MAFF

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

RESEARCH AND DEVELOPMENT - FINAL PROJECT REPORT

NF0307 - HEMP FOR EUROPE MANUFACTURING AND PRODUCTION SYSTEMS

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EXECUTIVE SUMMARY

Cannabis sativa has been grown for its fibre for industrial applications for millenia. Recent relaxation of cropping rules within the EU have seen increased interest in the crop within the EC, and approximately 2,400 ha were grown in the UK during 1998. Very little has been done to optimise any aspects of the hemp production chain from breeding through husbandry and agronomy, harvesting and post harvest treatment. Equally, the fibre characteristics required for different end uses have not previously been well quantified nor indeed has the feasibility of many end products been properly assessed. ADAS co-ordinated a multi-country project funded by the EC which addressed these issues (PL CT95-0396). Matching funding was provided by MAFF in order to determine the crop agronomy and physiological performance of hemp under UK conditions (through field experimentation) and to report on all elements of the project.

Crop agronomy and physiology

Through three years' multifactorial field trials it was established that later-flowering varieties were required for the UK in order to maximise the quantity of fibre produced. This would need a re-focussed breeding effort and a change in EC cropping reguations. Best annual stem yields in this study were 9-11 t ha-1; significantly greater than current commercial experience. Optimal yield of crop was achieved when high quantities of nitrogen (200kg ha-1) were available to the crop. Lack of nitrogen reduced crop height, internode length, canopy area, duration and radiation use efficiency and consequently yield. Further work should consider the timing of the application of nitrogen, and its rate of uptake, in order to provide precise application guidelines. Optimal plant densities combining high fibre quality with maximum yield were 115-135 plants m-2; significantly lower than current target densities.

Fibre Quality

Fibre yields were 70-80% of stem yield (7-8t of fibre ha-1 in the best treatments). Fibre quality was principally influenced by site; husbandry treatment within site had little effect (because variation within plots for fibre characteristics was much greater than variation between treatments), suggesting that agronomic treatment cannot be used as a tool to improve fibre quality. The exception was the impact of plant density. Lowest plant densities resulted in poor fibre quality (low fineness). The central third of the hemp stem had the highest fibre content and the highest tenacity. Spectroscopic characterisation indicated that lignin, increasing with time, and pectin, decreasing with time, could be used to predict harvest date.

Harvesting and post harvesting technology improvements

If hemp is harvested late in the season drying conditions are often poor. It would be an advantage to be able to increase the drying rate so that retting would start earlier. If leaves and heads, not of value in hemp harvested for fibre, could be removed at cutting, the stems may dry faster and nutrients would be returned to the soil. To this end a leaf stripping machine was developed which removed 95% of leaf material. The resultant swath dried more evenly and more rapidy than swathes where the leaves had not been stripped. In further studies aimed at reducing the time required in swath it was found that crimping or chopping stems into 0.5m sections further improved drying properties. However, periods of rainfall affected all swathes similarly. Thus, while we

can improve the drying characteristics in dry weather, we cannot manipulate the swathe to make it more robust during periods of unfavourable weather.

Fibre modification

Steam explosion and ultrasonic physical cleaning treatments were compared. Steam explosion offered signifcant improvements in fibre fineness. Ultrasonic cleaning did not confer any advantages. Chemical modification of plant fibres offers the potential to upgrade the value of fibres by tailoring their properties for specific end uses. For example, chemical modification can improve the resistance of plant fibres to biodegradation. In addition, it can make them potentially more compatible with plastics and resins, and thereby realise improvements in the physical properties of plant fibre reinforced plastics. Four chemical modification systems were considered by treating fibre products with acetic anhydride (AA); Succinic Anhydride (SA); Polypropylene-graft-maleic anhydride (MAPP) and Dimethyl meta-isopropenyl benzyl isocyanate (TMI). MAPP and TMI did not increase the reactivity of the fibres. Whilst both AA and SA significantly increased fibre reactivity, only SA did so without a concommittant reduction in other fibre quality aspects.

Industrial products development

The value of whole hemp stems and shiv material for medium density fibreboard, particle board, geotextile and thermoplastic applications was investigated. MDF was the market that demonstrated most opportunity for substiution of low levels <30% hemp. However, the cost of raw product would probably render hemp unsuitable. Hemp was not suited to particle board or geotextile manufacture. Thermoplastic products made with hemp fibre previously cleaned by steam explosion demonstrated adequate strength properties and may offer a future market outlet for hemp fibre.

Policy implications: There are currently proposals to reduce the area payment for hemp and flax, so there is increased need for farmers to maximise crop yield and for processors to expand into as many markest as possible. This research should enable both. It has identified that UK yields and fibre quality can be improved through the uptake of later maturing varieties that are de-leaved prior to chopping and windrowing, and that these fibres may find additional application in thermoplastic and medium density fibreboard markets. The project was demonstrated to both to farmers and policy makers, and has been reported in papers and conferences.

SCIENTIFIC REPORT

Introduction

The industrial uses of hemp fibre (Cannabis sativa L.) have been recognised for thousands of years, and the UK has a long history of its production (Cromack, 1998). It produces 25% more long fibre than flax. It is purported to have minimal requirements for agrochemicals and nitrogen fertiliser, beneficial effects on soils and biodegradability of its end products make it an environmentally friendly break-crop. Recent renewed interest in natural fibres has increased its cultivation in the EC to around 10,000 ha annually, and since EC regulations on growing the species were relaxed in 1993, the acreage in the UK has increased steadily to 2,400 ha in 1998 (J Hobson, Hemcore, pers. comm.). Modern processing interests are many and varied, and both the long 'bast' fibre and the short 'shiv' fibres are utilised. Commercial production in the UK focuses on paper, composite materials and thermoplastic applications of the fibre, whilst the shiv is successfully marketed as a horse bedding material. In 1996 an EU-funded project 'Hemp for Europe - Manufacturing and Production Systems', co-ordinated by ADAS, was initiated [PL95-0396]. The principal objective of the project was to stimulate the expansion of the hemp crop in the EU. A number of factors limiting the crops development were identified at each phase of the production chain and were addressed experimentally. The partners involved in the project, and their area of research, are shown at Annex 1.

