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Accumulation of biomass and bioenergy in culms of cereals as a factor of straw cutting height**

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A b s t r a c t. Cereal straw is an important biomass source in Europe. This work assessed: 1) the morphological and energetic characteristics of culms of spring and winter cereals, 2) the energy deposited in the different aboveground parts of cereals, 3) losses of energy due to different cutting heights. The straw of winter and spring cereals was collected from arable fields during the seasons 2009/10 and 2010/11 in southern Poland. Detailed biometric measurements of culms and internodes were performed. The losses of straw biomass and energy were assessed during simulation of cutting the culm at different heights, up to 50 cm. Longer and heavier culms were developed by winter wheat and triticale and oat. Cutting of straw up to 10 cm did not lead to significant losses in straw yield. The total amount of energy in the culms was as follows: triticale > winter wheat > oat > spring wheat > winter barley > spring barley. Cutting the culms above 20 cm led to significant differences in terms of biomass energy between cereal species. The smallest losses of energy were recorded for spring and winter barley. Oat and barley accumulated the highest energy in grains.

K e y w o r d s: culm, internode, yielding, harvest index, harvest index energy

INTRODUCTION

The growing awareness of societies regarding environmental protection has resulted in efforts undertaken to increase the share of renewable energy in the total energy consumption in various countries (Borjesson and Gustavsson, 1996; Gokcol *et al.,* 2009). Saidur *et al.* (2012) argue that wood and wood wastes, followed by agricultural crops and their by-products, are the most important sources of energy from biomass. Cereal straw and wood biomass are the two major sources of renewable energy in central Europe (McKendry, 2002a, 2002b), given the large forested areas and a significant acreage of cereals. Demirbas *et al.* (2009) place straw as the third main source of biomass in Europe. Currently, cereals occupy about 70% of the arable land in Poland (Statistical Yearbook 2015) and about 54% of the arable land in the EU-28 (EUROSTAT 2015). With such a large share of cereals in the crop arrangement in Europe, local overproduction of straw is often a consequence. This situation relates mostly to farms where plant production is carried out (cereals) without livestock. In recent years, a majority of cereal straw has been used as both fuel and organic fertiliser (Gauder *et al.,* 2011; Summers *et al.,* 2003). To obtain a full environmental assessment of the production of biomass for energy purposes, assessment of the life cycle should be carried out (Krzyżaniak *et al.,* 2016).

The primary focus of cereal breeders and farmers, since the so-called ‘green revolution’, has been to improve grain yield per area unit to reduce hunger in the world, as cereal grains have a leading role in the caloric contribution in the human diet. This has been approached by using breeding tools and medium and high-input agricultural practices adapted to local habitats. Genetic breeding is focused on shortening the cereal culm, thus maximizing productivity. Capturing the natural mutation of wheat in Japan, as a gene donor for short straw, and transfer thereof to the United States immediately after the Second World War resulted in the creation of the wheat cultivar ‘Norin 10’, which has significantly accelerated the process of culm shortening (Reitz

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and Salmon, 1968). From the agro-biological point of view, the spectacular increase in the grain yield was mainly related to the expected response of highly productive and short-culmed cultivars to continually optimised cultivation methods (Austin *et al.,* 1989). The second reason for shortening cereal culms is prevention of lodging, as it leads to reduced quantity and quality of cereal grains (Foulkes *et al.,* 2011). It is believed that the reduced length of the culm, in combination with the increase in the crop and cultivar flexibility, ensures high resistance to lodging in intensive production. Introduction of chemical growth-retardants to agricultural practices effectively limited culm length, which, in turn, improved the resistance of the crop to lodging (Berry *et al.,* 2004; Tripathi *et al.,* 2003). Olumekun (1996) reported that the Cycocel growth retardant (*i.e.* 2-chloroethyl-trimethylammonium chloride) reduces the length, but does not reduce the weight of the wheat culm. This phenomenon relates to the anatomical effects of retardants, mainly to the simultaneous thickening of the culm and increasing its diameter, while the length of the internodes is shortened (Lowe and Carter, 1972; Sanvicente *et al.,* 1999; Tripathi *et al.,* 2003; Zając 1987). Consequently, straw yield is reduced (Rebetzke *et al.,* 2011).

The amount of cereal stubble depends on the height of straw cutting during harvest, and the amount of energy deposited in this stubble is not known. The quantitative changes in straw yield and in the related amount of energy left in the stubble are a result of varying cutting height at harvesting (Zając *et al.,* 2013b). There are no discernment studies relating to the vertical distribution of biomass in the culms of cereal species and cultivars of both winter and spring forms. Until now, no objective method referring to the accurate distribution of yield and energy in cereal straw has been developed. Our approach, as a scientific novelty, can help to determine precisely straw yield and energy deposited in the stubble, based on cutting height harvest. This work assessed: 1) the morphological and energetic characteristics of culms of different spring and winter cereal species, 2) the energy amount deposited in the different aboveground parts of cereal organs, 3) energy losses due to different cutting heights.

MATERIAL AND METHODS

Cereal culms were collected from arable fields where growth retardants were not used, in the southern part of Poland (Silesia; 49.7-50.0°N, 18.5-19.1°E) in the vegetative seasons 2009/2010 and 2010/2011. The following cereals were included: spring and winter wheat (*Triticum aestivum* L.), spring and winter barley (*Hordeum sativum* Pers.), winter triticale (x *Triticosecale* Wittm. ex. A. Camus), and oats (*Avena sativa* L). Each of the species was collected before the harvest from 30 different fields and from five different locations within each field, in an area of 1 m^2, lined diagonally across the field. For each of the locations, the number of ears per square meter was counted and, subsequently, 10 culms were taken for further analyses. The culms were cut at the ground level. Samples with a minimum of 100 culms per species were chosen for the final measurements and placed in an airy barn for slow drying.

