Yield and quality of fibre and oil of fourteen hemp cultivars in Northern Germany at two harvest dates

Frank Höppner[1] and Ute Menge-Hartmann[1]

Abstract

During three growing seasons in Northern Germany eleven monoecious and three dioecious hemp cultivars of different ripeness groups were tested for their potential to provide satisfactory yields and qualities of fibre and/or oil at harvest dates as early as possible, meaning reduced rainfall risk for dry sheltering of straw. Harvests were performed at the stage of "intensive flowering" and at "initial seed maturity". Between the two harvests, stem diameter and yield, as well as fibre content and yield, did not increase significantly, except for stem length and filling degree of the primary bark fibres. Seed yield and seed oil content increased, while the content of the valuable fatty acid γ-linolenic acid decreased.

The cultivars with the longest vegetative period of growth grew tallest (r = 0.72***) and produced the highest stem yields (r = 0.65***), but not generally the highest fibre yields (r = 0.46***). Independent of the ripeness group fibre yields ranged between about 30.3 und 36.9 dt ha^{-1} at the stage of initial seed maturity, except for the early cultivar Fasamo (24.6 dt ha^{-1}), and the late dioecious cultivars Uniko-BF2 and Kompolti (40.0 resp. 44.9 dt ha^{-1}). Concerning the seed yield, the aforementioned late cultivars had the lowest yields and the early maturing cultivars Fasamo and Juso 14 ranked among the cultivars with the highest yields.

The growing season had a significant effect on nearly all the yield qualities, as well as on the investigated quality characteristics like stem structure and specific strength of bark fibres. An analysis of variance of selected characteristics, especially for Kompolti, Fedrina 74, Fedora 19 and the Ukrainian cultivars, showed a lower variability, and so their cultivation could mean a somewhat higher stability for the farmers.

Keywords: hemp cultivars, stem and fibre yield, stem structure, specific strength of fibres, seed yield, oil content

Zusammenfassung

Ertrag und Qualität von Fasern und Öl zu zwei verschiedenen Erntezeitpunkten von vierzehn in Norddeutschland angebauten Hanfsorten

In einem dreijährigen Anbauversuch wurden in Norddeutschland vierzehn Hanfsorten aus unterschiedlichen Reifegruppen auf ihr Potential hin untersucht, befriedigende Erträge an Faser und/oder Öl bereits zu möglichst frühen Ernteterminen zu liefern, die ein geringeres witterungsbedingtes Risiko für eine Trockenbergung des Ernteguts bedeuten. Dazu wurden Ernten im Stadium der intensiven Blüte und der beginnenden Fruchtreife durchgeführt. Zwischen den beiden Ernten nahmen lediglich die Stängellänge und der Füllgrad der primären Bastfasern signifikant zu, nicht jedoch Stängelertrag und -durchmesser, Fasergehalt und -ertrag. Die Erhöhung von Samenertrag und Gesamtölgehalt ging mit einer leichten Abnahme des Gehalts der wertvollen γ-Linolensäure einher.

Die Pflanzen der Sorten mit der längsten vegetativen Entwicklungsphase wurden am größten (r = 0.72***) und erzeugten die höchsten Stängelerträge (r = 0.65***), nicht jedoch generell die höchsten Fasererträge (r = 0.46***). Unabhängig von der Reifegruppe rangierten die Fasererträge der Sorten zur beginnenden Fruchtreife zwischen 30.3 und 36.9 dt ha^{-1}. Ausnahmen bildeten die frühe Sorte Fasamo (24.6 dt ha^{-1}) und die späten diözischen Sorten Uniko-BF2 und Kompolti (40.0 bzw. 44.9 dt ha^{-1}). Die späten Sorten hatten niedrige Samenerträge, während die frühen Sorten Fasamo und Juso 14 unter den Sorten mit den höchsten Erträgen rangierten.

Es war ein starker Einfluss des Anbaujahrs auf nahezu alle untersuchten Ertragsmerkmale sowie Stängelstruktur und spezifische Festigkeit von Bastfasern zu beobachten. Eine Variabilitätsanalyse ausgewählter Merkmale ergab für Kompolti, Fedrina 74, Fedora 19 und ukrainische Sorten eine etwas geringere Variabilität, welche somit auf eine höhere Sortenstabilität hinweist.

Schlüsselwörter: Hanfsorten, Stängel- und Fasererträge, Stängelstruktur, Samenerträge, Ölgehalte

[1] Federal Agricultural Research Centre (FAL), Institute of Crop and Grassland Science, Bundesallee 50, 38116 Braunschweig/Germany; Email: frank.hoeppner@fal.de

1 Introduction

Since 1996 in Germany, and since 1998 in other states of the European Union (EU), the cultivation of hemp for fibre and/or oil production is permitted again under specific constraints concerning the content of psychoactive ingredients (Heyland et al., 2006). Initially, the cultivation was extended considerably between 1997 and 1999, but then declined strongly until 2002 because of reduced EU subsidies. Since 2003, there has again been a slight upward trend (Karus, 2004), and the interest in this crop is reflected in numerous current research projects.

In Hungary, e.g., researchers intend to increase the oil content of the seeds by conventional breeding techniques (Bócsa et al., 2005). In Italy, a hemp production with so-called "baby hemp" under ecological conditions, and with biotechnological retting methods, is being tested (Amaducci, 2005), and the application of wide-angle X-ray diffractometry and CP-MAS ^{13}C- NMR for the exact definition of fibre quality (Carmen Grippo, cited in Mandolino and Ranalli, 2004). In Germany, the chemical composition of hemp during growth was monitored with a new combination of multivariate curve resolution and online spectroscopy (Kessler and Kessler, 2006), and in France the significant influence of specific contents of protein and of single sugars during bark fibre maturation was demonstrated (Cronier et al., 2005). In the Netherlands, scientists are genetically engineering hemp to improve fibre quality and quantity in connection with microarray analysis, (Marcel Toonen, cited in Mandolino and Ranalli, 2004).

Efforts are in progress for the direct technical application to upgrade composites with hemp bark fibres, and especially to improve the fibre-matrix bonding interactions, e.g., for automotive application (e.g., Bledzki et al., 2004; Behzad and Sai, 2005; Müssig et al., 2006; Pracella et al., 2006; Thomsen et al., 2006). Hemp fibre mats as insulating material for houses are already on the market. Till the end of 2006, German government granted subsidies to increase the use of these products. The spectrum of the hemp cultivars, admitted for cultivation in the EU has been widened and regularly updated, so that the potential for differentiated fields of application of hemp is increasing. Many technological tests are made with any hemp cultivar available, but it is quite possible that one cultivar could better be suited for a special purpose than another.

At the moment in the EU, 30 hemp cultivars are admitted (BLE, 2007), including also some new breeds. Only little information is available on the individual properties and the suitability of these cultivars for the different climatic areas in Germany (Struik et al., 2000; Vetter et al., 2000; Rottmann-Meyer, 2002). Here the results of several growing seasons' cultivation with a broader spectrum of cultivars in northern Germany could extend the knowledge.

A suitable production technique has been established, at first with two fibre hemp cultivars, since 1994 in Braunschweig-Völkenrode (Northern Germany) (Höppner and Menge-Hartmann, 1994). In the years 1996 to 1998, the cultivation scale was extended to 14 cultivars and the yields and some selected quality parameters were investigated at two harvest dates. The following questions were of particular interest: is it possible to achieve satisfactory yields and qualities of fibre and/or oil with early cultivars and/or early harvesting dates? Are the plants at lower risk climatically in terms of a safe sheltering of the fibre plants in Northern Germany? Are there cultivars with yield and quality parameters that show particularly low interaction with the environment and thus provide more even fibre quantities and qualities?

2 Materials and methods

From 1996 to 1998 field experiments with eleven monoecious cultivars: Fasamo (Germany), Juso 14, Juso 31, Solotonosker 11 and 15 (Ukraina ; Solotonosker 15 only in 1997 and 1998), Fedora 19, Ferimon, Felina 34, Fedrina 74, Futura (France), Secuieni 1 (Romania) and three dioecious cultivars: Lovrin 110 (Romania), Uniko-BF2, and Kompolti (Hungary) were carried out at the Institute of Crop Science at the Federal Research Centre of Agriculture in Braunschweig-Völkenrode (52 ° 17' longitude, 10 ° 26' latitude, Northern Germany) in a randomised complete block design with two to four blocks of 12.25 to 17.75 m^2 each. The soil type was loamy sand, and the previous crop white lupine. Sowing was performed at the end of April, or respectively at the beginning of May, with a mechanical single seed drill at a row distance of 12.0 cm and a seed rate of about 250 seeds m^{-2}. During the growing season of hemp (May to September), the sum of precipitation amounted to 262 mm in 1996, to 247 mm in 1997 and to 324 mm in 1998, and so, except for 1998, was lower than the 30-yr mean of 303 mm. The corresponding mean air temperatures were 14.5, 16.5, respectively 15.5 °C, the 30-yr mean 15.3 °C.