Crop growth, physiology and management

Current cultivars and cultivation techniques have mostly been developed in central France, based on the production of dual purpose crops for seed and fibre. Whilst a number of varieties are grown commercially across Europe for fibre only, and broad guidelines are in place for their production in the UK (Low, 1995), the relationship between husbandry, resource capture and yield productivity are poorly understood throughout Europe. An experimental programme in UK, The Netherlands and Italy was initiated to provide guidelines for the management of hemp crops grown specifically for fibre in different regions.

Fibre quality

The quality of fibre may be as important as the quantity of fibre for some industrial applications, therefore the crops produced in the crop growth and agronomy studies were examined for key characteristics such as tenacity, decortication resistance and fineness in order to provide management guidelines for the production of fibre of high quality. The proportion of structural components, lignin, cellulose, hemi-cellulose and pectin in stems was also measured during seasons and at different points within seasons.

Harvesting and post harvest treatment

Most hemp is allowed to lie in a swathe in the field for a period of 1-6 weeks in order to allow microbe mediated separation of long fibres from short fibres in the stem. This 'retting' process is very imprecise, and subject to the vagaries of the climate. The tall rough hemp plant poses considerable mechanisation problems but there has been little development of specialised machinery. Retting is desirable to release long fibres prior to extraction, but scientific predictive information for this biological process is limited. Current decortication processes are slow and costly; a novel device developed for flax has potential to improve efficiency. Techniques to further refine fibre quality, which have been developed for flax shows promise for hemp fibre. Mechanical techniques were developed in order to attempt to reduce the amount of time needed for field retting, and to improve the eveness of the retting process. Whether retted or not, the hemp stems require processing in the factory in order to strip the bast fibres away from other material. For some applications further fibre cleaning may be required. Three novel methods for fibre separation or cleaning were examined; decortication, steam explosion cleaning and ultrasonic cleaning.

End product development

Hemp fibre may be suitable for a number of other applications, in particular for a variety of non-woven materials, which could be used as reinforcements in composite materials, or in textile applications (e.g. geotextiles). Hemp fibres were evaluated for the production of wood-based panel products (particle board and MDF), thermoplastic products and geotextiles. Test products were manufactured, and standard measurements of their characteristics made, and their commercial viability determined.

Hemp breeding

Crop selection and breeding activities were undertaken with three component objectives. Currently, only cultivars with less than 0.3% δ-9 tetra-hydro cannabinol (THC), the narcotic component of cannabis, may be grown in the EC. From 2001/02 this will be further reduced to 0.2%. The development of zero THC lines, with linked genetic markers, would be a distinct advantage and allow the genetic base of the crop to be broadened. Secondly, hemp has been noted to be susceptible to root knot nematode, and this can severely limit yield potential. A selection programme for the development of genotypes with increased nematode resistance was undertaken. Finally, the development of a ‘yellow line’ of hemp with high fibre yield and quality was begun.

The ADAS component of the EC project (jointly funded by MAFF) consisted of two main elements - overall project co-ordination and crop physiological experimentation in the crop growth and agronomy module. The work was consistent with MAFF policy objectives in that it was intended to optimise husbandry and processing of the crop, thus minimise inputs and encourage sustainable production in what was already considered to be a low input crop. By identifying opportunities to increase yield and quality, the work also offered to provide mitigation against any reduction in the support level for hemp in the EU fibres regime. Current proposals (CEC, 1999) to reduce aid from £500/ha (1998 level) to parity with oilseeds (c, £345/ha) by 2000/01 will put tremendous pressure on the grower to reduce inputs and at the same time increase yield. This research project offers the potential to bridge this gap, thus helping to maintain a competitive, diversified agricultural landscape. Additionally, physiological evidence pertaining to the formation of yield would provide evidence for or against the perpetuation of current cropping regulations and support. All aspects of the project are summarised in this report, with particular emphasis placed on results which have benefit or relevance to the UK.

Methodology, results and implications for the UK

Crop agronomy and husbandry

Structured field experiments were carried out in Italy, The Netherlands and UK. In the UK an arable field site was chosen in Devon, during each season 1996 - 1998. In 1996 a 3-factorial field experiment was established with three varieties of differing maturation rates; Fedora, Felina & Futura ('early', 'medium' and 'late' flowering, respectively), three target plant densities (30, 90 and 270 plants m^{-2}) and three available nitrogen rates (100, 160 and 220 kg N ha^{-1}). Available nitrogen rates consisted of residual nitrogen amended with ammonium nitrate fertiliser. Two identical experiments were conducted in both 1997 and 1998. In one, four plant densities (45, 90, 180, 270 plants m^{-2}) of cv. Futura were grown. In the second experiment three levels of soil available nitrogen (residual, 160 and 220 kg N ha^{-1}) were applied in factorial combination to cv.s Futura and Felina. Varietal selection was consistent with current commercial cropping, where Fedora 19 and Felina 34 each represent approximately 50% of the UK crop (J Hobson, pers. comm.). Drilling dates varied between 10 April and 11 May. No herbicides or insecticides were applied in any of the three seasons. Prophylactic control of Botrytis spp. was attempted with the fortnightly application alternately of iprodione and vinclozolin fungicides. In order to accurately quantify the factors that were important in the yield formation of hemp the following measurements were made. In each year daily solar radiation levels, temperature and rainfall were recorded and six destructive measurements of biomass accumulation and leaf area development were made during the crops development. Radiation interception was measured weekly from plant emergence to harvest. The final two harvests which were timed to coincide with full flowering and full seed set. Full seed set is the harvest time that is currently required by EC law – commercial crops cannot be harvested before this date.

Hemp crop emergence was limited by low temperatures during the spring. Subsequent to warmer conditions the crop developed at a constant rate, producing a new leaf every 79 to 85°C of accumulated temperature. Leaf node development ceased when flowering was initiated. Knowledge of the relationship between temperature and leaf node production is important, because the quality of hemp fibre reduces around stem nodes (due to an increase in lignification of the tissue). The results are consistent with independent Dutch research (van der Werf et al., 1995) and suggests that under UK conditions we can now predict the number of nodes, the internodal lengths and hence the relative quality of fibre produced in any year. Seedling establishment was not an aspect of crop performance covered in this project, yet it was clear that hemp drilled into cold and/or dry seedbeds emerged slowly and erratically. Further research is needed to find out how best to improve the establishment of the crop in order to maximise the likelihood that a seed emerges successfully.