We measured the biometric factors number, length, diameter, and mass of each of the internodes. The diameter was measured in the middle of each internode, using the electronic calliper Yato-7201®. In addition, the inflorescence was evaluated, *i.e.* the length of ears or panicles as well as the mass of seeds per inflorescence. After the measurements, each culm and inflorescence was placed in separate paper bags, which were kept in the dryer for 24 h at 105°C. Internode mass and straw yield were calculated based on 15% water content.

The following parameters were calculated:

– mass density per 1 cm^2 (Sanvicente *et al.,* 1999) for each internode;
– harvest index (Zając *et al.,* 2013a) as the ratio between grain weight and total dry matter weight;
– harvest index energy (Sinha *et al.,* 1982) accumulated in the straw and grain;
– straw yield (t ha^{-1}) calculated by multiplying the mass of a single culm by the number of culms per 1 m^2 and expressed as mass per 1 ha; analogical calculation was performed for the accumulation of energy in straw and grains (GJ ha^{-1});
– loss of straw yield simulated using Excel 2010 and based on the different heights of cutting culms every 2.5 cm from 0 to 50 cm.

The concentration of energy in the different parts of cereals was determined experimentally by measuring the higher heating value in a calorimeter KL-10 (Precyzja, Bydgoszcz, Poland) at an oxygen pressure of 20 atm, according to the Polish Norm PN-81/G-04513 and ISO 1928. The combusted sample was weighed with a precision of 0.0001 g and the results were calculated for 1 g.

Based on the calorimeter measurements, the following indicators were calculated:

UDM – energy per unit of dry matter of internode (J g^{-1}), value measured in the calorimeter:

$$WI = \text{mass of internode} \times UDM, \tag{1}$$

where: *WI* – energy per whole internode:

$$CE = \sum WI_1 + \ldots + WI_n, \tag{2}$$

where: *CE* – total energy of a whole cereal culm;

$$SI \text{ in } CE = \frac{(WI\ 100)}{CE}, \tag{3}$$

where: *SI* in *CE* is share of energy of single internode in the *CE*.

Due to the different share of culms of different heights noted in both vegetative seasons, the weighted average values were calculated.

The results were analysed using one-way ANOVA, separately for the analysis of cereal species or vegetative seasons. Significant differences between means were calculated using Tukey test. Regression analysis was performed using the statistical software STATISTICA 10 (StatSoft 2011).

Analysis of weather conditions in the Silesia region during the two consecutive vegetative seasons was carried out based on average air temperatures and total precipitation within a 30-year period (Table 1).

In the growing season 2009/2010, excessive rainfall was noted in spring (especially in May 2010), which caused local flooding as well as water retention on the surface of flat fields. Also, the cloudiness in May 2010 caused a drop in air temperature. Favourable conditions for cereal growth occurred during the growing season 2010/2011, due to higher air temperatures in the months of April-June. Only July 2011 was cooler due to intensive rainfall (211.6 mm), causing difficulties in the harvesting of cereals, especially winter barley.

RESULTS

On average, during the vegetative season 2011, cereals developed longer culms and internodes, compared to the 2010 season (Table 2). This arrangement was determined by the weather conditions in the spring and summer 2011, when lower precipitation and higher air temperatures were noted (Table 1). Higher air temperatures, especially during the generative development, promoted the elongation of internodes and improved the conditions of culms growth. In 2011, the 1st basal internode was significantly longer, heavier and thicker. Internodes 2-5, although longer than in the 2010 season, were significantly lighter and thinner. The highest, 6th internode (peduncle), was also longer in 2011, compared to that in 2010, but its weight and diameter did not differ between both seasons.

The culms of spring wheat consisted of only five internodes (Table 3). The culms of winter wheat and barley consisted mostly of five internodes, 93 and 84% of the plants, respectively. The culms of triticale and spring barley were equally composed of both five and six internodes. Oat developed culms with mostly six internodes (73% of plants). As expected, the basal internodes were the shortest, especially the first one, and the peduncle was the longest one. Moreover, in a situation when the culm was composed of more internodes, the first internode was by about 50% shorter than the basal internode of a culm with a lower number of internodes. The basal internode of oat was significantly shorter than that of the other species and forms. The length of subsequent internodes was increasing, with the exception of spring barley, in which the next but one internode was the longest. The distribution of weight per internode was species-specific. Both forms of wheat as well as oat displayed a linear increase in internode weight, with the highest weight found for the peduncle. Winter and spring barley accumulated the highest biomass in the middle internodes, and winter triticale in the next but one internode. In most of the cereal species, the 2nd or 3rd internodes were the thickest ones, except for spring wheat, where the highest diameter was noted in the 4th internode (the next but one). Compared to the other species, spring barley developed thinner internodes.

