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Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe

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Abstract

Fibre hemp may yield up to 25 t above ground dry matter per hectare (20 t stem dry matter ha^{-1}) which may contain as much as 12 t ha^{-1} cellulose, depending on environmental conditions and agronomy. Its performance is affected by the onset of flowering and seed development. Effects of cultivar and management on yield and quality were tested at three contrasting sites in Italy, the Netherlands and the UK in three years, making use of standardised protocols for experimental design and research methodology. Highest yields (up to 22.5 t dry matter ha^{-1}) were obtained in Italy when later cultivars were used. Attainable yields proved slightly lower in the Netherlands and much lower in the UK. The quality of the cellulose was relatively stable over the growing season, but lignification may proceed rapidly some time after flowering. Crop development was very rapid and crops maintained green leaf area for a long time, thus radiation interception was considerable. The radiation use efficiency changed during development. It was lower after flowering (about 1.0 g MJ^{-1} PAR) than before (about 2.2 g MJ^{-1} PAR). Growing earlier cultivars to obtain some seed set advanced the reduction in radiation use efficiency. Nitrogen proved to affect yield only slightly. A relatively small amount of fertiliser will be adequate to cover the crop's needs. Plant density declined during growth in a site-specific manner when it was high initially. Very low plant densities may not show this self-thinning but reduced yield and (especially) quality. Final plant densities were proven to depend more on initial plant stands than expected from literature. This was true at all three contrasting sites and in the different years. Nitrogen and plant density hardly interacted within one site. Results suggest that hemp can yield large quantities of useful cellulose when ecologically adapted cultivars are sown in proper plant densities. The cultivation is environmentally friendly with little harmful accumulation or emission of chemical inputs. More research on ideotyping is required and breeding efforts should be broadened. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Fibre hemp; *Cannabis sativa*; Nitrogen; Plant density; Cellulose; Self-thinning

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1. Introduction

Fibre hemp (*Cannabis sativa* L.) is grown for a multitude of end products derived from the cannabinoids, seed, fibre and wooden core. It may also be grown as a shelter crop. As a fibre crop, it is one of the oldest non-food crops world-wide (Schultes, 1970). In Europe, flax and hemp were the most important fibre crops from the 16th to the 18th century. In the 19th century the cultivation of hemp in Europe declined but recently interest has been renewed, for example in Germany, France, the Netherlands, the UK, Spain and Italy, but also elsewhere in the world.

This renewed interest is triggered by several developments. Firstly, agricultural overproduction of some commodities within the EU has stimulated the search for novel uses of land, and hemp has been rediscovered as an interesting 'new' crop with a large plasticity, which allows it to be grown under a wide variety of agro-ecological conditions. Moreover, it is very high yielding compared with many other crops (Van der Werf et al., 1996). Due to this plasticity it may contribute to the (economic, environmental, agronomic and social) sustainability of arable farming. Secondly, hemp is an attractive non-food crop, which produces a wide variety of renewable resources, in a way that is much more efficient than with other non-food crops. Thirdly, because it produces many components that may be useful to mankind, it is an excellent model crop for the development of multi-output systems through stepwise breakdown of biomass into several useful components. The latter characteristic puts it ahead of many other non-food crops, which usually produce only one type of raw material.

Hemp also has one major disadvantage: it is associated with use of illegal narcotics and it is impossible without detailed costly analysis to discriminate before seed set between fibre types and drug types in a hemp crop. Consequently, only cultivars which set seed in a given member state are permitted to be grown in the EU.

Growing hemp is not difficult: the crop requires little or no biocide, suppresses weeds efficiently and has limited demands with respect to fertiliser usage or crop rotation (Van der Werf, 1994). The main problem might be crop establishment: hemp is very sensitive to poor soil structure and shortage or excess of water during early stages of growth (authors' personal experiences). The crop is high yielding, partly because it already shows full ground cover after a thermal time of about 400–450°C d (see e.g. Van der Werf, 1994; Van der Werf et al., 1995a), whereas a crop such as sugar beet requires 600–700°C d (see e.g. Smit and Struik, 1995).

Several physiological features, however, require special attention in breeding and crop management, because they are determinant for crop yield and quality. Firstly, hemp is a short day plant. This behaviour affects the crop production, because once the flowering starts the efficiency with which intercepted radiation is converted to dry matter drops rapidly (Van der Werf, 1994). It is therefore attractive to prolong the growing season by selecting later cultivars for higher latitudes (Van der Werf, 1994; Stutterheim et al., 1999). In southern Europe, genotypes should be selected with a longer critical photoperiod to profit optimally from the available growing season (S. Amaducci et al., unpublished data). The cultivars that are grown in Europe are usually of French origin, and have a critical photoperiod between 14 and 15.5 h. Their behaviour is therefore different in different eco-regions of Europe and they may not be able to make full use of the potential of the seasons all over Europe.