Hemp is a quantitative short day plant (Wareing & Philips, 1978) and the onset of flowering was related to daylength, with 'early' varieties flowering when the daylength declined to 16h (17 July; Felina 34) but late varieties not flowering until the daylength had declined to 15½ h (1 August; cv. Futura 77). The onset of flowering triggered a reduction in the radiation use efficiency of the crop; this is a measure of how efficiently a plant turns solar energy into fixed biomass (Table 1). This was due to flowering initiating the production of oils rather than structural carbohydrates which require proportionately more energy per unit of weight. The effect of earlier flowering was therefore to reduce the fibre-yield capability of the crop, and early flowering varieties were seen to yield less stem than late flowering varieties (Table 1). The biological implication of this is clear – for the highest yields the latest flowering varieties available should be grown in the UK, and if necessary a breeding effort to produce varieties with an even shorter daylength requirement developed. However, current EC regulations require that harvest be delayed until full seed set, and because of poor field conditions for retting and harvesting in September/October this constrains growers to earlier flowering varieties. There is a clear policy need to challenge this requirement, which has no real policy value, in order to allow growers to produce later maturing varieties but harvest them earlier.

Table 1. Average (1996-1998) stem yields (t ha^{-1}) and radiation use efficiency (RUE) for Felina and Futura.

	Stem yield @ H5[a] (t ha^{-1})	**RUE @ H1 - H5 (g MJ^{-1} PAR m^2)**	**Stem yield @ H6[b] (t ha^{-1})**	**RUE @ H1 - H6 (g MJ^{-1} PAR m^2)**
Felina	6.9	0.86	7.3	0.76
Futura	7.6	0.85	8.5	0.77

[a] H5 refers to the penultimate biomass assessment, at 95% flowering of Felina
[b] H6 refers to the final biomass assessment, at full seed set of Felina.

Crop height exceeded 3m in all treatments, in all years, except those where no additional fertiliser nitrogen was supplied. Internodal stem lengths were also most affected by nitrogen availability; being significantly reduced where only soil supplied nitrogen was available. A general trend, not consistent between seasons, was that Futura produced taller plants than Felina. Average yields (Table 1) were significantly depressed in all seasons through the inclusion of treatments receiving only soil residual nitrogen. Optimum stem yields of 11 t ha^{-1} were achieved in the best treatment combinations. This is considerably more than the UK average (Nix, 1999) and consistent with the best yields in Europe (Meijer et al., 1995; Sankari & Mela, 1998; van der Werf et al., 1996). Approximately 200kg N ha^{-1} was required for optimal yield expression (Figure 1). At higher rates than 200 kg N ha^{-1} no significant yield increase was seen. This in turn was due to the amount of green leaf area, and thus light capturing surface, that the crop produced. Annual cumulative green area, calculated as the green leaf area duration (GLAD) reflected how well the nitrogen was being used, and indicated that an optimal GLAD of 300 was required for optimal yield (Figure 2). This is the first time that such relationships have been developed in hemp. From a policy perspective this is important because it emphasises that, at least in terms of nitrogen requirement, hemp is not a low input crop. Further research is needed to determine how efficiently the crop uses nitrogen applied at different times during the growing cycle, and how much is returned to the soil during leaf fall.

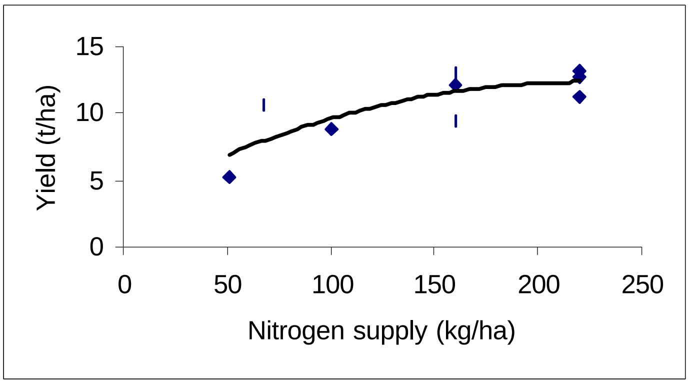

Figure 1 Relationship between mean total yield and nitrogen availability (SMN + inorganic), 1996-1998.

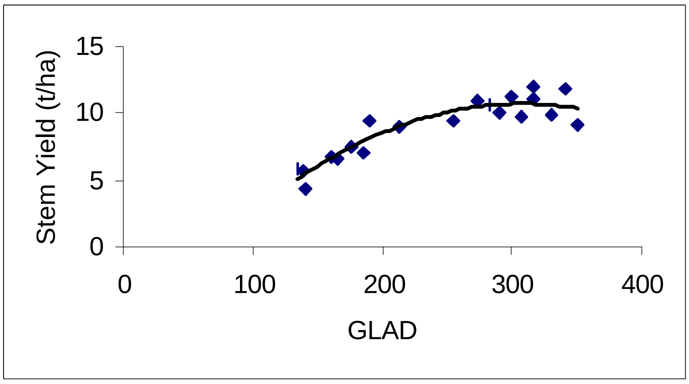

Figure 2. Curvilinear relationship (P<0.001) between green leaf area duration (GLAD) and stem yield (mean data from 1996-1998).

Generally, significant self-thinning occurred at high plant densities. However, the impact of sowing density on yield was seen to be insignificant. This self thinning behaviour, producing an optimal yield through regulation of stem number, is consistent with previous research (van der Werf et al., 1995) Even at the lowest density, where significant self thinning was not seen, the hemp plants compensated for reduced density by producing individually heavier plants. By far the greatest effect of sowing density was on the number of stems per unit area harvested, and the impact of this was on fibre quality not quantity. Low plant densities produced thick stemmed plants with low fibre quality (see next section). The optimal planting density to be attained was approximately 115-130 plants m^{-2}, and this was consistently achieved with a sowing rate of 180 seeds m^{-2}. This sowing rate is considerably lower than current rates in the UK (300 - 500 seeds m^{-2}, I Low, Hemcore, pers comm.), and could be reduced, whilst still attaining the target population, if the eveness of emergence and distribution of seedlings could be improved. These results clearly have a significant impact on the margins of hemp production, indicating that seed costs could be halved (from c.£90 to £45 ha^{-1}).