Table 1. Weather course during the months of cereal vegetation

Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Precipitation (mm)											
2009	–	–	–	–	–	–	–	–	47.5	32.7	18.9	43.2
2010	64.7	44.3	32.0	71.6	410.4	135.5	157.4	176.3	105.4	24.7	46.2	79.2
2011	49.4	26	43.8	68	128.2	133.9	211.6	95.5				
1967-2007	35.4	36.9	40.7	57.2	89.4	112.9	102.4	95.7	65.9	47.8	51.9	45.1
	Temperature (°C)											
2009	–	–	–	–	–	–	–	–	14.2	7.6	6.2	-0.6
2010	-5.7	-0.3	4.0	8.8	12.5	17.3	20.1	18.7	12.6	6.7	7.6	-3.6
2011	-0.2	-2.0	4.4	10.3	14.0	18.1	17.7	19.3				
1967-2007	-3.3	-1.7	3.4	8.7	13.0	16.5	18.3	17.7	14.21	9.6	3.7	-1.0

T a b l e 2. Comparison of selected characteristics of cereals culms in the vegetative seasons

Trait	Year	Internodes					
		1st (basal)	2nd	3rd	4th	5th	6th
Length (cm)	2010	2.8	8.5	13.2	17.6	24.5	22.3
	2011	4.3	10.2	14.6	21.3	27.8	31.3
LSD		0.26	0.36	0.47	0.85	1.21	2.57
p[1]		**	**	***	***	***	***
Weight (g)	2010	0.057	0.170	0.246	0.297	0.314	0.171
	2011	0.088	0.170	0.199	0.243	0.208	0.067
LSD		0.007	NS	0.013	0.018	0.020	0.029
p[1]		***	1.0	***	***	**	***
Diameter (mm)	2010	3.10	3.92	4.09	3.93	3.13	2.38
	2011	3.42	3.93	3.91	3.72	2.72	2.36
LSD		0.140	NS	NS	0.166	0.157	NS
p[1]		***	0.9	0.06	*	***	0.9

p[1] – level of significance, *p < 0.05, **p < 0.01, ***p < 0.001.

Generally, the longer the internode, the lower the biomass (Table 4). The biomass of 1-cm-long fragments of the culm differed significantly among the tested cereals. The share of each internode in the total culm mass of cereals relates to their length, but the correlation was not linear. The highest share in the total culm biomass for triticale, spring wheat, and spring barley had the next but one internode. In the case of winter wheat, winter barley, and oat, two internodes, the highest ones (peduncle) for wheat and oat and the 3rd and 4th in the case of barley, had the highest share in the biomass of their culms.

All tested cereals differed significantly in terms of culm length and weight (Table 5). In general, the winter cereals developed significantly longer and heavier culms than the spring ones, with the longest and heaviest culm being that of winter wheat and the shortest and lightest that of spring barley. In the vegetative season 2011, the culms of cereals were significantly longer, but lighter, compared to the previous year. Inflorescences were both longer and heavier in the vegetative season 2011.

The tested cereals had a different number of shoots per unit area, but this did not influence the final yield of grain or straw, *i.e.* spring barley developed the highest shoot density and, at the same time, had the lowest grain and straw yields (Table 6). The cereals yielded higher in the vegetative season 2011, when the agrometeorological conditions were more favourable than in the cooler and wetter season 2010. Both forms of barley, spring and winter, as well as oat had the highest values of the harvest index (HI) of all the cereals tested. On the contrary, HI of both forms of wheat, spring and winter, were lower due to the high yield of straw.

The cutting height of cereal straw at harvest determined the amount of losses in straw yield (Fig. 1). The cereals, regardless of the species, were characterised by a similar reaction to cutting. Low cutting, up to 10 cm, did not lead to significant losses in straw yield. Higher and visible losses in straw yield, within both forms of the cereals, *i.e.* spring and winter, occurred when the cutting height exceeded 20 cm. The increase in the cutting height up to 25 cm or more resulted in significant differences in straw yield losses between the cereal species.

Increased cutting height of winter wheat culms caused greater losses in straw yield, which for this cereal reached about 0.1 t ha^{-1} per each 1 cm of stubble left in the field. Among the spring cereals, oat was the most sensitive species, responding to increased cutting height with significant straw yield losses per unit area. Both forms of barley showed the lowest biomass losses with increased amounts of stubble left in the field.

T a b l e 3. Comparison of the morphological characteristics of cereal species culms, including groups of different numbers of internodes

Internodes	Winter species						Spring species					
	Wheat		Barley		Triticale		Wheat		Barley		Oat	
	Share (%)											
	7.3	92.7	84.3	15.7	55.5	44.5	100.0	0.0	50.0	50.0	27.3	72.7
	Length (cm)											
1st (basal)	6.2	3.3	4.4	1.7	4.8	2.7	4.0	–	4.7	2.5	4.3	1.7
2nd	12.5	9.9	11.9	8.4	9.7	8.2	9.0	–	11.4	8.0	9.5	6.1
3rd	24.0	16.1	16.8	14.7	13.7	10.6	14.4	–	14.8	10.2	13.9	9.9
4th	38.1	25.6	21.8	17.2	22.7	13.8	21.6	–	20.7	10.5	18.1	11.5
5th	–	34.5	28.5	20.8	29.3	23.2	30.7	–	18.8	12.8	35.4	17.8
6th	–	–	–	25.2	–	27.0	–	–	–	11.7	–	32.3
Σ	80.8	89.4	83.4	88.0	80.3	85.5	79.7	–	70.4	55.7	81.1	79.3
	Weight (g)											
1st (basal)	0.142	0.072	0.094	0.052	0.134	0.079	0.060	–	0.057	0.037	0.084	0.044
2nd	0.245	0.218	0.209	0.215	0.222	0.216	0.133	–	0.113	0.101	0.151	0.124
3rd	0.362	0.313	0.233	0.331	0.277	0.240	0.197	–	0.116	0.123	0.205	0.190
4th	0.368	0.413	0.232	0.321	0.378	0.281	0.292	–	0.121	0.119	0.238	0.209
5th	–	0.379	0.176	0.313	0.286	0.349	0.294	–	0.079	0.127	0.330	0.292
6th	–	–	–	0.232	–	0.240	–	–	–	0.094	–	0.391
Σ	1.116	1.395	0.944	1.464	1.297	1.405	0.976	–	0.486	0.601	1.009	1.251
	Diameter (mm)											
1st (basal)	–	3.21	3.64	3.44	4.12	3.79	2.88	–	2.82	2.67	3.49	3.08
2nd	–	3.74	4.29	6.04	4.76	4.50	3.40	–	3.34	3.19	4.04	4.01
3rd	–	3.97	4.28	5.13	4.93	4.77	3.42	–	3.16	3.18	3.95	4.32
4th	–	3.84	3.99	4.69	4.47	4.74	3.46	–	2.92	3.09	3.56	4.11
5th	–	2.69	2.60	4.12	2.72	4.07	2.62	–	2.07	2.82	3.07	3.73
6th	–	–	–	2.55	–	2.38	–	–	–	1.81	–	2.73