The nitrogen fertilisation of 80 kg ha^{-1} was accomplished in two equal doses (after seeding resp. four weeks later) in consideration of the soil N_{min} contents, and the base fertilisation consisted of 70 kg ha^{-1} P_2O_5, 140 kg ha^{-1} K_2O and 21 kg ha^{-1} MgO. Neither herbicides nor pesticides were used. Supplemental irrigation was applied whenever crops showed symptoms of water shortage. During the main growing phase, water was applied at a total of 120 mm (1996, five doses), 125 mm (1997, four doses), and 30 mm (1998, one dose). Plant densities at field emergence, as well as at the time of the two harvests were determined from denoted square meters. Of the dioecious cultivars, the actual percentage of male and female plants was specified and factored as weighted mean in the calculations of all the respective parameters.

The harvests, performed with a sheaf-binding harvester, took place at the stage of intensive flowering of hemp (first harvest) and at the stage of initial seed maturity (second harvest; in 1998 only the second harvest was performed). From these harvests the stem length and stem diameter (middle of stems of 25 plants), total dry biomass (stems with remaining leaves, without seeds), fibre, seed and oil yield in dt ha^{-1} were determined based on the above mentioned square metre harvests.

The oil content of the seeds was determined by nuclear magnetic resonance spectroscopy (Oxford 4000 NMR Analyser, Oxford Analytical Instruments, Abingdon, England) and the fatty acid composition after transesterification of the oil to fatty acid methyl esters (Schulte and Weber, 1989) by gas chromatography (Hewlett Packard 5890 GC-FID system; Heliflex capillary column AT-Silar (30 m x 0.25 mm x 0.25 µm)), Alltech Assoc. Il., USA; carrier gas N_2, oven temperature 240 °C, and temperature of the FID 280 °C).

For the determination of the fibre content, in 1996 hand-harvested, air-dried stalks (12 per cultivar) were decorticated with the help of enzyme retting (0.3 % aqueous Flax Zyme (Novo Industries, Copenhagen, Denmark), 30 °C, 3 to 4 days), and in 1997 and 1998, after a simulated field retting, with the help of a laboratory decorticator, constructed according to the Bahmer laboratory flax breaker Flaksy (Gebrüder Bahmer Maschinenbau GmbH, Steinheim-Söhnstetten, Germany), with some modifications. A total of 25 stems with the mean of five passages were decorticated per replication, sometimes with additional hand-removal of the shives.

For the testing of bark fibre tensile strength, 3 stripes each, about 1.0 mm broad and 10.0 cm long, of green unretted dry bark (composed of fibre bundle collectives) from the middle of 5 stems each of all the replications of a cultivar from the second harvest were prepared by hand, dried at 40 °C (3 h) and stored over desiccant till use. Tensile testing was done with a Zwick Material Testing Machine (Zwick-Roell AG, Ulm, Germany) with a frame length of 25 mm and a test speed of 3.5 mm min^{-1} (modified after Pütz, 1993). The strength of hemp fibre bundle collectives in cN/tex was calculated from the breaking mass of the bundle collective (kg) divided by the mass-related fineness of the tested collective (tex) according to Müssig and Martens (2003).

Only in 1996, was the adsorption of water vapour (60 % relative air humidity, 25 °C, 2 h) after drying (16 h, 40 °C) each of 5.0 g of mechanically decorticated green hemp fibres of the second harvest investigated in a climatic exposure test cabinet (according to Heyland and Kromer, 1995). Also, the acid detergent lignin (ADL) and cellulose content of the decorticated fibres was determined only for the second harvest in 1996, as described by Höppner and Menge-Hartmann (1994).

For microscopical investigation from two to four replications of every cultivar and harvest (in 1998 only of the second harvest) of five plants each 2.0 mm thick cross cuttings were taken from the middle of the stems and prepared for embedding in LR-White resin as in Menge-Hartmann and Höppner (1995). After milling and polishing, the specimens were coloured with 0.5 % aqueous Safranin-solution (2 h, room temperature). Besides the number of primary and secondary fibre layers, their total layer thickness and that of the wooden core layer were also determined (mean of three measures a cross section). The diameter of primary fibres was respectively calculated from the thickness of total primary cell layers through the number of cell layers. Of the total cross sections the degree of primary fibre filling was rated visually on a scale of 1 to 6 (1: all the fibres of a stem cross section well-filled, i.e., the portion of cell wall thickness to fibre lumen > 1; 2: two thirds of fibres well-filled, ….6: all the fibres poorly filled).

Analyses of variance and of correlations were performed with the statistical programme SAS. Comparisons of mean values of main effects for testing for significance were performed by Tukey. When F-ratios were significant ($P < 0,05$), least significant difference values (LSD, $P < 0,05$) were calculated and used to compare means of statistically significant sources of variance.

3 Results and discussion

3.1 Plant development

The field emergence of the cultivars took place about one week after sowing. Within a cultivar, growth generally depends on establishing a good seed emergence. About 200 to 250 plants per square metre should be obtained (Höppner and Menge-Hartmann, 1994). Generally, depending on the cultivar and growing season, there were 110 to 238 plants with means over all cultivars of 191 (1996), 200 (1997) and 188 (1998). Initially plants grew slowly, but with the rising temperatures at the end of May/ beginning of June a period of faster growing started. The well known phenomenon of "self-thinning" of hemp (Werf, 1991) led to mean final plant densities at the first, respectively second, harvests of 150 resp. 130 plants (1996), 184 resp. 180 plants (1997) and 159 plants (1998, only second harvest). For 1996 this meant a strong mean plant reduction of about 20 resp. 33 % for the first, resp. second, harvest, a more moderate reduction of about 8.0, resp. 10.0 %, for 1997, and of 15.5 % for 1998.

Many authors describe changes in phenological development when adapted hemp populations are moved to other latitudes. Cultivation at a lower latitude results in earlier anthesis, and cultivation at a higher latitude in delayed anthesis (reviewed in Ranalli, 1998; Bócsa, 1998). Though with the formation of flowers cultivars reacted at different sensitivities. According to their provenance, the start of flowering spread from the beginning of July through the middle of August. Generally the main period of growth ends with the setting of flower formation. So the date of anthesis can significantly affect growth height and yield potential.

The cultivars reached the stage of intensive flowering, the first harvest, after about 80 to 115 days after emergence (Table 1) and the stage of initial seed maturity, the second harvest, after about 100 to 134 days (Table 2). So four ripeness groups could be distinguished: early cultivars: Fasamo, Juso 14 and 31, Fedora 19, Ferimon, medium-early cultivars: Solotonosker 11 and 15, Felina 34, medium-late varieties: Fedrina 74, Futura, Secuieni 1, Lovrin 110, late varieties: Uniko-BF2, Kompolti.

At the first harvest, the mean stem length of the cultivars was 171.7 cm and increased to 183.7 cm at the time of second harvest (Table 3), whereas the stem diameters did not change significantly (Table 3). There was a significant effect of the growing season on the stem length as well as on the stem diameter at both harvests (Table 1 and Table 2). At the stage of intensive flowering, the mean stem length of the cultivars was between 165.5 and 238.5 cm in 1996 and between 120.3 and 207.1 cm in 1997 (Table 1). In 1996 it increased to between 181.5 and 266.4 cm at the stage of initial seed maturity, in 1997 there was no further growth (Table 2). So, in 1996, the growing season with the lowest plant density per square metre at harvest, plants grew higher and thicker, whereas in the warm and dry growing season 1997, the growing season with the highest plant density with most of the cultivars, plants were shorter and thinner. The stem length showed a positive correlation (r = 0.72***) to the duration of the vegetative phase. Early maturing cultivars like Fasamo, Juso 14 and Juso 31 achieved the lowest, while late ones like the dioecious Uniko-BF2 and Kompolti the highest values (Table 1 and Table 2). Also the highest values of stem diameter were obtained by the late dioecious cultivars.

