methionine, and threonine in selected high protein Nebraska lines over their low protein parent per unit weight of grain.

Variety	Increase over low protein parent			
	Protein	Lysine	Methionine	Threonine
	%	%	%	%
Atl 66 x Cmn 2509	22.0	30.1	33.4	14.2
" 2500	22.0	20.5	20.2	8.6
" 2499	21.3	23.1	21.6	5.8
" 2504	19.3	24.6	-18.7	24.4
" 2507	14.7	31.6	19.0	-15.5
" 2510	10.0	14.8	10.0	0.0

Table 11. Comparative essential amino acid composition of high lysine and high protein wheats.

Amino acid	High protein wheats (17.2% protein)*		High lysine wheats (8.3% protein)*	
	% of protein	% of grain**	% of protein	% of grain**
Lysine	2.9	0.49	3.6	0.29
Isoleucine	3.7	0.64	3.7	0.31
Leucine	7.1	1.22	7.3	0.61
Methionine	1.6	0.28	1.7	0.14
Phenylalanine	5.2	0.89	4.9	0.41
Threonine	3.0	0.51	3.4	0.28
Valine	4.5	0.77	4.7	0.39
Tryptophan	1.1	0.19	1.5	0.12

*14% moisture basis
**dry weight basis

Table 12. Comparative essential amino acid composition of opaque-2 maize and high protein wheat.

Amino acid	Opaque-2 maize (10.0% protein) 1/		High protein wheat (17.2% protein) 1/	
	% of protein	Grams per 100 g. grain	% of protein	Grams per 100 g. grain
Lysine	4.8	0.48	2.9	0.49
Isoleucine	3.4	0.34	3.7	0.64
Leucine	9.1	0.91	7.1	1.22
Methionine	2.1	0.21	1.6	0.28
Phenylalanine	4.5	0.45	5.2	0.87
Threonine	4.0	0.40	3.0	0.51
Valine	5.1	0.51	4.5	0.77
Tryptophan	1.3	0.13	1.1	0.19

1/ 14% moisture basis

List of Figures

Figure 1. Yield relationships of Scout, Gage, and Triumph winter wheat varieties to Tharkof predicted from the linear regression analysis of variety yields on nursery mean yields in the Southern Regional Performance Nursery, 1961 to 1963.

Figure 2. Grain protein frequency distribution of plants of Wichita and Atlas 66 and their F_2 generation grown at Lincoln, Nebraska in 1957.

Figure 3. Nitrogen content of the foliage and grain of two winter wheat varieties at Lincoln, Nebraska, 1963.

Figure 4. Nitrogen content of the foliage and grain of two winter wheat varieties at Lincoln, Nebraska, 1963.

Figure 5. The relationship of lysine expressed as percent of protein with protein in the grain of 7000 wheat varieties from the World Collection.

Figure 6. The relationship of lysine expressed as percent of dry grain weight among 7000 wheat varieties from the World Collection.