The total accumulation of bioenergy in the whole internodes (*WI*) as well as per 1 g of dry weight (*UDW*) of the compared cereals is given in Table 7. Winter cereals accumulated more energy in the individual internodes than the spring cereals, especially barley. In winter wheat and triticale, the fourth internode was the most abundant in energy. Oat accumulated the highest amount of energy in the highest internode, the peduncle, which was exceptional within the compared species. The accumulation of energy in 1 g of dry matter (kJ g^{-1}) in the particular internodes was generally insignificant. The relative share of individual internode energy in the total energy of culms was arranged in a similar way as for biomass (Table 4).

In the cooler and wetter season 2010, the 3rd to 5th internodes were more abundant in energy (Table 8). The accumulation of energy per 1 g of dry matter (kJ g^{-1}) in each of the internodes was insignificant between the vegetative seasons. A slightly higher energy was deposited in the 1st internode. The relative contribution of energy of the successive internodes in the total energy of the culm differed

T a b l e 4. Dry weight per unit length (1 cm) of straw of cereals and the estimated share of each of internodes in the total culm weight (the average of both vegetation seasons)

Internodes	Winter species						Spring species					
	Wheat		Barley		Triticale		Wheat		Barley		Oat	
	Dry weight per unit length (mg cm^{-1})											
Share (%)	7.3	92.7	84.3	15.7	55.5	44.5	100.0	0.0	50.0	50.0	27.3	72.7
1st	22.78	21.97	21.97	31.13	25.89	28.93	15.29	–	12.52	15.24	21.28	26.15
2nd	19.55	22.31	17.70	25.83	23.17	26.42	15.38	–	10.11	12.71	15.85	20.66
3rd	15.34	19.40	13.90	22.49	20.32	22.64	13.93	–	7.73	12.15	14.88	19.66
4th	9.89	16.14	10.63	18.66	16.65	20.28	13.69	–	5.82	11.38	13.00	18.43
5th	–	11.05	6.25	14.99	10.00	15.28	9.01	–	4.05	9.91	9.38	16.41
6th	–	–	–	9.32	–	9.11	–	–	–	8.25	–	12.02
LSD	0.847	1.349	1.236	3.269	2.007	2.480	1.271	–	1.016	1.205	2.586	1.938
p[1]	**	**	**	**	**	**	**	–	**	**	***	**
	Share (%) of each of internodes in the total culm weight											
1st	12.6	5.2	10.2	3.6	9.9	5.6	6.7	–	11.7	6.0	8.4	3.5
2nd	21.8	15.8	22.0	14.7	17.2	15.5	14.3	–	23.3	16.6	14.9	10.2
3rd	32.6	22.3	24.6	22.5	21.5	17.1	20.7	–	23.7	20.6	20.5	15.4
4th	33.1	29.5	24.6	21.9	29.2	19.9	30.3	–	25.0	19.8	23.5	16.8
5th	–	27.1	18.6	21.5	22.2	24.8	28.0	–	16.3	21.2	32.7	23.2
6th	–	–	–	15.9	–	17.1	–	–	–	15.8	–	30.9
LSD	3.952	0.847	0.861	1.454	1.287	1.130	1.246	–	1.720	1.124	2.128	1.043
p[1]	**	**	**	**	**	**	**	–	**	**	**	**

Explanations as in Table 2.

between the vegetative seasons. More energy was accumulated in the three basal internodes (1st to 3rd) in the 2011 season, compared to 2010. However, in the 2010 season, significantly more energy was accumulated in the upper, 5th and 6th, internodes.

Winter barley and spring wheat accumulated average amounts of energy in the culms; at the same time, the amount of energy accumulated in their culms was lower than in oat (Table 9). The lowest amount of energy in the culm was accumulated by spring barley, which has the shortest culm, as discussed earlier.

Among all the cereals tested, the highest amount of energy accumulated in the grain was found for oat and triticale. Both forms of wheat stored similar amounts of energy in the grain. Triticale and both forms of wheat, winter and spring, accumulated reasonable amounts of energy in the rachis and the chaffs. The energy accumulated in the culms, rachis, and chaffs was the highest in triticale. The other species can be ranked as follows: winter wheat > oat > spring wheat > winter barley > spring barley. Hereby, the significantly lower accumulation of energy in the culm and rachis of spring barley is interesting.

All the species tested accumulated lower amounts of energy in the straw yield per ha, compared to the grain yield (Table 10). Winter wheat accumulated the highest amount of energy of straw per ha, surpassing the other cereals in this respect. Three species, namely triticale, oat and spring wheat, accumulated similar amounts of energy in the straw per ha, whereas both forms of barley accumulated the lowest energy amounts.

