Ann. appl. Biol. (1996), **129**:109–123
Printed in Great Britain

The potential of hemp (*Cannabis sativa* L.) for sustainable fibre production: a crop physiological appraisal

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(Accepted 15 July 1996)

Summary

Hemp (*Cannabis sativa* L.) fibre can be used as a raw material for paper and textile production. A comprehensive research programme in the Netherlands has concluded that fibre hemp is a potentially profitable crop, having the right profile to fit into sustainable farming systems. This paper presents an appraisal of the crop physiological characteristics and the agronomic potential of hemp. Parameter values of basic crop physiological characteristics such as light interception potential, radiation use efficiency and dry matter partitioning coefficients are given. The effect of crop management decisions such as cultivar choice, sowing date, plant density, and harvest date on the value of these parameters is discussed. A simple crop growth model was used to assess the yield potential of hemp for the climate of the Netherlands. Calculations made for a non-stressed late-flowering hemp crop sown on 15 April and harvested on 15 September give a stem dry matter yield of 17.1 t ha^{-1}. The effects of advancing or delaying sowing or harvest date on stem yield were calculated. Crop physiological characteristics of hemp are compared to those of kenaf (*Hibiscus cannabinus* L.). Radiation use efficiency and dry matter partitioning coefficients of the two crops are similar. Base temperatures for development and growth are lower in hemp than in kenaf. In a temperate climate with cool springs, canopy establishment will be more rapid in hemp than in kenaf. Hemp seems an excellent candidate to fill the niche for an annual fibre crop in a temperate climate.

Key words: *Cannabis sativa* L., dry matter partitioning, hemp, *Hibiscus cannabinus* L., light interception, radiation use efficiency, potential production

Introduction

Hemp (*Cannabis sativa* L.) is grown for the production of fibre (Rabelais, 1546), cannabinoids (Beaudelaire, 1860) or seed (Deferne & Pate, 1996). *Cannabis* originates from Central Asia but has been cultivated from the Equator to the Polar Circle (Vavilov, 1926).

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Human use of hemp goes back at least 6000 years and it may be one of the oldest non-food crops (Schultes, 1970). For thousands of years, hemp bast fibre has been used to manufacture rope, fabric and paper. Cannabinoids have been used for medical, spiritual and recreational purposes, whereas the seed was produced mainly for its oil.

From the sixteenth to the eighteenth century, hemp and flax (*Linum usitatissimum* L.) were the major fibre crops in Russia, Europe and North America (Pounds, 1979; Abel, 1980). Both crops were used for the production of fabrics for garments. Worn-out flax and hemp fabrics were used as raw materials in paper mills. However, the large-scale cultivation of cotton, jute and other tropical fibres, and the development of new technologies to process wood into paper pulp caused the world area of hemp and flax to decline in the nineteenth century. This decline has continued in this century, due to the advent of synthetic fibres. The presence of psychoactive components in hemp was another reason for its decline, as this became a motive to prohibit hemp cultivation in many countries (Dempsey, 1975). Since the second world war, the main areas of fibre hemp production have been in China, the Soviet Union and Eastern Europe. In 1994 there were 119 000 ha under fibre hemp in the world (Anon., 1995).

During recent decades the paper pulp industry has been criticised for its negative impact on the natural environment: deforestation, or the replacement of old-growth forests by tree plantations (Postel & Ryan, 1991), the emission of chemical waste, high energy use and the production of toxic and mutagenic waste products by chlorine bleaching (McDougall *et al.*, 1993). Measures taken to tackle these problems include increased recycling of paper, more sustainable management of tree plantations and forests and a shift towards less harmful pulp and paper technologies.

Intensive cotton (*Gossypium* L.) production has also been severely criticised for its negative effects on the environment: intensive use of pesticides (cotton can be treated 20 times per season), high fertiliser and irrigation requirements (Anon., 1990; Pimentel *et al.*, 1991). These problems can be reduced to some extent by introducing integrated pest management techniques or by shifting to organic farming methods (Pimentel *et al.*, 1991; Pleydell-Bouverie, 1994).

A comeback of hemp as a raw material for paper and textile may further contribute to the sustainability of the paper and textile industry. Growing an annual crop on farmland to produce fibre obviously lessens the need to cut down forests. In addition, less energy is required to produce pulp from hemp than from wood (Van Roekel, Lips, Op den Kamp & Baron, 1995), and the lignin content of the former is lower, offering better opportunities for non-chlorine bleaching or the production of unbleached pulp (McDougall *et al.*, 1993). Relative to cotton, hemp can be produced more sustainably, as it requires little pesticide and its fertiliser requirements are modest.

From the second world war until the 1980's, hemp was a largely forgotten crop. However, in eastern and central Europe and in France breeding work continued (De Meijer, 1995), leading to more productive hybrid varieties (Bócsa, 1971), increased fibre contents (Bócsa, 1995) and very low contents of psychoactive substances (Fournier *et al.*, 1987; Goloborod'ko, 1995). The potential of hemp as an attractive crop for sustainable fibre production was pointed out in the early 1980's (Hanson, 1980). Its yield was reported to be high, and it was said to improve soil structure (Du Bois, 1982). Furthermore, hemp was claimed to suppress weeds effectively, and to be virtually free from diseases or pests. A few years later, Herer (1985) claimed that hemp yielded several times more cellulose than other crops such as corn (*Zea mays* L.), kenaf (*Hibiscus cannabinus* L.) or sugar cane (*Saccharum* L.).