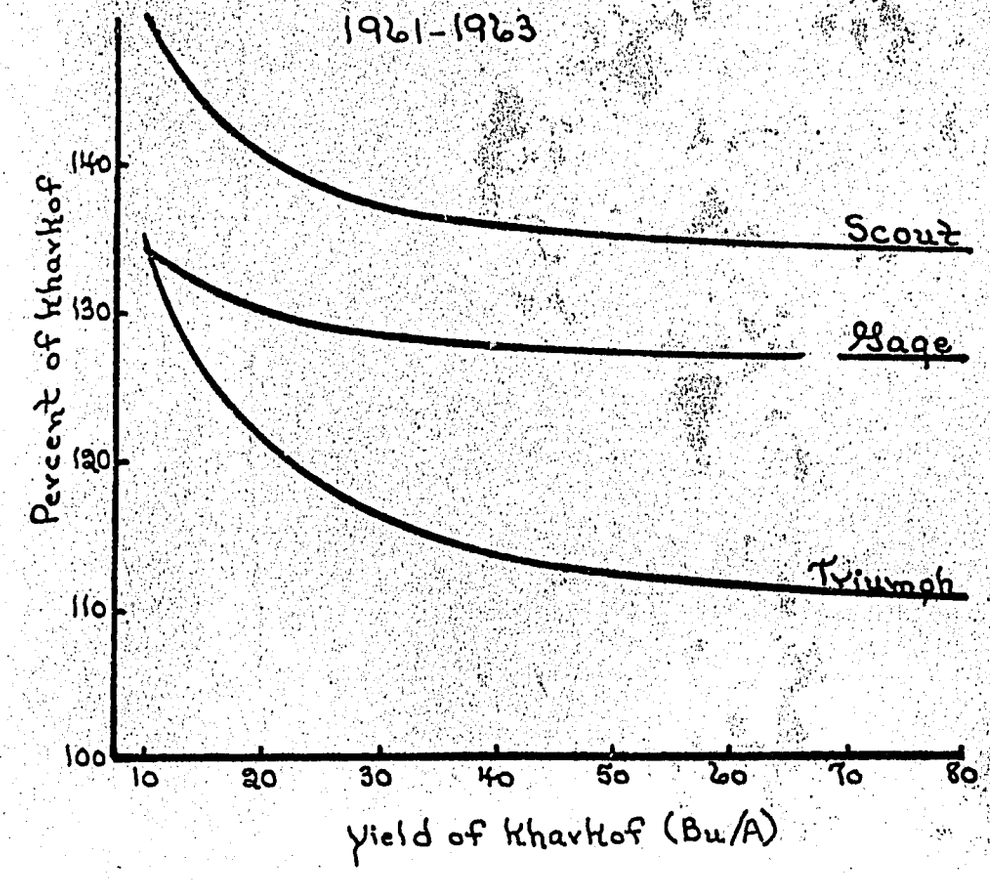

1961-1963
Fig. 1
Percent of Kharkof
140
130
120
110
100
Scout
Sage
Triumph
10
20
30
40
50
60
70
80
Yield of Kharkof (Bu/A)