Two species, namely oat and triticale, accumulated the highest amounts of energy in the grain yield per ha. Both forms of wheat accumulated a similar amount of energy in the grain per ha, despite their significantly different yields (Table 6). Non-hulled wheat and triticale cereals accumulated higher amounts of energy in the rachis, chaffs, and hulls; however, one can expect that the fraction of chaff and, especially, hulls will be lost in combined harvesting. It is worth emphasising that the non-hulled cereals accumulated more energy in the straw biomass, including culms, rachis, and chaffs. These relations were arranged

Table 5. Comparison of length and weight of components of the single culm of cereal

Species	Lenght (cm)			Weight (g)			
	Culm	Ear or panicle	Shoot	Culm	Ear or panicle	Grain	Shoot
Winter wheat	88.7	8.6	97.3	1.38	1.66	1.34	3.03
Winter barley	84.1	11.9	96.0	1.03	1.69	1.47	2.71
Triticale	82.6	9.9	92.6	1.35	2.31	1.83	3.65
Spring wheat	79.7	8.4	88.1	0.98	1.63	1.32	2.61
Spring barley	63.1	7.2	74.9	0.54	1.00	0.89	1.55
Oat	79.8	15.4	95.2	1.19	1.73	1.56	2.92
LSD	1.94	0.72	2.49	0.079	0.128	0.107	0.188
p[1]	**	**	**	**	**	**	**
2010	76.6	8.6	85.2	1.20	1.62	1.36	2.82
2011	82.7	11.8	96.1	0.95	1.71	1.44	2.67
LSD	1.59	0.53	1.65	0.060	NS	0.075	0.145
p[1]	***	**	**	***	0.05	*	*

Explanations as in Table 2.

Table 6. Density of cereals shoots per area, including the share of selected yield components and the harvest index

Species	Shoot density (pcs m^2)	Yield		Grain and straw biomas	Total aboveground biomas	Harvest index
		grain	straw			
		(t ha^{-1})				
Winter wheat	484	6.44	6.65	13.1	14.6	0.44
Winter barley	415	6.08	4.27	10.4	11.3	0.54
Triticale	388	7.05	5.21	12.3	14.1	0.50
Spring wheat	491	6.48	4.82	11.3	12.8	0.51
Spring barley	577	5.37	3.11	8.5	9.1	0.57
Oat	440	6.83	5.19	12.0	12.8	0.53
LSD	15.1	0.51	0.35	0.76	0.84	0.016
p[1]	**	***	**	**	**	**
2010	436	5.90	5.24	11.1	12.3	0.48
2011	495	6.85	4.52	11.4	12.6	0.55
LSD	12.0	0.29	0.26	NS	NS	0.010
p[1]	**	***	***	0.36	0.28	**

Explanations as in Table 2.

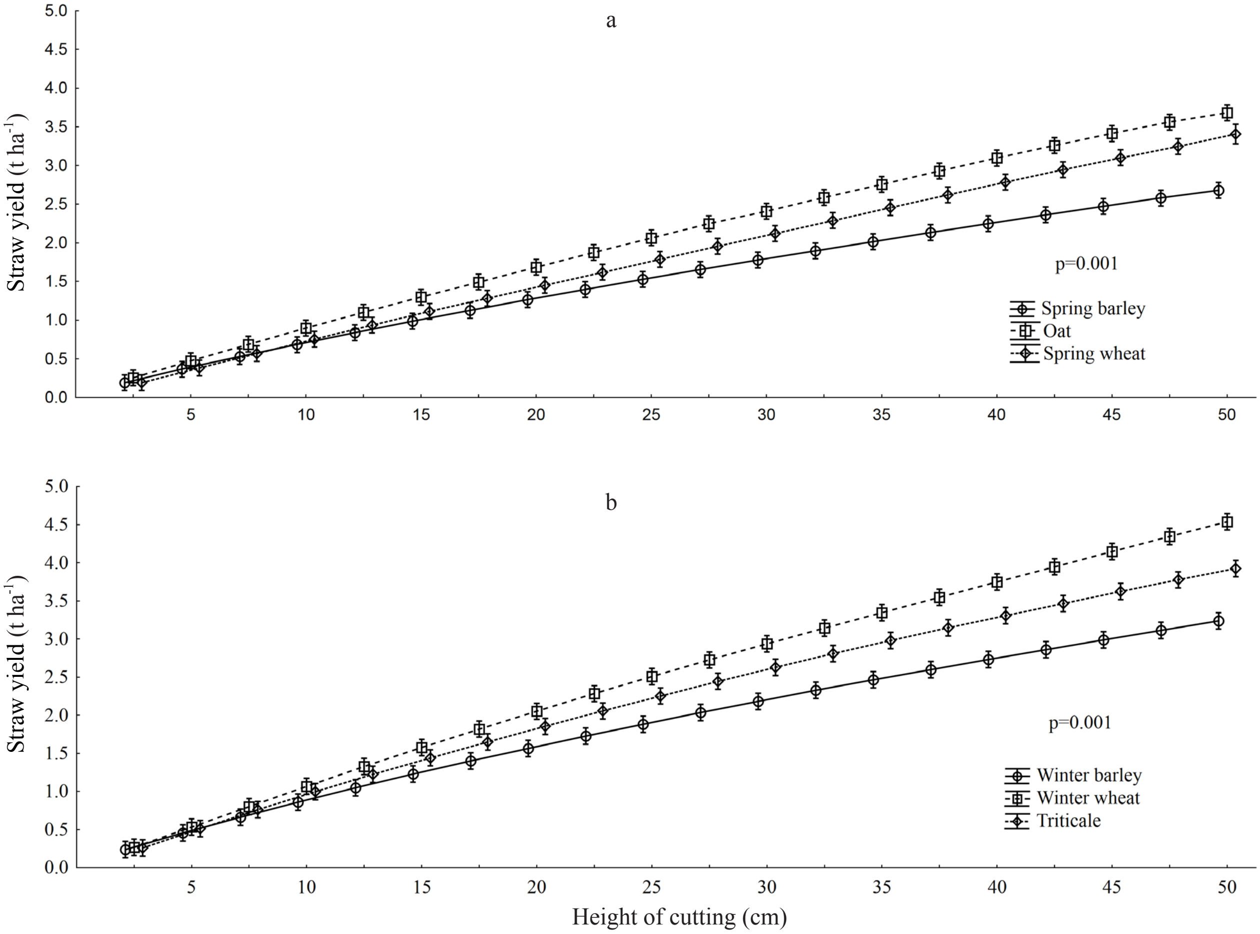

Fig. 1. Effect of the cutting height at the harvest time of: a – spring and b – winter cereals on the losses of straw yield (t ha^{-1}).

differently for hulled cereals, such as oat and barley, which accumulated most of the energy in the grains. This pattern is also confirmed by the energy index values.