As a result of this renewed interest in hemp, preliminary research was conducted during the 1980's into the best ways of growing, harvesting and pulping fibre hemp in the Netherlands (e.g. Du Bois, 1984; De Groot, Van Zuilichem & Van der Zwam, 1988). The results were encouraging, and in January 1990 a comprehensive 4-year study, the Hemp Research

Programme, was started to investigate the potential of fibre hemp as a new raw material for the pulp and paper industry, and to establish whether the production of fibre hemp for paper pulp would be economically attractive. The major research disciplines within the programme were: plant breeding (De Meijer, 1994; Hennink, 1994), crop physiology and agronomy (Van der Werf, 1994), plant pathology (Kok, Coenen & De Heij, 1994), harvest and storage technology (De Maeyer & Huisman, 1994), pulp technology (De Groot, Van Dam, Van der Zwam & Van 't Riet, 1994; Van Roekel, 1994) and economics and market research.

From this research programme, it was concluded that potentially fibre hemp is a profitable crop for arable farmers in the Netherlands, provided a pulp factory is set up (Bakker & Van Kemenade, 1993). Agronomically, hemp proved to be attractive, as most of the claims made by early hemp advocates proved to be true (Van der Werf, Van Geel & Wijlhuizen, 1995*a*): hemp can supply high fibre yields, requires little or no pesticide and suppresses weeds and some major soil-borne diseases. However, in the maritime climate of the Netherlands the crop is not disease-free, as the fungus *Botrytis cinerea* can cause severe damage in wet years (Van der Werf *et al.*, 1995*a*). In spite of this, hemp manifestly will fit into sustainable farming systems.

This paper examines the crop physiological and agronomic characteristics of hemp, and a simple crop growth model is used to assess its yield potential. Hemp is compared with kenaf, another annual fibre crop. This article is based on recent research conducted in the Netherlands and on data from the literature.

Crop physiological characteristics

A crop achieves its full potential when not limited by shortage of water or of nutrients, by pest or disease attack, or by other stresses. In such ideal conditions, its dry matter production is approximately proportional to the amount of light (photosynthetically active radiation, PAR) intercepted by the crop canopy (Monteith, 1977). Dry matter yield (Y) of such a non-stressed crop can be described as:

$$Y = L \times RUE \times HI$$

where L is the amount of light intercepted during a growing season, RUE is the radiation use efficiency (the amount of dry matter produced per unit of light intercepted), and HI is the harvest index (the proportion of total dry matter consisting of plant parts of economic value). These three parameters will be considered.

Interception of light during the growing season

The amount of light an annual crop intercepts depends on its emergence date, its rate of canopy establishment, the proportion of incident light intercepted by a fully established canopy, the date of onset of canopy senescence and the rate at which light interception by the canopy declines during senescence. These factors can be affected by environmental parameters (temperature, radiation, daylength) and by crop management. The main crop management decisions affecting light interception by a non-stressed fibre hemp crop are cultivar, plant density, sowing date and harvest date. To avoid cultivar and plant density limiting hemp yield, the cultivar should not flower (Van der Werf, Haasken & Wijlhuizen, 1994*a*) and plant density should be sufficiently high without exceeding the maximum density that can be sustained at the expected yield (Van der Werf, Wijlhuizen & De Schutter, 1995*b*; Van der Werf & Van den Berg, 1995). We will examine the effect of sowing date and harvest date on light interception by a non-flowering hemp crop grown at a plant density appropriate for a high yield.

Sowing date

In North-west Europe, incoming radiation is greatest in May, June and July, whereas temperatures are highest in July and August (Table 1). In May and June, the interception of incident light by spring-sown crops is generally incomplete, because of slow canopy expansion at sub-optimum temperatures. However, hemp grows at low temperatures, and might therefore be well adapted to the temperate climate of North-west Europe. Its base temperature for leaf appearance is 1°C, and for canopy establishment is 2.5°C (Van der Werf, Brouwer, Wijlhuizen & Withagen, 1995*c*). In this respect, hemp is similar to one of the major arable crops in North-west Europe *viz.* sugar beet, also a spring-sown dicotyledon. Sugar beet has a base temperature of 1°C for leaf appearance and of 3°C for leaf expansion (Milford, Pocock & Riley, 1985*a*). From sowing to 50% plant emergence, sugar beet requires about 90°Cd (base 3°C, Smit, 1989), whereas hemp requires 56°Cd (base 3°C, Van der Werf *et al.*, 1995*c*). To reach canopy closure, sugar beet grown at its optimal density of about eight plants m^{-2} requires another 500°Cd (base 3°C) (Milford, Pocock, Riley & Messem, 1985*b*), whereas hemp (at 64 plants m^{-2}) requires another 340°Cd (base 2.5°C) (Van der Werf *et al.*, 1995*c*). As a result, under similar circumstances, hemp establishes a closed canopy more rapidly than sugar beet.

To maximise the yield of sugar beet in the Netherlands, the crop should be sown from the end of March, as soon as soil and weather conditions permit (Smit, 1993). As sugar beet and hemp have similar base temperatures for growth, one might expect their optimal sowing dates to be similar. However, frost resistance is another factor which may affect the optimal sowing date of a crop. Sugar beet is most sensitive to frost at emergence: seedlings may be killed by a frost of about −5°C, though once fully emerged, the plants tolerate frosts of up to −10°C (A L Smit, personal communication, 1994). Hemp seedlings survive a short frost of up to −8°C to −10°C (Grenikov & Tollochko, 1953); older hemp plants tolerate frosts of up to −5°C to −6°C (Senchenko & Timonin, 1978). Sugar beet is more at risk from frost during emergence than hemp, whereas hemp is more at risk than sugar beet for a much longer period.

