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Characterization of the Caryopsis of Common Wheat Varieties and F_2 Generation Hybrids by Means of Multivariate Analysis

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Summary. Nineteen parameters of common wheat kernels were investigated by the multivariate procedure. A relationship between the DBC parameter and both specific gravity and kernel filling was found. In some populations an interdependence of the DBC parameter and the subaleurone endosperm thickness was found. In the analysis of principal components the DBC parameter was represented mostly by particular component. Significant dependences were found between the dimensions as well as the weight of the caryopsis and some dimensions of the crease and endosperm cavity. The dendrite constructed on the basis of the calculated Mahalanobis's generalized distances matrix represents the near affinity of reciprocal hybrids or pure lines originating from a single cultivar as well as hybrids and their parental forms.

Key words: Common wheat – Caryopsis – Multivariate analysis

Introduction

All considerations of the dependence of caryopsis features and the description of wheat populations by them, may be reduced to the problem of grain ideotype. Hence, Popov et al. (1973) proposed a spherical form for the wheat kernel, obtained, among other ways, by crossing with the *T. sphaerococcum* form. This form is most useful for drying, cleaning and milling of grain. The aleurone layer cells should be uniform in shape, permitting the best separation of the endosperm (Creve and Jones 1951). Kamra (1971) and Konarev (1974) postulate an increased number of aleurone layers, while Kent (1966) also proposes an increase of the thickness of subaleurone endosperm. Some data concerning variation of both these parameters have already been presented (Kosina 1979a). The change of the quality of grain may depend also on the ratio embryo: endosperm (Kamra 1971; Kosina 1979a). Fritsch et al. (1977) indicated some possibilities in this respect. The results presented below are of spring wheat caryopsis multivariate analysis and should elucidate certain problems of the grain ideotype formulation. One should emphasize that multivariate analysis applied to study of the cereals yield structure (Kaltsikes 1973, 1974) has not been helpful so far in detailed investigations of cereal grain.

Materials and Methods

The caryopses of pure lines and F_2 generation hybrids of the spring cultivars of *Triticum aestivum* (L.) Thell. ssp. *vulgare* (Vill.) MK were studied. The hybrids and parental forms were planted in equal soil-climatic conditions, each on a single plot. Each plot consisted of two rows of twenty plants each. The plant grew on podsol at the Agricultural Research Station Swojec near Wrocław. The material was submitted to one-way classification in a completely randomized design. The following cultivars were investigated (in brackets are given the symbols denoting the pure lines used further in the text): 'Nagradowicka' (N), 'Opolska' (01, 02, 03, 04), 'Gorzowska Sztywna' (GS1, GS2), 'Rokicka' (R1, R2), 'Ostka Popularna' (OP2, OP3, OP4, OP5), 'Manitoba' (M), 'Oktawia' (Ok1, Ok2, Ok3), 'Capega' (C1, C2, C3, C4), as well as the pairs of reciprocal hybrids originating from parental forms: OP5 – GS1; OP3 – M; C1 – N; Ok1 – R1; Ok2 – C2; OP4 – C3; R2 – O3; C4 – O4; Ok3 – GS2 and OP2 – O2.

The investigated samples represent awned and awnless types of Central European wheats with the Manitoba cultivar as a quality standard. The latter is also interesting with regard to transgressions of structural features of the kernel in some of its hybrids (Kosina 1979c). The above named cultivars are derived from Galician and German local forms. A soft Galician wheat, 'Red Fife' played an important part in their origin. For the mentioned lines and hybrids, random samples for homozygous populations (n = 50) and for heterozygous populations (n = 100) were chosen.

Nineteen characters of each caryopsis were determined:

