Growth and dry matter accumulation of three hemp (*Cannabis sativa* L.) cultivars sown on three dates in Canterbury

H.M. Wulff[1], T. Ryan-Salter[2], M. P. Andreucci[1], N. Pyke[2], M. Collie[2] and D.J. Moot[1]

[1]Faculty of Agricultural Sciences, Lincoln University, PO Box 89084, Canterbury, New Zealand

[2]Carrfields Limited, 60-62 Cass Street, Ashburton 7700, New Zealand

derrick.moot@lincoln.ac.nz

Abstract

Hemp fibre is a durable, environmentally sensitive and a fast-growing alternative to cotton and synthetics. Hemp fibre production is dependent on the stem as the major yield component. An experiment was conducted to investigate the growth, dry matter accumulation and composition of hemp crops with the focus of fibre production. Three cultivars (Ferimon, Kompolti and Futura 75) were sown on three dates (22/10/2020, 11/11/2020 and 9/12/2020). The contribution of stem, leaf and flower to the total dry matter yield were recorded over time in Canterbury, New Zealand. Futura 75 consistently yielded the most stem dry matter with an average of 9.12 t DM/ha (± 0.495) while Ferimon yielded the most flower dry matter at 2.57 t DM/ha (± 0.113). In this experiment, earlier sowing dates gave greater ($P<0.001$) stem yields and later sowing dates produced greater ($P<0.001$) flower biomass. Futura 75 is recommended for stem production, regardless of sowing date, due to later flowering and homogenous crop development. Ferimon had the greatest flower mass, attributed partly to early flowering. Stem yield was consistent for Ferimon and the dioecious cultivar, Kompolti. Late October is the recommended sowing date to maximize stem yield based on this experiment in Canterbury. swards.

Additional keywords: fibre, biomass, stem, leaf, flower, Kompolti, Futura 75, Ferimon

Introduction

Industrial hemp (*Cannabis sativa* L.) is a versatile crop that has been cultivated and utilised for fibre, oil and cannabinoid production over several millennia (Yang, 1991). Despite its historical importance, interest in industrial hemp dwindled throughout the mid-20th century as a result of competing land uses, more profitable fibre crops (cotton; *Gossypium sp.*), the development of petrochemical alternatives (e.g. polyester) and associations with its psychoactive counterpart (Zatta *et al*., 2012). Recent technology advances and an increased global demand for non-synthetic, sustainable fibres, has led to a relaxing of government controls on industrial hemp (Cosentino *et al*., 2012). New Zealand regulations now allow the sale of fibre products and seed for human consumption, when grown under strict conditions (Misuse of Drugs (Industrial Hemp) Regulations 2006). There is also renewed public, industry and farmer interest in industrial hemp. Marsh (2020) estimated that industrial hemp could contribute $2 billion to the New Zealand economy by 2030, due its multitude of uses for medicinal, nutritional, construction and textile purposes. Despite this potential, previous reports (Marsh, 2020; Merfield, 1999; Swanepoel *et al*., 2018) suggest that little domestic research has been conducted on its growth and agronomic characteristics.

Hemp is a short-day annual species that is commonly planted in mid-spring and harvested 100 – 140 days later depending on its development and end use (Amaducci *et al*., 2015). Hemp is naturally dioecious, where separate male and female plants exist in the same population. However, monoecious crops have also been developed through selection. Monoecious varieties contain both male and female reproductive organs on single individuals. Industrial crops may be either dioecious or monoecious, depending on their end use and growth characteristics. Monoecious cultivars are more often used for seed due to their ability to effectively self-pollinate (Amaducci *et al*., 2015). Dioecious cultivars have been suggested for fibre production, due to the presence of suspected higher quality fibres produced in male plants. However, differences in maturity between male and female plants can also cause harvest challenges due to a lack of homogeneity (Horkay, 1996). Hemp is often reported as having a low nitrogen requirement. Most papers agree that maximum yields of both seed and fibre can be obtained at N fertilisation rates of 50 to 180 kg N/ha (Amaducci *et al*., 2015; Schäfer, 2005; Vera *et al*., 2010; Zatta *et al*., 2012). However, high nitrogen rates may also have a negative effect on fibre quality (Weserhuis, 2016).

Hemp has a critical photoperiod of ~14 hours (Amaducci *et al*., 2008a; Cosentino *et al*., 2012; Lisson *et al*., 2000). This means flowering will take place in the least time possible once the daylength is shorter than 14 hours. Therefore, it is expected that vegetative growth would be maximised for early sown crops that are subjected to daylengths greater than 14 hours. Individual cultivars have different flowering times, owing to differences in photoperiod sensitivity (Salentijn *et al*., 2015). For example, Futura 75, has a medium to late maturity (Amaducci *et al*., 2008a), thus, has greater potential for high biomass yields. Futura 75 is a monoecious cultivar commonly used for fibre production due to its yield potential and homogenous harvesting characteristics (Finnan and Burke, 2013; Vandepitte *et al*., 2020). Kompolti is a mid-flowering dioecious cultivar (Lisson *et al*. 2000) that has been selected for high fibre content and yield potential (Meijer 1995). Ferimon is a dual-purpose cultivar commonly grown for seed throughout Canterbury and New Zealand. It is an early maturing, monoecious cultivar (Cosentino *et al*., 2013; Meijer, 1995). Its earlier flowering is associated with greater seed yields (Zatta *et al*., 2012). Because of its earlier maturation, Ferimon has a relatively low biomass yield (Aubin *et al*., 2016; Finnan and Burke, 2013). These cultivars are available for fibre and seed production in Canterbury (Medsafe, 2021).

Canterbury has the equivalent daylength of central-southern Europe (latitude ≈ 43° S). Kompolti was bred for a similar latitude, in Hungary (≈ 47° N), with Italian genetics. In contrast, Futura 75 is a French cultivar, bred in a German programme in northern Europe (≈ 51° N) (Meijer *et al*., 1995). This potential phenological difference may result in changes in the plant growth and flowering pattern of Futura 75 when grown at a latitude different from where it was bred. Similar latitudes to Canterbury, in Europe, tend to have warmer average growing season temperatures than those reported by Amaducci *et al*. (2008b). This difference in temperature will affect hemp growth and development because the optimum temperatures for growth are suited to slightly warmer climates (Cosentino *et al*., 2012), but the cooler temperatures can be expected to delay development. Altering sowing dates will be essential in ensuring optimal yields in new geographical regions.

There is no published data on dry matter (DM) yields of these cultivars grown in Canterbury, New Zealand. This information will be useful for improving grower's management, and confidence in growing the crop. This study will measure dry matter yields and growth patterns of hemp crops grown under Canterbury environmental conditions. To do this, the experiment measured the total biomass, stem, and leaf yields in dry matter of three industrial hemp cultivars sown on three sowing dates over one growing season.