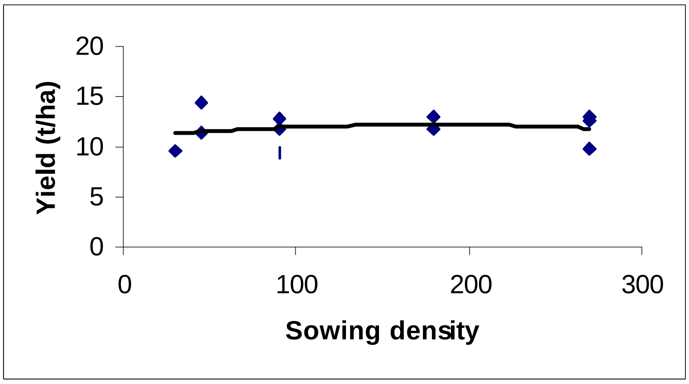

Figure 3. Relationship between mean yield and initial seedling density, 1996-1998.

A key feature of an efficiently performing crop is that of rapid canopy development prior to the onset of flowering; canopy duration post-flowering is of less importance because RUE declines rapidly. Radiation efficiencies in 1996 and 1997 were generally very low compared with literature figures for C_3 crops in the UK, yet final total and stem yields were consistent with previous reports indicating that a high leaf area duration was responsible for the yields noted. Moisture stress and nutrient stress, poor canopy structure, a high extinction coefficient, high growth respiration due to a high proportion of lignin being produced in the stem, high tissue and plant mortality throughout the season may all cause a reduction in radiation use efficiency (Meijer et al., 1995; van der Werf et al., 1996). These effects should be further investigated under UK conditions.

Yields in the UK were lower than either Italy or The Netherlands, where peak seasonal yields of as much as 25t ha^{-1} were attained. Italian yields were slightly higher than those achieved in the Netherlands, which in turn were much higher than UK yields. The proportion partitioned into stem (averaging 70 - 80%), and the proportion of stem which was long fibre (c.30%) was similar between sites. Other than yield, the greatest differences between country were that no nitrogen effects were seen in I or NL (the crops were grown in soils with high residual nitrogen levels) and lower planting densities produced lower yields.

Fibre Quality

Hemp plants were analysed both for the contribution of fibre structural materials (cellulose, hemi cellulose and lignin) and also for the whole fibre mechanical and chemical properties of fineness, tenacity (strength) and decortication resistance. The contribution of cellulose, hemi-cellulose and lignin was not affected by any cultural treatment in the UK, and averaged 52%, 14% and 7%, respectively. Harvesting at full flowering rather than seed set did not alter the structural composition of stems significantly. In 1996 only, the composition of UK fibre was different to that of I or NL. Total fibre yield was lower, due to 10% less cellulose. The reasons for this are not clear, but must be related to the maturation rate of the crops in the different countries in 1996.

Tenacity and decortication resistance of fibres showed variation between cultivars grown only in Italy and The Netherlands (Kompolti & Carmagnola), although little difference was discernible between the UK's two main varieties, Felina and Futura. Increasing the plant density increased the homogeneity of fibres and the fineness of fibres. Fibre quality was principally influenced by site; husbandry treatment within site had little effect (because variation within plots for fibre characteristics was much greater than variation between treatments), suggesting that agronomic treatment cannot be used as a tool to improve fibre quality. The exception was the impact of plant density. Lowest plant densities resulted in poor fibre quality (low fineness). The central third of the hemp stem has the highest fibre content and the highest tenacity. The fibre content of the bottom of the stem declined with time, the middle was fairly stable and the top increased. The fibres tended to become coarser with time. Final plant densities of 115 - 130 plants m^{-2} were needed to provide the highest quality fibre. Spectroscopic characterisation indicated that lignin, increasing with time, and pectin, decreasing with time, could be used to predict harvest date. Fibre yields were 28-30% of stem biomass for UK samples, with little variation between country (Table 2). Delaying harvest from full flowering to seed set increased the decortication resistance of fibre, indicating that an earlier than current harvest date would not only increase the fineness of fibres, but would allow

Table 2 : Fibre contents and decortication resistance of samples at full flowering (H5) and seed set (H6) for crops receiving a total N supply of 160 kg N ha^{-1}, 1998.

	Harvest time	Decortication resistance	Fibre content (%)
Dutch samples	5	2.9	28.7
	6	5.3	27.6
UK samples	5	3.5	28.1
	6	4.5	30.0
Italian samples	5	3.3	28.7
	6	3.2	29.5

The results discussed thus far relate to hemp prior to retting and indicate that an earlier harvest might be preferable. Obviously a significant proportion of commercial scale production deals with field retted hemp, where the crop has been cut and laid in windrows for as much as 6 weeks to encourage fibre separation from the other stem material. The influence of the harvest date on industrially produced field retted samples of hemp was studied. Futura (produced by Hemcore ltd in the UK) was harvested either one week or 5 weeks after first flowering (mid August or mid September).

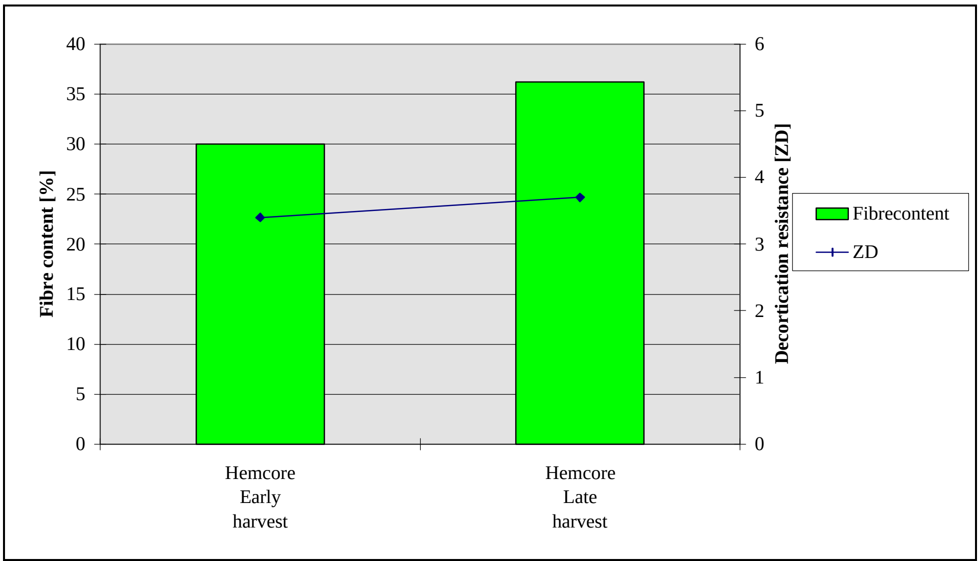

Figure 4 : Decortication resistance (ZD) and fibre content of commercially produced, retted hemp.