1. Width (mm)
2. Thickness (mm)
3. Length (mm)
4. Weight (mg)
5. Depth of crease (mm)

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6. Width of crease (mm)
7. Length of the endosperm cavity appendices (μm). It is the sum of two distances between the aleurone layer and seed coat penetrating into the crease, measured on both sides of the latter.
8. Height of the cavity (μm). It is the distance between the aleurone layer and seed coat forming the crease, measured along the crease.
9. Thickness of the fruit and seed coats (μm)
10. Thickness of aleurone layer (μm)
11. Thickness of high-protein subaleurone endosperm layer (μm). This layer is strongly stained with bromophenol blue and contains fewer starch grains.
12. Specific gravity of caryopsis (g/cm^3). This character was determined by measurement of weight in air atmosphere of caryopsis and in absolute ethanol.
13. Empirical volume of caryopsis (mm^3). The data from measurement of character no. 12 were used.
14. Maximum theoretical volume (mm^3). This is the volume of the three-axial ellipsoid with the dimensions of the caryopsis as axes.
15. Coefficient of caryopsis filling (abstract number). It is calculated from the ratio of both volumes.
16. Coefficient of caryopsis shape (abstract number). The increase of this character value indicates elongation of the caryopsis.
17. Coefficient of endosperm yield (abstract number). Its value is negatively correlated with the amount of endosperm. On the grain cross-section it is the ratio of elements reducing the amount of endosperm (fruit and seed coats, aleurone layer, crease, endosperm cavity) to the cross-section as a whole.
18. Coefficient of endosperm quality (abstract number). On the grain cross-section it is the ratio of protein layers (aleurone and subaleurone layer) to the cross-section as a whole.
19. Quality of caryopsis = the DBC parameter. Amount of Acilane Orange G12 (mg) bound to 10 mg of flour from a single caryopsis.

For each pure line and hybrid the 100-kernel weight was determined. Anatomical measurements were performed on the middle part of the caryopsis and the DBC analyses on the part with the brush; the part of the kernel with the embryo was preserved from specimens as it was considered valuable for examining features for sowing. The variability and correlations between the characters were analysed with application of methods of simple correlation, Hotelling's principal components, stepwise multiple regression, and canonical correlation (Morrison 1967; Press 1972; Bartkowiak 1978). The investigated wheat forms were arranged in the dendrite according to Mahalanobis's generalized distance (Lee and Kaltsikes 1972; Bartkowiak 1978).

Results

Simple Correlation

A number of significant correlations between the characters of the caryopsis were found. Nine matrices of coefficients of correlation for the parental forms and ten matrices for hybrids were analysed. Table 1 shows as example the correlation matrix for the 'Capega 3'/'Ostka Popularna 4' hybrid. The dependences of the kernel width and thickness with the other features are typical for the majority of hybrids and parental forms. However, a negative dependence of the coefficient of endosperm quality appears more often, while a positive correlation with the coefficicient of endosperm yield, like the one indicated in the Table, is rarer. The correlation of thickness with filling of the kernel appears in these forms sporadically. A low but significant correlation between thickness of the caryopsis and that of the aleurone layer is noteworthy. The correlations between kernel length and its specific gravity, or filling of the grain, are sporadical, while correlation with width of the crease is more frequent. The high correlations of kernel weight with the depth of the crease, length of the cavity appendices and thickness of the high-protein endosperm layer are interesting. The dependences of the kernel weight with other features are characteristic for the majority of forms. The width of the crease is often positively correlated with kernel shape, while negatively correlated with length of the cavity appendices as well as with thickness of the subaleurone endosperm. These dependences did not appear in the C3/OP4 hybrid. The length of the cavity appendices depends sporadically on specific gravity and shape of the kernel. Positive dependences between the height of the cavity and the thickness of the subaleurone endosperm as well as a negative relation with the width of the crease, length of the cavity appendices and the coefficient of kernel shape were noted. These correlations do not appear in the C3/OP4 hybrid. The thickness of the fruit and seed coats, in contrast to the correlation matrix presented, often depends positively on the width of the crease and sporadically on the characters numbers 10, 11, 16, 18. In some of the populations the dependence of this feature on the DBC parameter appears. A small number of wheat forms showed a dependence of the thickness of the aleurone layer on the thickness, weight and volume of the grain, the length of the cavity appendices and the thickness of the subaleurone endosperm. In the C3/OP4 hybrid the correlation between the aleurone layer thickness and the DBC parameter is noteworthy. The thickness of the subaleurone layer correlates positively most often with the dimensions, weight and volume of the grain, depth of the crease, length of the cavity appendices, thickness of the seed coat, thickness of the aleurone layer, specific gravity, filling of the grain, and the DBC parameter. The subaleurone layer is thinnest in elongated kernels (negative relation with the coefficient of kernel shape). Some of these dependences were ascertained in the C3/OP4 hybrid. The specific gravity of the grain depends positively on the width, thickness, weight and volume of grain, the thickness of the subaleurone endosperm, and negatively on the width of the crease, elongation of the kernel (shape) and the DBC parameter. Both volumes depend positively on the dimensions and weight of the grain, thickness of the fruit and seed coats, thickness of the aleurone layer and subaleurone endosperm, specific gravity and filling of the grain, and sporadically

Table 1. Matrix of the significant simple correlation coefficients for the caryopsis characters in the Capega 3/Ostka Popularna 4 hybrid. (n = 100, r X 10^3)