Secondly, there is a large degree of heterogeneity in the crop (Van der Werf et al., 1995b). This is partly caused by sexual dimorphism: the differences in rate of growth and development between male and female plants are large (Van der Werf and Van den Berg, 1995). The male plants tend to flower and senesce earlier. Also within the same sex, large plants are suppressing smaller ones and thus plant-to-plant variation can become considerable and may even result in self-thinning (Van der Werf et al., 1995c). Particularly in dense stands intra-specific competition generates a size hierarchy and thus increases variability (Van der Werf et al., 1995b). This variation may limit yields, may reduce the efficiency of resource use, and may result in variable quality.

Thirdly, growers should aim at a high cortical surface area compared to the crop volume because this will realise a high bark:core ratio. The fibre quality in the bark (mainly primary bast fibres and some secondary bast fibres) is much better than in the core (mainly high-lignin, libriform fibres) (Bedetti and Ciareli, 1976; Bosia, 1976). This can be realised by aiming at high densities (Van der Werf et al., 1995b). The bast fibre content of the stem increases with plant density (Jakobey, 1965). Moreover, a dense crop causes strong elongation of the primary bast, producing long low-lignin fibres (F. Engels, personal communication). This means that despite the self-thinning, large quantities of hemp seeds are sown to establish a very dense crop. Farmers thus have to cope with the difficulties caused by the fierce plant-to-plant competition.

Finally, the development of the individual internodes over time is important. Individual internodes produce increasing amounts of cellulose until the lumen of the cells is completely filled. There is an asynchrony in this event along the stem (F. Engels, personal communication), but for the crop as a whole there may be a clear (but difficult to assess) moment at which the cellulose yield is maximal and after which the main process that continues is the encrustation of lignin in the cell walls. Timing of the harvest in relation to environmental conditions may therefore be crucial.

These four aspects of growing hemp in Europe mean that the genotype × environment × crop management interaction is relevant and should be studied in more detail. This paper evaluates the yield formation and the effects of cultivar and crop management thereon for three years and three contrasting sites as recorded in field experiments based on the same protocol and methodology.

The objectives of this paper are:

1. to assess the range of effects of cultivar, nitrogen, plant density and harvest date on yield and quality of hemp grown for fibre;
2. to estimate attainable yield and quality of hemp under field conditions at different locations in Europe;
3. to identify production constraints in northern and southern Europe, and
4. to make suggestions for optimum crop management of fibre hemp in Europe.

2. Materials and methods

The data discussed in this work were obtained from a series of fields trials carried out in the framework of the FAIR project Hemp for Europe — Manufacturing and Production systems, in 1996–1998. The experiments were performed at three different sites in England, Italy and The Netherlands, making use of standardised experimental designs and protocols for harvesting and parameter assessments. All seeds were purchased from the Fédération Nationale des Producteurs de Chanvre, Les Mans, France.

In 1996, at each site, three cultivars were compared over three nitrogen levels and over three plant populations in a four replicate split-plot design, with cultivar as the main plot factor. Cultivars were selected as representative of early, medium and late maturity genotypes, and were different for England and The Netherlands (Fédora 19, Félina 34, Futura 77 and in the Netherlands also Kompolti) and for Italy (Félina 34, Futura 77 and Carmagnola). Cultivars will be named Fédora, Félina, Futura, Kompolti and Carmagnola in Section 3 of this paper. Details on the response of these cultivars to photoperiod will be reported in a future paper by Stutterheim et al.

Three levels of available nitrogen were obtained by supplementing the natural reserves of the top 0.6 m soil layer at the onset of the growing season up to 100, 160, 220 kg N ha^{-1}.

Three target plant populations (30, 90, 270 plants m^{-2}) were obtained sowing different amounts of seed and thinning the crop after emergence when expected plant stands exceeded target densities.

In 1997, two experiments were carried out at each location. The first one was laid out as a single factor randomised complete block design with three target plant stands (45, 90, 180 plants m^{-2}), whilst in the second two cultivars were compared over three levels of available nitrogen (soil available N plus fertiliser N: 100, 160, 220 kg ha^{-1}). At all sites, Futura 77 was used in both experiments, while the second cultivar in the nitrogen experiment was Félina 34 in England and Kompolti in Italy and The Netherlands.

In 1998, the same experiments carried out in 1997 were repeated in England. In Italy and The Netherlands, only the density trial, comparing Futura 77 over three densities (45, 90, 180 plant m^{-2}) was performed.