Fig. 2

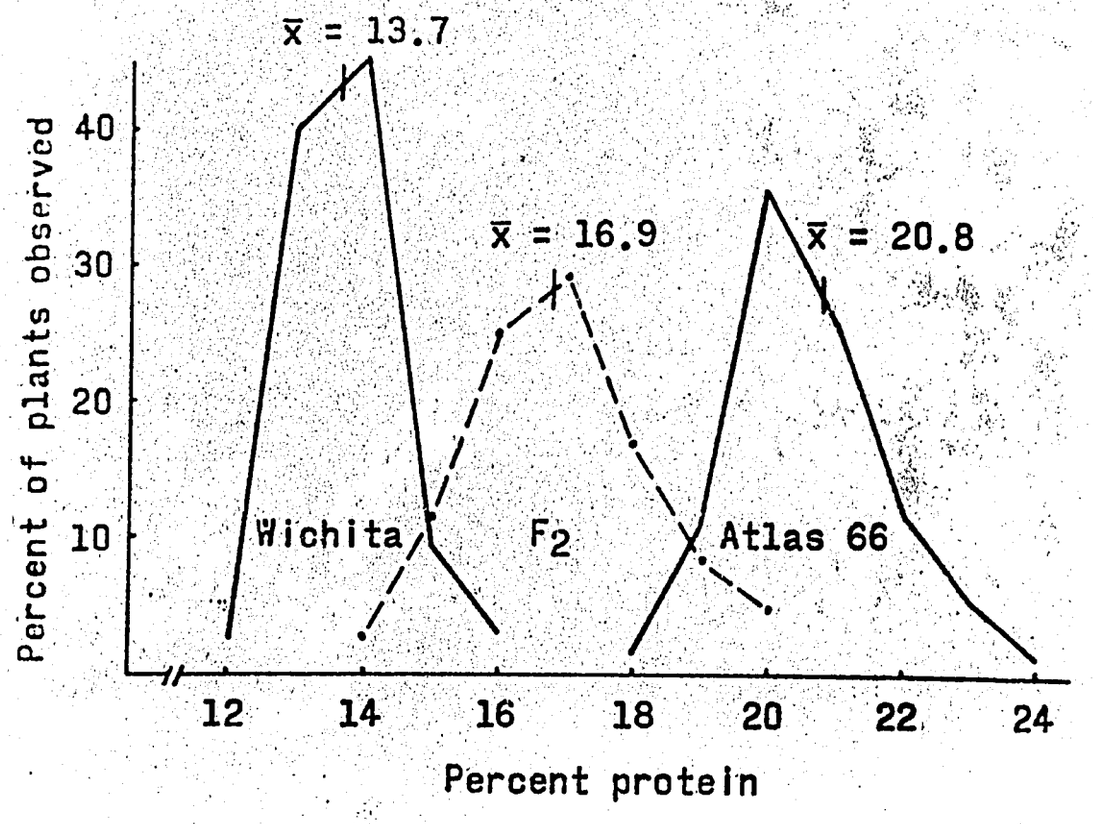

x̄ = 13.7
x̄ = 16.9
x̄ = 20.8
Wichita
F2
Atlas 66
Percent of plants observed
40
30
20
10
12
14
16
18
20
22
24
Percent protein