No. of characters	1	2	3	4	5	6	7	8	9
19	–	–	–	–	–	–	–	–	321***
18	–	–	–	–	–	–267**	–	–	226*
17	260**	305**	394***	299**	642***	684***	462***	224*	285**
16	–807***	–572***	–	–596***	–445***	–	–567***	–	–235*
15	286**	307**	346***	486***	293**	–	379***	–	–
14	890***	935***	868***	979***	860***	–	642***	–	384***
13	874***	920***	864***	996***	849***	–	665***	–	331***
12	364***	435***	254*	443***	–	–382***	227*	–	–
11	493***	496***	340***	506***	333***	–	311**	–	408***
10	–	277**	–	–	–	–	–	–	223*
9	343***	326***	287**	301**	342***	–	231*	–	
8	–	–	–	–	–	–	–		
7	709***	540***	455***	662***	564***	–			
6	–	–	344***	–	376***				
5	686***	869***	790***	828***					
4	869***	924***	855***						
3	633**	821***							
2	738***								

Table 1. (continued)

No. of characters	10	11	12	13	14	15	16	17	18
19	284**	261**	–303**	–	–	–245*	–	–	358***
18	450***	757***	–	–	–	–	–	–259**	
17	–	–	–352***	350***	338***	–	–		
16	–	–469***	–477***	–585***	–606***	–			
15	–	–	255**	479***	328***				
14	213*	519***	354***	985***					
13	–	510***	366***						
12	–	218*							
11	313**								

*, **, *** Significance levels at α = 0.05, 0.01, 0.001 respectively

on the DBC parameter. The filling of the grain in some forms correlates negatively with the DBC parameter. The shape of the kernel (its elongation) most often correlates negatively with most of the characters. The yield of the endosperm is higher with thicker subaleurone layer and higher specific gravity, while it decreases with large dimensions of crease, long cavity appendices and thick fruit and seed coats. The coefficient of endosperm quality is greater for elongated caryopses, this being connected with a higher content of aleurone and subaleurone layers in them. This coefficient depends negatively on the kernel weight and also on the dimensions of the crease. A few of the investigated forms showed a positive dependence of the DBC parameter on the thickness of the seed and fruit coats and subaleurone layer, volume of the grain as well as a negative dependence on specific gravity and filling of the grain.

In the whole examined material of common wheat the 100-kernel weight showed a high and significantly positive dependence on, successively:

weight and volume of grain (r = 0.967; 0.926),

width and thickness of grain (r = 0.909; 0.760),

length of cavity appendices and filling of grain (r = 0.689; 0.637).

thickness of subaleurone endosperm and length of kernel (r = 0.529; 0.505),

depth of crease and thickness of fruit and seed coats (r = 0.474; 0.355),

and a negative relation with elongation of the kernel (r = –0.454).

Table 2. Stepwise multiple regression analysis of the caryopsis characters, the DBC parameter as the regressand

Partial coefficients of regression	Populations			
	01	N/C1	C3/OP4	Ok2/C2
b_0	–1.015	0.435	1.981	3.270
b_1	095	028	– 119	– 108
b_2	113	005	– 102	– 095
b_3	– 182	065	017	026
b_4	020	– 017	– 017	031
b_5	– 101	099	– 124	– 094
b_6	119	020	– 124	– 148
b_7	000	000	– 000	– 000
b_8	000	000	– 000	– 000
b_9	001	000	– 000	– 001
b_{10}	– 004	– 000	– 001	– 002
b_{11}	– 002	000	– 002	– 001
b_{12}	– 472	186	224	– 732
b_{13}	– 020	028	014	– 036
b_{14}	007	– 013	019	009
b_{15}	– 556	– 272	128	– 163
b_{16}	2.582	– 065	–1.265	– 986
b_{17}	– 368	– 463	790	554
b_{18}	2.260	120	3.152	1.357
R^2	0.624**	0.374**	0.441***	0.442***
Regression set after reduction	b_0 1.269	b_0 0.577	b_0 1.032	b_0 1.059
	b_{15} –0.572***	b_3 0.025*	b_2 0.034***	b_6 –0.054**
		b_7 0.0001***	b_{12} –0.277***	b_{12} –0.238***
		b_{11} 0.004*	b_{15} –0.152	
		b_{15} –0.107*	b_{18} 0.780***	
R^2	0.256***	0.312***	0.332***	0.185***

*, **, *** Significance level of the determination coefficient and the partial coefficients of regression at α = 0.05, 0.01, 0.001, respectively. The partial coefficients of regression for the variables remaining in the regression set after its reduction are given in the lower rows of the table

Stepwise Multiple Regression Analysis (Table 2)