Recovered fibre content increased from the later harvest (Fig. 4), thus even though there is no discernible difference in fibre content of the stems, a greater quantity is made available from retting more mature stems. This was due to a simultaneous decrease in the pectin content of stems. There was no significant difference in sample tenacity, decortication resistance or fineness. Thus, commercial harvest must strike a compromise between harvesting late in order to recover high quantities of retted bast fibre and harvesting much earlier to increase fibre quality.

Harvest & post harvest treatment

If hemp is harvested late in the season for bast fibre production, drying conditions are often poor, with a consequential loss of fibre yield and quality in the drying swath. It would be an advantage to be able to increase the drying rate so that retting would start earlier. If leaves and heads, not of value for fibre, could be removed at cutting, the stems might dry faster. Equipment was developed in order to strip leaf material from the hemp crop prior to harvest on the assumption that this would allow more uniform field retting to subsequently take place. The stripping machine was evaluated in two seasons, and the effects of varying swath structure evaluated. Mechanically stripping leaves prior to cutting removed 95% of leaf material and improved the drying characteristics of the swath and reduced the amount of time the stems required to be swathed. The effectiveness of drying in the swath and retting was evaluated. The benefits and drawbacks of swathing treatments depended on the weather. Chopping the crop exposed it better to the air, allowing faster drying and reducing the amount of time needed for swathing. Any improvements in drying and/or retting rate were lost in periods of heavy rainfall. Thus, we were able to demonstrate that we could reduce the amount of time necessary for the crop to be swathed, but could not reduce susceptibility to rain damage.

Decortication offers a process whereby the vagaries of retting conditions are removed. A novel decorticator, developed by SRI and which had been proven to improve separation of bast fibre from retted straw of flax and linseed was evaluated. Initial studies on a laboratory apparatus showed that decortication was achieved and that the quality of the fibre was attractive to the project partners. However there were problems with fibre wrapping on certain rotating parts of the laboratory machine. These problems were overcome by chopping the stems and changing the design of the rollers and fibre combs. The influence of chopping was to reduce the fibre yield, i.e. the percentage by weight of fibre produced by decortication of ingoing material. This was probably because the processing in the decorticator was less effective on short pieces of stems than on whole stems. Collection by machine is likely to be less effective on chopped than on whole stems so a reduction in fibre produced per unit area of crop may be expected. Turning the crop in the field increased the yield of fibre, probably because of loss of shiv in the field on turning. There was no effect of harvest timing or of spreading in swath on fibre yield. Decortication of non-retted stems produced equivalent fibre quality to conventionally field retting and processed fibres. Thus the work presented a number of innovatory mechanical solutions which could increase the amount and quality and fibre recovered and dramatically reduce the probability of weather-induced crop loss - which until now has been a significant economic risk in hemp production.

Post-harvest enhancement of fibre quality

Hemp fibre extracted from stems using conventional retting and decortication techniques tends to be relatively coarse compared with other competing fibre types e.g. flax. Accordingly, in order to make it better suited for added value uses such as plastic reinforcement, spinning etc., there is a need to apply treatments which will improve the quality of the fibre, in particular with respect to fibre fineness (total fibre surface area) and surface cleanliness. In this work two types of treatment were considered, namely steam explosion (STEX) and ultrasonics; both these have the potential to break down fibre bundles and remove natural binding constituents from fibre surfaces.

Four key process variables were investigated for STEX treatment: degree of chemical (sodium hydroxide) dosing; treatment time; extrusion pressure; type of post treatment (boiling / washing). Similarly, for ultrasonic treatment, degree of chemical (sodium hydroxide) dosing, treatment time, temperature and optimum raw material type e.g. degree of retting, cleanliness (in terms of shiv content) were investigated to determine optimum processing conditions.

It was evident that processing variables had a significant effect on the properties of STEX treated fibre. Mild STEX treatments tended to maximise fibre properties such as length and strength, and improved fibre cleanliness. In contrast, more severe STEX treatments tended to reduce fibre length and strength, but resulted in marked improvements to fibre fineness in particular. It was concluded from this that STEX treatments would generally need to be tailored to suit specific individual applications.

From the ultrasonic studies there was evidence that the most important processing variable was the level of chemical dosing. In general, fibre treated with higher concentrations of sodium hydroxide, at higher temperatures and for longer periods had the best properties. The tenacity of fibres appeared to be improved under such processing conditions (in contrast to STEX treatments, where the more severe treatment resulted in a lowering of fibre tenacity). However, even the most severe ultrasonic treatments only gave modest improvements in fibre fineness; there was also little evidence that the cleanliness of fibres was significantly improved.

It was concluded that STEX was the most promising technique available for improving fibre cleanliness and fineness, and that it has potential to be exploited on a commercial scale. In contrast, considerably more work would appear to be required in order to prove whether ultrasonic treatment was viable; the evidence from this work suggests that it would probably never have the same efficacy as STEX treatments, particularly with respect to improving fibre fineness and cleanliness.

Chemical Modification of fibres

Chemical modification of plant fibres, in which selected aducts are covalently bound onto the hydroxyl sites of holocellulose, lignin and pectin etc., offers the potential to upgrade the value of fibres by tailoring their properties for specific end uses. For example, chemical modification can improve the resistance of plant fibres to biodegradation. In addition, it can alter the surface characteristics / energy of plant fibres, making them potentially more compatible with plastics and resins, and thereby realise improvements in the physical properties of plant fibre reinforced plastics.

In this work a number of chemical modification systems were considered. These included: acetic anhydride (AA); succinic anhydride (SA); and dimethyl meta-isopropenyl benzyl isocyanate (TMI). All three systems have the potential to lower the surface energy of fibres by making them more hydrophobic, thereby making them more compatible with thermoplastics (fibre reinforced plastics) and improving resistance to biodegradation (external horticultural applications e.g. geotextiles). Chemical modification with Polypropylene-graft-maleic anhydride (MAPP) was also considered; MAPP has been used as a compatibiliser between polypropylene and plant fibres, though normally simply as an additive for thermoplastic/fibre mixtures produced by extrusion. It has been claimed that the heat and pressure generated during processing promotes covalent bonding between hydroxyl groups on the fibre and the maleic anhydride part of the MAPP molecule, whilst the polypropylene chain is entangled amongst those of the thermoplastic matrix, the whole resulting in improved bonding between fibres and matrix and consequently improved product properties.