Fig. 3

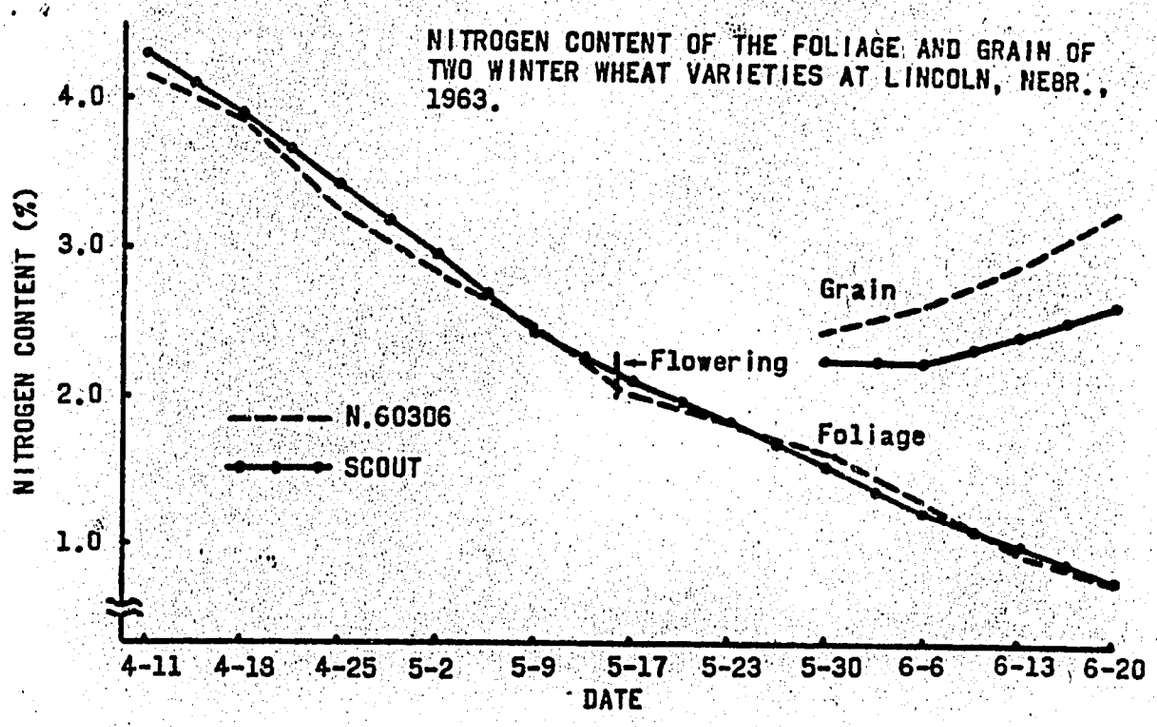

NITROGEN CONTENT OF THE FOLIAGE AND GRAIN OF TWO WINTER WHEAT VARIETIES AT LINCOLN, NEBR., 1963.
NITROGEN CONTENT (%)
4.0
3.0
2.0
1.0
Grain
Flowering
Foliage
N.60306
SCOUT
4-11
4-18
4-25
5-2
5-9
5-17
5-23
5-30
6-6
6-13
6-20
DATE