3.2 Stem dry matter, fibre content and fibre yield

Stem dry matter yield was between 71.4 and 135.7 dt ha^{-1} (1996) and 66.3 and 119.1 dt ha^{-1} (1997) at the stage of intensive flowering (Table 1). At the stage of initial seed maturity a moderate increase in yield could be realized particularly in 1996. On the basis of a longer vegetation period, the significantly highest yields of stems were obtained by the later maturing cultivars Futura, Uniko-BF2 and Kompolti in all growing seasons (Table 2).

It is known that for hemp, the length of the vegetation period and the stem yield are in strong positive correlation to each other (Bócsa, 1998), as late-flowering cultivars invest more dry matter in vegetative and less in reproductive organs. In this experiment, the correlation was highly significant with r = 0.65. In Northern Germany, Rottmann-Meyer (2002) also observed higher straw yields with the later cultivars than with the earlier ripening cultivars: e.g., whereas Juso 31, with a mean of 87.4 dt ha^{-1}at the stage of initial seed maturity, reached a medium straw yield, Kompolti, with 133.7 dt ha^{-1} was a high-performance cultivar.

At both harvest stages there was a significant growing season effect in stem yield. In the mean of all cultivars the lowest stem yield was achieved in the year 1997. The lower rainfall and higher mean temperature during the vegetation period compared to the other years were therefore responsible and could not be compensated by higher irrigation rates.

Generally, in the mean of the investigated cultivars, there was stagnation in the fibre content from the first to the second harvest (Table 3). The mean values over all the cultivars and the years 1996 and 1997 accounted to 29.7 % at the first resp. to 30.1 % at the second harvest. The highest fibre contents were noticed in the Ukrainian and Hungarian cultivars with up to 37.4 %, the lowest in Fasamo with 23.0 % (Table 2). In comparison of the years, in 1996 the tall plants with higher stem diameters of all the investigated cultivars achieved lower fibre contents than the plants of the other two years with shorter and especially thinner stems. Sankari (2000), who investigated a range of monoecious and dioecious cultivars in Finland, observed that the fibre content in the stems decreased systematically with increasing stem diameter only for the dioecious cultivars Kompolti and Uniko B, and that the fibre content seemed to be less sensitive to changes in stem diameter in the monoecious cultivars.

Highest fibre yields achieved the dioecious, longest and late maturing cultivars Kompolti and Uniko-BF2, the lowest, the monoecious, shortest and early maturing cultivar Fasamo (Table 1 and Table 2, Figure 1). But the high fibre content of the Ukrainian cultivars led to respectable fibre yields comparable to the yields of some French cultivars and the Romanian cultivars Secuieni 1 and Lovrin 110 (Table 1 and Table 2).

So, in contrast to the stem yield, which was increasing with the duration of vegetation period at the stage of initial seed maturity, the fibre yield of most of the cultivars did not generally increase (r = 0,46***, Figure 1). The fibre yield ranged between 31.0 and 37.0 dt ha^{-1}, and did not show any significant differences.

Table 1:

Harvest date and parameters of growth and yield of different hemp cultivars at stage of intensive flowering

	Harvest date days after emergence no.		Stem					
			Length cm		Diameter mm		Yield DM dt ha-1	
Cultivar	1996	1997	1996	1997	1996	1997	1996	1997
Fasamo	86	72	165.5	120.3	5.6	3.8	71.4	66.3
Juso 14	86	72	178.5	132.2	6.7	5.5	84.4	75.8
Juso 31	86	72	177.0	120.6	6.2	4.7	85.5	65.1
Solotonosker 11[1]	86	81	187.0	134.6	6.4	5.2	84.5	87.5
Solotonosker 15[1]		81		147.7		4.9		93.5
Fedora 19	100	90	185.5	146.2	6.4	4.7	109.6	99.4
Ferimon	106	90	196.5	144.9	6.3	4.6	108.7	92.2
Felina 34	106	90	193.5	148.4	5.8	3.8	105.6	100.4
Fedrina 74	113	102	209.5	165.3	6.4	4.5	125.8	116.4
Futura	113	102	204.5	187.2	6.5	4.7	135.7	113.4
Secuieni 1[1]	113	99	206.5	158.7	6.6	4.5	115.0	99.9
Lovrin 110	113	99	223.5	183.6	7.0	4.0	106.9	111.7
Uniko-BF2[1]	121	106	254.5	200.3	7.6	4.5	128.3	106.5
Kompolti	121	109	238.5	207.1	7.0	4.4	124.3	119.1
LSD (0.05)[2]			20.7	33.7	1.7	1.4	14.2	27.5
Mean of cultivars			201.6	157.6	6.5	4.5	106.6	96.8
LSD (0.05)[3]			13.4		0.3		9.1	

	Fibre				Seed			
	Content %		Yield dt ha-1		Yield DM kg ha-1		Oil content %	
Cultivar	1996	1997	1996	1997	1996	1997	1996	1997
Fasamo	20.2	25.1	14.4	16.8	2.4	0.7		
Juso 14	27.6	34.2	23.3	25.9	12.1	15.4		12.8
Juso 31	25.8	34.2	22.1	22.2	25.2	13.6	14.3	13.6
Solotonosker 11[1]	26.0	30.7	21.9	27.0	3.1	15.2		8.6
Solotonosker 15[1]		30.3		28.4		10.3		11.6
Fedora 19	24.5	30.1	26.8	30.0	55.6	34.2	17.1	14.9
Ferimon	24.9	32.2	27.1	29.8	86.8	10.5	20.7	19.1
Felina 34	24.7	32.4	26.1	32.7	56.8	21.6	19.0	18.5
Fedrina 74	26.5	31.5	33.2	36.7	140.5	21.9	19.7	16.3
Futura	25.4	29.5	34.4	33.5	35.4	68.4	18.4	15.1
Secuieni 1[1]	27.3	29.9	31.4	29.9	107.4	7.5	16.1	15.1
Lovrin 110	22.5	28.8	23.8	32.0	11.4	4.3	16.7	
Uniko-BF2[1]	30.5	34.6	39.0	36.9	5.1	1.9		
Kompolti	32.1	38.2	39.9	45.2	0.7	0.5		
LSD (0.05)[2]	10.4	4.5	11.7	10.1	70.6	23.6	5.8	7.3
Mean of cultivars	26.0	31.5	28.0	30.6	41.7	17.3	17.7	14.6
LSD (0.05)[3]	not possible		not possible		14.9		2.0	

[1] no permission to cultivate, because till now no license from the EU [2] Least significant difference to compare cultivars within a year
[3] Least significant difference to compare years

Table 2:
Harvest date and parameters of growth and yield of different hemp cultivars at stage of initial seed maturity

	Harvest date days after emergence no.			Stem								
				Length cm			Diameter mm			Yield DM dt ha^{-1}		
Cultivar	1996	1997	1998	1996	1997	1998	1996	1997	1998	1996	1997	1998
Fasamo	106	103	89	181.5	121.8	169.6	5.6	3.8	4.0	76.8	80.3	100.2
Juso 14	106	103	89	186.7	132.1	180.7	6.5	4.5	5.2	100.1	84.5	94.5
Juso 31	106	103	89	191.3	128.1	185.1	6.4	4.0	5.5	97.5	82.6	88.9
Solotonosker 11[1]	106	111	95	199.3	151.6	196.6	6.7	5.0	5.4	100.6	88.4	113.6
Solotonosker 15[1]		111	103		160.3	224.4		4.7	6.2		94.5	126.6
Fedora 19	113	110	92	213.0	152.2	199.3	6.5	4.3	5.2	114.3	99.3	116.1
Ferimon	121	110	92	214.0	162.6	201.9	6.8	4.5	5.2	113.2	99.0	117.5
Felina 34	121	110	109	226.0	149.4	187.6	6.7	4.1	4.8	125.3	100.3	124.2
Fedrina 74	127	117	117	225.5	171.4	206.4	6.9	4.6	5.2	115.7	107.7	114.7
Futura	127	123	117	242.0	192.3	205.7	7.6	4.7	5.4	128.0	115.4	125.6
Secuieni 1[1]	127	117	117	241.5	171.2	230.1	8.0	4.9	6.5	118.2	95.7	113.3
Lovrin 110	127	117	116	253.8	179.7	212.5	7.8	4.6	5.2	119.1	104.3	116.9
Uniko-BF2[1]	141	130	130	269.1	207.6	239.2	8.9	4.4	6.4	137.8	109.0	122.0
Kompolti	141	130	130	266.4	206.2	226.5	7.9	4.2	5.5	132.5	112.1	130.1
LSD (0.05)[2]				45.6	34.2	34.0	1.7	0.9	1.0	27.1	24.3	23.4
Mean of cultivars				221.7	163.3	204.7	7.1	4.5	5.4	112.5	98.1	114.6
LSD (0.05)[3]					13.8			0.4			7.5	