Every year and for each experiment, six periodical samplings were carried out in all plots. At each sampling time, all plants growing in an area of 1 m^2 (2 m^2 in the last couple of samplings) were cut above soil level, except 12 plants, which were up-rooted.

Fresh biomass of the sampled area was determined and the number of plants was counted.

For the 12 plants-sample, the following parameters were assessed: fresh and dry weight of leaves, stem, roots and inflorescence, when present; Leaf Area Index (using a LI-COR 3100); number of plants in bloom (distinguishing males from females and monoecious plants when possible); number of nodes per stem, plant height and root length.

Daily standard meteorological data were recorded at each site. Light interception was measured on a weekly basis till canopy closure and then simultaneously with each harvest.

Table 1 summarises some experimental details.

Sub-samples of harvested stem dry matter were analysed for cell-wall constituents (cellulose, hemi-cellulose and lignin) according to the methods described by Van Soest et al. (1966).

In this paper we only report on the following experiments: Italy: 1996, 1997 and 1998, The Netherlands: 1996 and 1997; UK: 1996 and 1998.

3. Results and discussion

In all year × site combinations, the later or latest cultivar yielded similar or higher amounts of above-ground dry matter and stem dry matter than the earlier (or earliest) one, both in the nitrogen treatments (Table 2) and in the plant density treatments (Table 3). This effect was hardly associated with a consistent improvement of leaf-area duration (and thus a higher accumulated radiation interception), but mainly due to the effect of cultivar on date of flowering (data not shown). A later cultivar flowered later and therefore postponed its reduction in radiation use efficiency associated with the reproductive phase (Table 4). This result shows that it is attractive to grow later cultivars, and that the EU policy to require a certain proportion of seed set in fibre hemp may reduce yields considerably.

Typically, the cellulose content in the stem dry matter of a harvestable crop was 60–65%, with a slight increase during maturation. This increase over time, however, was associated with an increase of the lignin content as well (Fig. 1a). Cellulose yields increased until the end of the growing season (Fig. 1b), but the quality might have been slightly lower at the end, because of advanced encrustation with lignin.

The cultivar Futura was grown at all sites in all years reported. Its yields in the best agronomic treatment were 13.7 t ha^{-1} in the UK in both years, varied from 17.6 to 20.4 t ha^{-1} in the Netherlands, and from 15.1 to 22.5 t ha^{-1} in Italy. These maximum yields were attained in very different combinations of agronomic treatments. When we compare these ranges with the highest yields obtained for each site, it is likely that in northern Europe Futura has attainable yields similar to Félina, but in Italy later cultivars such as Carmagnola may out-yield Futura under conditions favouring hemp growth. This was for example the case in 1996. Moreover, Futura may have higher potential yield in Italy than in Northern Europe, due to the earlier sowing date and the higher light intensity. Attainable yields varied among years: they were about 15–22.5 t ha^{-1} above ground dry matter (7.5–12 t cellulose ha^{-1}) in Italy, 17.5–19.5 t ha^{-1} (9–10 t cellulose ha^{-1}) in the Netherlands, and 9–10 (5–6 t cellulose ha^{-1}) in the UK.

Interactions between factors were generally absent and therefore we will only discuss the main effects of nitrogen and plant density.

The soil in Italy was very rich in nitrogen; therefore the response to nitrogen was limited (Table 2). Only when no N fertilisation (soil avail-

Table 1
Dates of sowing and harvest, thermal time (growing degree–days; GDD) and rainfall from sowing (S) to harvest (H) for the three locations and the three years of the described experiments

	1996			1997			1998		
	Italy	Netherlands	United Kingdom	Italy	Netherlands	United Kingdom	Italy	Netherlands	United Kingdom
Sowing	9–27 April[a]	7 May	7 May	28 March	24 April	10 April	2 April	22 May	8 May
Harvest	2 September	3 October	5 September	3 August	8 September	8–14 September[b]	3 September	–	31–26 August[b]
GDD S-H	2660–2923[a]	2126	–	2459	2224	1943–2048[b]	3328	–	1653–1584[b]
Rain (mm)	222–257[a]	220	–	240	294	478–484[b]	212	–	311

[a] First data refer to Carmagnola, the second to Félina and Futura.

[b] First data refer to the nitrogen experiment, the second to the density experiment.