To estimate the effect of sowing date on canopy establishment and potential light interception by fibre hemp in the Netherlands, a simple crop growth model was used, based mainly on the results of Van der Werf *et al.* (1995*c*). The model is a modified version of the "light interception and utilisation" (LINTUL) model proposed by Spitters (1990). It was assumed that the crop required 77°Cd (base 1°C) from sowing to emergence (Van der Werf *et al.*, 1995*c*). Canopy establishment was described using the relation between the proportion of light intercepted and thermal time for crops grown at 64 plants m^{-2} (Van der Werf *et al.*, 1995*c*). Maximum interception was assumed to be 99% until harvest (Van der Werf *et al.*, 1995*b,c*). Average (1961–1990) temperature and radiation data recorded at De Bilt in the centre of the Netherlands were input in the model.

The second half of April is often recommended as the best period for sowing hemp (Heuser, 1927; De Jonge, 1944; Senchenko & Demkin, 1972; Mathieu, 1980). For a hemp crop sown on 15 April, the model calculated emergence on 26 April and canopy closure (90% PAR interception) on 1 June (Table 2). For a crop sown 30 days earlier, on 16 March, emergence

Table 1. *Average global radiation and temperature at De Bilt, 1961–1990*

	Month							
Parameter	March	April	May	June	July	Aug.	Sept.	Oct.
Mean temperature (°C)	5.0	8.0	12.3	15.2	16.8	16.7	14.0	10.5
Global radiation (MJ m^{-2} day^{-1})	7.9	12.9	16.8	17.9	16.7	14.7	10.3	6.1

Table 2. *Simulated effects of sowing date on the date of emergence and canopy establishment and on the accumulated intercepted PAR until 1 August by the canopy of fibre hemp. Average (1961-1990) temperature and radiation data were input in the model*

Sowing date	Sowing to emergence (days)	Emergence to 90% interception (days)	Date of 90% interception	PAR intercepted until 1Aug. (MJ m^{-2})
16 March	16	49	20 May	737
31 March	13	42	25 May	686
15 April	11	36	1 June	617
30 April	8	32	9 June	538
15 May	7	29	20 June	432

and canopy establishment would take longer, but canopy closure would still be advanced by 12 days and intercepted PAR would increase by 120 MJ m^{-2}. Sowing hemp on 15 May instead of 15 April would delay canopy closure by 19 days and intercepted PAR would decrease by 185 MJ m^{-2} (Table 2).

In conclusion, therefore, as hemp grows well at low temperatures, advancing its sowing date from 15 April to 31 or 16 March will advance canopy closure and increase the amount of PAR intercepted by the canopy. However, advancing the sowing date will also increase the probability of frost damage. This risk should be taken into account, particularly at frost-prone sites.

Harvest date

The currently available French and Hungarian cultivars flower in August, and after flowering stem growth slows down and ceases in the first half of September (Meijer, Van der Werf, Mathijssen & Van den Brink, 1995*a*; Van der Werf *et al.*, 1994*a*, 1995*b*; Van der Werf, Van Geel, Van Gils & Haverkort, 1995*d*). To obtain maximum stem yield these cultivars should be harvested in early September. In later-flowering cultivars stem growth continues longer, and optimum harvest date will be later.

Traditionally, harvesting hemp involves a period of field drying. In the Netherlands, the weather in September is rarely favourable for field drying of the crop, and for this reason, the potential of ensiling as an alternative way of preserving hemp stems was investigated (De Maeyer & Huisman, 1994). The results obtained so far indicate that ensiling is a promising, but more expensive, technique than field drying. Field drying involves harvesting in August and, as a result, a lower stem yield. In order to assess which technique is most promising economically, the effect of harvest date on potential PAR interception and yield should be quantified. To do this, the crop growth model and the average weather data described above

Table 3. *Simulated effect of harvest date on accumulated light interception by fibre hemp sown on 15 April*

Harvest date	Sowing – harvest (days)	PAR intercepted by harvest (MJ m^{-2})
1 August	108	617
16 August	123	732
31 August	138	841
15 September	153	927
30 September	168	1000
15 October	183	1050

were used. It was assumed that a non-flowering cultivar sown on 15 April, intercepted 99% of incident PAR from full canopy establishment until harvest.

In the current French and Hungarian hemp cultivars, stem growth ceases in the first half of September. According to the crop growth model, a hemp crop sown on 15 April would have intercepted 927 MJ m^{-2} PAR by 15 September (Table 3). Advancing harvest date by 30 days from 15 September to 16 August, in order to make field drying possible, would reduce intercepted PAR by 195 MJ m^{-2}. Delaying harvest date by 30 days to 15 October would increase intercepted PAR by a smaller amount: 123 MJ m^{-2}.

Radiation-use efficiency

Radiation-use efficiency (RUE) is defined here as the amount of dry matter produced per unit of intercepted PAR by a non-stressed crop (Monteith, 1977). The RUE of non-stressed crops depends on crop gross photosynthesis, maintenance respiration and growth respiration (Charles-Edwards, 1982). Losses of dry matter during the growing season may cause an apparent reduction in RUE.