Winter wheat, triticale, and oat accumulated the highest amounts of energy in the aboveground biomass. In contrast, in the spring and winter barley, the amounts of energy accumulated in the aboveground biomass were the lowest. During both vegetation seasons and under different weather conditions, the different fractions of the energy yield accumulated in the grain or straw showed significant differences, but the total yield of energy accumulated in the aboveground biomass was similar.

The increase in the straw cutting height of more than 20 cm at harvesting led to visible differences between cereal species, which were similarly arranged in the case of spring wheat and oats (Fig. 2). Significantly lower losses of energy were noted for both spring and winter barley, which is also expressed by the high harvest index value of this species (Table 6).

DISCUSSION

In this work, we presented a detailed study of accumulation of biomass and energy in the internodes and whole culms of different species of both winter and spring cereals growing in the temperate climate of southern Poland. Up to now, there have been no other studies comparing the differences in section mass of culms of cereals in central Europe. In field experiments, straw yield is usually expressed in values of biomass per hectare, which changes as the cereal grows (Summers *et al.,* 2003) and depends on a variety of factors, *i.e.* mineral fertilisation (Jarosch *et al.,* 2008) or application of growth regulators (Rajala and Peltonen-Sainio, 2001).

We have found that the basic number of internodes in the culms of each of the cereal species is five, except for oat culms, which consist mainly of six internodes. Biometric measurements showed that the upper internode, the peduncle, is the longest one in all tested cereals, except barley. Agro-climatic conditions during the two growing seasons 2010-2011 significantly determined the length, weight,

T a b l e 7. Comparison of accumulation of energy in the whole internodes (*WI*) and per unit of dry matter (*UDM*) and the share of energy of individual internode in the total energy of a whole cereal culm (*SI* in *CE*)

Internodes	Winter species						Spring species					
	Wheat		Barley		Triticale		Wheat		Barley		Oat	
						UDM (kJ g^{-1})						
Share (%)	7.3	92.7	84.3	15.7	55.5	44.5	100	0.0	50.0	50.0	27.3	72.7
1st	18.24	18.33	17.74	17.60	17.73	17.77	18.07	–	18.63	18.61	18.33	17.61
2nd	16.27	17.05	16.65	17.71	17.80	17.88	17.38	–	18.35	16.82	16.17	16.80
3rd	17.70	17.58	17.97	17.30	17.79	17.79	18.38	–	17.01	16.09	19.25	17.37
4th	16.99	17.70	16.57	17.01	16.87	16.70	18.46	–	17.13	17.69	16.09	16.23
5th	–	17.56	17.07	17.77	17.86	17.87	18.31	–	19.21	16.26	16.40	16.61
6th	–	–	–	16.65	–	18.11	–	–	–	17.97	–	16.88
LSD		0.12	0.16		0.08	0.08	0.13					0.21
p[1]		**	**		**	**	**					**
						WI (kJ)						
1st	2.83	1.31	1.67	0.92	2.37	1.41	1.08	–	1.06	0.68	1.58	0.78
2nd	4.08	3.72	3.50	3.81	3.96	3.87	2.33	–	2.07	1.70	2.49	2.07
3rd	6.54	5.49	4.17	5.72	4.93	4.27	3.63	–	1.97	1.99	4.02	3.28
4th	6.26	7.33	3.86	5.46	6.37	4.71	5.37	–	2.08	2.10	3.88	3.38
5th	–	6.67	3.03	5.56	5.12	6.24	5.36	–	1.52	2.06	5.49	4.84
6th	–	–	–	3.86	–	4.35	–	–	–	1.70	–	6.58
LSD	0.97	0.40	0.32	0.62	0.47	0.50	0.44		0.24	0.17	0.64	0.42
p[1]	***	**	**	**	**	**	**		**	**	**	**
						SI in *CE* (%)						
1st	14.4	5.4	10.5	3.6	10.1	5.7	6.7	–	12.2	6.5	9.1	3.7
2nd	20.6	15.3	21.4	14.9	17.5	15.7	13.6	–	23.9	16.4	14.3	10.1
3rd	33.3	22.4	25.8	22.3	21.8	17.2	21.0	–	22.5	19.4	23.2	15.9
4th	31.7	29.7	23.8	21.5	28.1	18.8	30.8	–	23.9	20.6	22.1	16.2
5th	–	27.2	18.5	22.3	22.6	25.1	28.1	–	17.5	20.3	31.3	23.0
6th	–	–	–	15.5	–	17.5	–	–	–	16.7	–	31.0
LSD	3.98	0.84	0.90	1.21	1.31	1.16	1.21		1.77	1.14	2.15	1.13
p[1]	***	**	**	**	**	**	**		**	**	**	**

Explanations as in Table 2.

and diameter of individual internodes. During the warmer season in 2011, the mass and diameter of the upper internodes (3rd to 6th) were reduced, whereas the inflorescences were both longer and heavier. So far, such detailed measurements of the length of internodes have been undertaken to analyse the impact of growth retardants on the formation of cereal culms and have shown that the expected reduction in culm length was a result of shortening the length of individual lower internodes from the 2nd to the 4th one (Savicente *et al.,* 1999; Tripathi *et al.,* 2003).