Materials and Methods

Site

This experiment was conducted at an irrigated coastal site approximately 8 km south of Southbridge, Canterbury (43°52'S, 172°15'E). The experimental area covered 3 hectares within a larger (31 ha) paddock sown in pasture and beans. The soil is a Templeton silt loam, classified as a moderately deep (45 - 90 cm) to deep (>100 cm) immature Pallic soil (Manaaki Whenua, 2015) with an approximate water holding capacity of 150 mm in the upper 1 m of the profile (McNeill *et al*., 2018). To ensure the experiment had non limiting mineral nutrition, soil samples (0-150 mm) were collected for basic nutrient analysis using a standard sampling protocol on 7 September 2020 (Table 1).

Table 1. Soil test results at the experimental site in Canterbury, New Zealand on 7/09/2020.

Ammoniacal N	Nitrate N	Mineral N	Olsen P	Potassium	Sulphate sulphur	Moisture content	pH
(mg N/kg)			(mg/l)	(MAF QT)	(mg/kg)	(%)	
3	20	23	26	3	4	17	6.6

Additional samples (0-600 mm) were collected using a 25 mm powered auger on 16 November 2020 to assess mineral N status (Table 1). All samples were analysed by Eurofins, Auckland. Soil test results indicated a potential potassium deficiency, so 200 kg/ha of 50% Potassic Super (0-4.5-25-5.5) was broadcast across the site on 30 September 2020

The paddock history included cut-and-carry lucerne for approximately 10 years before being sown into annual ryegrass in autumn 2020. On 03/09/2020, the site was sprayed with 2.7 l/ha Glyphosate 540 (540 g/l glyphosate) and 450 ml of Starane Xtra (333 g/l fluroxpyr) at 200 l/ha of water. On 17/09/2020 the site was ploughed, rolled with a Cambridge roller, top-worked with a maxi-till and heavy rolled on the 19/09/2020. Prior to the third sowing date, fathen (*Chenopodium album)* and narrow-leaved plantain (*Plantago lanceolata*) had become established. Therefore, Roundup-Ultra®MAX (570 g/l glyphosate) was applied via mini-boom at a rate of 6.3 ml/l on 7/12/2020.

On-site climate data were monitored using an iMetos 3.3 weather station (Pessl Instruments GmbH, Austria). Daily evapotranspiration was calculated with the FAO-56 Penman-Monteith equation (Allen *et al*., 1998) using measurements of air temperature, air humidity, solar radiation, and wind speed. Irrigation was applied based on the water demand of all crops within the 31-ha paddock, thus, was not scheduled for a particular crop. All irrigation was applied through a centre pivot irrigator (BAUER

GmbH, Austria). All rainfall and irrigation water received are shown in Figure 1.

The site was near field capacity at both Sowing Date 1 on 22/10/2020 (SD1), and Sowing Date 2 on 11/11/20 (SD2). By 9/12/20 for Sowing Date 3 (SD3), the site was below 50% of field capacity water.

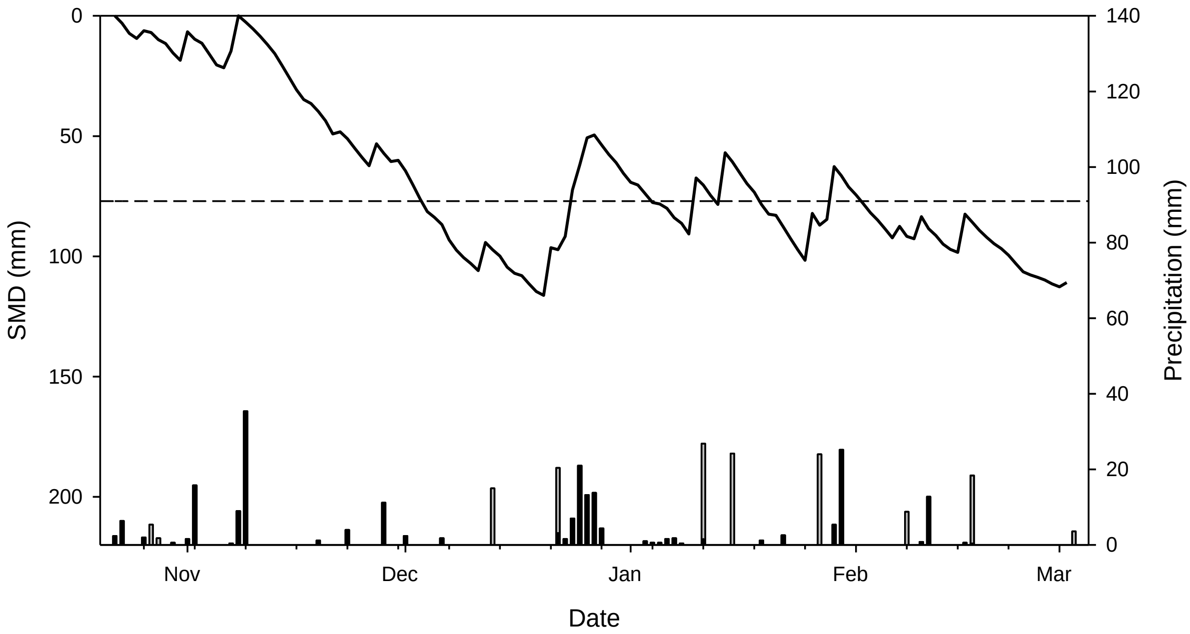

Figure 1: Rainfall (black), irrigation (grey) and soil moisture deficit (SMD) from October 2020 – March 2021 at Southbridge, Canterbury, New Zealand. 50% of field capacity (- - -).

Long term rainfall data (10-year mean) recorded at Broadfields Meteorological Station in Lincoln, Canterbury (NIWA: New Zealand) are presented in Figure 2. This is about 30 km north of the experimental site. On-site data were incomplete in October and March so were replaced with Broadfields data. PET on site and Broadfields data differed due to different locations and a potential shading effect from the hemp onto the on-site weather once the crop became taller than 1.5 m from January. Rainfall in October and March was 38 and 39 mm respectively, lower than the long-term mean of 50 and 47 mm respectively. November actual rainfall was 31 mm higher than the long-term means.

Experimental Design

The experiment was a randomised split-plot design with three hemp cultivars and three sowing dates. Sowing dates were arranged as the main plot (6.3 m x 45 m) and cultivars formed the sub-plots (6.3 m x 15 m) (Plate 1). Large plots were used to avoid edge effects due to the height of the crop. Treatments were replicated four times giving a total of 36 plots. Crops were sown on 22/10/2020 (SD1), 11/11/20 (SD2), and 9/12/20 (SD3). The 22 October was chosen as the earliest sowing date to avoid the last of the winter frosts.