Analysis of the experiments conducted in the 1980's yielded RUE's of 2.0 to 2.2 g MJ^{-1} before flowering, and of 1.1 to 1.2 g MJ^{-1} after flowering (Meijer *et al.*, 1995*a*). These RUE values are at the lower end of the range of values found for other C_3 crops; several factors are probably responsible. The crop gross photosynthesis of hemp is negatively affected during most of the growing season by the high extinction coefficient of the hemp canopy. Furthermore, growth respiration is probably relatively large in hemp, because lignin is being synthesised in the stem. After flowering, growth respiration increases further, because fat and protein are synthesised in the seed. Finally, losses of dry matter during the growing season are large as dead leaves are shed rapidly and many plants may die during the growing season as a result of self-thinning. In the experiments conducted in the 1980's, almost half of the plants had died before harvest in September, even at the lowest densities. Taken together, shed leaves and dead plants may represent up to 3 t ha^{-1} of dry matter, which is subject to biotic and abiotic degradation and is difficult to collect (Meijer *et al.*, 1995*a*). Obviously these losses reduce the apparent RUE of hemp. Of all the possible factors involved in the low RUE of fibre hemp, we selected flowering and self-thinning for further investigation, because increased understanding of these two factors seemed most likely to lead to improving the RUE of fibre hemp.

Flowering

Earlier studies had revealed that RUE post-flowering was low in hemp (Meijer *et al.*, 1995*a*). In subsequent experiments, RUE remained high (2.3 g MJ^{-1}) throughout September when flowering was prevented, but, post-flowering RUE was low (0.6 g MJ^{-1}) when flowering was not prevented (Van der Werf *et al.*, 1994*a*). These results were further corroborated in another experiment, where a very late cultivar maintained a high RUE (2.2 to 2.3 g MJ^{-1}) until it flowered in September, whereas the RUE's of the other cultivars, which had flowered in August, were lower (1.9 g MJ^{-1}) in late August and early September (Van der Werf *et al.*, 1995*b*).

A minor part of the post-flowering decline in the RUE of hemp can be accounted for by larger losses of shed leaves and increased growth respiration due to the synthesis of fat and protein in the seed (Van der Werf *et al.*, 1994*a*). However, the decline seems to be caused in the first place by an important reduction of crop gross photosynthesis, probably as a result of senescence of the leaves.

Breeding late-flowering cultivars may offer scope for the prevention of the low RUE post-flowering in hemp.

Self-thinning

In an experiment conducted in 1988, the RUE prior to flowering was 2.2 g MJ^{-1} in a crop with an initial plant density of 86 plants m^{-2} and 2.0 g MJ^{-1} in a crop with an initial plant density of 342 m^{-2} (Meijer *et al.*, 1995*a*). During the growing season more plants died in the high-density crop than in the low-density crop; as a result, in August and September the dry weight of dead plants was greater in the high-density crop. As dry matter of dead plants is inevitably degraded, measurements underestimate dead dry matter by an unknown amount. Thus, total dry matter production will be underestimated more at a high plant density than at a low plant density, and this seems a major cause of the lower RUE at the high plant density.

To examine this hypothesis further, hemp was grown at four plant densities (10, 30, 90 and 270 m^{-2}) to investigate the course of biomass yield and plant mortality during two growing seasons. It was established that inter-plant competition resulted in density-induced mortality, i.e. self-thinning (Van der Werf *et al.*, 1995*b*). In a self-thinning hemp crop, an increase in biomass yield is accompanied by a reduction in plant density. An increase in the number of plants dying from self-thinning at 270 plants m^{-2} was associated with an increased amount of dead plant dry matter and a decline of the RUE, confirming the hypothesis outlined above. Unexpectedly, at 10 plants m^{-2}, the amount of dead plant dry matter was also large, not as a result of plant mortality, but because the plants shed relatively large amounts of branches and leaves. Here too, the RUE declined as dead plant dry matter increased. At the two intermediate plant densities, little or no self-thinning took place, and little dead material was present. Apparent post-flowering RUE was 1.9 g MJ^{-1} at the intermediate densities, 1.3 g MJ^{-1} at 270 plants m^{-2} and 1.1 g MJ^{-1} at 10 plants m^{-2}.

Plant mortality resulting from self-thinning can be prevented by ensuring that the plant density at emergence does not exceed the maximum plant density possible at the expected yield (Van der Werf *et al.*, 1995*b*). For an above-ground dry matter yield of 15 t ha^{-1}, this plant density would be about 120 m^{-2}; at 20 t ha^{-1} it would be about 50 m^{-2}.

Dry matter partitioning

Fibre hemp is grown for the production of stem dry matter; within the stem the bark is more valuable than the core (Van der Werf, Harsveld van der Veen, Bouma & Ten Cate, 1994*b*). Therefore, both a high proportion of stem in the above-ground dry matter and a high proportion of bark in the stem dry matter are desirable. Both levels of dry matter partitioning will be examined below.

Stem in the above-ground dry matter

Data from Meijer *et al.* (1995*a*) and Van der Werf et al. (1994*a*, 1995*b,d*) on the partitioning of the above-ground dry matter to the inflorescence, leaves and stem have been summarised in Table 4. In the experiments conducted in 1987, 1988 and 1989, the proportion of stem material in the above-ground dry matter of the monoecious cv. Fédrina 74 at harvest in September varied between 78% and 84%. The proportion of stem was not greatly affected by flowering and seed filling, because the increase in dry weight of the inflorescence was about as large as the decline in leaf dry weight (Meijer *et al.*, 1995*a*). In 1989, cv. Fédrina 74 was compared with the dioecious cvs Kinai unisexualis and Kenevir, both of which flowered about 2 wk later than cv. Fédrina 74. In that year, the proportion of the stem in the above-ground dry matter was 82% in cv. Fédrina 74, 87% in cv. Kinai unisexualis and 86% in cv. Kenevir (Table 4).