On average, winter wheat had the longest culms and spring wheat and spring barley the shortest ones. Fufa *et al.* (2005) points out a decreasing trend in the length of wheat straw in the last decades. Austin *et al.* (1989) assessed, using multiple regression analysis, that in the last 150 years of wheat growing, straw yield decreased by about 21% as a result of culm shortening (by 46%), whereas the grain yield increased by about 59%. The deposition of assimilates within plants favours grain yield, due to the relocation of assimilated carbon in the winter wheat from culm to ear (Bell and Incoll, 1990).

T a b l e 8. Impact of the growing seasons on the accumulation of energy in the whole internodes (*WI*), per unit of dry matter of each internode (*UDM*) and the share of individual internodes in the total energy of a single culm of the average cereal (*SI* in *CE*)

Indicators	Years	Internodes					
		1st (basal)	2nd	3rd	4th	5th	6th
UDM (kJ g^{-1})	2010	17.94	17.57	17.24	17.46	17.39	17.63
	2011	18.14	16.84	18.09	16.92	17.67	17.02
	LSD	0.06	0.12	0.11	0.12	0.13	0.22
	p^1	***	**	**	**	***	***
WI (kJ)	2010	1.02	2.99	4.28	5.24	5.52	4.48
	2011	1.59	2.87	3.61	4.10	3.71	4.50
	LSD	0.13	NS	0.24	0.33	0.35	NS
	p^1	**	0.159	***	***	**	0.961
SI in *CE* (%)	2010	5.0	14.6	20.2	24.4	25.5	10.3
	2011	9.9	17.9	22.4	25.1	21.3	3.4
	LSD	0.57	0.70	0.63	NS	0.99	1.66
	p^1	**	**	***	0.09	***	***

Explanations as in Table 2.

In this study, the mass of 1 cm long straw sections was the highest in the lower parts of the culm. Winter cereals, as well as oat, were characterised by a higher mass of straw sections, compared to that of spring wheat and spring barley. Studies of Summers *et al.* (2003) showed that the increase in the weight of cereal culm corresponds to the higher yield and lower stand density. However, the lack of understanding of the detailed distribution of biomass in the internodes prevents precise estimation of straw losses left in the field as stubble. In Canada (Alberta), Dassanayake and Kumar (2012) estimated the maximum straw yield of new cultivars of triticale at the level of 4.95 Mg ha^{-1}, but agreed on a net straw yield of 2.43 Mg ha^{-1}, due to several important sources of biomass losses: field (3%), handling (5%), and storage (10%). They estimated that the amount of straw harvestable by machines is about 75%, whereas the remaining straw is retained for soil conservation as stubble. Stubble can serve as a source of organic matter for soil and is later transformed into humus. O'Leary and Connor (1997) found that untilled stubble increased soil water storage by 27 mm in only one year and that the additional water, stored due to stubble retention, was located at a depth of up to 2 m in the soil profile. Stubble left in the field as a 'cereal prairie' is also important for birds (Delgado and Moreira, 2002). According to McKenzie *et al.* (2011), cereal stubbles are a foraging habitat for overwintering granivorous farmland bird species. In this light, leaving high stubble in the field may provide a niche for beneficial animals and facilitate agro-biodiversity.

Our study has demonstrated that a substantial increase in the height of culm cutting (25 cm or higher) results in significant losses of straw yield, which can be logically expected, although this was proved in an objective manner in this study.

In general, each internode per culm accumulated a similar amount of energy per 1 g of dry matter (J g^{-1}). This information is particularly useful as it indicates the uniformity of straw biomass as a source of bioenergy. Both forms of wheat accumulated similar amounts of energy in the grain, despite the significantly different grain yields. This could be attributed to the different chemical compositions of grains of spring and winter wheat, especially in terms of protein content. Wheat and triticale accumulated reasonable amounts of energy in rachis, chaffs, and hulls. However, one can expect that the fractions of chaffs and hulls will be lost during combined harvesting.

CONCLUSIONS

1. The basic number of internodes per culms of cereals grown in the temperate climate of Poland is five. Winter cereals, especially wheat and triticale, develop longer and heavier culms. Among spring cereals, only oat has long, massive culms. Winter cereals and oat are characterised by a greater mass of 1 cm – segments of straw.

2. Low straw cutting height, up to 10 cm, does not lead to significant losses in straw yield. A systematic increase in the cutting height of winter wheat straw causes estimated straw losses of about 0.1 t ha^{-1} for each of 1 cm of stubble left on the field.

T a b l e 9. Comparison of the energy accumulated (kJ) in the culms, grain, rachis and chaffs, as well as in the total aboveground biomass of cereal species, including the vegetative seasons