	Fibre						Seed					
	Content %			Yield dt ha^{-1}			Yield DM kg ha^{-1}			Oil content %		
Cultivar	1996	1997	1998	1996	1997	1998	1996	1997	1998	1996	1997	1998
Fasamo	23.0	25.8	28.3	17.5	20.9	28.3	538.3	376.5	157.0	26.6	23.2	17.1
Juso 14	31.4	33.2	35.9	31.5	28.1	33.9	376.6	223.1	381.3	23.9	20.6	23.5
Juso 31	33.6	33.2	37.0	32.4	27.5	33.0	408.4	250.2	330.0	22.3	21.0	24.5
Solotonosker 11[1]	27.2	30.2	36.1	27.4	26.8	40.9	217.3	235.6	139.7	19.2	24.9	25.2
Solotonosker 15[1]		30.1	32.6		28.4	41.3		148.1	120.1		23.5	23.4
Fedora 19	26.1	28.3	29.5	29.8	28.1	34.2	307.3	271.0	128.8	22.1	24.0	24.1
Ferimon	28.9	32.8	33.9	32.7	32.4	39.8	440.9	309.8	42.8	29.7	25.2	20.6
Felina 34	27.6	29.6	29.5	34.6	29.8	36.8	427.5	221.6	135.6	28.0	25.1	23.5
Fedrina 74	25.1	29.5	31.1	29.0	31.8	35.7	381.2	230.4	192.8	26.5	21.6	22.2
Futura	26.9	29.6	31.8	34.3	34.0	39.9	321.7	526.2	66.5	26.0	23.0	17.4
Secuieni 1[1]	26.7	32.0	33.2	31.5	30.6	37.6	206.9	234.3	149.1	27.1	20.2	20.5
Lovrin 110	24.9	28.9	30.0	29.5	30.0	34.8	47.2	50.6	24.5	22.4	17.7	16.7
Uniko-BF2[1]	29.7	34.7	34.9	41.1	37.6	42.4	49.7	51.2	26.6	22.8	21.4	20.6
Kompolti	33.9	37.4	36.7	44.8	41.9	47.8	52.4	36.8	9.0	22.5	21.1	14.9
LSD (0.05)[2]	7.7	3.6	3.5	8.2	9.0	9.7	230.0	194.7	102.2	4.8	4.3	2.1
Mean of cultivars	28.2	31.1	32.9	31.8	30.6	37.6	286.7	226.1	136.0	24.2	22.6	21.0
LSD (0.05)[3]		ns[4]			2.8[4]			70.1			1.5	

[1] no permission to cultivate, because till now no license from the EU [2] Least significant difference to compare cultivars within a year
[3] Least significant difference to compare years [4] Least significant difference to compare years, only possible for the years 1997 and 1998

Table 3:

Comparison of the two different harvest stages of hemp (Mean of cultivars and two years)

	Stem				Seed		
	Length	Diameter	Yield DM	DM	Yield DM	Oil content	γ-linolenic acid
Stages at harvest	cm	mm	dt ha^{-1}	%	kg ha^{-1}	%	%
Intensive flowering	171.7	5.2	99.3	29.6	25.5	16.4	4.3
Initial seed maturity	183.7	5.4	103.1	34.0	247.2	23.2	3.2
LSD (0.05)[1]	11.9	ns	ns	1.0	35.4	1.2	0.3

	Fibre		Primary fibre			Secondary fibre	Wood layer
	Content	Yield	Layers	Fibre diameter	Filling	Layers	Thickness
	%	dt ha^{-1}	No.	µm	rating	No.	µm
Intensive flowering	29.7	29.8	7.7	17.5	3.3	1.3	562.5
Initial seed maturity	30.1	31.0	7.4	17.9	2.8	1.4	577.3
LSD (0.05)[1]	ns	ns	ns	ns	0.2	ns	ns

[1] Least significant difference to compare harvest stages

3.3 Stem structure

Hemp stems can be separated into two components: the stem tissues outside the vascular cambium, the bark, and the stem tissues inside the vascular cambium, the core. About 65 % of the weight is represented by the woody core (Groot et al., 1999), consisting of large vessels, thin walled libriform fibres (only 0.55 mm long) and parenchymatous cells. In the classical fibre production these so-called shives accumulate as “waste” and are discarded or burned. But they can absolutely also be used with added value, e.g., as insulation material or for light weight construction in the building industry.

From the first harvest to the second one there was no significant increase in the thickness of the woody core layers regarding the mean of all cultivars and of the years 1996 and 1997 (Table 3). Between the three growing seasons the thickness of the woody core layers differed significantly at the second harvest (Table 4). In 1996 the layers of the thick stems were in the mean double as thick as those of the thin stems in 1997. Within the growing seasons the ranking of the extreme positions was similar in 1997 and in 1998: Uniko-BF2, Kompolti and Fedrina 74 possessed thicker and Juso 14 (additionally in 1996), and Fasamo (in 1996 and 1997) significantly thinner wood layers than most of the other cultivars (Table 4).

Outside the woody core, the cambium and the bark with the bark fibres affiliate, composed of the thick walled high valence primary or long fibres (mean 20 mm), belonging to the strongest natural fibres, and the, for most purposes useless, secondary or short fibres. The secondary fibres are only 2 mm long (Hoffmann, 1961), small, angular and thin walled. The length of the single primary fibres varies depending on the position of the fibres in the stem (Herzog, 1926). The longest and especially well-developed fibres Menzel (1937) found about in the middle of the stem, the region which is established during the phase of the strongest growth. Also in the middle of the stem both the fibre content (Bredemann, 1940) and the fibre strength (Funder, 1973) are highest, from there decreasing to the top and to the bottom.

The primary fibres are arranged in bundle complexes, whereas the number of fibres in a complex can amount to between 2 and 20 (Anonymous, 1962). For technical purposes (classical textile aspects) belt-like bundles of primary fibres with thick cell walls and small lumen are well-suited (Anonymous, 1962).

Between the two harvests, the number of primary fibre layers laid out did not increase further and also the fibre diameters did not change (Table 3). However the fibre filling degree upgraded slightly but significantly from 3.3 to 2.8 (Table 3) at the second harvest, as was to be expected in the course of fibre ripening.

Between the three growing seasons the mean number of primary fibre layers of the cultivars at the second harvest differed significantly but only slightly (Table 4). The mean fibre diameters and filling degrees also were similar in two of the three growing seasons (Table 4).

Within the growing seasons the cultivars also resembled each other in the number of fibre layers. Only Juso 14 and Fasamo had significantly higher respectively lower values than the other cultivars in two of the three growing seasons (Table 4). The fibre diameters did not differ significantly between the cultivars in 1996, and were mostly similar in