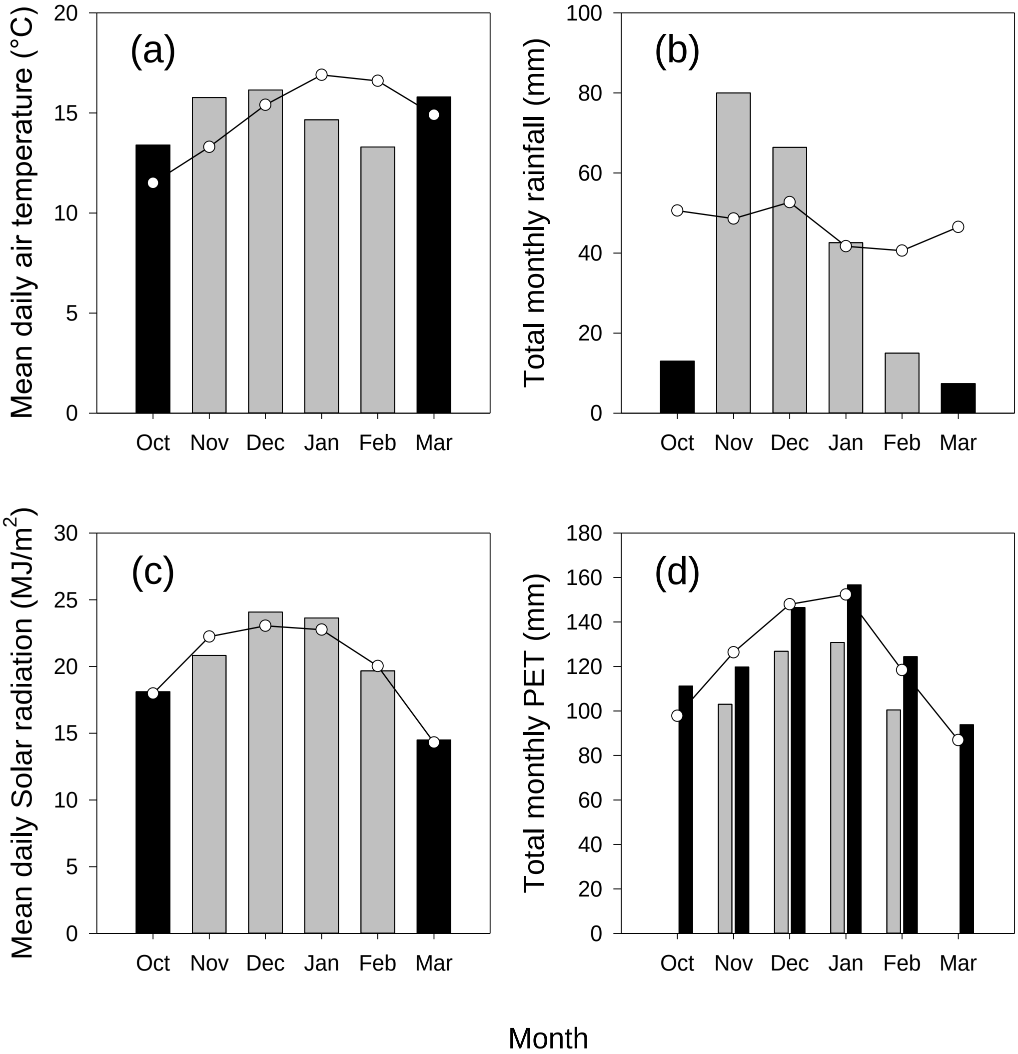

Figure 2: Mean air temperature (a), sum of rainfall (b), mean monthly solar radiation (c) and total monthly PET (d) over experiment duration. Data from on-site weather station (grey) and Broadfields NIWA meteorological station (black). 10-year Broadfields means (○).

Three commercial hemp cultivars, Ferimon (early flowering, monoecious cultivar), Kompolti (mid-late flowering, dioecious cultivar) and Futura 75 (mid-late flowering, monoecious cultivar) were selected because they are currently approved (Medsafe, 2021). and grown in New Zealand. All plots were sown at a rate of 40 kg/ha, to reach a target population of 100 plant/m^2 (Kerckhoffs *et al*., 2017). This population was within the recommendations of Swanepoel *et al*. (2018), Amaducci et al. (2002) and Tang *et al*. (2017b) for high total biomass or dual cropping. Guard rows, between main plots were sown at SD2 and the remainder of the buffer crop around the experimental area was sown on 17/11/2020. All plots and guard rows were sown with an Oyjord cone seeder with 15 cm row spacings. To replicate field conditions the four replicates (blocks) had a large area of buffer hemp sown around the outside and between, as demonstrated by Plate 1.

Measurements

Total biomass was measured from destructive harvests taken every two weeks, from 28, 39, and 42 days after sowing (DAS) for SD1, SD2, and SD3 respectively. A 0.2 m^2 quadrat was placed randomly within each plot and all live plants were cut at ground level, dead material was excluded. The number of plants was recorded, samples were weighed fresh, sub sampled, and then separated into leaf, stem and flower. Samples were dried in a forced-air oven for 48 hours at 60 °C. Leaves were removed along with the petiole. Flowers were weighed with stems until they comprised a larger component of the total DM.

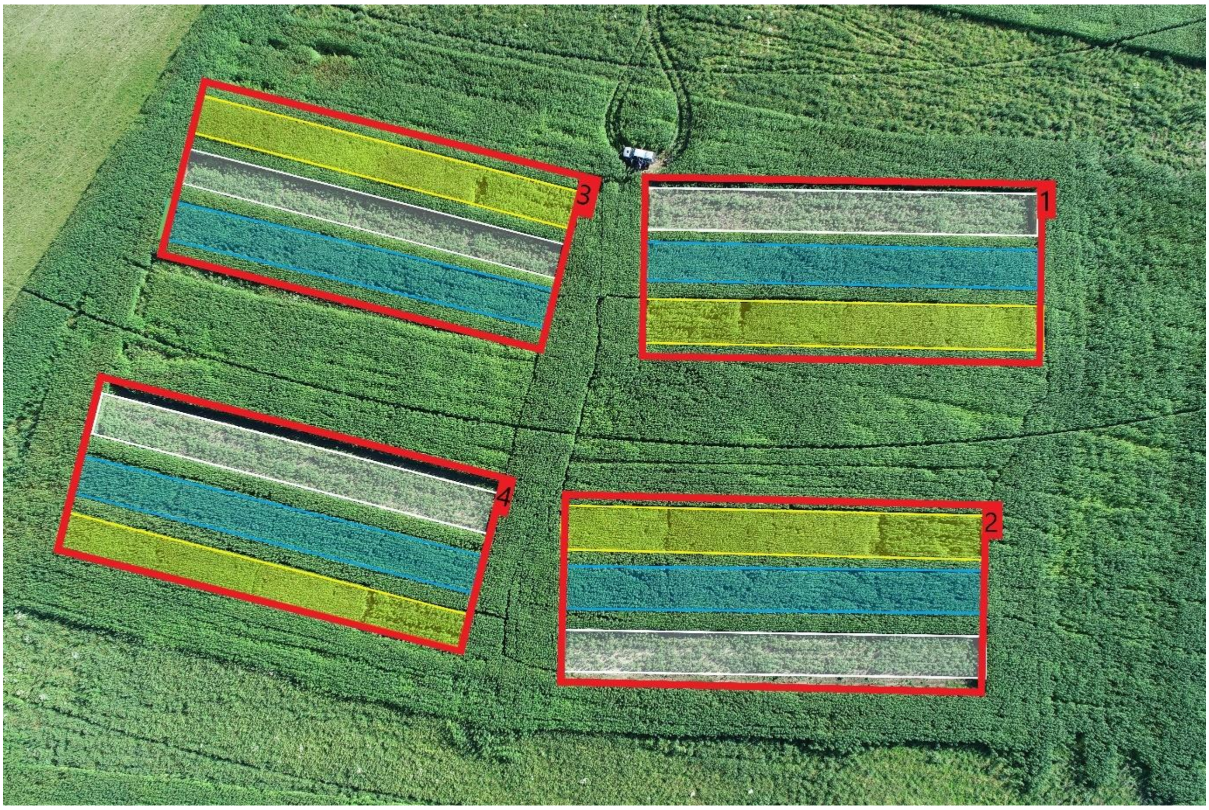

Plate 1: Hemp experimental site Southbridge, Canterbury, aerial photograph. Red squares represent replicates (blocks) and shaded area represents the three sowing dates. Strips between sowing date main plots are guard rows. Photo taken 12/02/2021.