Further experiments were conducted to examine the effect of flowering on the proportion of stem (Van der Werf *et al.*, 1994*a*). In cv. Fédrina 74, the prevention of flowering by 24-h days reduced inflorescence dry matter from 1.1 to 0.2 t ha^{-1} and increased leaf dry matter from 1.1

Table 4. *Dry matter in the inflorescence, in the leaves attached to the plant and in the stem and the proportion of stem in the total dry matter, of living hemp plants harvested in September. data summarised from Meijer* et al., *1995 and Van der Werf* et al., *1994a, 1995a,c*

Year	Treatment	Dry matter (t ha^{-1})			
		Inflorescence	Leaves	Stem	Stem in total (%)
1987	Fédrina 74, 104 plants m^{-2}	0.25	1.23	7.58	84
1988	Fédrina 74, 86 plants m^{-2}	1.57	1.60	11.32	78
1989	Fédrina 74, 114 plants m^{-2}	0.68	2.26	13.35	82
	Kinai unisexualis	0.07	1.94	13.19	87
	Kenevir	0.06	2.05	12.69	86
1990–91	Fédrina 74, 24-h daylength	0.16	1.49	13.42	89
	Fédrina 74, normal daylength	1.13	1.12	10.65	83
	Kompolti Hybrid TC, 24-h daylength	0.06	1.41	15.92	92
	Kompolti Hybrid TC, normal daylength	0.45	0.89	13.22	91
1991–92	Kompolti Hybrid TC, 10 plants m^{-2}	1.16	1.84	10.80	78
	Kompolti Hybrid TC, 30 plants m^{-2}	0.84	2.04	14.50	83
	Kompolti Hybrid TC, 90 plants m^{-2}	0.58	1.85	15.10	86
	Kompolti Hybrid TC, 270 plants m^{-2}	0.45	1.76	12.90	85
	Kompolti Hybrid Elite, 90 plants m^{-2}	0.50	1.75	15.20	87
	Kozuhara zairai, 90 plants m^{-2}	0.41	2.61	15.40	84
1991–92	Kompolti Hybrid TC, 80 kg ha^{-1}N	0.26	0.99	10.35	89
	Kompolti Hybrid TC, 200 kg ha^{-1}N	0.32	1.25	11.30	88

to 1.5 t ha^{-1} and stem dry matter from 10.7 to 13.4 t ha^{-1} (Table 4). As a result, cv. Fédrina 74 contained 89% of stem when flowering had been prevented, compared with 83% when it had flowered. In the dioecious cv. Kompolti Hybrid TC, which flowers about 20 days later than cv. Fédrina 74, the prevention of flowering reduced inflorescence dry matter from 0.5 to 0.1 t ha^{-1} and increased leaf dry matter from 0.9 to 1.4 t ha^{-1} and stem dry matter from 13.2 to 15.9 t ha^{-1}. As a result, the proportion of stem was 92% when flowering had been prevented and 91% when flowering had occurred. When both cultivars flowered normally, inflorescence dry weight was larger in cv. Fédrina 74 than in cv. Kompolti Hybrid TC; when flowering was prevented, cultivar differences were smaller. There are probably two reasons for the large inflorescence in cv. Fédrina 74. First, cv. Fédrina 74 flowers earlier than cv. Kompolti Hybrid TC, so allocation of dry matter to the inflorescence starts earlier. Secondly, cv. Fédrina 74 is monoecious, so all plants invest dry matter in floral clusters and seeds, whereas cv. Kompolti Hybrid TC is dioecious, containing about 50% of male plants, which die after flowering and contain a much smaller fraction of the above-ground dry matter in the inflorescence.

In another experiment with cv. Kompolti Hybrid TC, the proportion of stem in the above-ground dry matter was found to be affected by plant density (Van der Werf *et al.*, 1995*b*). At harvest in the middle of September it increased from 78% at 10 plants m^{-2} to 86% at 90 plants m^{-2}; at 270 plants m^{-2} it was 85% (Table 4). This increase in the proportion of stem resulted mainly from the dry weight of the inflorescence declining with increasing plant density.

In the same experiment, cv. Kompolti Hybrid TC was compared with cv. Kompolti Hyper Elite, a high bast fibre cultivar and with Kozuhara zairai, a late-flowering cultivar. At harvest all three cultivars had high dry matter yields (about 18 t ha^{-1}). The proportion of stem in the above-ground dry matter was 86% in cv. Kompolti Hybrid TC, 87% in cv. Kompolti Hyper Elite and 84% in cv. Kozuhara zairai (Table 4). The dry weight of leaves was 2.6 t ha^{-1} in the late-flowering cultivar and 1.8 t ha^{-1} in the two other cultivars, and this was the major cause of the smaller proportion of stem in the late cultivar.

The level of soil nitrogen (Van der Werf *et al.*, 1995*d*) barely affected the proportion of stem in the above-ground dry matter: in early September it was 89% at 80 kg ha^{-1} N and 88% at 200 kg ha^{-1} N.

In conclusion, therefore, flowering date, plant density and the proportion of male plants are the main factors affecting the proportion of stem in the above-ground dry matter of a hemp crop. The later a cultivar flowers, the smaller the fraction of the inflorescence and the larger the fraction of the leaves and the stem in the above-ground dry matter will be. The resulting effect of flowering date on the proportion of stem is variable so that, relative to an early cultivar, a late cultivar may contain a similar, smaller or larger proportion of stem. To obtain a high proportion of stem in the above-ground dry matter the crop should be grown at a the highest possible density not causing self-thinning. The more male plants are present, the larger the stem proportion.