The DBC parameter (character no. 19) was assumed to be the regressand (y) while the remaining characters of grain were considered as independent variables (x). Analyses were carried out for 01, N/C1, C3/OP4 and Ok2/C2 populations. All variables located in the regression set provide 37 to 62% of the information on the DBC parameter. This character contains a great deal of its own information (see the R^2 value for complete regression sets). After stepwise reduction of the regression sets there remains in them such characters as specific gravity of the grain or the degree of its filling. A dependence of the DBC parameter on other variables such as: thickness and length of caryopsis, width of the crease, length of cavity appendices and thickness of the subaleurone layer also appears. The R^2 values are highly significant after reduction, but the R^2 value for the reduced sets is considerably lower, for example as in the Ok2/C2 hybrid.

Hotelling's Principal Components Analysis

Examples of the results of this analysis for the pure line of the 'Opolska' cultivar are presented in Table 3. The first component contains mainly information on the dimensions, weight and volume of the grain, the depth of the crease, the thickness of the fruit and seed coats, the thickness of the aleurone and subaleurone layers, the filling and shape of the grain. All the mentioned characters are correlated negatively with the component, except kernel shape. The first component contains 47.5% of all information concerning the nineteen characters examined. This component characterizes mainly 'the size of the caryopsis and its outer anatomical parts'. The second component provides information mostly on the width of the crease, specific gravity of the caryopsis and the amount of endosperm in the grain. One may designate it as 'the component of endosperm yield from a single kernel'. The third component explains the variability of the height of the

Table 3. Hotelling's principal components analysis for the kernel characters of Opolska pure line (01): The correlation of characters with components $\times 10^2$

No. of character	Components I	II	III	IV	V	VI	VII	VIII	IX	X	Sum of variation exhausted by the components for the successive characters (p.c.)
1	−95	−03	08	−08	−08	−03	03	−00	−10	19	97.4
2	−97	−04	03	−12	−02	03	−04	03	06	−03	96.2
3	−69	38	19	01	−29	17	−25	27	−00	−17	93.3
4	−99	−04	06	−09	−05	−00	−01	02	03	−05	99.1
5	−84	41	09	−22	02	08	−01	−04	05	−10	95.9
6	01	85	02	−07	15	34	17	−01	13	11	92.6
7	−53	21	14	54	−10	−29	−38	−28	−20	−00	98.9
8	−24	−18	−51	−51	50	−17	−25	02	−14	02	97.5
9	−56	28	−11	08	−09	−49	49	−13	17	01	94.2
10	−57	−28	−37	30	11	12	−28	−05	47	20	99.6
11	−72	06	−56	06	−22	11	15	02	−27	03	98.8
12	−46	−59	15	−11	02	35	12	−44	04	−29	99.2
13	−98	02	05	−09	−05	−03	−02	07	03	−03	99.0
14	−98	04	06	−12	−12	01	−05	03	01	02	99.6
15	−59	−17	02	32	49	−21	12	28	06	−30	95.5
16	91	23	−02	11	−08	05	−11	09	06	−21	97.7
17	09	86	−17	−05	32	−05	−15	−26	00	−11	99.0
18	00	05	−90	26	−18	21	09	03	−05	−13.	99.3
19	48	01	−26	−41	−49	−36	−17	−04	21	−15	93.5
Sum of variation exhausted by the successive components (p.c)	47.5	12.9	9.2	6.0	5.7	4.6	3.9	2.8	2.5	2.2	97.2

In the columns, the value of the correlation coefficient of the character with the component for components from I to X is given

Table 4. Hotelling's principal components analysis for the kernel characters of *Triticum aestivum* ssp. *vulgare* (together with 100-kernel weight): The correlation of characters with components $\times 10^2$