Statistical analysis

Growth rates were calculated based on the linear growth phase of a sigmoid growth curve. The linear phase starts after the initial lag phase ends and this was estimated to be around 40 days after sowing (DAS). Growth rates were calculated as the DM gain per day from the harvest closest to 40 DAS, to the maximum total biomass harvest.

Analyses were done in Genstat 20^{th} edition (VSN International Ltd: UK). Initial harvests, that included only SD1 and/or SD2, were analysed as a one-way ANOVA to determine differences among cultivars. The remainder were analysed as a split-plot ANOVA. Significance was determined at $P<0.05$. Fishers protected LSD (least significant difference) was used for means separation at $P<0.05$.

Results

There was no difference in final plant populations between cultivars, however SD3 did have a lower population ($P<0.001$) at 30 plants/m^2 compared with SD1 and SD2 with 89 and 74 plants/ m^2 (± 4.22). Total biomass yields at the final harvest were consistent (P=0.202), despite the sowing date treatments (Table 2). Futura 75 produced the greatest average biomass yield across sowing dates (P=0.004), at the conclusion of the experiment at 12.8 t DM/ha. In comparison, Kompolti and Ferimon produced 10.4 and 10.5 t DM/ha (±0.495), respectively (Table 2). The mean of Ferimon was reduced by an unexplained low total biomass from SD2.

Table 2: Final harvest total dry matter yield (t DM/ha) of three cultivars of hemp, sown on three dates in Canterbury, New Zealand.

Cultivar	SD1 22/10/20	SD2 11/11/20	SD39/12/20	Mean
Ferimon	11.6	8.7	11.2	10.5 (b)
Kompolti	10.9	10.8	9.4	10.4 (b)
Futura 75	12.6	12.8	13.1	12.8 (a)
Mean	11.7	10.8	11.2	11.2
	P value	**SEM**	**LSD**	
Sowing date	0.202	0.300	1.04	
Cultivar	0.004	0.495	1.47	
Interaction	0.218	0.761	2.23	

Note: means within columns or rows followed by the same letter do not differ (LSD 0.05).

Growth of hemp crops was slow during the lag phase of establishment for each sowing date and cultivar (Figures 3, 4, and 5). This period lasted for approximately 40 DAS, after which crops transitioned to a linear phase of rapid biomass accumulation, irrespective of cultivar. Maximum growth rates calculated for this phase were not significantly different among the three cultivars. Mean treatment growth rates ranged from 160-258 kg DM/ha/day with a mean result of 203 kg DM/ha/day. The mean linear growth phase for SD1 was longer (P=0.008) at 64.2 days (± 3.07), than SD2 (50.2 days) and SD3 (52.5 days).

Following these linear growth periods biomass yields remained constant or began to decline. Maximum yield values occurred at the final harvest for all treatments except Kompolti and Ferimon in SD2. These cultivars had maximum yields at the previous harvest 82 DAS (Figures 3b and 4b). The biomass yields ranged between 9.4 t DM/ha (± 0.76) (Final harvest for SD3 of Kompolti) and 14.1 t DM/ha (± 1.86) for the penultimate SD2 Kompolti harvest.

Before ~ 40 DAS for SD1 and SD2, and ~ 60 DAS for SD3, leaf and stem represented equal proportions of total DM. The proportion of leaf weight in total biomass increased during the first 40-60 DAS, this was the linear growth phase for leaf components. Leaf contribution to total biomass was then constant at ~2 t DM/ha for all treatments. At this point, as leaf contributions reached their maximum, leaf and stem DM accumulation patterns became distinct from each other. As the leaf proportion stopped increasing, the stem proportion continued the linear increase of contributing to total biomass. Leaf senescence caused total biomass to decline for SD1 and SD2 at 70 – 90 DAS (Figures 3b, 4a, 4b, 5a and 5b).

At ~ 40 DAS, stem became the dominant contributor to total biomass as a result of stem elongation. Mean stem biomass represented 69% of the 11.2 t DM/ha mean total biomass yield. Total biomass growth ceased when stem growth stopped (Figures 3a, 4a, 4c, 5a and 5b). In those treatments where the maximum yield occurred as a peak at 82 DAS the total biomass yield reflected the stem contribution (Figures 3b and 4b).

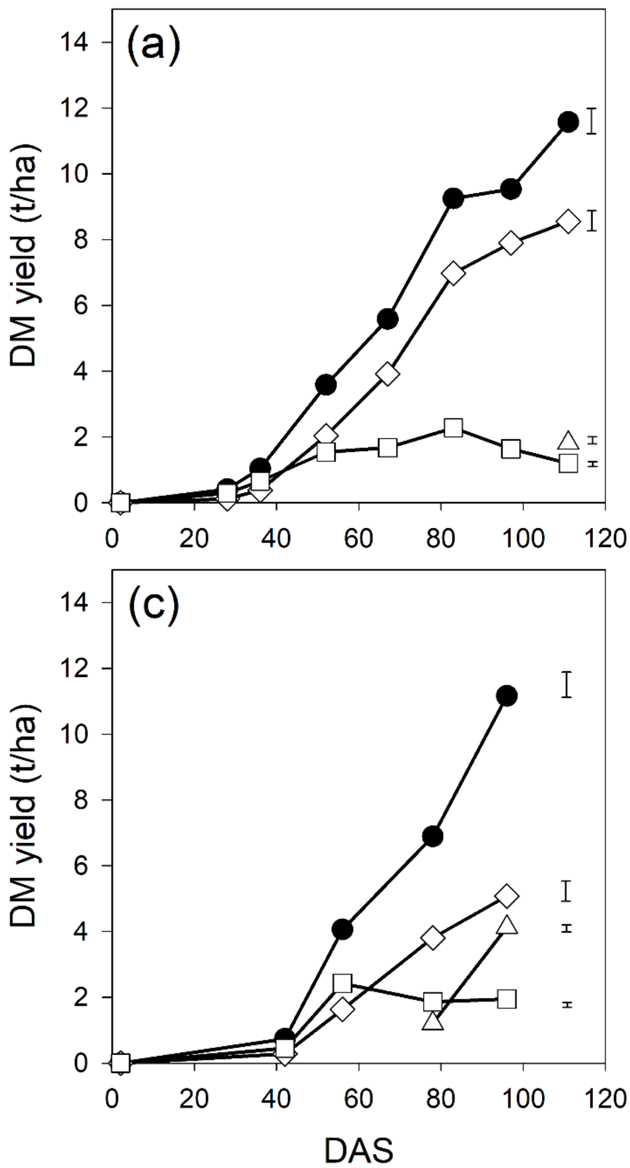

Figure 3: Ferimon accumulated total (●), stem (◇), leaf (□) and flower (△) dry matter (t DM/ha) over time (days after sowing; DAS) for hemp crops sown on 22/10/2020 SD1 (a), 11/11/20 SD2 (b) and 9/12/20 SD3 (c) in Canterbury, New Zealand, 2020/2021. Error bars are SEM of final harvest.