Table 2
Effects of nitrogen treatments in various experiments at three sites and in three years on above-ground dry matter and stem dry matter[a]

	1996									1997				1998		
	I[b]			NL[b]			UK[b]			I[b]		NL[b]		UK[b]		
Nitrogen	Carm.[c]	Fel.[c]	Fut.[c]	Fed.[c]	Fel.[c]	Fut.[c]	Fed.[c]	Fel.[c]	Fut.[c]	Fut.[c]	Komp.[c]	Fut.[c]	Komp.[c]	Fel.[c]	Fut.[c]	Average
Above ground dry matter (t ha^{-1})																
100	20.9	13.7	20.4	11.5	13.0	13.4	5.6	9.7	9.1	12.6	11.6	14.8	15.1	11.0	10.2	13.1
160	16.7	15.0	15.4	14.0	15.2	12.9	10.6	9.5	10.8	14.2	13.6	17.6	12.9	12.2	13.7	13.8
220	17.8	14.8	17.7	15.1	16.1	19.5	15.3	10.7	11.9	15.1	14.5	16.5	16.7	12.1	13.5	15.4
Average	18.4	14.5	17.8	13.5	14.7	15.3	10.5	10.0	10.8	13.9	13.2	16.3	14.9	11.8	12.5	14.1
Stem dry matter (t ha^{-1})																
100	16.3	8.3	13.7	9.2	10.9	11.1	3.6	6.8	6.6	10.6	10.6	12.1	13.5	7.9	8.0	10.2
160	13.0	9.7	11.0	11.0	12.2	10.4	7.1	6.5	8.2	12.2	12.3	14.5	11.6	8.9	11.1	10.8
220	14.4	9.5	13.0	11.4	13.2	16.1	10.6	6.8	8.8	12.3	12.7	13.8	15.1	9.0	10.7	12.1
Average	14.6	9.2	12.6	10.5	12.1	12.5	7.1	6.7	8.0	11.7	11.9	13.4	13.4	8.6	9.9	11.0
Plant density (plants m^{-2})																
100	70	74	74	53	75	62	85	99	107	86	91	79	66	75	85	77
160	70	77	75	63	62	55	75	82	65	78	78	79	65	86	83	72
220	61	79	76	46	65	56	82	59	66	81	75	77	61	79	87	69
Average	67	76	75	54	68	58	81	80	76	82	81	78	64	80	85	73

[a] Summary of statistics: Italy 1996: Cultivar effect significant ($P<0.01$), for both yield parameters, Carmagnola being significantly higher than the other two, and no difference between the latter. N effects not significant. Italy 1997: Cultivar effect not significant. Nitrogen effect significant ($P<0.05$) for both yield parameters, with N100 being significantly lower than N160 and N220 and no difference between the two highest N levels. N100 significantly higher plant density than the other two N treatments. Netherlands 1996: Significant cultivar × nitrogen interactions for above ground dry matter, but not for stem dry matter. N effect significant for both yield parameters, with N220 being higher than the other two levels and no significant difference between N100 and N160. N effect on plant density significant. Netherlands 1997: No statistically significant differences, except for the cultivar effect on plant density. UK 1996: Cultivar effects not significant, but nitrogen effects significant for both yield parameters and final plant density. UK 1998: Cultivar effect significant for stem dry matter yield only. Nitrogen effects (highly) significant for both yield parameters. No N effects on final plant density.

[b] Sites: I, Italy; NL, The Netherlands; UK, United Kingdom.

[c] Cultivars: Carm., Carmagnola; Fed., Fédora; Fel., Félina; Fut., Futura; Komp., Kompolti.

able N ranging from 40–100 kg N ha^{-1}) was applied, a small yield effect was observed compared to the other treatments in 1997. In Northern Europe, the response to nitrogen was stronger, also due to the relatively wet summers experienced by the crops. In the UK, crops reliant

Table 3
Effect of plant density treatments in various experiments at three sites and in three years on above-ground dry matter and stem dry matter[a]

	1996									1997		1998		
	I[b]			NL[b]			UK[b]			I[b]	NL[b]	I[b]	UK[b]	
Density	Car.[c]	Fel.[c]	Fut.[c]	Fed.[c]	Fel.[c]	Fut.[c]	Fed.[c]	Fel.[c]	Fut.[c]	Fut.[c]	Fut.[c]	Fut.[c]	Fut.[c]	Average
Above Ground Dry Matter (t ha^{-1})														
30	13.9	10.4	14.2	14.5	13.9	15.2	10.2	9.2	9.7					12.7
45										14.2	17.6	22.5	11.5	16.4
90	16.7	15.0	15.4	14.0	15.2	12.9	10.6	9.5	10.8	14.3	20.4	20.9	12.8	14.7
180										13.2	15.9	21.7	13.1	16.0
270	20.1	15.9	17.5	12.7	14.6	13.8	12.3	17.1	13.7				13.0	15.0
Average	17.5	14.4	16.0	13.7	14.5	14.0	11.0	11.9	11.4	13.9	18.0	21.7	12.6	14.7
Stem Dry Matter (t ha^{-1})														
30	9.9	6.6	9.3	11.1	11.4	12.9	6.8	5.8	6.8					9.5
45										12.0	14.2	18.5	9.2	13.5
90	13.0	9.7	11.0	11.0	12.2	10.4	7.1	6.5	8.2	11.9	16.9	17.6	10.4	11.4
180										10.6	13.3	17.9	11.0	13.2
270	15.4	9.7	12.1	10.1	12.0	12.0	8.9	10.8	10.5				11.1	11.4
Average	13.4	9.1	11.1	10.7	11.9	11.8	7.6	7.7	8.5	11.5	14.8	18.0	10.4	11.5
Plant density (plants m^{-2})														
30	15	15	16	31	32	27	33	32	27					27
45										46	47	41	39	43
90	70	77	75	63	62	55	75	82	65	80	86	77	76	72
180										144	122	143	130	134
270	145	160	151	108	123	102	237	342	233				142	162
Average	89	97	93	67	72	62	115	152	108	90	85	87	97	90