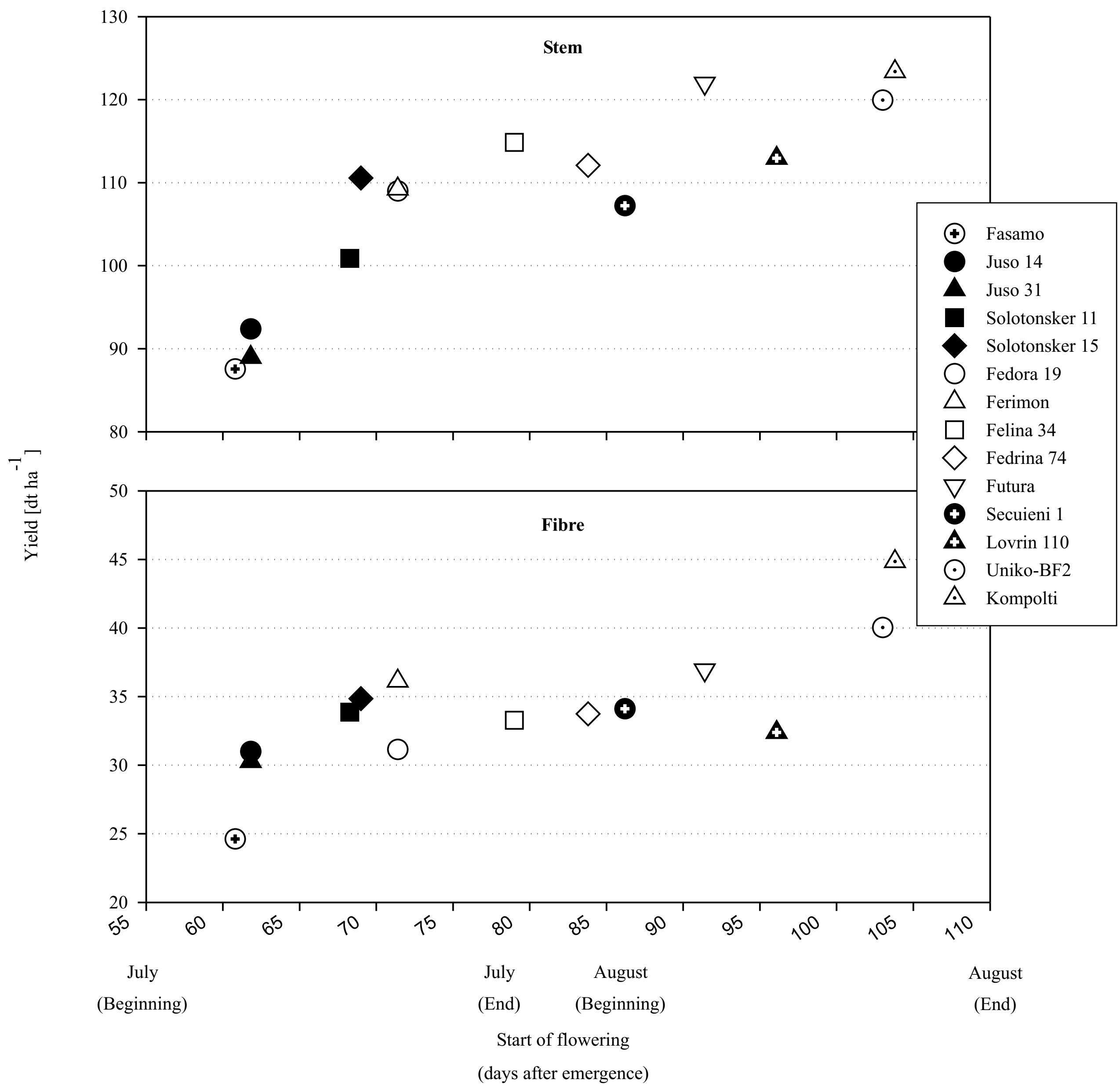

Figure 1:
Stem and fibre yield of hemp cultivars at the harvest stage of initial seed maturity (Mean of three years)

the other two years, again Fasamo representing significantly smaller diameters than the other cultivars (Table 4).

The development of secondary fibres is caused by the growth in thickness of the stem. It starts in the first maturing internodes and generally goes on during the whole plant life, so that the greatest and thickest fibres are situated at the bottom of the stem (Kundu, 1942). The complexes of secondary fibres can not be dismantled by biological or chemical processes and therefore only come out as tow (Menzel, 1937; Haraszty and Jakobey, 1968).

Between the first and the second harvest the secondary fibre layers, investigated in the middle of the stems, did not increase significantly (Table 3). At the second harvest the thin stems of 1997 had slightly but significantly more secondary fibre layers than the thick ones of 1996 (Table 4), which seems contradictory to the above mentioned relations. Within the three growing seasons Fasamo, Fedora 19 and Lovrin 110 showed significantly less, respectively no, secondary fibre layers, whereas Kompolti represented significantly more (Figure 2), also in direction, Unico-BF2 and Secuieni 1, than the other cultivars (Table 4).

In a former experiment with Kompolti Hybrid TC about 5 layers of secondary fibres in the middle of the stem meant about 6 % of extracted secondary fibres in the total fibre

Table 4:
Fibre characters at stage of initial seed maturity

	Wood layer Thickness µm			Primary fibre Layers No.			Primary fibre Fibre diameter µm		
Cultivar	1996	1997	1998	1996	1997	1998	1996	1997	1998
Fasamo	730.0	362.0	628.4	6.5	7.4	5.5	19.3	14.1	17.4
Juso 14	727.1	349.2	577.5	8.3	7.6	7.4	19.6	16.9	24.7
Juso 31	771.7	408.0	561.6	8.3	8.1	8.3	20.3	15.4	21.1
Solotonosker 11[1]	724.6	371.3	621.9	7.7	6.6	6.9	19.3	18.1	21.2
Solotonosker 15[1]		418.9	732.8		7.0	6.9		17.7	20.8
Fedora 19	818.8	398.9	678.8	6.5	7.6	6.1	20.5	16.0	19.9
Ferimon	813.8	409.9	698.1	7.5	7.2	6.6	20.0	17.2	19.8
Felina 34	1053.1	401.1	600.0	9.0	7.3	6.1	18.4	17.2	19.4
Fedrina 74	1037.3	501.0	771.3	9.0	7.2	6.2	19.8	17.0	19.3
Futura	913.8	467.0	762.2	9.0	6.1	6.2	18.4	19.3	21.9
Secuieni 1[1]	952.5	453.4	766.3	8.5	7.4	6.8	21.6	15.1	22.7
Lovrin 110	765.5	480.5	579.0	7.1	6.6	5.8	20.9	16.6	18.4
Uniko-BF2[1]	802.6	676.8	843.6	7.5	8.5	8.0	23.4	17.2	19.8
Kompolti	915.5	545.8	803.5	8.0	7.6	7.3	21.4	15.6	21.4
LSD (0.05)[2]	249.6	134.0	212.3	2.3	1.6	1.6	5.7	3.7	5.2
Mean of cultivars	832.0	438.0	686.1	7.8	7.2	6.7	20.3	16.7	20.5
LSD (0.05)[3]		55.3			0.5			1.1	

	Primary fibre Filling rating			Secondary fibre Layers No.			Bark stripes Specific strength cN tex^{-1}		
Cultivar	1996	1997	1998	1996	1997	1998	1996	1997	1998
Fasamo	3.0	2.0	2.2	0.0	0.0	0.0	73.5	58.7	61.6
Juso 14	3.3	2.7	3.1	0.0	1.8	1.0	74.9	61.5	59.8
Juso 31	3.3	2.6	2.9	0.1	1.2	0.8	77.3	66.7	61.1
Solotonosker 11[1]	3.3	2.1	3.2	0.7	2.1	0.6	74.2	57.5	71.2
Solotonosker 15[1]		2.6	2.7		2.0	0.4		59.0	58.9
Fedora 19	4.0	2.5	3.0	0.0	0.8	0.0	72.0	60.4	64.9
Ferimon	4.0	2.8	3.4	0.2	1.3	0.9	74.1	61.4	67.9
Felina 34	4.0	2.8	2.8	0.0	1.4	0.0	73.1	63.0	62.7
Fedrina 74	4.0	2.7	2.7	1.6	2.5	1.6	74.5	61.0	66.5
Futura	4.0	2.5	3.1	1.0	2.6	0.9	75.0	59.9	73.0
Secuieni 1[1]	3.5	2.7	2.8	1.8	3.0	0.7	78.8	58.5	71.3
Lovrin 110	2.1	2.5	2.5	0.0	0.4	0.0	74.2	51.2	59.8
Uniko-BF2[1]	3.7	2.0	2.3	1.0	2.9	4.5	71.1	48.3	56.7
Kompolti	2.7	2.1	2.2	1.9	3.6	3.0	71.8	55.4	54.8
LSD (0.05)[2]	2.4	1.2	1.2	1.6	2.0	2.2	21.2	19.5	17.2
Mean of cultivars	3.4	2.5	2.8	0.6	1.8	0.9	74.4	58.7	63.6
LSD (0.05)[3]		0.3			0.6			3.9	

[1] no permission to cultivate, because till now no license from the EU [2] Least significant difference to compare cultivars within a year
[3] Least significant difference to compare years

fraction (Menge-Hartmann and Höppner, 1995). So, the high fibre content of Kompolti, Uniko-BF2, Secuieni 1 could partly be caused by a higher share of secondary fibres in the fibre fraction. Generally the share of secondary fibres increases with the weight of the stem (Bredemann, 1961; Werf, 1994), obviously also applying to Uniko-BF2 and Kompolti, which had the highest stem masses of all investigated cultivars. Werf (1994) reported that the secondary fibre fraction increased, e.g., from 10 % at a stalk weight of 10 g, to 45 % at a stalk weight of 170 g.