Bark in the stem dry matter

In a 1990 experiment (Van der Werf *et al.*, 1994*b*), the proportion of bark in the stem dry matter (bark content) in September was higher at 90 plants m^{-2} than at 10 plants m^{-2}, and higher in the cv. Kompolti Hybrid TC than in cv. Fédrina 74.

Further experiments (Van der Werf *et al.*, 1994*a*) confirmed the difference in bark content between cv. Fédrina 74 (31%) and Kompolti Hybrid TC (35%). In both cultivars, the bark content decreased during August and September, the decrease being slight in cv. Kompolti Hybrid TC and more pronounced in cv. Fédrina 74. For both cultivars, the decrease in bark content was associated with an increase in stem dry weight. When flowering had been artificially prevented, the increase in stem dry weight and the decrease in bark content were larger than when flowering had taken place normally.

The effect of plant density on bark content (Van der Werf *et al.*, 1995*b*) was similar to its effect on the proportion of stem such that, at harvest in the middle of September, bark content increased from 33% at 10 plants m^{-2} to 36% at 90 plants m^{-2}; at 270 plants m^{-2} it was 35%. In the same experiment, cv. Kompolti Hybrid TC was compared with cv. Kompolti Hyper Elite, a high bast fibre cultivar, and with cv. Kozuhara zairai, a late-flowering cultivar (Van der Werf *et al.*, 1995*b*). At harvest, all three cultivars had high stem yields (15 t ha^{-1} of dry matter) and bark contents were 21% (cv. Kozuhara zairai), 36% (cv. Kompolti Hybrid TC) and 40% (Kompolti Hyper Elite).

The level of soil nitrogen affected the bark content: in early September it was 36% at 80 kg ha^{-1} N and 34% at 200 kg ha^{-1} N (Van der Werf *et al.*, 1995*d*). The effect of soil nitrogen probably resulted mainly from a difference in plant density which had arisen as a result of self-thinning. In early September, plant density was 129 m^{-2} at 80 kg ha^{-1} N and 92 m^{-2} at 200 kg ha^{-1} N.

It seems, therefore, that cultivar and plant density are the main factors affecting the proportion of bark in the stem. To maximise bark content a high fibre cultivar should be grown at the highest possible density not causing self-thinning.

Potential yield

The simple crop growth model referred to previously (Fig. 1) was used to estimate the potential stem yield of fibre hemp. The major factors affecting the amount of light intercepted by a fibre hemp crop are the dates of sowing and harvesting. For this simulation, 15 April was chosen as a reference sowing date and the effect of earlier and later sowing dates was