No. of character	Components I	II	III	IV	V	VI	VII	VIII	IX	X	Sum of variation exhausted by the components for the successive characters (p.c.)
1	−95	−08	−14	−07	00	−12	−12	−05	−02	09	97.8
2	−78	−48	−05	31	03	13	−02	02	−12	−13	97.5
3	−42	−10	82	−17	−24	−12	−06	14	08	−08	99.5
4	−98	−08	15	07	−08	−03	01	00	02	01	99.6
5	−44	−83	09	22	14	−04	−10	02	08	−05	98.2
6	28	−80	25	15	39	01	−01	−13	03	−01	97.5
7	−76	−02	−41	−38	−13	−21	01	01	08	16	97.6
8	−22	61	−42	17	−16	33	−40	02	22	−17	99.7
9	−45	08	−31	−73	30	14	−08	04	−09	−13	97.9
10	−23	06	67	−20	−12	58	−08	−29	−02	14	99.7
11	−56	62	23	07	46	02	−06	13	−01	09	99.6
12	−32	82	−05	25	−06	−24	−07	−10	10	18	95.3
13	−96	−23	15	04	−07	01	03	02	−00	−02	99.6
14	−92	−29	21	04	−08	−05	−08	03	−05	−01	99.7
15	−70	22	−20	03	05	27	53	−02	23	−07	99.9
16	56	14	73	−21	−21	−09	04	14	12	−05	99.9
17	22	−84	−03	−18	29	−11	−11	−05	30	07	99.7
18	−06	73	39	11	50	13	−01	14	−00	05	99.5
19	21	−71	−27	07	−16	44	−01	31	−01	24	99.4
20 (100-kernel weight)	−97	−04	12	03	−02	−08	05	00	−03	01	96.4
Sum of variation exhausted by the successive components (p.c.)	39.0	25.8	13.1	5.5	5.1	4.6	2.6	1.5	1.3	1.2	98.7

In the columns, the value of the correlation coefficient of the character with the component for components from I to X is given cavity and of the coefficient of endosperm quality. A considerable amount of information on the height of the cavity is also given in the fourth component. The latter informs in principle about the length of cavity appendices (a great part of information on this character is also contained in the first component). The fifth component refers to the DBC parameter. Component I also contains much information about this character. Five components exhaust 81.3% of the information concerning the examined features, while ten components exhaust 97.2% of it. Similar analyses for N/C1, C3/OP4 and Ok2/C2 forms were performed. For the N/C1 hybrid the information on the DBC parameter in component IV is given together with information on filling of the grain. The first and second components are similar, as in the 01 cultivar. Ten components exhaust 95.6% of information of all characters. In the C3/OP4 hybrid the DBC parameter together with the thickness of the seed coat and specific gravity of the kernel is most higly correlated with component III while in the Ok2/C2 hybrid it is correlated as a separate character with component V. These remarks on exhaustion of the DBC parameter information by various components in various populations point to the distinctiveness of the morpho-anatomical structure of the examined caryopses. Similarities of principal components are revealed by the analyses. Thus: component I informs mainly about the size and shape of the grain as well as on some dimensions of the crease and cavity or about the layers enveloping the caryopsis; component II refers most often to the quantity of endosperm in the caryopsis; component III concerns the quality of the endosperm. Principal component analysis realized for all forms of *Triticum aestivum* ssp. *vulgare* for twenty characters (together with 100-kernel weight) finds in component I information on the width, thickness, weight, volume and filling of grain, the length of cavity appendices and 100-kernel weight. This component exhausts 39% of the information about these features. The second component exhausts the variability of the crease dimensions, height of cavity, thickness of subaleurone endosperm, specific gravity, quantity and quality of endosperm as well as DBC parameter. The thickness of the subaleurone endosperm and DBC parameter are inversely correlated with this component. The third component informs about caryopsis length, thickness of the aleurone layer and kernel shape. Component IV exhausts the basic variation of the fruit and seed coats thickness. These four components exhaust as much as 83.4% of information on all characters (Table 4).

Canonical Correlations

Three sets of characters were established conventionally:

1. Character nos. 10, 11, 12, 18, 19 – the set of parameters denoting 'the quality of grain' determined by anatomical measurements and chemical analysis.
2. Character nos. 1, 2, 3, 4, 13, 14, 15 – the set indicating 'the shapeliness of caryopsis' decisive for the yield.
3. Character nos. 5, 6, 7, 8, 9, 16, 17 – the set indicating 'the yield of endosperm from the caryopsis'.

Canonical analyses for the O1, N/C1, C3/OP4, Ok2/C2 populations as well as for all populations of *Triticum aestivum* ssp. *vulgare* with inclusion of the 100-kernel weight in the second set, were carried out. In Tables 5 and 6 are shown the complete sets of multiple correlation coefficients of each character from one set with the second set. Observation of R^2 gives the following results:

I (correlation of sets 1 and 2) – The highest R^2 value in correlation with the second set is displayed by character no. 12 from set 1 (specific gravity of the kernel – 'shapeliness of caryopsis'). In an inverse combination in all populations, character 1 from set 2 has a high value of R^2 in correlation with the first set (width of the caryopsis – 'quality of grain').

II (correlation of sets 1 and 3) – Most dependent on the third set are character nos. 11, 12, 18 in the first set. However, the R^2 values are considerably lower than in combination I; in the inverse situation in the third set it is character no. 16 (the shape of the caryopsis) that is most dependent on set 1. The R^2 values are considerably higher here.