It was evident that little or no reaction occurred between bast fibres and either TMI or MAPP. This was believed to be attributable in part to stearic problems caused by the size of the reactant molecules (this was likely to have been particularly true in the case of MAPP, where the mean molecular weight is of the order of 9000). In contrast, significant reaction was obtained between fibres and both succinic and acetic anhydride; the use of pyridine with the latter significantly improved the rate and extent of reaction. The rate of reaction was generally greatest with normally retted untreated fibre. STEX treated fibre typically showed much lower levels of reactivity; this was attributed to the fact that such fibre was comprised of much higher levels of cellulose (the least reactive component of plant fibres), and as such confirmed the view that STEX treatments were effective in improving fibre cleanliness. In contrast, the ease of reaction with ultrasonically treated fibre more closely resembled that of untreated fibre. This latter observation reinforces the view that ultrasonic treatment has little effect in removing components such as pectin and hemicelluloses from fibres.

Although the greatest reactivity was obtained with succinic anhydride, this also had drawbacks. Succinic anhydride opens up fibres and causes significant embrittlement. Given this, it was concluded that modification with acetic anhydride was likely to be the optimum treatment. Treated fibres were likely to possess a degree of resistance to biodegradation, whilst their increased surface hydrophobicity should also increase their compatibility with thermoplastic matrices.

Industrial applications

Wood-based Panels

Although wood is the by far the most common raw material used for the manufacture of wood-based panels, a number of non-wood materials e.g. straw, bagasse, bamboo, flax shiv etc. are used in some parts of the world for the manufacture of composition panels. This work investigated the potential for using hemp, either in the form of whole stem material or shiv separated from the long fibre component, as a raw material for chipboard and medium density fibreboard (MDF). For both products a range of process variables were investigated, including resin type, resin catalyst level, wax addition level, particle size, panel density, time of harvest of the hemp crop and the degree of retting of the material.

Results of extensive studies suggested that the most promising raw material / product combination would be the use of hemp shiv as a partial substitute for softwood in the manufacture of MDF. Providing a suitable catalyst was used with urea formaldehyde (UF) resin, wood substitution levels up to 30% appeared to be viable. There was also evidence that whole hemp stem could be utilised in MDF, but viable inclusion levels would probably be limited to around a maximum of 10%. Where hemp stem material was included in panels there was some evidence, in terms of panel properties, that there were advantages in using material which had been harvested at an earlier than normal date and had been subjected to minimal retting. However, such evidence was not strongly supported from statistical analysis of data. The main advantage of using minimally retted material was in the processing phase of the operation, whereby sliced / chopped material behaved in a similar fashion to wood chips i.e. it mixed and flowed in a similar manner; the fibre and shiv component of retted material tended to separate, leading to ‘balling’ of fibre, uneven mixing with wood chips and subsequent feeding and processing difficulties.

Hemp shiv did not appear to be a viable alternative raw material for wood-based chipboard, at least at inclusion levels of 10% and greater. Inclusion of the material significantly increased the thickness swelling of the product; this was the case with both UF and MDI resins (use of the latter did reduce thickness swelling compared with UF resin, but thickness swelling was still greater compared with UF-bonded wood-based panels). The increased thickness swelling associated with the inclusion of shiv in chipboard can be attributed to the highly absorbent nature of the material; this is supported by the fact that the primary commercial outlet for shiv at present is as an animal bedding material. It is believed that the increased thickness swelling caused by the inclusion of shiv in panels would not be considered acceptable to panel manufacturers, given that thickness swelling is already a key limiting property which ultimately determines the efficiency of the production process.

Although no rigorous analysis was conducted regarding the likely costs that would be associated with replacing wood with hemp material, some broad observations and conclusions can be made. Wood is currently widely available at relatively low cost throughout the EC. Whilst prices do vary across the EC, the wood raw material used for the manufacture of chipboard and MDF might typically be available at the mill gate for between 40 and 70 Euro / tonne (oven dry mass basis). This is significantly less than the price that can currently be commanded for shiv in the livestock bedding market. Accordingly, until there is a significant oversupply situation with respect to hemp shiv, it is unlikely that the material will be used for the manufacture of panel products. Whole stem material is, therefore, the more likely of the hemp raw materials considered in this work that might be utilised by the panel products industry. However, cost is again likely to be a major determining factor. Even with the current subsidy in place, the ‘market’ price for hemp stem is likely to be significantly higher than that of wood. Whilst the use of hemp might enable panel manufacturers to attract a ‘green’ premium on their product, it is uncertain whether this would be sufficient to off-set or even exceed the higher cost of the raw material.

Fibre-reinforced thermoplastics

Conventional thermoplastics are typically characterised by having high toughness and impact resistance properties, but they lack strength and stiffness and are also not easily biodegradable. However, such materials can be strengthened and stiffened by including fibres in them and there are also a range of biodegradable thermoplastics now available which could be used in their place. This work investigated the potential for using untreated, STEX and ultrasonically treated hemp bast fibres as reinforcements for a range of biodegradable plastics and the potential for using chemically modified (acetylated) / surface treated (silanes, MAPP) normally retted fibre as reinforcements for polypropylene.

It was evident that the inclusion of STEX treated fibre in most types of biodegradable plastic resulted in the highest increases in strength and stiffness of the materials. Ultrasonically treated fibre produced similar results to untreated fibre (increases in strength and stiffness compared to the plastics alone, but less marked compared with STEX treated fibre). The inclusion of all fibre types tended to reduce the impact resistance of materials. However, the impact resistance of the reinforced materials would generally be considered to be acceptable. The superior performance of STEX fibre was attributed to its higher fineness and cleanliness, resulting in improved bonding with the matrix materials. All reinforced biodegradable plastics exhibited marked reductions in strength properties when they were exposed to water. This was not unexpected (almost by definition, biodegradable materials will be susceptible to exposure to water or moisture) and is indicative of the limitations in potential applications that are imposed when there is a requirement for materials to be biodegradable.