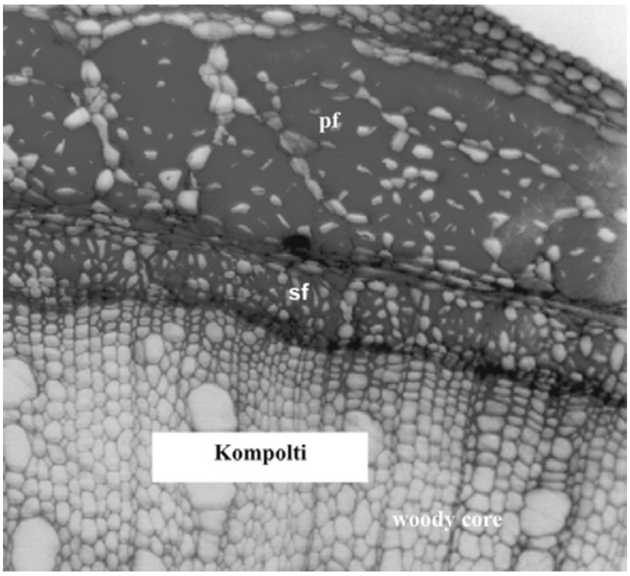

Figure 2:

Cross cutting from the stem middle of the cultivar Kompolti (pf = primary fibre, sf = secundary fibre)

3.4 Specific strength, uptake of humidity and contents of cellulose and lignin of bark fibres

The item quality of natural fibres in broad terms can be defined on the one hand as the collective of fibre features as a neutral characteristic of the particular material, on the other hand, in closer terms, as the suitability of the particular fibre for a specific purpose (Kohler, 1994). While the traditional use of fibres was for textiles, newer possible uses are for the technical area. The fibres have a load-carrying function in many applications of hemp fibres, such as polymer reinforcement or textile area products.. Therefore their tensile strength is a crucial parameter (Keller et al., 2001; Scheer-Triebel and Léon, 2000).

In the three years test at the second harvest, the specific strength of the fibre bundle collectives (bark stripes) showed significantly different yearly mean values over all the cultivars of 74.4 in 1996, 58.7 in 1997, resp. 63.6 cN tex^{-1} in 1998 (Table 4), and a mean over the three years of 63.9 cN tex^{-1}. Also, in a one year test in Northern Germany with nine hemp cultivars, eight the same as in our test, Müssig (2001) for all the investigated cultivars observed a rather similar level, with a mean strength of fibre bundle collectives of about 61 cN tex^{-1}. In a review paper (Scheer-Triebel and Léon, 2000), for hemp a range of 35 to 74 cN tex^{-1} is represented. A possible explanation for this wide range may be that among many other factors such as, e.g., cultivar and environmental effects, different production and harvesting techniques and measurement adjustments were chosen in the experiments, and there has been no standardisation up until now. In the present investigation, a gauge length of 25 mm was applied, and, assuming a length of single hemp fibres of 5 to 40 mm, it is difficult to assess if the apparatus measured either the breaking of cell walls or that along the middle lamella, as has been discussed by Rennebaum et al. (1998).

No significant differences existed between the cultivars in 1996 and in 1997. Only in 1998 Futura showed a significantly stronger and Kompolti a significantly weaker specific strength of bark stripes than all the other cultivars (Table 4). In the tendency bark stripes of the late maturing dioecious cultivars were of lower strength in all three growing seasons.

An important aspect of quality for the use of natural fibres for fibre reinforced composites also is a low adsorption of water vapour, which has a positive influence on the cohesion between fibre and polymer and thus finally on the effect of reinforcement of the fibre in the composite (Scheer-Triebel and Léon, 2000). The investigated 13 fibre hemp cultivars in a one year test (1996, without Solotonosker 15) showed little variation in the adsorption of water vapour. In the mean of the cultivars it was 7.3 % ± 0.3 (min. 6.9 % Secuieni, max. 8.2 % Fasamo). As was shown in three years' cultivation with Felina 34 in Braunschweig-Völkenrode, neither a harvest date three weeks earlier nor three weeks later than optimal lead to a change in water adsorption. Scheer-Triebel and Heyland (1994) in experiments with flax fibres have shown that for comparable results the test conditions for adsorption of water vapour have to be exactly defined, as there was an influence of the fibre amount, of the level of temperature and air humidity and the residence time in the climatic exposure test cabinet.

For a possible application of complete hemp stems or isolated hemp bark fibres for the production of paper pulp besides a high content in cellulose, a low content in lignin is a positive quality aspect, as fewer chemicals for paper bleaching are to be employed.

In the present investigation with 13 cultivars in a one year test (1996, second harvest) the lignin contents of isolated bark fibres were very low and amounted from only 0.8 % with Secuieni 1 and Lovrin 110, to a maximum of 1.5 % with Fasamo. The bark fibres of the latter variety with

71 % possessed the lowest cellulose content, whereas Juso 14 and Juso 31 reached 76 % and Uniko-BF2 77.5 %. In a three year test in Braunschweig-Völkenrode with Felina 34, the lignin content of the bark fibres was about 2 %, also a harvest date three weeks later showed in general no increase. In the literature somewhat higher lignin values of 3 to 4 % for hemp bark fibres were specified (Groot et al., 1999; Cronier et al., 2005).

Lignin contents were determined for complete hemp plants, which were 10 % less than those of hardwood, containing 20 to 25 % (Karus et al., 1993), and which were neither influenced by a varied plant density nor by the intensity of the nitrogen fertilisation (Höppner and Menge-Hartmann, 1994). The lignin content of the separated woody core with 22.1 % (Groot et al., 1999) resembles that of hardwood.

3.5 Seed yield, oil content and fatty acid composition

For a remunerative exploitation of the seeds (botanically correct: fruits), the first harvest at the stage of intensive flowering, representing only few ripe seeds at the base of the inflorescences, was too early of course, and so the seed yields generally were very low (Table 1). From the first harvest to the second one at initial seed maturity, the seed yield increased from a mean value of 25.5 to 247.2 kg ha^{-1} (Table 3). Between the growing seasons, the variability was high: e.g., in 1998 the mean yield was less than half that of 1996 (Table 2). Within the three growing seasons the ranking of the early maturing cultivars Fasamo and Juso 31 was always between the upper five cultivars with the highest yields (Table 2), the ranking of most of the other cultivars being very variable, whereas the late maturing dioecious cultivars Uniko-BF2, Lovrin 110 and Kompolti always had the lowest yields.

The oil content of the seeds from the first to the second harvest over all growing seasons and cultivars increased to a mean of 23.2 % (Table 3), and in 1996 at the second harvest was significantly higher than in the other two years (Table 2). Within two of the three years, the seed oil contents of Solotonosker 11 and of Ferimon were significantly higher than those of the other cultivars, additionally the seed oil content of Felina 34 ranged within the upper five cultivars with the highest content in all three years (Table 2).