III (correlation of sets 2 and 3) – The following characters of the second set are most highly correlated with set 3: 1, 2, 3, 4, 13, 14 (the entire set except the filling of the kernel); in an inverse situation the depth of the crease and the shape of the kernel from the third set are most highly correlated. The R^2 values here are very high in both situations.

Essential information about the canonical correlations is found in the lambda^2 column (square of the canonical correlation coefficient). Combination I is characterized by a highly significant correlation (chi-square test) of two to four canonical variables, combination II by a significant correlation of one to three canonical variables often at a lower significance level, and combination III by a highly significant correlation of two to five canonical variables. The existing correlations indicate a strong relation between the morpho-anatomical characters and the quality of the wheat caryopsis. The dependences between various sets of characters are not identical. And so, sets 2 and 3 are most strongly correlated ('shapeliness of kernel' – 'yield of endosperm'), more weakly are the sets 1 and 2 ('quality of kernel' – 'shapeliness of kernel') and most weakly correlated are sets 1 and 3 ('quality of kernel' – 'yield of endosperm'). Canonical analysis performed for *Triticum aestivum* ssp. *vulgare* (pure lines and hybrids) gives results similar to those mentioned above (Table 6). The 100-kernel weight is correlated most strongly with set 3, and somewhat weaker with set 1.

Table 5. Canonical correlations for the caryopsis characters of some pure lines and hybrids of common wheat

Sets of characters						01									N/C1								
						I			II			III			I			II			III		
I		II		III		R^2		lambda²	R^2		lambda²	R^2		lambda²	R^2		lambda²	R^2		lambda²	R^2		lambda²
x	y	x	y	x	y	x	y		x	y		x	y		x	y		x	y		x	y	
10	1	10	5	1	5	369	979	980***	351	584	946***	947	822	998***	167	970	973***	178	464	908***	896	779	997***
11	2	11	6	2	6	488	814	909***	513	222	377***	961	291	953***	176	527	916***	238	215	308***	924	462	983***
12	3	12	7	3	7	920	410	329**	486	311	153	923	440	380**	914	262	119	256	512	148*	937	494	397***
18	4	18	8	4	8	042	892	153	120	127	072	965	314	359*	280	755	095	276	085	084	940	149	225**
19	13	19	9	13	9	454	882	007	300	302	015	965	337	122	238	762	012	262	236	026	939	354	088
	14		16	14	16		892			903		978	998	051		800			844		980	996	028
	15		17	15	17		369			233		336	315	012		166			277		144	335	001
						C3/0P4									0k2/C2								
10	1	10	5	1	5	192	972	975***	165	545	909***	903	833	996***	122	962	970***	097	540	929***	936	934	996***
11	2	11	6	2	6	332	652	896***	437	274	416***	939	516	977***	293	547	924***	322	590	373***	936	768	968***
12	3	12	7	3	7	898	440	284***	512	481	229*	951	545	481***	914	326	197**	295	629	090	938	670	478***
18	4	18	8	4	8	153	797	059	229	055	035	961	113	377***	492	769	098**	437	121	037	953	336	427***
19	13	19	9	13	9	327	793	007	148	337	010	965	327	146*	255	762	071	098	180	002	957	284	086
	14		16	14	16		830			648		982	992	041		826			823		983	991	033
	15		17	15	17		200			375		267	460	001		119			189		183	588	002

R^2 = determination coefficient (square of multiple correlation coefficient between the character of the x-set and all the characters of the y-set, and vice versa). The value of $R^2 \times 10^3$ is given. Lambda² = square of the canonical correlation coefficient for the successive canonical variables (number of significant lambda² values and level of their significance determine the strength of the relation between two sets). The value of lambda² $\times 10^3$ is given.
*, **, *** Significance levels of lambda² at $\alpha = 0.05, 0.01, 0.001$, respectively

Table 6. Canonical correlations of kernel characters in *Triticum aestivum* ssp. *vulgare* (together with the 100-kernel weight – character no. 20)

Sets of characters						*Triticum aestivum* ssp. *vulgare*								
						I			II			III		
I		II		III		R^2		lambda²	R^2		lambda²	R^2		lambda²
x	y	x	y	x	y	x	y		x	y		x	y	
10	1	10	5	5	1	407	990	993***	469	612	972***	857	954	998***
11	2	11	6	6	2	600	661	965***	509	526	688***	649	958	994***
12	3	12	7	7	3	962	479	447**	665	775	622***	792	990	794***
18	4	18	8	8	4	478	889	208	469	396	201	545	964	659***
19	13	19	9	9	13	635	879	087	422	352	110	588	976	214
	14		16	16	14		865			628		997	989	111
	15		17	17	15		412			599		635	501	003
	20				20		873						918	

