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Response of forage maize yield and quality to mulch film and harvest time in Northern Europe

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Forage maize (*Zea mays* L.) yield and nutritional quality fluctuate markedly in Northern Europe due to weather conditions. A field experiment was conducted in Southern Finland (Helsinki, 2018–2020) and in Central Finland (Maaninka, Kuopio, 2019–2020) to study the effect of harvest time and use of mulch film, in order to optimize the dry matter (DM) yield and quality. Treatments included oxo-biodegradable mulch film and no mulch, and three harvest times (the latter only in Helsinki). Mulch film increased DM yield on average by 2.3 Mg ha^{-1} in Helsinki and by 3.8 Mg ha^{-1} in Maaninka. Mulch film had a minor effect on the quality, and overall, the quality improved, although DM yield accumulation had already ceased. Nevertheless, the starch contents fluctuated and remained mostly below the target rate – 300 g kg^{-1} DM – especially in Central Finland. The results indicate that mulch film improves forage maize yield, but a late harvest is still required to improve forage quality. However, climate conditions still restrict starch accumulation to ears in Northern European climate conditions, especially in the important milk production area in Central Finland.

Key words: forage production, silage maize, *Zea mays* L., feed quality, mulching, forage harvest

Introduction

Forage maize (*Zea mays* L.) cultivation area has increased markedly in Finland in the 2000s and 2010s (Luke 2022). However, the cultivation of forage maize in Finland remains marginal due to limiting factors, namely frosts in the early growing season, the relatively short growing period, and the low effective temperature sum (Pulli et al. 1976, Struik 1983, Hetta et al. 2012). In the future, climate change will result in a longer growing season with a higher mean temperature in Northern Europe, including Finland (Peltonen-Sainio et al. 2009, Bindi and Olesen 2011). Hence, maize cultivation is expected to expand (Elsgaard et al. 2012) and the yield of forage maize is expected to increase (Olesen and Bindi 2002) in Northern Europe.

The yield of forage and bioenergy maize harvested in Finland has fluctuated from 6 to 30 Mg dry matter (DM) ha^{-1}, depending mainly on the weather conditions and maize cultivars (Pulli et al. 1979, Kara and Pulli 1981, Seppälä et al. 2012, Huuskonen et al. 2014, Epie et al. 2018, Liimatainen et al. 2022). Starch content – typically the most important forage maize quality trait – has also varied markedly, and has remained rather low in comparison to the forage starch target of 300 g kg^{-1} DM (Phipps et al. 2000) as documented in previous Finnish studies (Seleiman et al. 2013, Liimatainen et al. 2022).

One method to improve forage maize yield and quality is the use of mulch film. Mulch films are made of synthetic or natural materials, and are either non-degradable, photo-, bio- or oxo(-bio)degradable (Kasirajan and Ngouajio 2012, Markowicz and Szymánska-Pulikowska 2019, Serrano-Ruiz et al. 2021). The mulch film increases soil temperature and moisture content during the early growing season (Easson and Fearnehough 2000, Keane et al. 2003). Other benefits of mulch film include, e.g., protecting plants from chilling during the early growing season (Keane et al. 2003), reduced weed pressure (Kwabiah 2004, Tofanelli and Wortman 2020), and diminished erosion risk (Tofanelli and Wortman 2020). The use of mulch film has been shown to increase forage maize DM yield and starch content in Western Europe (van der Werf 1993, Easson and Fearnehough 2000, Keane et al. 2003, Farrell and Gilliland 2011). Nevertheless, the use of mulch film has not been studied in Northern Europe, where climate conditions for forage maize cultivation are more marginal in comparison to Western Europe.