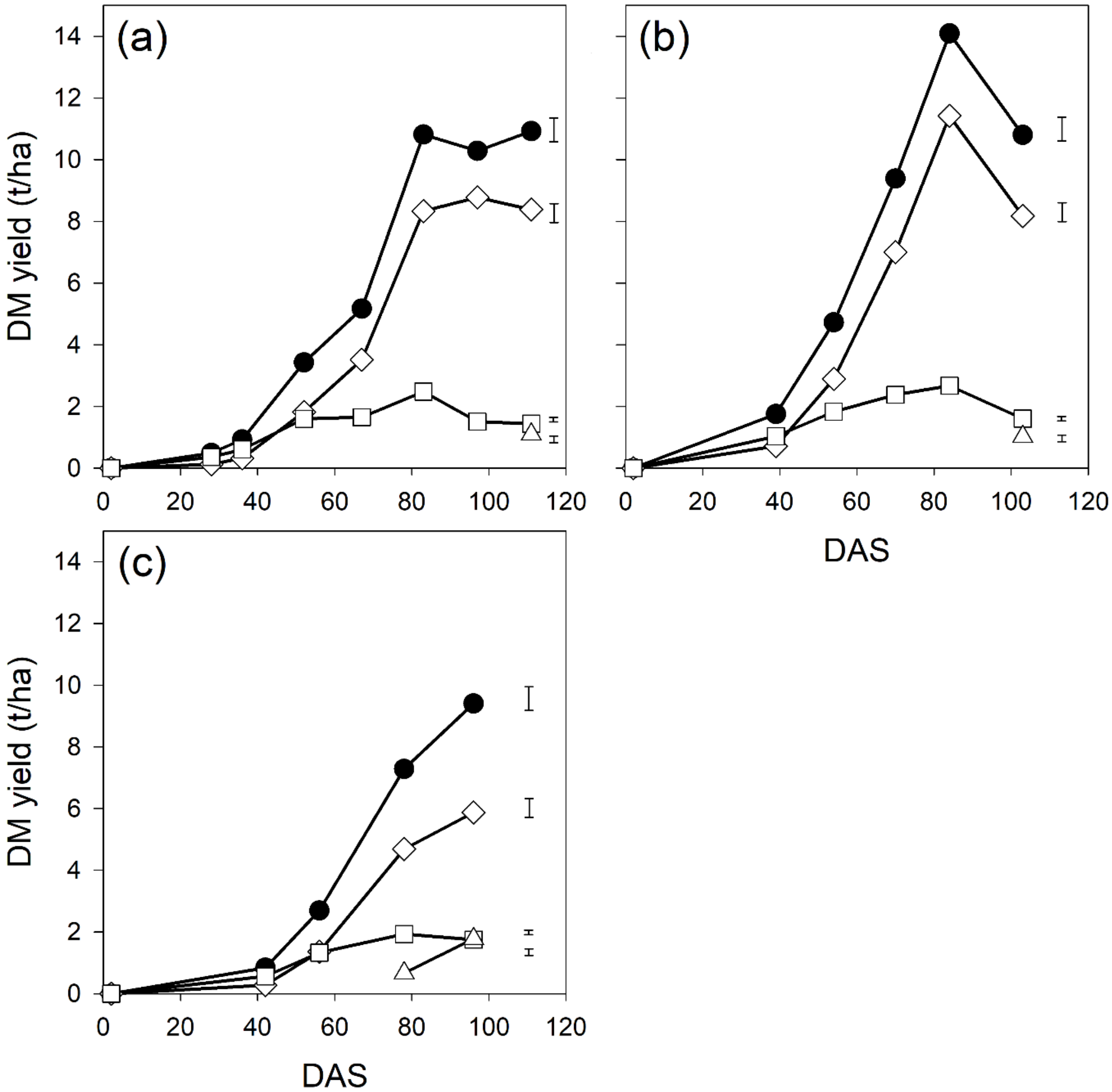

Figure 4: Kompolti accumulated total (●), stem (◇), leaf (□) and flower (△) dry matter (t DM/ha) over time (days after sowing; DAS) for hemp crops sown on 22/10/2020 SD1 (a), 11/11/20 SD2 (b) and 9/12/20 SD3 (c) in Canterbury, New Zealand, 2020/2021. Error bars are SEM of final harvest.