Explanation as in table 5

Differentiation of the Populations

The matrix of Mahalanobsis's D^2 statistics between populations of *Triticum aestivum* ssp. *vulgare* caryopses was calculated. Figure 1 presents the dendrite of the shortest distances. In the dendrite some pure lines of the cultivars 'Opolska', 'Nagradowicka', 'Rokicka', 'Capega', 'Manitoba', and 'Ostka Popularna' are distinct. The position of the pure lines of 'Ostka Popularna', 'Oktawia' and 'Opolska' varieties indicates their similarity within the limits of the given cultivar. The pure lines of other cultivars are more differentiated. The parental forms are often intermediately joined through their hybrids. All reciprocal hybrids within a pair are directly connected. The D^2 value between hybrids OP4/C3 and C3/OP4 is not significant. The remaining distances in the dendrite are statistically highly significant. The highest D^2 values in the Mahalanobsis distences matrix were found for:

OP3 – R2, $D^2 = 37.1$
Ok2/C2 – OP4, $D^2 = 39.0$
OP4 – 03, $D^2 = 41.6$
OP5 – 03, $D^2 = 45.7$

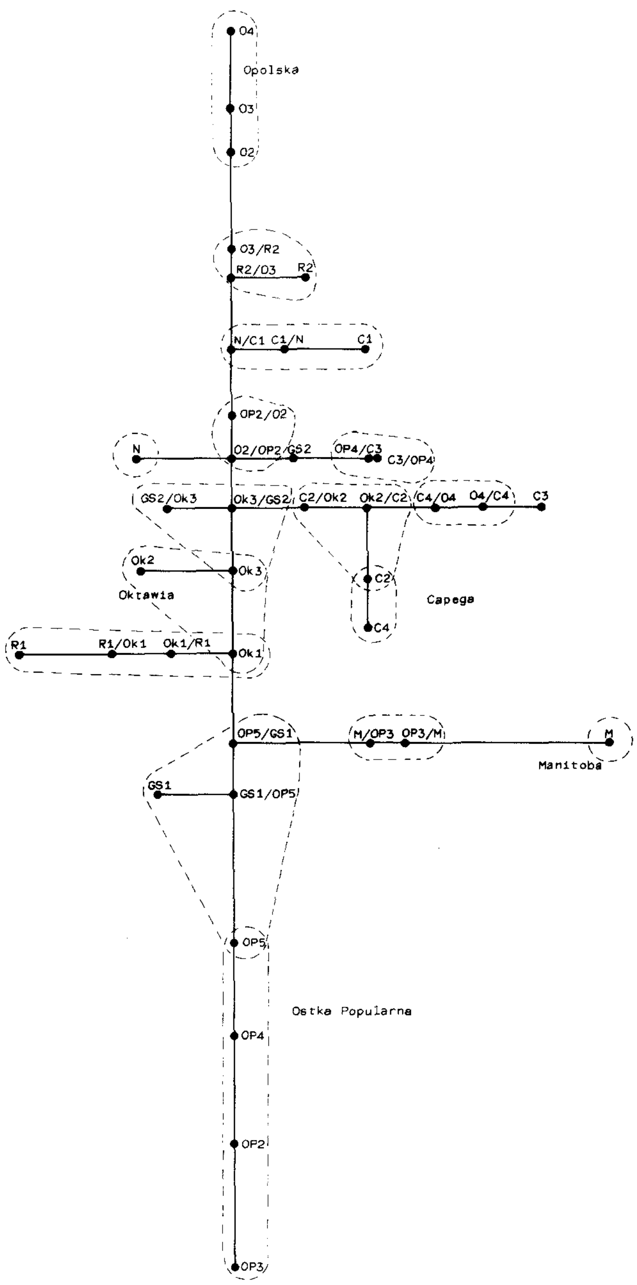

Fig. 1. Dendrite of the pure lines and F_2 generation hybrids of the *vulgare* form. Examples of Mahalanobis's distances in dendrite. minimum for OP4/C3 – C3/OP4 = 0.263; maximum for M – OP3/M = 6.681

Discussion

All the analysed characters of the caryopsis have a definite practical value. On the basis the author's own results and observations as well as of the literature, it may be said in general that caryopses with lower values of character nos. 3, 5, 6, 7, 8, 9, 16, 17 as well as with a higher value of character nos. 1, 2, 4, 10, 11, 13, 14, 15, 18, 19 and 20 are more useful for milling and baking. The specific gravity (character no. 12) for a well-filled caryopsis should have lower values: this would indicate a higher protein content in the caryopsis. The characters display a wider range of relative variability, from several per cent for specific gravity, filling and shape of grain, and DBC parameter to more than 100% for height of the cavity. Analysis of distributions of the characters shows their symmetry and skewness within the limits allowing for the realization of multivariate analysis (Kosina 1978b). The results presented above were intended to indicate the relationships between the quality and the morpho-anatomical structure of the caryopsis.