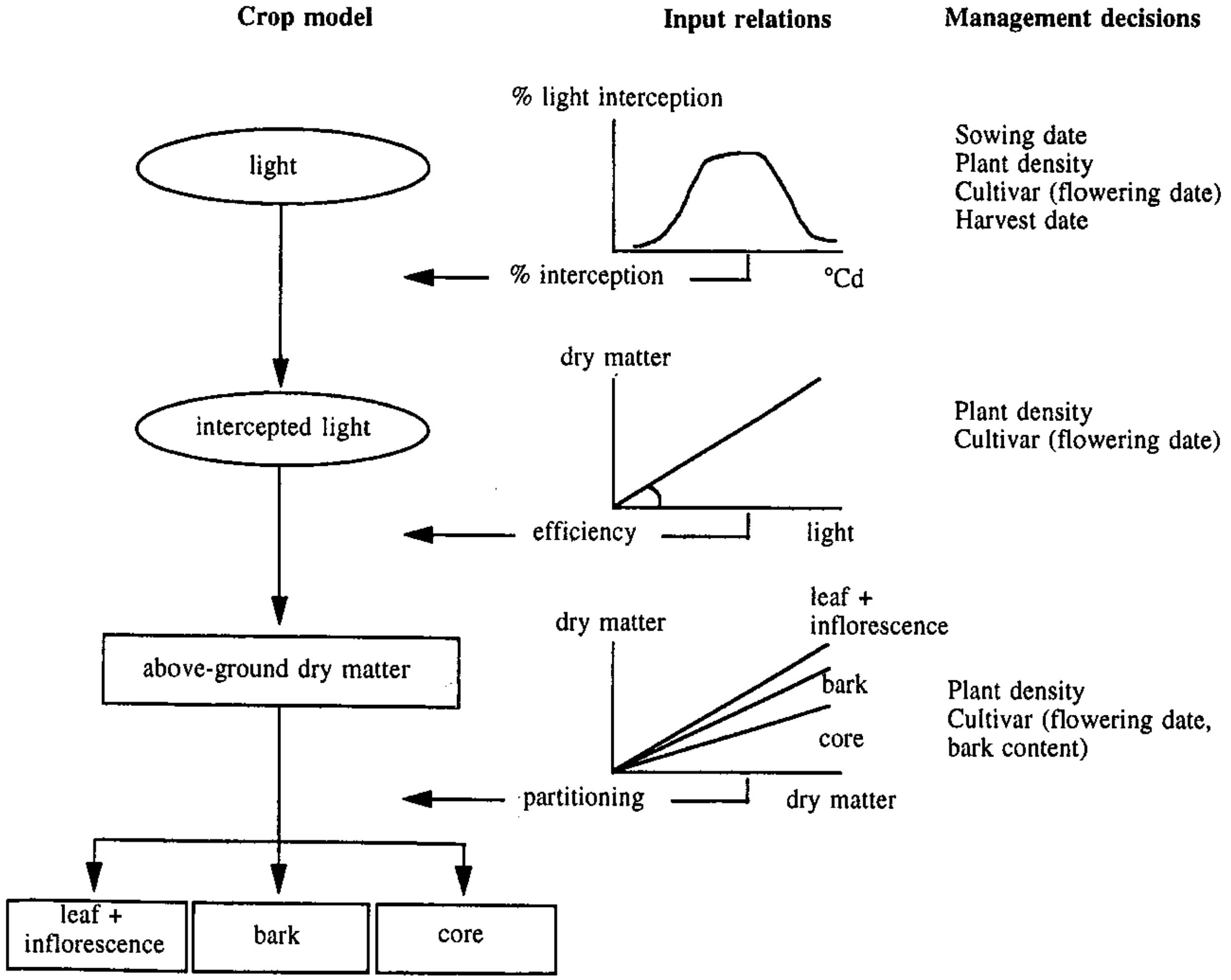

Fig. 1. Schematic representation of the LINTUL crop growth model (Spitters, 1990) and of crop management decisions affecting the input relations.

examined. Likewise, 15 September was used as a reference harvest date and the effect of varying harvest date was also examined.

As mentioned previously, radiation-use efficiency ranged from 0.6 to 2.3 g MJ^{-1}. Before flowering, and when no or little self-thinning occurred, the RUE was 2.2 to 2.3 g MJ^{-1}. For the simulations it was assumed that a hypothetical non-flowering cultivar was being grown, at a plant density (64 m^{-2}) which does not cause significant self-thinning unless yields exceed 20 t ha^{-1} of dry matter. Given these conditions, a RUE of 2.2 g MJ^{-1} is a realistic assumption.

In our experiments, the proportion of stem in the above-ground dry matter varied from 78–92%, and therefore it was difficult to choose a reference value. In the case of a non-flowering cultivar, the above-ground dry matter would consist of leaf and stem only. Based on the results obtained with the very late cv. Kozuhara zairai (Van der Werf *et al.*, 1995*b*), the proportion of stem in the above-ground dry matter was assumed to be 84% in the simulation.

As pointed out earlier, bark content in the stem was affected by plant density, but more by cultivar. The plant density of 64 m^{-2} used in the model is close to the density at which bark content peaked. The highest bark content (40%), was found in the high bast fibre selection "Hyper Elite" from the cv. Kompolti. Breeding research has shown that flowering date and fibre content are not necessarily linked (Hennink, 1994). Genetic variability for flowering date is large (De Meijer & Keizer, 1994) so that it should be feasible to breed a very late flowering,

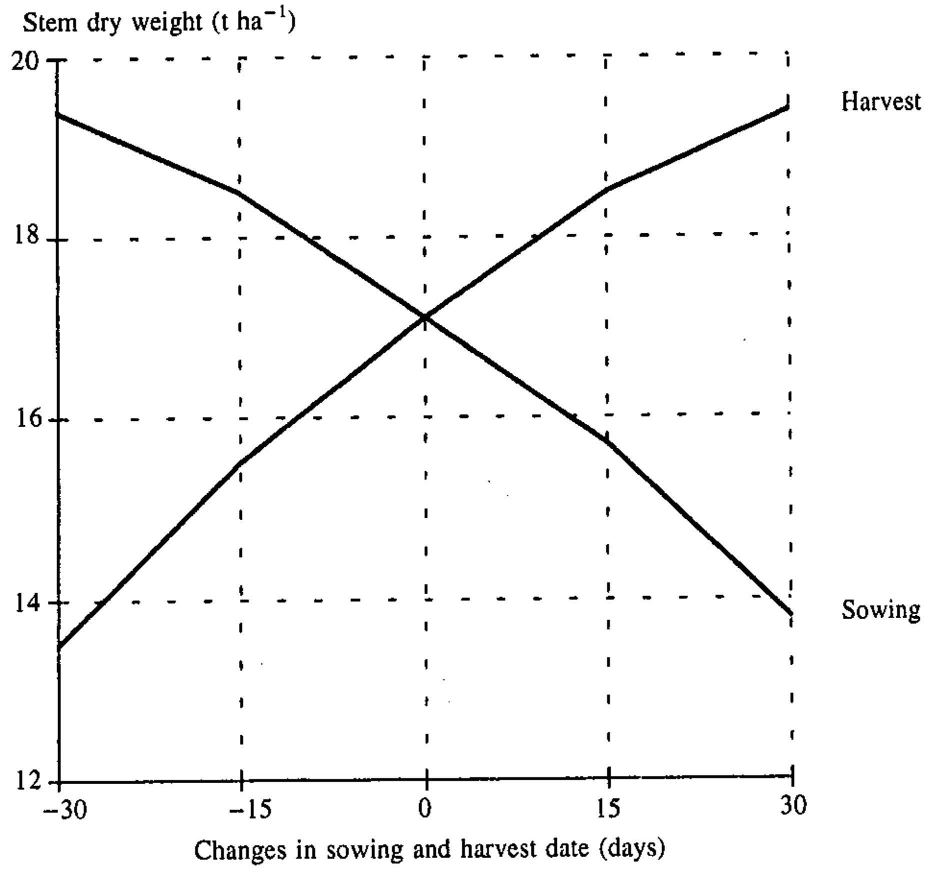

Fig. 2. The effect of advancing (−15, −30 days) or delaying (15, 30 days) sowing date or harvest date on the simulated stem yield of a hypothetical non-stressed non-flowering hemp cultivar. Reference date (0 days) for sowing: 15 April, for harvest: 15 September

high bast fibre cultivar. A bark content of 40% was assumed for the hypothetical non-flowering cultivar.