Species	Internodes	Culm	Grain	Rachis + chaff	Culm + rachis + chaff	Total aboveground biomass
Winter wheat	low 4 (5)	19.70	19.46	5.54	25.24	44.70
	high 5 (6)	24.52	21.97	5.54	30.06	52.03
LSD and p[1] for low and high		4.20*	NS	NS	NS	NS
Winter barley	low 5	16.23	24.25	3.44	19.67	43.91
	high 6	25.33	24.48	4.42	29.75	54.23
LSD and p[1] for low and high		2.36***	NS	0.41***	2.68***	4.49***
Triticale	low 5	22.74	29.41	7.78	30.52	59.94
	high 6	24.84	30.43	8.46	33.30	63.73
LSD and p[1] for low and high		2.05*	NS	NS	NS	NS
Spring wheat	high 5 (6)	17.77	21.55	4.97	22.74	44.28
Spring barley	low 5	8.69	18.20	1.91	10.60	28.80
	high 6	10.23	12.39	1.77	11.99	24.39
LSD and p[1] for low and high		0.83***	1.24***	NS	0.91**	1.94***
Oat	low 5	17.46	27.09	3.06	20.52	47.61
	high 6	20.93	30.94	2.81	23.75	54.69
LSD and p[1] for low and high		2.33**	NS	NS	2.60*	6.32*
LSD and p[1] for species	low 5	2.51**	3.85***	1.04**	3.26**	6.51**
	high 6	2.20**	2.86**	0.61**	2.67**	5.21**
2010		21.03	23.86	4.38	25.41	49.27
2011		16.57	23.72	4.60	21.17	44.89
LSD and p[1] for year		1.05***	NS	NS	1.37***	2.49***

Explanations as in Table 2.

3. The accumulation of energy ($J\ g^{-1}$) in the dry weight of each internode per culm is similar, which indicates the energetic homogeneity of cereal straw.

4. The total amount of energy in the culms, rachis, and chaffs is as follows: triticale > winter wheat > oat > spring wheat > winter barley > spring barley.

5. Increasing culm cutting height to above 20 cm leads to significant differences in the amounts of wasted energy between cereals. The smallest energy losses due to cutting height can be observed for spring and winter barley.

Conflict of interest: The Authors do not declare conflict of interest.

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T a b l e 10. Accumulation of energy in the particular parts of the yield of cereal species per unit area (GJ ha^{-1}) and in different vegetative seasons

Species	Internodes	Culm	Grain	Rachis + chaff	Culm + rachis + chaff	Total aboveground biomass
Winter wheat	116.8	105.2	26.8	143.6	248.8	0.42
Winter barley	73.4	100.7	14.9	88.3	189.0	0.54
Triticale	91.6	115.3	30.8	122.5	237.7	0.48
Spring wheat	85.7	105.4	24.1	109.9	215.3	0.49
Spring barley	53.6	91.9	10.7	64.3	156.3	0.57
Oat	87.5	130.5	12.7	100.2	230.8	0.56
LSD	6.07	8.65	1.67	7.28	14.67	0.015
p[1]	**	**	**	**	**	**
2010	91.8	103.2	19.2	111.1	214.3	0.48
2011	77.8	113.1	20.8	98.7	211.8	0.54
LSD	4.43	5.26	1.50	5.61	NS	0.011
p[1]	***	***	*	***	0.6	**

Explanations as in Table 2.

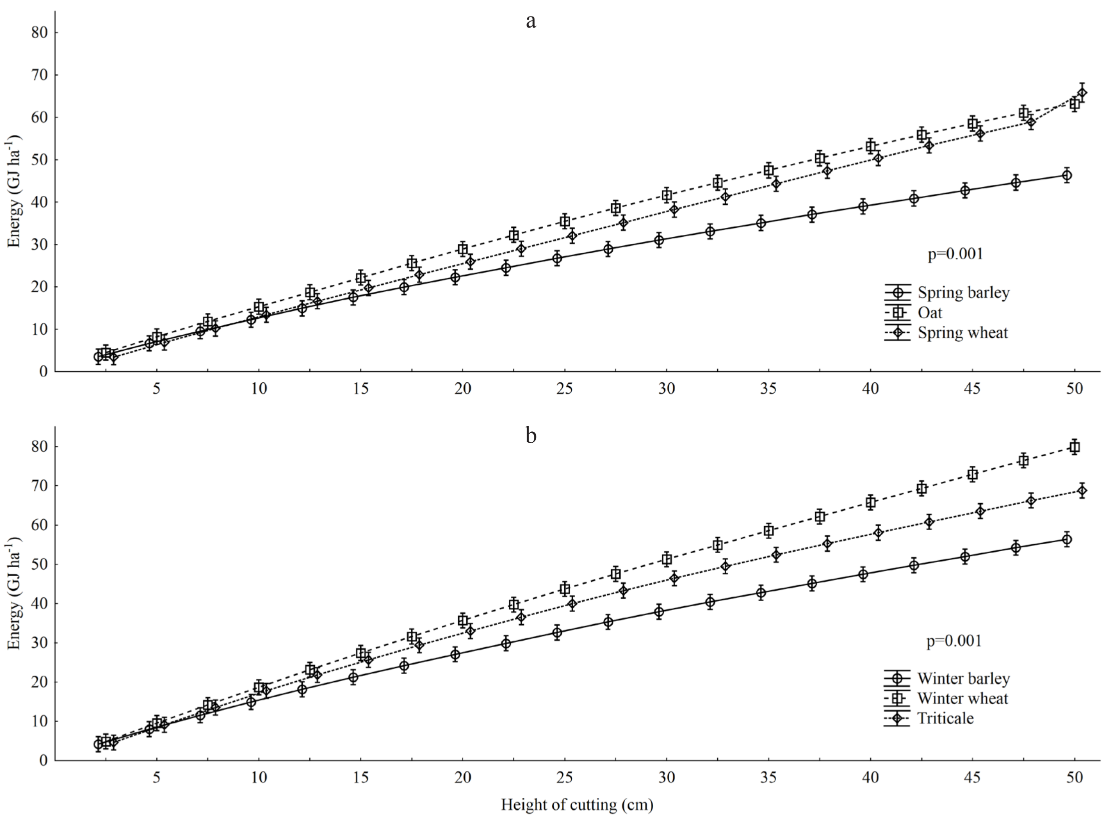

Fig. 2. Effect of the cutting height at the harvest time of: a – spring and b – winter cereals on the losses of bioenergy accumulated in the straw (GJ ha^{-1}).

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