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Agricultural and Food Science (2023) 32: xx–xx
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Another method to improve forage maize yield and animal nutritional quality is the optimisation of the harvest time, i.e., ear developmental stage at harvest (Hetta et al. 2012, Lynch et al. 2012, Lynch et al. 2013). Traditionally in Finland, the recommended harvest time for forage maize is as late as possible, while still soon after the first night frosts. However, recent advances in plant breeding have enabled the availability of early-maturing maize cultivars in the European market (Mussadiq 2012), which could potentially enable an earlier harvest of forage maize in comparison to the traditional recommendation in Finland. Notably, the use of mulch film typically advances ear maturation (Kwabiah 2003, Farrell and Gilliland 2011), which could enhance earlier forage maize harvest or cultivation of forage maize at even higher latitudes. Despite its benefits, the use of mulch film on forage maize cultivation remains unexplored in Northern European climate conditions.

The aim of this study was to examine whether mulch film and harvest time affect the forage maize yield and quality in Northern European climate conditions. This study further aimed to investigate whether mulch film could promote earlier attainment of high DM yield and target quality in forage maize.

Materials and methods

Experimental site and plant material

Field experiments were conducted in 2018, 2019, and 2020 at Viikki Research Farm (60° 13´ N, 24° 02´ E; 8 m asl) of the University of Helsinki, Helsinki, Finland, and in 2019 and 2020 at Maaninka Research Station (63° 09´ N, 27° 18´ E; 90 m asl) of the Natural Resources Institute Finland, Maaninka, Kuopio, Finland. Field experiments conducted in Helsinki (2019 and 2020) and Maaninka (2019 and 2020) are described in more detail in Liimatainen et al. (2022). The soils at Viikki Research Farm are typically Luvic Gleysols and Luvic Stagnosols while soils at Maaninka Research Station are Dystric Regosols (IUSS Working Group WRB 2015). Samples of topsoil (0–25 cm) were collected before sowing and analysed to determine topsoil fertility (Appendix Table A1).

Table 1. Fertilizer application rates and fertilizer products used in forage maize field experiments in Helsinki (2018–2020) and Maaninka (2019–2020)

	Helsinki			Maaninka	
	2018	2019	2020	2019	2020
Nitrogen, N kg ha^{-1}	170[1, 2]	150[2, 3]	150[2, 3]	150[1]	150[6]
Phosphorus, P kg ha^{-1}	20[2]	20[2]	20[2]	0	0
Potassium, K kg ha^{-1}	170[1, 4]	170[4]	150[5]	6[1]	82[6]

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Plots were fertilized before sowing with nitrogen (N), phosphorus (P) and potassium (K) (Table 1). In Helsinki, pendimethalin was sprayed at sowing (Appendix Table A2). Maize, cv. P7326 (FAO 180; Pioneer Hi-Bred International, Johnston, IA, USA) was used in the experiments, as it is currently the most common forage maize cultivar grown in Finland. Seeds were sown 5 cm deep with an average sowing density of 90 000 seeds ha^{-1} either under mulch film (Oxo-Biodegradable Clear Mulch Film, Samco Agricultural Manufacturing, Limerick, Ireland) or without mulch (Table 2). The approximate time when plants broke through the mulch film was 3–4 weeks after sowing.

Plots consisted of four rows with a total size of 30 m^2 in Helsinki and 15 m^2 in Maaninka. The field experiments were arranged in a randomized complete block design (RCBD) with four replicates. The total number of plots per study year was 24 in Helsinki and 8 in Maaninka. The three harvest times (only in Helsinki) were considered as blocks, within which the mulch treatments were placed. In Helsinki, herbicides were applied on the plant stand 1–2 times after sowing (Appendix Table A2). In Maaninka, weeding was done by hand and no herbicides were applied.