Previous investigations of the cereal grain referred to a few of its characters and their dependences. Among other things the negative dependence between the weight of a single caryopsis and protein percentage was described by Favret et al. (1970), Doll (1972), Munck (1972) for barley; Tanaka and Takagi (1970) for rice. Positive correlations yield/protein were described (Račinski and Račinska 1966; Bojadžieva 1972; Brej 1973; Johnson et al. 1973 for wheat; Doll 1972 for barley mutants; Tanaka and Takagi 1970 for rice mutants).

In the material studied the correlations between weight, volume, dimensions of kernel, and thickness of subaleurone endosperm or DBC parameter indicate a similar situation. In a few forms a positive correlation appears between the DBC parameter and the volume or dimensions of the caryopsis. An ascertained negative dependence between the yield of endosperm in the grain and thickness of the fruit and seed coats confirms the results of Vogel et al.

(1976) concerning the negative correlation of the flour yield from kernel and the weight of the coats. The dimensions of the caryopsis are strongly correlated and this confirms the previous results (Kosina 1974). The correlations between the crease and both the cavity dimensions and the DBC parameter are very interesting. The correlation of the DBC parameter with thickness of the subaleurone endosperm confirms the data indicating the importance of this layer for quality of grain (Kent 1966; Kosina 1979a). The negative correlation of the DBC parameter with the specific gravity or grain filling shows the relation: caryopses poorly developed – higher percentage of protein. In the described results the specific gravity indicates deviations from normal grain filling (negative correlation with width of crease), and not the value of the starch/protein ratio. In this sense it does not confirm the opinion of Jonard (1961) concerning a relation between specific gravity and the amount of protein in the caryopsis. The analysed correlation matrices differ from each other in a number of correlation coefficients; this indicates a somewhat different way of forming some kernel structures in the various forms examined. The DBC parameter in the above investigations was recognized as a determinant of protein amount in the caryopsis (Kosina 1978a). Its dependences on other features were analysed by means of stepwise multiple regression. The results confirm the data obtained in simple correlation and simultaneusly indicate, that this feature has its own distinct character, conditioned by other, unexamined features. The investigated populations differ considerably in the R^2 values for the total regression sets; it can also be seen that a considerable amount of information on the DBC parameter was not elucidated by measurement of other caryopsis characters. All four populations differ in the set of characters after reduction. This indicates, just as in the case of simple correlation, the dissimilarity of their caryopses formation.

Vogel et al. (1976), by means of multiple regression analysis, supplied data concerning the high dependence of protein and lysine percentage in the kernel on their content in the endosperm and less so, but also significant, on their content in the coats (fruit and seed coat and aleurone layer). In the presented results it was shown that there is a higher dependence of the DBC parameter on the thickness of subaleurone endosperm than on the thickness of the aleurone layer. This confirms partly the data of Vogel et al. (1976).

Factorial analysis for investigation of the yield components of cereals was used lately (Walton 1971, Kaltsikes 1973, 1974), while Kazakova (1975) presented the results of factorial analysis of eleven characters of the wheat grain and bread. She distinguished two factors representing 84% of the total variability of characters. The first factor exhausts information on the quantity of protein and gluten, and the second factor on the vitreousness of grain. The author concludes a distinctiveness of characters of both complexes. Up till now, the literature often contained data concerning their dependence. The principal components analysis performed confirms the results of simple correlation and stepwise multiple regression relating to the differences of the examined populations. The DBC parameter as a separate character or together with a small number of correlated characters is represented by distinct principal components. The obtained canonical correlations confirm the logical dependences of the character sets. Analysis of representation of the characters showed that the DBC parameter in the four-character first set is always represented. The set of 'grain quality' includes characters each of which brings its own information (Kosina 1979b). Biometric analysis performed, showed that the examined features differentiate well the investigated varieties and their hybrids. This appears distinctly in the dendrite. The close relationship of the pure lines of a single cultivar as well as of reciprocal hybrids or hybrids and their parental forms is evident. The results concerning some species of spring wheat and their hybrids show considerably wider Mahalanobis's distances between wheat species than between varieties of the *vulgare* form (Kosina 1978b).

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