Fig. 4

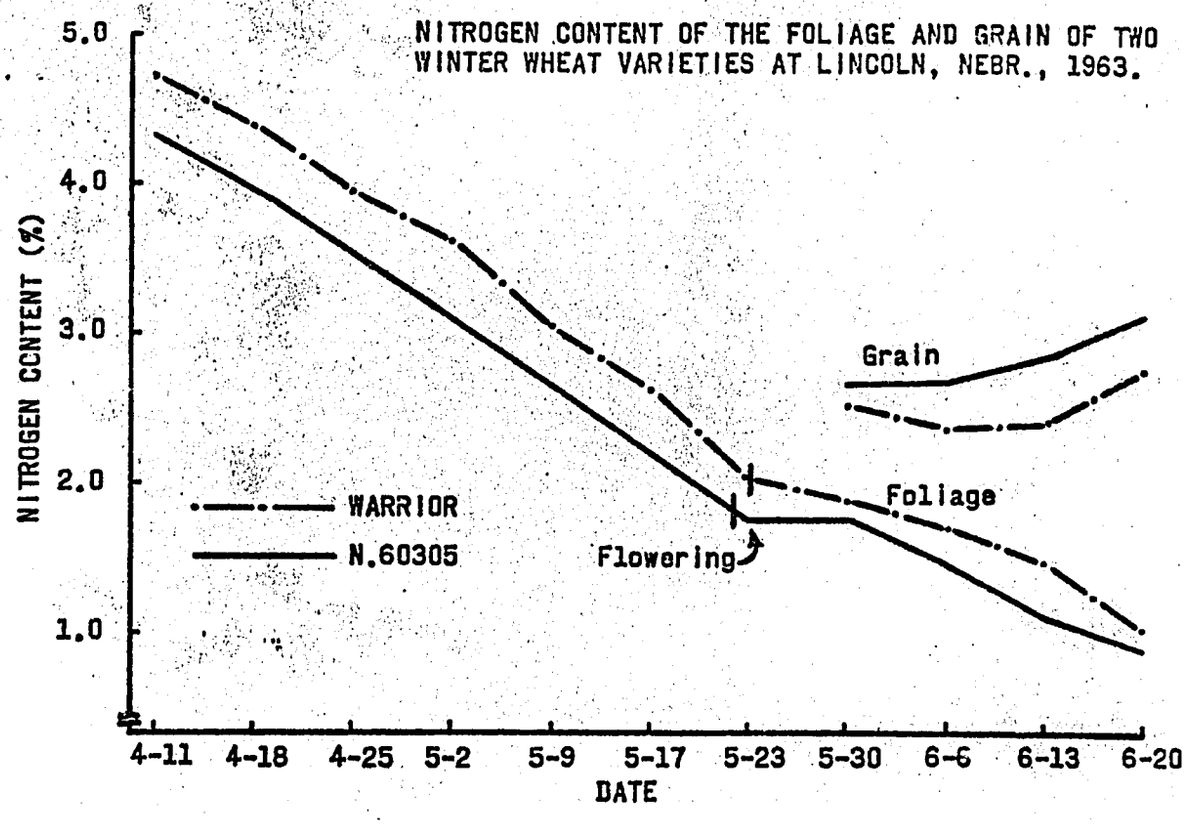

NITROGEN CONTENT OF THE FOLIAGE AND GRAIN OF TWO WINTER WHEAT VARIETIES AT LINCOLN, NEBR., 1963.
NITROGEN CONTENT (%)
5.0
4.0
3.0
2.0
1.0
Grain
Foliage
WARRIOR
N.60305
Flowering
4-11
4-18
4-25
5-2
5-9
5-17
5-23
5-30
6-6
6-13
6-20
DATE