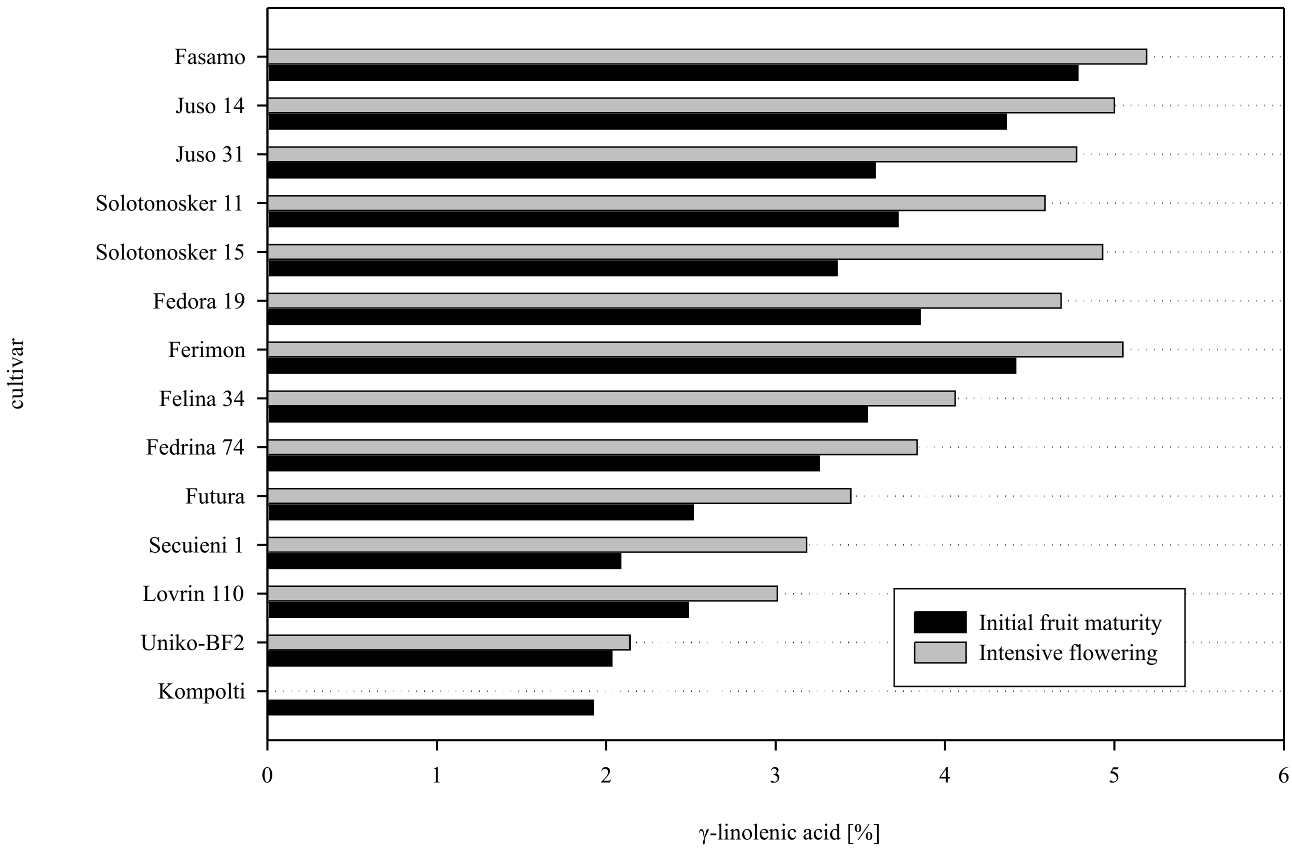

Figure 3:

Concentration of γ-linolenic acid in seeds of hemp cultivars at the stages of intensive flowering and initial seed maturity (Mean of two years)

Fasamo and Futura had the highest oil yields (not shown) in the three years with a mean of about 100 kg ha^{-1}, whereas the late maturing dioecious cultivars with a share of male plants of 40 to 50 % had the lowest, and so are negligible for dual use (Höppner, 1997)

In literature for completely mature hemp seeds of course much higher oil contents and yields are given: an oil content of 30 - 35 % (like sunflower seed with 30 to 35 %), and an oil yield of at most around 300 kg ha^{-1} (e.g. Höppner and Menge-Hartmann, 1994, Bócsa et al., 2005). Though also when such high yields still cannot compete with the 1500 kg ha^{-1} oil yield of sunflower seed, hemp oil has a more favourable fatty acid composition, unusually high in polyunsaturated fatty acids (up to 80 %), especially the essential fatty acids linoleic and linolenic acid (reviewed in Pate, 1999). Hemp breeders recently have developed modern oilseed varieties for specific end uses. \`FIN-314\`, the first hemp cultivar strictly for grain seed production (Clarke, 1999), contains a high level of the essential fatty-acid γ-linolenic acid (4.4 %), which is valuable as nutraceutical and dietary supplement. In the investigated fibre hemp cultivars at the first harvest in the mean of cultivars and years γ-linolenic acid amounted to 4.3 % (Table 3). With this the content was significantly higher than at the second harvest (Table 3), as during seed maturation its share is reduced (there is a shift to linoleic acid). Highest values of γ-linolenic acid content were found at both harvests in the earlier maturing cultivars, especially in Fasamo and Ferimon (Figure 3), and lowest in the late cultivars Kompolti and Uniko-BF2.

3.6 Variability of selected characteristics

There was a general relatively high effect of the growing season on all the investigated hemp cultivars. So, as has been discussed by Sankari (2000), it can be one method for the farmer to select stable genotypes that interact less with the environment in which they are grown in order to obtain a higher degree of more even fibre and oil quantities and qualities. Looking after the most stable cultivars in our experiment over all years, the variation coefficient of some main selected characteristics should be regarded (Figure 4). Here the fibre and oil content achieved the lowest coefficients and the cultivars sprinkled not as high as by the yield characteristics. There was no cultivar with lowest values in all characteristics, but for fibre production the cultivars Kompolti, Fedrina 74, Fedora 19 and Juso 14 particularly seemed to be most qualified. There will be no modification of the cultivars at stage of intensive flowering. Under the aspect of dual use of fibres and seeds the Ukrainian cultivars showed the highest stability (Figure 4).

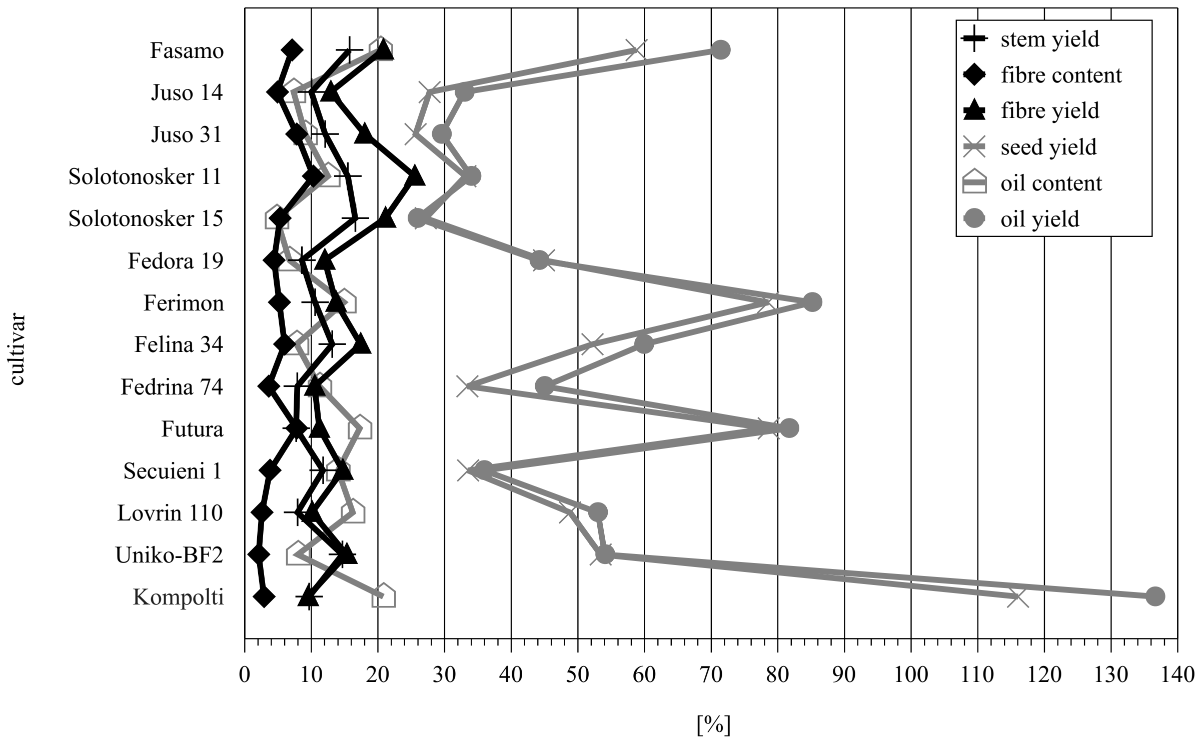

Figure 4:
Variation coefficient of different characters at stage of initial seed maturity (all years)

4 Conclusions

The earlier the harvest date, the lower the risk of weather conditions with higher precipitation and lower temperatures, unfavourable for the safe sheltering of fibre plants in Northern Germany and comparable regions. An efficient risk reduction could be to choose early-maturing cultivars for culture and additionally to harvest them as early as possible. It was shown that already at the early harvest at the stage of intensive flowering, satisfactory yields and qualities of hemp fibres are attainable, as nearly all of the investigated relevant characteristics did not change significantly in comparison to the common harvest at the stage of initial seed maturity. If growers are interested in a dual use of fibre and oil, then growing early-maturing cultivars and harvesting at the stage of initial seed maturity or later could be a good compromise. Being interested in highest fibre yields only, then the late maturing dioecious cultivars can be recommended and already harvested at the stage of intensive flowering.

Acknowledgement

The technical assistance of Claudia Aukamp-Timmreck and Martin Dohlenburg is gratefully acknowledged. We thank Dierk-Dieter Strauss for the statistical analysis of experimental data.