According to the crop growth model, a non-stressed, non-flowering hemp cultivar sown on 15 April and harvested on 15 September would yield 17.1 t ha^{-1} of stem dry matter (Fig. 2). Sowing the crop on 31 March instead of 15 April would increase stem yield by 1.4 t ha^{-1}; sowing on 16 March would increase stem yield by 2.3 t ha^{-1} (Fig. 2). These yield increases are substantial, but should be weighed against the increased risk of frost damage. Sowing on 30 April instead of 15 April would reduce stem yield by 1.4 t ha^{-1}, sowing on 15 May would reduce stem yield by 3.3 t ha^{-1}. The more the sowing date is delayed, the more rapidly the potential stem yield drops, because light interception in the period of maximum incident radiation (May and June; Table 1) is increasingly incomplete.

The yield increase obtained by delaying harvest date by 15 or 30 days is almost identical to the yield increase obtained by advancing sowing date by 15 or 30 days (Fig. 2). Advancing the harvest date by 15 days reduces the yield by 1.6 t ha^{-1}; advancing the harvest by 30 days reduces the stem yield by 3.6 t ha^{-1}. The effect of advancing harvest date on stem yield is slightly larger than the effect of delaying sowing date. The effect of simultaneous changes in sowing date and harvest date can be calculated from Fig. 2 by summing the effects of both changes.

In conclusion, therefore, the dates of sowing and harvest both have large effects on the potential stem yield of a non-flowering hemp cultivar. Sowing earlier than 15 April can increase yield, certainly on soils which are not frost-prone. Harvesting in August instead of

September decreases potential yield but will allow field drying. Delaying the harvest date offers scope for increased stem yields, but requires the breeding of very late-flowering cultivars.

Hemp *vs* kenaf

Interest in 'new' fibre crops is increasing, for example to replace cotton by a less polluting alternative or to relieve the pressure of the paper industry on remaining natural forests (Postel & Ryan, 1991). For the warmer parts of the world, ramie (*Boehmeria nivea* L.) may be an alternative to cotton and kenaf seems to have excellent potential as an alternative source of paper pulp (Carberry *et al.*, 1992). For the temperate regions of the globe, the perennial C_4-grass *Miscanthus sinensis* has been proposed as a raw material for paper (Van der Werf, Meijer, Mathijssen & Darwinkel, 1993; Wegener, 1993) and flax remains a valuable crop, providing raw material for textile but also for speciality paper. Although *M. sinensis* is highly productive and virtually disease-free, the length of its production cycle (10 years) makes it less attractive to arable farmers. Furthermore, the establishment of the crop is expensive and often hampered during winter by frosts and diseases. Flax, which like hemp is an annual bast fibre crop, continues to be grown in temperate climate zones, demonstrating that a market for bast fibres does exist. One of the major problems limiting the market potential of flax fibre is its high price (Judt, 1993). Under similar growing conditions, hemp yields generally are 50–100% higher than flax yields (Jordan, Lang & Enfield, 1946; Meijer *et al.*, 1995*b*). As production costs are similar, hemp fibre should be cheaper than flax fibre and therefore have a better market potential. At these higher yield levels, hemp fibre will be coarser than flax fibre (Van der Werf *et al.*, 1995*b*), which makes it less suitable for textile production but does not affect its quality as a raw material for paper.

The potential of hemp to produce raw material for paper in the temperate climate zone may be evaluated by comparing its crop physiological characteristics with those of kenaf, which has been proposed as a paper raw material for the sub-tropics and tropics.

The better a spring-sown crop grows at low temperatures (i.e. the lower its base temperature), the more rapidly it will establish its canopy. Hemp's base temperature for emergence and leaf appearance is 1°C, for canopy establishment it is 2.5°C (Van der Werf *et al.*, 1995*c*). In kenaf, the base temperature is 9°C for emergence (Angus, Cunningham, Moncur & Mackenzie, 1981), and 10°C for early growth (Carberry & Abrecht, 1990). In a temperate climate with a long period of low spring temperatures, hemp can be sown early and canopy establishment will be rapid. As a result, total light interception over the growing season will be large.

Before flowering, and when no self-thinning occurred, the RUE of hemp in our experiments was 2.2 to 2.3 g MJ^{-1}. This is slightly less than the RUE value of 2.4 g MJ^{-1} which Carberry & Muchow (1992) reported for kenaf, so that, in this respect, the two crops do not seem to differ much. This is not surprising as the chemical composition of their stem is largely similar; both crops have a relatively large extinction coefficient and both crops lose dry matter during the growing season as dead leaves are shed rapidly.

Dry matter partitioning in hemp and kenaf is quite similar. According to Carberry & Muchow (1992) the proportion of the stem in the above-ground dry matter of kenaf varies from 83–89%, which is fully within the range we found for hemp. For kenaf, bark contents of up to 40% have been reported (Muchow *et al.*, 1990), which again is similar to our results for hemp.

Radiation-use efficiency and dry matter partitioning are similar in hemp and kenaf. Due to its low base temperature, hemp is adapted to the cool springs of a temperate climate.

Therefore, hemp seems an excellent candidate to fill the niche for an annual fibre crop in a temperate climate.

Acknowledgements

Our thanks to W J M Meijer and P C Struik for their helpful comments on the manuscript.

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(Received 29 February 1996)