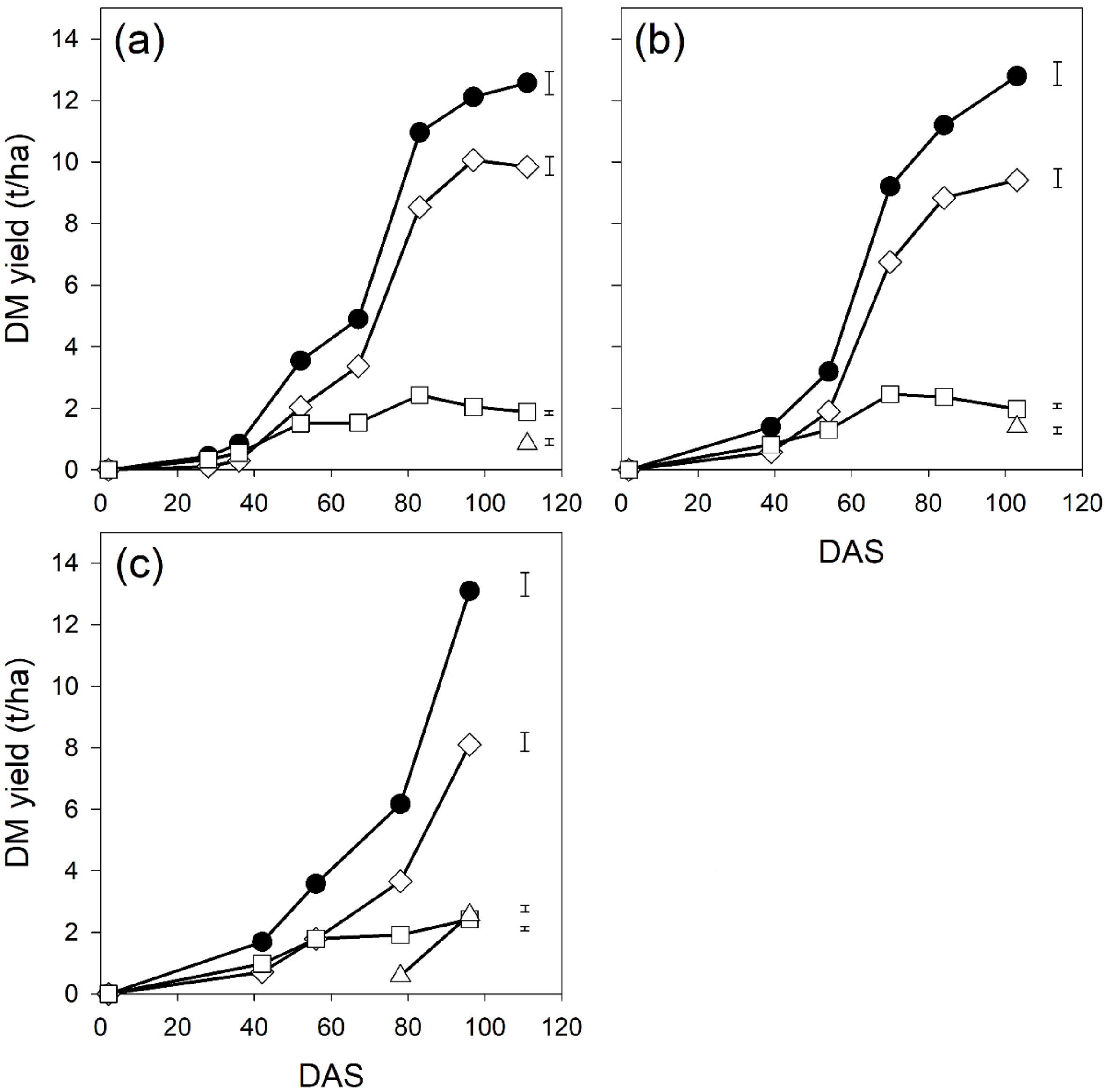

Figure 5: Futura 75 accumulated total (●), stem (◇), leaf (□) and flower (△) dry matter (t DM/ha) over time (days after sowing; DAS) for hemp crops sown on 22/10/2020 SD1 (a), 11/11/20 SD2 (b) and 9/12/20 SD3 (c) of in Canterbury, New Zealand, 2020/2021. Error bars are SEM of final harvest.

Futura 75 produced 9.12 t DM/ha (±0.584) of stem. This was 17.7% greater (P=0.001) than Ferimon and Kompolti which had a mean stem yield of 7.03 t DM/ha. SD1 had higher (P<0.001) stem yield than SD2, which again had a higher (P<0.001) stem yield than SD3 (Table 3).

Futura 75 leaf yield was higher (P<0.001) than Ferimon and Kompolti. SD3 produced or maintained more leaf DM (P=0.002) at the final harvest than SD1 (Table 4).

Flower yield had an interaction (P=0.002) between sowing date and cultivar due to Ferimon flower production being higher than Kompolti and Futura 75 at SD1 and SD3 but not SD2. Also Futura 75 and Kompolti produced similar flower DM at SD1 and SD2 but not SD3 (Table 5). All cultivars produced greatest flower yield at SD3. SD1 and SD2 had no differences within each cultivar. Ferimon SD1 and SD2, Futura 75 SD2 and Kompolti SD3 all yielded the same.

Table 3: Final harvest stem dry matter yield (t DM/ha) of three cultivars of hemp, sown on three dates in Canterbury, New Zealand.

Cultivar	SD1 22/10/20	SD2 11/11/20	SD39/12/20	Mean
Ferimon	8.55	6.08	5.08	6.57 (b)
Kompolti	8.39	8.17	5.88	7.48 (b)
Futura 75	9.85	9.42	8.10	9.12 (a)
Mean	8.93 (a)	7.89 (b)	6.35 (c)	7.72
	P value	**SEM**	**LSD**	
Sowing date	<0.001	0.172	0.594	
Cultivar	0.001	0.413	1.23	
Interaction	0.483	0.608	1.79	

Note: means within columns or rows followed by the same letter do not differ (LSD 0.05).

Table 4: Final harvest leaf dry matter yield (t DM/ha) of three cultivars of hemp, sown on three dates in Canterbury, New Zealand.

Cultivar	SD1 22/10/20	SD2 11/11/20	SD39/12/20	Mean
Ferimon	1.20	1.02	1.95	1.39 (b)
Kompolti	1.44	1.61	1.75	1.60 (b)
Futura 75	1.88	1.98	2.42	2.09 (a)
Mean	1.51 (b)	1.53 (b)	2.04 (a)	1.69
	P value	**SEM**	**LSD**	
Sowing date	0.002	0.065	0.224	
Cultivar	<0.001	0.103	0.305	
Interaction	0.316	0.159	0.465	

Note: means within columns or rows followed by the same letter do not differ (LSD 0.05).

Table 5: Final harvest flower dry matter yield (t DM/ha) of three cultivars of hemp, sown on three dates in Canterbury, New Zealand.

Cultivar	SD1 22/10/20	SD2 11/11/20	SD39/12/20	Mean
Ferimon	1.82 c	1.77 c	4.14 a	2.57
Kompolti	1.11 d	1.02 d	1.78 c	1.30
Futura 75	0.85 d	1.40 cd	2.57 b	1.61
Mean	1.25	1.41	2.83	1.83
	P value	**SEM**	**LSD**	
Sowing date	<0.001	0.132	0.458	
Cultivar	<0.001	0.113	0.334	
Interaction	0.002	0.207	0.609	

Note: means within columns or rows followed by the same letter do not differ (LSD 0.05).

Discussion

At the final harvest there was no difference in biomass accumulation across all sowing dates and cultivars. This suggests that the crops could be sown on a range of dates and produce a consistent total biomass yield. However, the sowing date did affect yield components of the hemp crops. Stem yields were greater in earlier sown crops while later sown crops had less stem production and a greater contribution of flowers. In SD3 biomass was partitioned to the reproductive components earlier. The yields and timing of maximum yields indicate differences among cultivars. The proportion of leaf and stem in total yield followed the same temporal pattern across SD1 and SD2 and was consistent with those reported by Mediavilla *et al*. (2001) and van der Werf (1994). SD3 was following a similar growth curve but was harvested before it had time to reach maturity (Figure 3, Figure 4, Figure 5).

Futura 75 had the highest average final total DM yield across sowing dates (Table 2), made up of stem and leaf components, and a higher flower yield than Kompolti at SD3 (Table 5). This may have been influenced by the high degree of heterogeneity within Kompolti (van der Werf *et al*., 1995), partially caused by sexual dimorphism. This was the only dioecious cultivar, which other studies have found to have higher growth rates than monoecious cultivars (van der Werf and van den Berg, 1995). The lighter male plants had begun to senesce and die in the Kompolti plots by the final harvest, which was reflected in the reduction in mean total DM. Amaducci *et al*. (2008b) also found dioecious cultivars had lower stem yields than monoecious although this result was not repeated by Cosentino *et al*. (2013) in a warm, semi-arid environment. Equally, Struik *et al*. (2000) found Kompolti yielded higher than Futura 75 in both the Netherlands and the UK, both of which are at a higher latitude than this experiment. Mediavilla *et al*. (2001) observed that Kompolti lost 2 t DM/ha of stem yield between the end of male flowering and female seed maturity. This is consistent with the early peak between the last and second to last harvests of Kompolti and also Ferimon SD2 (Figures 4b and 3b). Under local conditions Futura 75 appears to be the most appropriate of the three cultivars for fibre production due to it having the highest stem yield across all three sowing dates. Futura 75 may also have the potential to continue to produce stem DM after the final harvest at SD2 and SD3. In these treatments there was no peak at the penultimate harvest and a larger leaf DM at the final harvest which suggests there was still potential to continue light interception and therefore increase yield. Thus further investigation of canopy architecture and consequent light interception throughout the season would provide valuable information to compare the cultivars.