References

Amaducci S (2005) Hemp production in Italy. J Indust Hemp 10(1): 109-115

Anonymous (1962) Die Hanfpflanze. CIBA-Rundschau 5:2-32

Behzad T, Sain M (2005) Cure simulation of hemp fiber acrylic based composites during sheet molding process. Polymers Polymer Composites 13(3):235-244

BLE (2007) Beihilfefähige Faserhanfsorten [online]. Zu finden in <http://www.ble.de/data/0001774671281623A2F66521C0A8D816.0.pdf> [zitiert am16.07.2007]

Bledzki AK, Fink H-P, Specht K (2004) Unidirectional hemp and flax EP- and PP-composites : influence of defined fiber treatments. J Appl Polym Sci 93(5):2150-2156

Bócsa I (1998) Genetic improvement : conventional approaches. In: Ranalli P (ed) Advances in hemp research. New York : Food Products Press, pp 153-184

Bócsa I, Finta-Korpelová Z, Máthé P (2005) Preliminary results of selection for seed oil content in hemp *Cannabis sativa* L.. J Indust Hemp 10(1):5-15

Bredemann G (1940) Fasergehalt und Faserausbeute beim Hanf in verschiedener Stengelhöhe. Forschungsdienst 10:57-67

Bredemann G, Garber K, Huhnke W, Sengbusch R von (1961) Die Züchtung von monözischen und diözischen, faserertragreichen Hanfsorten (Fibrimon und Fibridia). Z Pflanzenzücht 46:235-245

Clarke RC (1999) Botany of the genus Cannabis. In: Ranalli P (ed) Advances in hemp research. New York : Food Products Press, pp 1-19

Cronier D, Monties B, Chabbert B (2005) Structure and chemical composition of bast fibres isolated from developing hemp stem. J Agric Food Chem 53(21):8279-8289

Groot B de, Roekel Jr GJ van, Dam JEG (1999) Alkaline pulping of fiber hemp. In: Ranalli P (ed) Advances in hemp research. New York : Food Products Press, pp 213-242

Heyland K-U, Kromer K-H (1995) Methodenbuch Industriefaser Lein. Bonn : Institut für Landtechnik der Rheinischen Friedrich-Wilhelms-Universität, Arb Inst Landtechnik Univ. Bonn 18

Heyland K-U, Hanus H, Keller ER (eds) (2006) Handbuch des Pflanzenbaues Stuttgart : Ulmer, pp 290-307

Höppner F, Menge-Hartmann U (1994) Anbauversuche zur Stickstoffdüngung und Bestandesdichte von Faserhanf *Cannabis sativa*. Landbauforsch Völkenrode, 44(4):314-324

Höppner F, Menge-Hartmann U (1996) Nachwachsende Rohstoffe : Hanf - alte Kulturpflanze mit neuen Chancen? Forschungsrep Ern Landwirtsch Forsten(2):12-15

Hoffmann W (1961) Hanf, *Cannabis sativa* L. In: Kappert H, Rudorf W (eds) Handbuch der Pflanzenzüchtung : Bd 5, Züchtung der Sonderkulturpflanzen. Berlin : Parey, pp 204-263

Karus M, Linden W, Murr C, Waskow F (1993) Weshalb der Hanf wiederkehren wird : über die universelle Nutzpflanze Hanf. In: Herer J, Bröckers M (eds) Die Wiederentdeckung der Nutzpflanze Hanf, Cannabis Marihuana. Frankfurt a M : Zweitausendundeins, pp 299-345

Karus M (2004) First international conference of the European industrial hemp association (EIHA). J Industl Hemp 9(1):117-127

Keller A, Leupin M, Mediavilla V, Wintermantel E (2001) Influence of the growth stage of industrial hemp on chemical and physical properties of the fibres. Indust Crops Prod 13:35-48

Kessler W, Kessler RW (2006) Multivariate curve resolution : a method of evaluating the kinetics of biotechnological reactions. Anal Bioanal Chem 384(5):1087-1095

Kundu BC (1942) The anatomy of two Indian fibre plants, Cannabis and Corchorus with special reference to fibre distribution and development. J Indian Bot Soc 21:93-129

Mandolino G, Ranalli P (2004) An international symposium on the most advanced applications that can be foreseen for hemp. J Indust Hemp 9(2):103-107

Menge-Hartmann U, Höppner F (1995) Einfluß variierter Anbaubedingungen auf die Faserausbildung zweier Faserhanfsorten. Landbauforsch Völkenrode 45(4):168-176

Menzel A (1937) Beiträge zur Kenntnis von Bau und Entwicklung der Hanfpflanze *Cannabis sativa* L. mit besonderer Berücksichtigung der Faser. Faserforschung 13(1):1-14

Müssig J (2001) Untersuchung der Eignung heimischer Faserpflanzen für die Herstellung von naturfaserverstärkten Duroplasten – vom Anbau zum Verbundwerkstoff. Düsseldorf : VDI-Verl, Fortschritt-Berichte VDI : Reihe 05 Grund- und Werkstoffe, Kunststoffe 630

Müssig J, Martens R (2003) Quality aspects in hemp fibre production – influence of cultivation, harvesting and retting. J Industrial Hemp 8(1):11-32

Müssig J, Schmehl M, Buttlar H-B von, Schönfeld U, Arndt K (2006) Exterior components based on renewable resources produced with SMC technology – considering a bus component as example. Indust Crops Prod 24:132-145

Pate DW (1999) Hemp seed : a valuable food source. . In: Ranalli P (ed) Advances in hemp research. New York : Food Products Press, pp 243-255

Pracella M, Chionna D, Anguillesi I, Kulinski Z, Piorkowska E (2006) Functionalization, compatibilization and properties of polypropylene composites with hemp fibres. Comp Sci Technol 66(13):2218-2230

Pütz P (1993) Datenbank für physikalische Eigenschaften von festen landwirtschaftlichen Stoffen und deren Anwendung für Faserlein. Bonn, Forschungsber Agrartechnik 239

Ranalli P (1999) Agronomical and physiological advances in hemp crops.. In: Ranalli P (ed) Advances in hemp research. New York : Food Products Press, pp 61-84

Rennebaum H, Grimm E, Diepenbrock W (1998) Qualität von Ölleinfasern. Mitt. Ges. Pflanzenbauwiss 11:73-74

Rottmann-Meyer M-L (2002) Hanfanbau 2002 : Erntevorgaben werden erleichtert. Landwirtschaftsbl Weser-Ems 2002(16)

Sankari HS (2000) Comparison of bast fibre yield and mechanical fibre properties of hemp *Cannabis sativa* L. cultivars. Indust Crops Prod 11(1):73-84

Scheer-Triebel M, Heyland K-U (1994) Entwicklung von Schnelltests zur Untersuchung von Faserleistung und Faserqualität von Lein *Linum usitatissimum* L. und Bewertung von Genotyp und Umwelt im Hinblick auf industrielle Nutzung. VDLUFA-SchrR 38:497-500

Scheer-Triebel M, Léon J (2000) Industriefaser - Qualitätsbeschreibung und pflanzenbauliche Beeinflussungsmöglichkeiten bei Faserpflanzen : ein Literaturreview. Pflanzenbauwiss 4(1):26-41

Schulte E, Weber K (1989) Schnelle Herstellung der FS-Methylester aus Fetten mit Trimethylsulfoniumhydroxid oder Natriummethylat. Fett Wiss Techn 91(5):181-183

Struik PC, Amaducci S, Bullard MJ, Stutterheim NC, Venturi G, Cromack HTH (2000) Agronomy of fibre hemp *Cannabis sativa* L. in Europe. Indust Crops Prod 11(2-3):107-118

Thomsen AB, Thygesen A, Bohn V, Nielsen KV, Pallesen B, Jorgensen MS (2006) Effects of chemical-physical pre-treatment processes on hemp fibres for reinforcement of composites and for textiles. Indust Crops Prod 24(2):113-118

Tunder A (1973) Die Qualitätsbeurteilung von Bastfasern mittels einer Bündelfestigkeitsprüfung. Text Prax 22:549-555

Vetter A, Graf T, Mieck K-P (2000) Ertrags- und qualitätsbeeinflussende Faktoren beim Faserpflanzenanbau. UFOP-Schriften 14:185-191

Werf HMG van der (1991) Agronomy and crop physiology of fibre hemp : a literature review – CABO Rep 142:1-16

Werf HMG van der (1994) Crop physiology of fibre hemp *Cannabis sativa* L.. Wageningen : Agricultural Univ, 152 pp [Dissertation]