Compared with untreated retted fibre, neither acetylation or the surface treatment of fibres with silanes resulted in any significant improvement in the physical properties of fibre reinforced polypropylene composites. However, significant improvements were realised when fibre was treated such that it was coated with MAPP. The level of property improvement was broadly related to the loading level of MAPP on the bast fibres, with the highest MAPP loading of 3-4% producing the composites with the highest mechanical properties. The improved properties obtained with MAPP appeared to be attributable to improved bonding between the fibres and matrix, the fracture surfaces of MAPP treated samples exhibiting less fibre pull-out than with other treatments.

Horticultural Geotextiles

Geotextile materials are used predominantly in mulching applications in the horticulture and forest industries. Their purpose is primarily to suppress weed growth around plants and trees and to help retain moisture. The most common materials which have been used in the past are polythene sheeting and spun / woven polypropylene. These materials have the advantage of being relatively cheap, are easy to put down and are durable. However, this latter property can be undesirable, since the materials can last for much longer periods than actually required; consequently, their removal and disposal can be costly. There are a number of natural fibre alternatives available on the market. These are predominantly comprised of wool or coir (coconut fibre), but are often mixed with plastics as well. This work was aimed at investigating whether non-woven hemp fibre materials, either untreated, acetylated or treated with a biocide, could compete favourably with commercially available mulch materials and other experimental non-woven materials made from other plant fibre types e.g. flax, jute.

A trial site located on the island of Anglesey was selected for the study. The site had been previously used for rough grazing of sheep, but was scheduled to be planted with a range of locally indigenous tree species. Once the trees (predominantly ‘whips’) had been planted, commercial and experimental mats were placed around the trees and their corners dug in to prevent them being lifted by wind etc. An average of nine replicates were used for each mat type; the positioning of mats was random with respect to both location on the site and tree species.

The relative performance of the mats after eleven months service was determined. Each mat was scored on its ability to suppress weed growth and its rate of biodeterioration. The average score for a mat type was then divided by its cost (for experimental mats the price was a best estimate) to give a performance / cost index. It was evident that those mat types which were made predominantly of plastic had by far the highest performance / cost index. This is unsurprising, since such materials are unlikely to degrade significantly and are relatively cheap. Untreated hemp had a similar performance in service to untreated flax, but the lower cost of the latter resulted in it having a higher performance / cost index. Whilst acetylation appeared to improve the performance in service of hemp, the estimated costs associated with acetylation actually reduced its performance / cost index below that of untreated hemp. In contrast, hemp treated with biocide had a markedly improved performance, whilst the costs associated with such treatment were about half those estimated for acetylation, thereby resulting in an improved performance / cost index compared with untreated hemp. Products containing wool typically had equal or significantly better performance in service compared with hemp; however, their relatively high cost markedly lowered their performance / cost index.

Untreated hemp fibre mats appeared to be suitable for tree mulching applications where product life in excess of one year was not a requirement. Such materials would have the added benefit that they would not create environmental / disposal problems. However, such materials would have difficulty competing on a cost basis with other fibre types such as flax (this has certainly been cited by one UK manufacturer of non-woven tree mats as being the key reason for selecting flax over hemp). Increasing the durability of the product appeared to be feasible with the application of a biocide or through acetylation, though the high cost of the latter might be prohibitive. In addition, it is not known to what extent product life might actually be extended with such treatments.

Plant Breeding

The objectives of the breeding programme within this project were to develop improved hemp varieties for northern Europe with a THC content of almost zero, an improved fibre yield and fibre quality and improved resistance to pests and diseases.
Resistance to root knot nematodes (Meloidogyne spp) was of main interest. A hemp plant showing resistance to M. hapla but having poor agronomical characteristics (H5) was used as a parent in a cross with a high performing, low THC containing but susceptible available variety (Kompolti Hyper Elite). A mass-selection scheme was applied to obtain F3 offspring from this cross with improved resistance combined with low THC and high fibre production. After two successive in vitro selections fully resistant plants were obtained against M. hapla. Seed was generated from these resistant plants and 10,000 plants were evaluated individually in a field trial. Of these plants 578 showed good agronomical performance and were analysed in more detail. The fibre and wood content of these plants varied greatly (9.6 to 22.1% and 66.4 to 77.6%, respectively) as well as the THC and CBD content (0.01 to 1.27% and 0.10 to 2.26%, respectively). All plants were very late flowering.

On the basis of fibre and THC content 4 groups were formed having the following characteristics: Group 1.1: THC: 0.02 to 0.06%; fibre: 19.6 to 22%; Group 1.2: THC: 0.03 to 0.09%; fibre: 11.9 to 17.5%; Group 1.3: THC: 0.35 to 0.76%; fibre: 19.2 to 24.8%; Group 1.4: THC: 0.34 to 0.81%; fibre: 12.2 to 16.6%. Group 1.1 and 1.2 were multiplicated and used for further selection. The full resistance of the F1 offspring decreased somewhat in further generations (F3 and F4) but the resistance level was still much higher than that of the susceptible parent. In the progeny of the resistant parent some susceptible plants were found, suggesting that the resistant parent plant was heterozygous and that the trait is dominant. This may also explain the segregation of susceptible plants in the F3 and F4 generations obtained from resistant F2 plants.

Group 1.1 and 1.2 were evaluated further. Seven families per group consisting of 40 plants were investigated on single plants basis in a field trial. The following characteristics were scored: THC and CBD content, fibre and wood content, stem diameter, stem length, dry matter production, branching degree and date of flowering. Large variation was found for all traits except for THC, and the THC content was for almost all families < 0.03%. The fibre and dry matter production potential of the families varied between 1492 to 2605 kg/ha and 6663 to 12636 kg/ha , respectively. Thus by the end of the project some promising lines had been developed but further selection and refinement is required before any material is marketed as a new variety.

The CPRO-DLO pre-commercial variety ‘yellow line’ was evaluated for fibre yield and quality, and found to be significantly improved over current varieties (Fig. 5). Work in the Netherlands will now move towards commercial development of this line in order to enable European growers to produce higher fibre yields.