The consistency of growth rates of each cultivar during the linear phase allows the optimisation of harvest times across cultivars. Differences were observed in the duration of this phase, with SD1 having a longer linear growth phase than other sowing dates. This indicates a possible temperature effect due to differences in average temperatures experienced by the crops among the sowing dates. A thermal time analysis is expected to explain this difference, owing to the potentially colder days experienced by SD1 during this period.

Mean stem biomass represented the largest portion of total biomass. Total and component dry matter at the final harvest were not different for Ferimon and Kompolti across sowing dates, with the exception of flower dry matter in SD3 (Tables 2, 3, 4 and

5). A reduction in stem weight of Kompolti SD1 was observed between 84 DAS and final harvest (Figure 4a), probably due to the onset of senescence in male plants. This suggests it may be appropriate to harvest Kompolti earlier than Ferimon when maximum stem yield is the aim. Ferimon also had a greater flower yield than the other cultivars, which is typical of the earlier flowering cultivars referred to by Cosentino *et al*. (2013).

In SD3 all plants were reproductive earlier (in fewer days after sowing) than for SD1 and SD2. This means plants from SD3 were remobilising energy away from stem growth and into flower and seed production after fewer days. The results were higher flower and lower stem yields than from the earlier sowing dates. These results are consistent with hemp having a critical photoperiod requirement of ~14 hours. At longer photoperiods flowering was inhibited. This has been shown for a range of cultivars including Futura 75 and Kompolti (Amaducci *et al*., 2008a; Cosentino *et al*., 2012; Lisson *et al*., 2000). However, the current results suggest a potential difference in photoperiod requirements, and/or the strength of this requirement. Kompolti, SD3, had a final stem yield of 5.88 t DM/ha compared with 8.10 t DM/ha for Futura 75. This is a larger difference than what was observed in SD1 and SD2. If Kompolti had a facultative photoperiod influence, at the same daylength of ~14 hours, the cultivar would flower earlier if its thermal time requirement was satisfied, when compared with other cultivars with a more obligate response. This would also apply for Ferimon, for which no pervious photoperiod data were found. It is reported to be early flowering (Cosentino *et al*., 2013). However, this could be a result of a higher base photoperiod or a more facultative response than for Kompolti and Futura 75.

The measured stem yields were lower than those reported previously. Westerhuis *et al*. (2009) measured a stem DM yield of 6.8-11.7 t DM/ha (±0.66) for Futura 75. Amaducci *et al*. (2008b) recorded a similar stem yield, with a mean of 11.9 t DM/ha (±0.08) for Futura 75. Our result was 2.5 t DM/ha lower than these with the highest stem yield from Futura 75 (SD2) of 9.42 t DM/ha (±0.584). Previous experiments were in Bologna, Italy at about the same latitude (44°49'N vs 43°52'S) but the mean growing season temperatures in Bologna are 17-28 °C compared with 13.4-17.4 °C for Canterbury. According to Tang *et al*. (2017a) the optimum temperature for photosynthesis of hemp (Futura 75) is 25-35 °C. Meaning, the average temperatures for this experiment were below the optimum (Figure 2). The implication is that the lower yields in Canterbury reflect a lower rate of photosynthesis.

The current experiment also had a lower plant population of 30-90 plants/m^2 compared with 120-360 plants/m^2 in Bologna. The higher plant population may allow earlier canopy closure and therefore more light interception and higher yields. A higher plant population may be worth investigating for the cooler Canterbury climate, particularly for earlier sowing. Higher planting densities have been shown to increase stem (Tang *et al*., 2017b) and total biomass (Swanepoel *et al*., 2018) yields. However the results are currently inconsistent (Westerhuis *et al*., 2009) but suggests an area for further work.

The weather pattern in the season reported differed from the historical trend (Figure 2). A drier than average October and February were amended with irrigation and would have otherwise caused yield losses. The drop below 50% field capacity (Figure 1) came before the rainfall event that resulted in a wetter than usual December. This illustrates the extent of irrigation required to keep the crop irrigated at non limiting soil moisture levels.

This experiment indicates farmers growing a hemp fibre crop should sow it as early as possible in frost free conditions. This should allow maximum leaf and stem growth before the plant goes reproductive. Futura 75 consistently had the highest stem yields and therefore was considered the most appropriate of the three cultivars tested for fibre production. It was also the most uniform due to it being monoecious. Kompolti, because of the presence of male plants, could suit high quality fibre production, however more research and well-defined fibre quality parameters are required before it can be recommended. Both Ferimon and Kompolti stem yields were more negatively affected by later sowing dates than Futura 75, which indicates Futura 75 offers a wider range of potential sowing dates.

Conclusion

These data suggest that Futura 75 would be the preferred cultivar for maximum stem yields, compared with Ferimon and Kompolti, particularly at later sowing dates. The potential role of selecting an optimum harvest date and understanding the effect this has on dioecious plants should be further investigated. The critical photoperiod for flowering of hemp is important in determining the components of yield and should be accounted for when choosing cultivars and sowing dates. When crops are grown for a fixed number of days, earlier sowing dates will give higher stem yields, while a later sowing will allow for greater flower yields. Earlier sowing dates will also provide a longer 'harvest window' facilitating the harvest schedule. A sigmoid growth curve with a clear lag phase at the start, followed by a linear growth phase, ending with a maximum yield was shown before senescence for some treatments, particularly for SD1 and SD2. SD3 had not finished growing by the final harvest on 15/03/2021, so future research should investigate the true yield potential of this later sowing date.

Acknowledgements

This research was conducted by Lincoln University with funding from Carrfields Ltd., Callaghan Innovation. We thank Jason Nolan who supported the field experiment and Dr Annamaria Mills, Lincoln University, for statistical advice.

References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome* 300, D05109.

Amaducci, S., Colauzzi, M., Bellocchi, G. and Venturi, G. 2008a. Modelling post-emergent hemp phenology (*Cannabis sativa* L.): Theory and evaluation. *European Journal of Agronomy* 28: 90-102.

Amaducci, S., Errani, M. and Venturi, G. 2002. Plant Population Effects on Fibre Hemp Morphology and Production. *Journal of Industrial Hemp* 7: 33-60.

Amaducci, S., Scordia, D., Liu, F.H., Zhang, Q., Guo, H., Testa, G, and Cosentino, S.L. 2015. Key cultivation techniques for hemp in Europe and China. *Industrial Crops and Products* 68: 2-16.

Amaducci, S., Zatta, A., Pelatti, F. and Venturi, G. 2008b. Influence of agronomic factors on yield and quality of hemp (*Cannabis sativa* L.) fibre and implication for an innovative production system. *Field Crops Research* 107: 161-169.