[a] Summary of statistics: In all site × year combinations: density effects on final plant number highly significant. Italy 1996: Cultivar effect see Table 2; density effect significant ($P<0.01$) for above ground and stem dry matter yield, with the lowest density (actually only 15 plants m^{-2}) less productive than the other densities (which did not differ significantly). Italy 1997 or 1998: Cultivar or density effects on yield parameters not significant. Netherlands 1996: No effects of density on yield parameters. Netherlands 1997: Cultivar effect see Table 2; No effects of density on yield parameters. UK 1996: No significant effects. UK 1998: Plant density only affected stem dry matter yield (with the lowest density yielding less than the other densities).

[b] Sites: I, Italy; NL, The Netherlands; UK, United Kingdom.

[c] Cultivars: Carm., Carmagnola; Fed., Fédora; Fel., Félina; Fut., Futura.

Table 4
Selected information on radiation interception and radiation use efficiency

	Italy 1997	The Netherlands 1996	Van der Werf (1994)
Radiation interception (MJ m^{-2})	784	855	1050
Radiation use efficiency (g MJ^{-1})			
Before flowering	2.26	2.16	2.2
After flowering	0.95	1.09	1.1

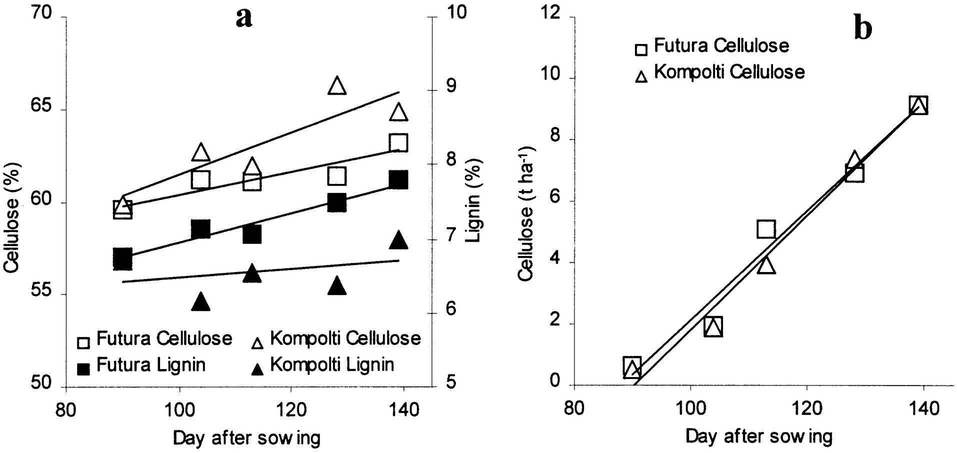

Fig. 1. Development over time (days after sowing) of (a) cellulose and lignin contents and (b) cellulose yields in the 1997 hemp crop of the Netherlands (Cvs Futura and Kompolti, 90 plants m^{-2} and 160 kg available N ha^{-1}).

on soil available N produced shorter plants and smaller crop canopies, intercepted less radiation, had lower RUEs and consequently yielded less dry matter and fibre. Nevertheless nitrogen had only a small effect on the phenological behaviour of the crop. Moreover, the effects on cellulose content were negligible (data not shown). Averaged over NL and UK, the two years and the cultivars tested, there was a gradual increase (N100: 9.0, N160: 10.2, N220: 11.6 t stem dry matter ha^{-1}) in useable yield with an increase in N supply. Extra nitrogen slightly increased the competition among crop plants and therefore enhanced self-thinning: averaged over all agro-ecological situations the number of remaining plants at final harvest declined with an increase in N supply (Table 2). However, there was a significant genotype × year × environment interaction for this phenomenon. The combination of the overall effects of nitrogen on crop yield and final plant number resulted in a considerable increase of the weight per stem with an increase in N supply (data not shown).