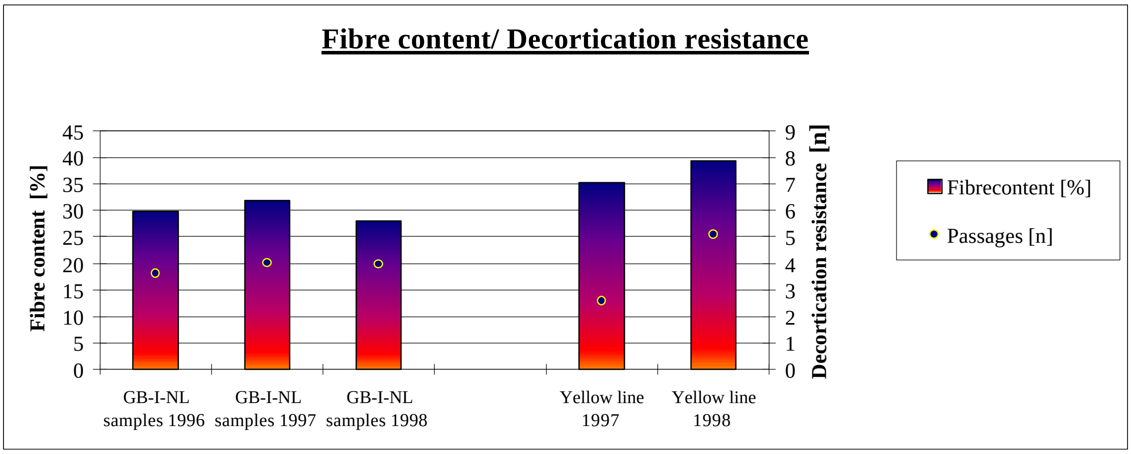

Figure 5. Fibre content and quality of a newly developed European hemp line compared with registered varieties assessed in the crop agronomy work.

Policy implications of the research

The publication of this research coincides with EU proposals to bring hemp and flax within the Arable Area Payment Scheme (AAPS) and reduce the area payment from £500 ha^{-1} to parity with oilseeds. Linked to this will be supplementary processing aid. At a time when the area aid payment for hemp and flax is to be reduced, the work reported here is particularly pertinent because it has identified ways in which the yield of hemp can be maximised whilst at the same time identifying diversified uses for the crop. Thus the saleable commodity will increase for the farmer and the processor. The crop agronomy research identified physiological parameters that control the productivity of hemp in the UK, and produced robust criteria upon which to base selection of variety, crop density, and nitrogen fertiliser regime. The experimental yields from the best treatments in this study were significantly greater than most current commercial yields, indicating that a step towards bridging the subsidy gap had been started. However, further, necessary, gains will only be achieved if later maturing varieties are grown in the UK and this can only happen if EC cropping regulations regarding crop harvesting are relaxed.

This work has identified improved harvesting and post-harvesting systems such as modification to swath structure and new methods for cleaning fibre (steam explosion).

The project has identified that fibre with a particular set of physical properties cannot be 'grown to order'. By far and away the most important component of fibre quality was site; agronomic treatments had little repeatable impact on quality parameters, other than the control of plant density. Optimal yield of fibre must therefore be the primary agronomic goal, with post harvest treatment (via decortication, steam explosion or fibre treatment) the mechanism by which quality parameters are modified.

From a product performance point of view the results of this work suggest that the most promising raw material / product combination would be the use of shiv as a partial substitute for softwood in the manufacture of MDF. Providing a suitable catalyst is used, wood substitution levels up to 30% would appear to be viable. There was also evidence that whole hemp stem could be utilised in MDF, but viable inclusion levels would probably be limited to around a maximum of 10%. Hemp fibre or shiv material did not appear to offer suitable characteristics for particle board, thermosplastics or geotextiles, either due to cost considerations or quality. All aspects of the work reported have been fed through to the commercial hemp producers in the UK and thus this project has increased the competitiveness of the UK industry.

Further Work

Further agronomic work should consider the following areas:

1. It is currently advocated that nitrogen should be applied pre-drilling. The principal motivation of this strategy is ease of husbandry. Post emergence or even split applications may provide a more economic and environmentally friendly mechanism of providing the optimum amount of nutrients, and might be a useful tool to overcome establishment difficulties. Experiments should be established which test this hypothesis.

2. Stratified sampling for biomass accumulation and canopy development characteristics in numerous commercial crops will allow the study of crop uptake requirements for N as well as P and K. This will enable refinement of our recommendations for nitrogen requirement in the crop, and, linked with (1) above, reduce environmental fate of N by targeting nitrogen when most needed.

3. This work has shown that improvements in yield can be attained which will improve the viability of hemp cropping in the UK. This can be achieved by optimising inputs, but also by switching to later maturing varieties. The current work demonstrated this effect with varieties that flowered 15 days apart. There are many continental European varieties with much later maturity. These are currently precluded from growth in the UK due to EC regulations. It is advocated that these restrictions are relaxed, and that additional germplasm is screened for suitability to the UK.

4. This work has shown that yield and quality of fibre are linked to plant density and self-thinning regulates plant densities. However, the work has also shown that establishment of hemp seed is sporadic and spatially patchy. Improvements in yield, refinement of quality and reduction in input costs could be achieved if establishment were improved. Research that identifies the causes of seedling loss and ways of overcoming these losses should be undertaken.

PUBLICATIONS RESULTING FROM THIS MAFF FUNDED WORK:

The following paper has been accepted for a refereed journal, and summarises the joint agronomic/crop physiology research of the UK (ADAS), Dutch and Italian partners of the EC project:

- Struik, P C, Amaducci S, Bullard M J, Stutterheim N C, Venturi G and Cromack, H T H (1999) Agronomy of fibre hemp (Cannabis sativa L.) in Europe. Industrial Crops & Products In Press.

Further joint publications, dealing with specific aspects of physiology across the three countries, such as yield modelling, canopy development and density characteristics will follow. Specific to the UK, the following paper is under preparation, and a draft is provided (Annex 1):

- Bullard, M.J. & Cromack HTH (1999). Growth, development and productivity of Cannabis sativa L.; the influence of plant spacing, available nitrogen level and cultivar under UK conditions. Undergoing final editorial comments before submission to J. Exp. Bot.

Technology Transfer

On 3 September 1998 ADAS ran a Hemp demonstration day. Based at the Devon field site and attended by 50 farmers, scientists and MAFF policy staff, the day consisted of formal presentations followed by a field visit and harvesting demonstration. Formal presentations on crop agronomy/physiology, commercial production, harvest and post harvest technology and end use applications were made. In June 1999, a poster presentation of the crop physiological work was made at the 4th European Symposium on Industrial Crops, held in Bonn, Germany.

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