Aubin, M.P., Seguin, P., Vanasse, A., Lalonde, O., Tremblay, G.F., Mustafa, A. F. and Charron, J.B. 2016. Evaluation of Eleven Industrial Hemp Cultivars Grown in Eastern Canada. *Agronomy Journal* 108: 1972-1980.

Austin, R.B., Ford, M.A. and Morgan, C. L. 1989. Genetic improvement in the yield of winter wheat: a further evaluation. *The Journal of Agricultural Science* 112: 295-301.

Cosentino, S.L., Riggi, E., Testa, G., Scordia, D. and Copani, V. 2013. Evaluation of European developed fibre hemp genotypes (*Cannabis sativa* L.) in semi-arid Mediterranean environment. *Industrial Crops and Products* 50: 312-324.

Cosentino, S.L., Testa, G., Scordia, D. and Copani, V. 2012. Sowing time and prediction of flowering of different hemp (*Cannabis sativa* L.) genotypes in southern Europe. *Industrial Crops and Products* 37: 20-33.

Finnan, J. and Burke, B. 2013. Nitrogen fertilization to optimize the greenhouse gas balance of hemp crops grown for biomass. *Global Change Biology Bioenergy* 5: 701-712.

Horkay, E.aI B. 1996. Objective basis for evaluation of differences in fibre quality between male, female and monoecious hemp. *Journal of the International Hemp Association* 3: 67-68.

Kerckhoffs, L., O'Neill, S., Barge, R. and Kawana-Brown, E. 2017. Plant density effects on yield parameters of three industrial hemp cultivars in the Manawatu. *Agronomy New Zealand* 47: 47-54.

Lisson, S.N., Mendham, N.J. and Carberry, P.S. 2000. Development of a hemp (*Cannabis sativa* L.) simulation model 2.The flowering response of two hemp cultivars to photoperiod. *Australian Journal of Experimental Agriculture* 40: 413-417.

Manaaki Whenua. 2015. "Templeton_35a.1 Soil Report."

Marsh, N. 2020. "NZ HEMP EXPORT DRIVEN INVESTOR REPORT." New Zealand Hemp Industries Association.

McNeill, S.J., Lilburne, L.R., Carrick, S., Webb, T.H. and Cuthill, T. 2018. Pedotransfer functions for the soil water characteristics of New Zealand soils using S-map information. *Geoderma* 326: 96-110.

Mediavilla, V., Leupin, M. and Keller, A. 2001. Influence of the growth stage of industrial hemp on the yield formation in relation to certain fibre quality traits. *Industrial Crops and Products* 13: 49-56.

Medsafe. 2021. Approved Cultivars of Industrial Hemp. Retrived from https://www.health.govt.nz/system/files/documents/pages/approved-cultivars-of-industrial-hemp-oct21.pdf

Meijer, E.P.M. d. 1995. Fibre hemp cultivars: A survey of origin, ancestry, availability and brief agronomic characteristics. *Journal of the International Hemp Association* 2: 66-73.

Meijer, W.J.M., van der Werf, H.M.G., Mathijssen, E.W.J.M. and van den Brink, P.W.M. 1995. Constraints to dry matter production in fibre hemp (*Cannabis sativa* L.). *European Journal of Agronomy* 4: 109-117.

Merfield, C. 1999. Industrial hemp and its potential for New Zealand. Lincoln University. Faculty of Commerce. Kellogg Rural Leaders Programme Lincoln, Canterbury.

Misuse of Drugs (Industrial Hemp) Regulations 2006. (2020 amendment). Retrived from https://legislation.govt.nz/regulation/public/2006/0163/latest/DLM389407.html

Salentijn, E.M.J., Zhang, Q., Amaducci, S., Yang, M. and Trindade, L.M. 2015. New developments in fiber hemp (*Cannabis sativa* L.) breeding. *Industrial Crops and Products* 68: 32-41.

Schäfer, T. 2005. The Influence of Growing Factors and Plant Cultivation Methods on Biomass and Fibre Yield as Well as on Fibre Quality of Hemp (*Cannabis sativa* L.). *Journal of Natural Fibers* 2: 1-14.

Struik, P.C., Amaducci, S., Bullard, M.J., Stutterheim, N.C., Venturi, G. and Cromack, H.T.H. 2000. Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe. *Industrial Crops and Products* 11: 107-118.

Swanepoel, Q.M., Barge, R., Kawana-Brown, E. and Kerckhoffs, L.H.J. 2018. Impact of varying plant densities on two industrial hemp cultivars grown in the Manawatu. *Agronomy New Zealand* 48: 125-135.

Tang, K., Struik, P.C., Amaducci, S., Stomph, T.J. and Yin, X. 2017a. Hemp (*Cannabis sativa* L.) leaf photosynthesis in relation to nitrogen content and temperature: implications for hemp as a bio-economically sustainable crop. *GCB Bioenergy* 9: 1573-1587.

Tang, K., Struik, P.C., Yin, X., Calzolari, D., Musio, S., Thouminot, C., Bjelková, M., Stramkale, V., Magagnini, G. and Amaducci, S. 2017b. A comprehensive study of planting density and nitrogen fertilization effect on dual-purpose hemp (*Cannabis sativa* L.) cultivation. *Industrial Crops and Products* 107: 427-438.

van der Werf, H.M.G. 1994. Crop physiology of fibre hemp (Cannabis sativa L.). WUR.

van der Werf, H.M.G. and van den Berg, W. 1995. Nitrogen fertilization and sex expression affect size variability of fibre hemp (*Cannabis sativa* L.). *Oecologia* 103: 462-470.

van der Werf, H.M.G., Wijlhuizen, M. and de Schutter, J.A.A. 1995. Plant density and self-thinning affect yield and quality of fibre hemp (*Cannabis sativa* L.). *Field Crops Research* 40: 153-164.

Vandepitte, K., Vasile, S., Vermeire, S., Vanderhoeven, M., Van der Borght, W., Latré, J., De Raeve, A. and Troch, V. 2020. Hemp (Cannabis sativa L.) for high-value textile applications: The effective long fiber yield and quality of different hemp varieties, processed using industrial flax equipment. *Industrial Crops and Products* 158: 112969.

Vera, C.L., Malhi, S.S., Phelps, S.M., May, W.E. and Johnson, E.N. 2010. N, P, and S fertilization effects on industrial hemp in Saskatchewan. *Canadian Journal of Plant Science* 90: 179-184.

Weserhuis, W. 2016. Hemp for testiles: plant size matters, Wageningen University.

Westerhuis, W., Amaducci, S., Struik, P.C., Zatta, A., Van Dam, J.E.G. and Stomph, T.J. 2009. Sowing density and harvest time affect fibre content in hemp (*Cannabis sativa*) through their effects on stem weight. *Annals of Applied Biology* 155: 225-244.

Yang, X. 1991. History of cultivation on hemp, sesame and flax. *Agric. Archaeol* 3: 267-274.
Zatta, A., Monti, A. and Venturi, G. 2012. Eighty Years of Studies on Industrial Hemp in the Po Valley (1930--2010). *Journal of Natural Fibers* 9: 180-196.