In general the effects of plant density on aboveground and stem dry matter yield were small and statistically not significant (Table 3). Only with extremely high plant densities (if lodging and disease infections could be prevented in the densest stands) or densities well below the lowest target density some effect could be observed. However, initial plant density is a crucial husbandry tool for obtaining a proper quality (Van der Werf et al., 1995b). Crops with an initial plant density of 30–90 plants m^{-2} generally maintained this density throughout the growing season at all sites (Fig. 2). Crops of 180 or 270 plants m^{-2} showed self-thinning, but the severity was variable: final plant densities for these dense crop varied between 110 and 180 plants m^{-2}, but were in all cases significantly higher than the final plant density of the lower two plant densities. This is in contrast with findings of (for example) Meijer et al. (1995) who showed that final plant density was about the same irrespective of initial plant density as long as the latter was between 30 and 200 plants m^{-2}. There was a consistent trend that denser crops grew shorter (Fig. 3). Largest effects of density on plant height were observed in the Netherlands. Detailed crop measurements over a wide range of plant densities in Italy showed that denser crops produced plants, which were lower in dry mass (Fig. 4a), shorter (Fig. 4b) and thinner (Fig. 4c) and therefore had a lower cortical surface (Fig. 4d), and a much larger ratio between surface and volume (Fig. 4e) and surface density (i.e. the cortical surface per unit land area; Fig. 4f). These effects cause a significant positive effect of plant density on the yield of high quality fibres, since the best quality fibres are obtained when the ratio between cortical surface and volume is high (see Section 1).

Non-uniform germination sometimes disturbed the general patterns described above. This was most obvious from the UK data and illustrates that uniform crop establishment is crucial. Hemp proved to be very sensitive to soil structure. Especially in a very wet or very dry year, such effects become visible. Actually, the 1998 crop in the Netherlands completely failed because seedlings did not survive the extreme rains.