Fig. 5

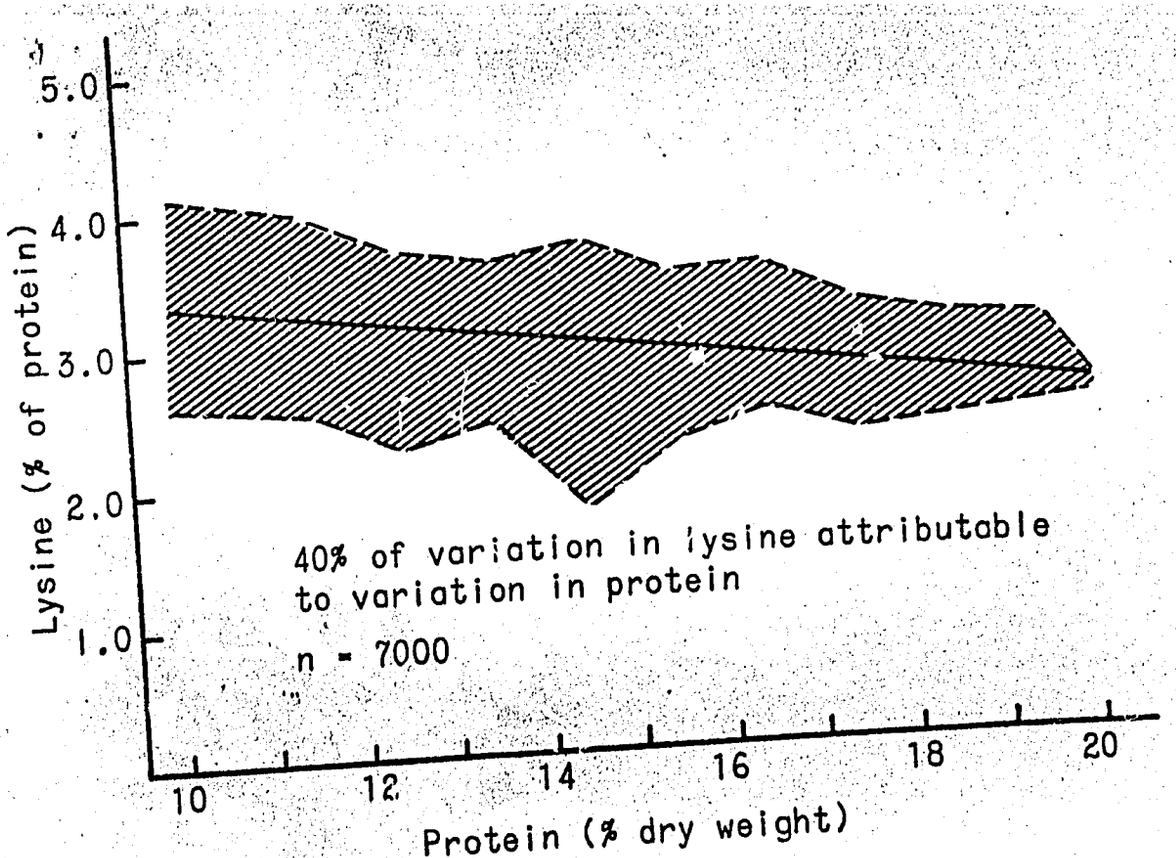
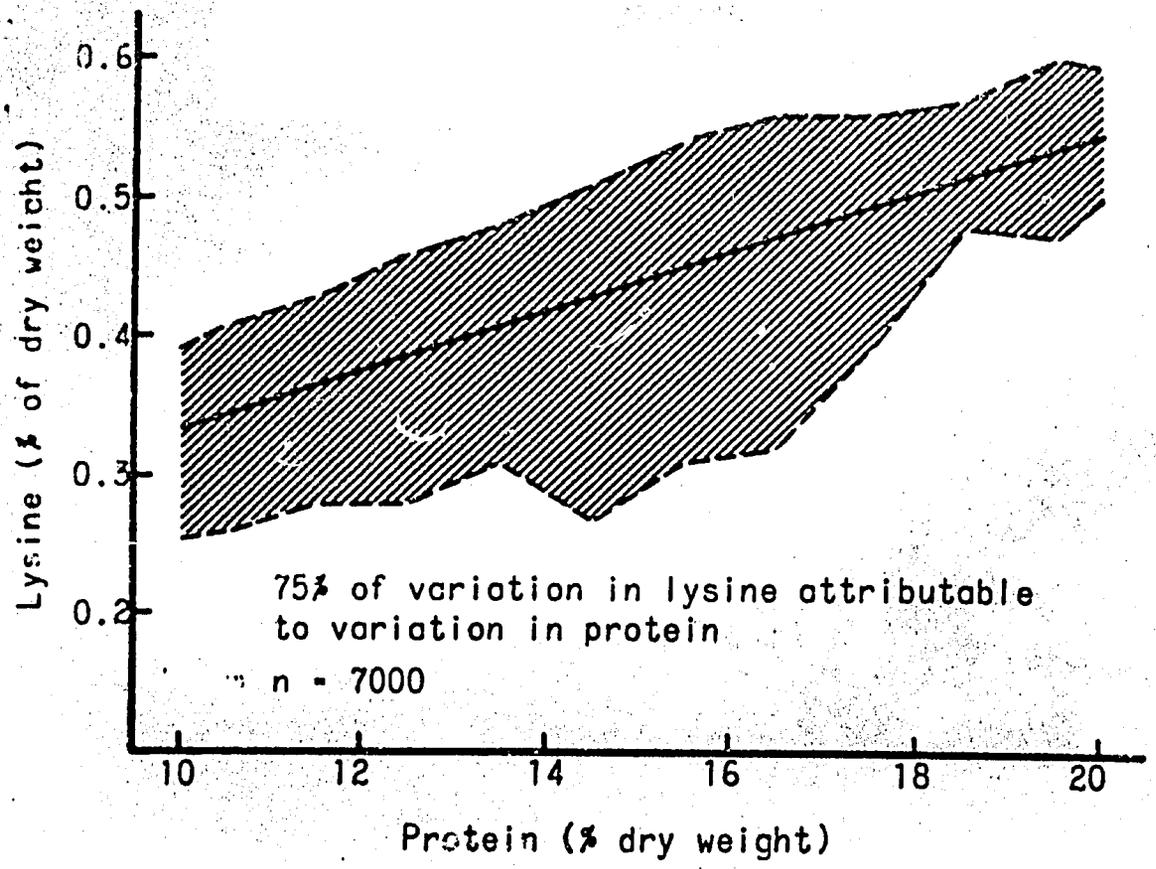

Lysine (% of protein)
5.0
4.0
3.0
2.0
1.0
40% of variation in lysine attributable to variation in protein
n = 7000
10
12
14
16
18
20
Protein (% dry weight)

Fig. 6


0.6
0.5
0.4
0.3
0.2
Lysine (% of dry weight)
75% of variation in lysine attributable
to variation in protein
n = 7000
10
12
14
16
18
20
Protein (% dry weight)