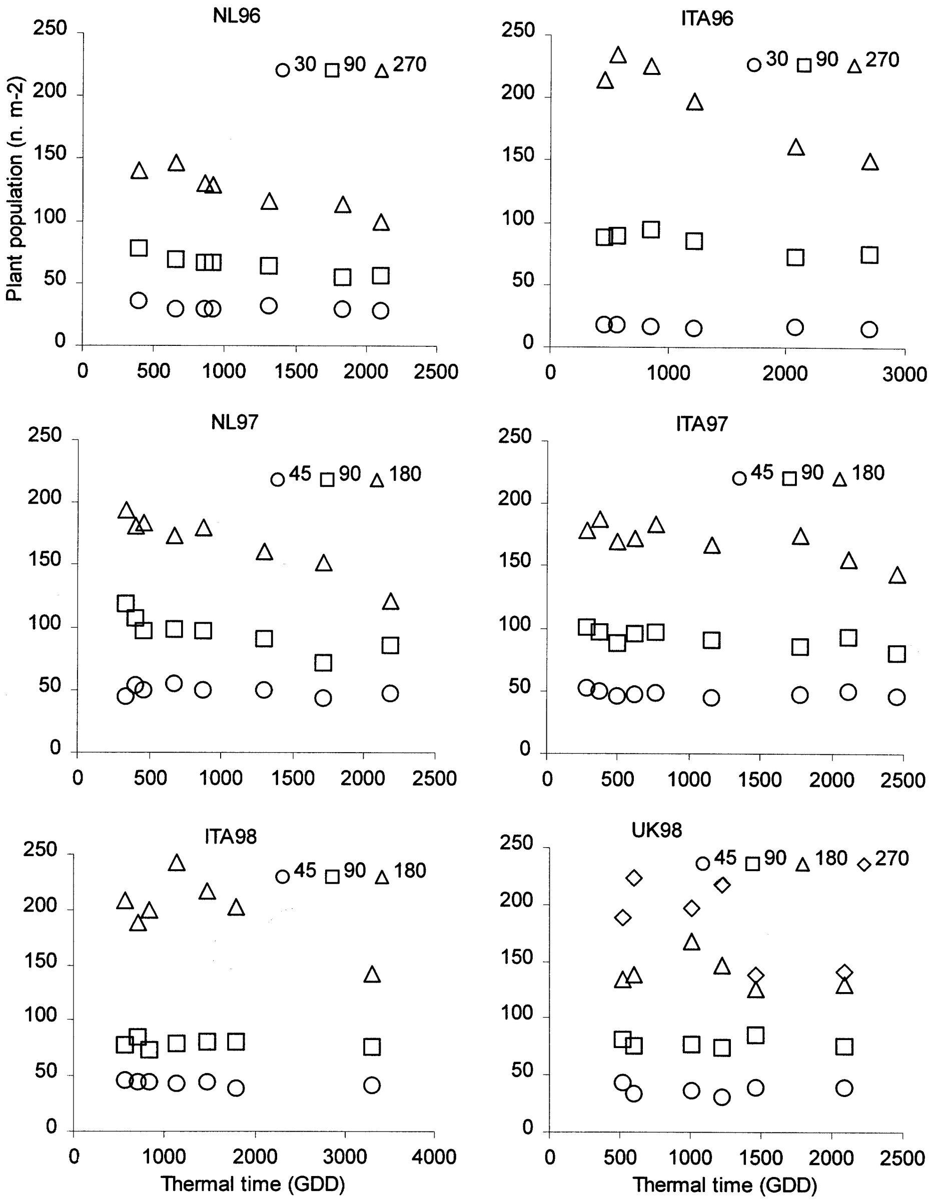

Fig. 2. Development over accumulated temperature sum (thermal time) of plant density starting from different initial stands for the three years at two sites for each year.

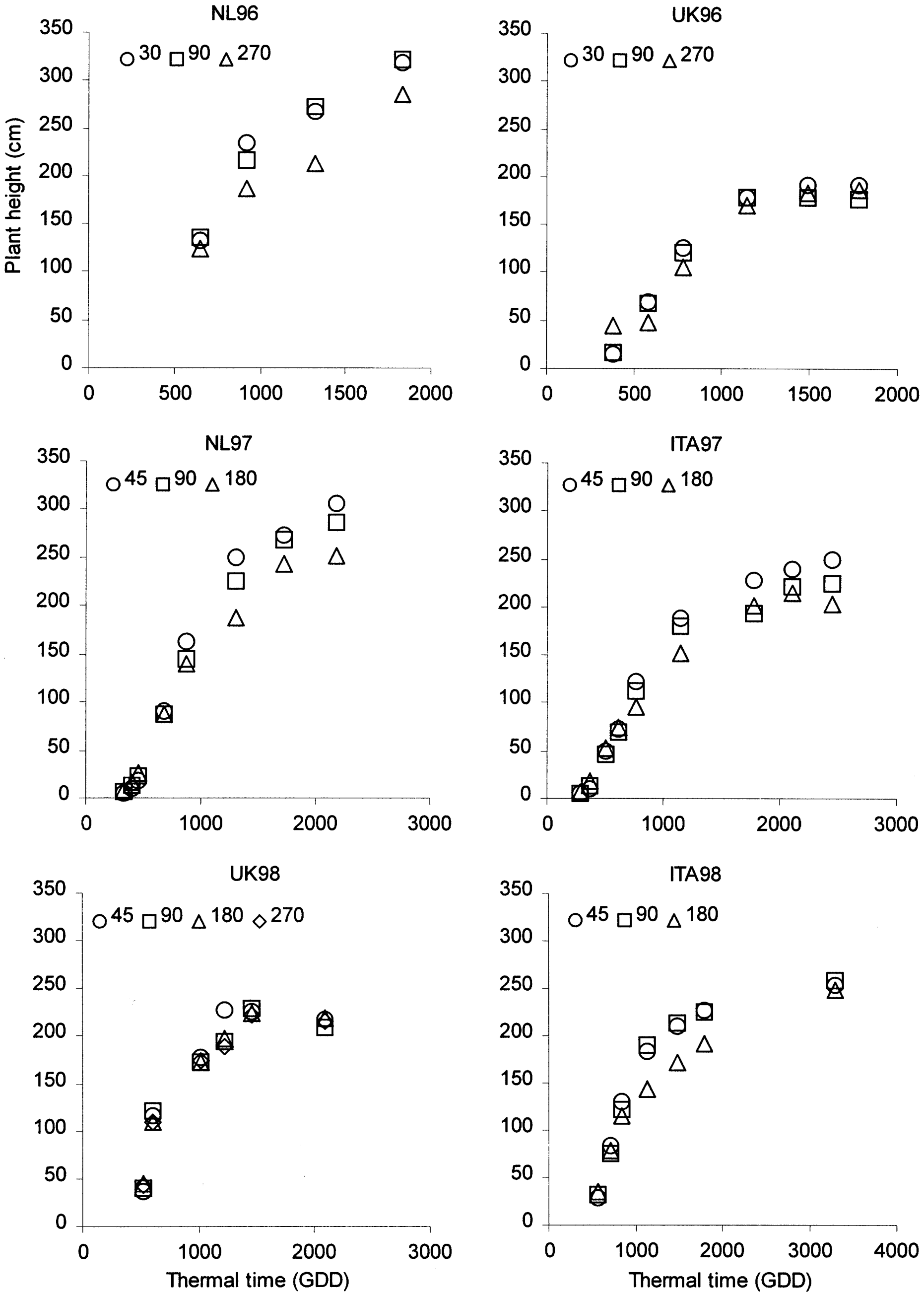

Fig. 3. Effect of plant density on the course of plant height over accumulated temperature sum for the three years at two sites for each year.

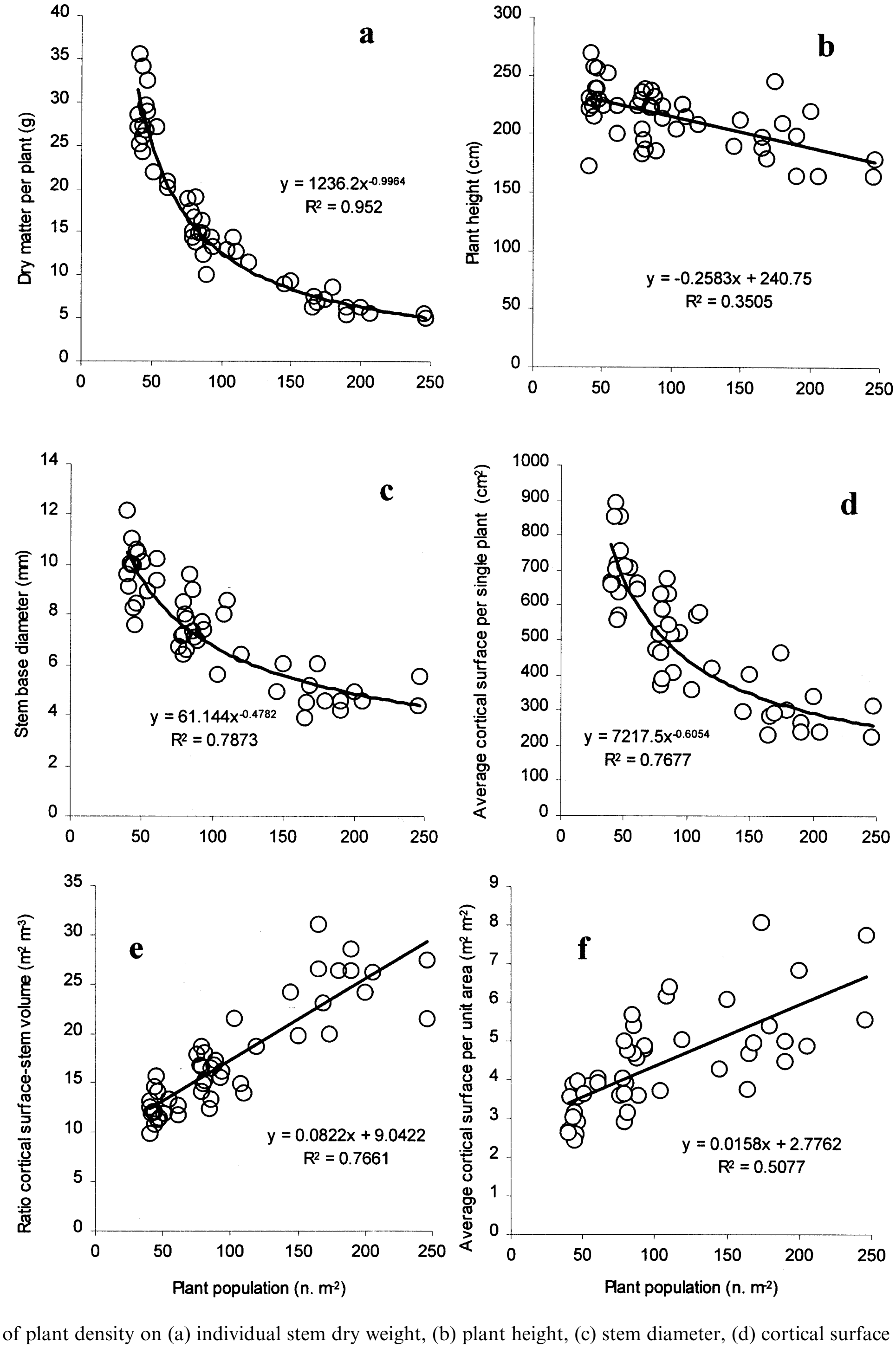

Fig. 4. Effect of plant density on (a) individual stem dry weight, (b) plant height, (c) stem diameter, (d) cortical surface area, (e) ratio surface to volume and (f) surface density. Data from Italy 1997.

4. Conclusion

High yields of good quality fibres are possible throughout Europe. The cultivation of hemp is not difficult. Plant density should be high, while preventing excessive lodging and development of fungal infection. Maturity class and photoperiodic response of the cultivars, however, are important and therefore more research on ideotyping and a wider breeding effort are recommended.

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