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

Table 2. Dates of sowing and harvest times of the forage maize experiments and accumulated effective temperature sums at harvest in Helsinki (2018–2020) and Maaninka (2019–2020)

Location			2018	2019	2020
Helsinki	Sowing	Date	21 May	17 May	26 May
	First harvest time	Date	21 Aug	26 Aug	1 Sep
		DAS	92	101	98
		TSUM	779	713	703
	Second harvest time	Date	25 Sep	17 Sep	22 Sep
		DAS	127	123	119
		TSUM	975	844	789
	Third harvest time	Date	10 Oct	8 Oct	14 Oct
		DAS	142	144	141
		TSUM	990	861	857
Maaninka	Sowing	Date	–	16 May	28 May
	Harvest	Date	–	3 Oct	15 Oct
		DAS	–	140	140
		TSUM	–	668	709

DAS = days after sowing; TSUM = effective temperature sum accumulation (°Cd) between sowing and harvest dates, base temperature +10 °C

Weather conditions

The effective temperature sum (°Cd) for maize was calculated with a +10 °C base temperature as described in Liimatainen et al. (2022). The accumulated effective temperature sum between sowing and harvest dates is presented for each of the different harvest times in Table 2.

The weather in Helsinki was warm and dry in 2018, with monthly mean temperatures above and precipitation below the long-term average (Table 3). In 2019 and 2020, the mean temperatures and precipitation sums were parallel and slightly above the long-term average. However, the precipitation was unevenly distributed in 2019, as June was dry and September–October was relatively wet. In Maaninka, the growing season in 2019 was cooler and drier than the growing season in 2020.

Table 3. Dates of the first night frost, monthly mean temperatures and monthly precipitation sums during the growing seasons of 2018, 2019, and 2020, and the long-term average (1991–2020) in Kaisaniemi (60°18’N, 24°94’E; 3 m asl), Helsinki, and in Maaninka (63°14’N, 27°31’E; 91 m asl), Kuopio (FMI 2022)

		Helsinki				Maaninka		
		2018	2019	2020	1991–2020	2019	2020	1991–2020
First night frost, date		8 Oct	5 Oct	11 Nov	–	17 Sep	15 Oct	–
Temperature, °C	May	14.5	10.3	9.6	10.4	8.6	7.8	9.1
	June	15.3	17.3	17.9	14.9	16.1	18.0	14.4
	July	21.1	17.5	16.7	18.1	15.2	15.8	17.1
	August	18.6	17.3	17.1	16.9	15.1	15.4	15.1
	September	13.9	12.2	13.8	12.3	9.6	11.0	10.0
	October	7.7	6.2	9.3	6.6	2.7	6.3	3.9
Precipitation, mm	May	8	62	53	38	66	32	49
	June	40	16	75	60	39	76	71
	July	44	73	83	57	14	76	85
	August	52	82	77	81	41	36	66
	September	68	77	55	56	44	122	55
	October	40	102	64	73	80	92	55

First night frost = Daily minimum temperature below 0 °C at the end of the growing season

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

The first night frosts in the late growing season occurred before the last harvest time in Helsinki in 2018 and 2019 (Table 3). In 2020 in Helsinki, September–October was relatively warm, and the last harvest was conducted before the first night frost. In Maaninka, the first night frost occurred before the harvest in 2019, while in 2020, the first night frost was recorded on the harvest day.

Plant sampling, sample preparation and measurements

In Helsinki, plants were harvested at three different times within a growing season based on the different ear maturation stages and DM contents (Table 2). In Maaninka, all plants were harvested at the same time (Table 2). Before the harvest, plants from 1 m of either of the inner rows were cut, weighed, and measured for plant height, ear proportion of yield, and ear DM content (described in detail in Liimatainen et al. [2022]). The ear DM content was not determined in 2018. Ears were photographed and the ear developmental stage was evaluated based on R stages (Brown 2017). After plant sampling, two middle rows of the plots were harvested at approximately 15 cm height. Harvesting in Helsinki was performed using a mechanical chopper with a chop length of 0.5–1 cm (JF FH 1300, Kongskilde Agriculture, Albertslund, Denmark), while in Maaninka a hand sickle was used and then plants were further chopped with a laboratory chopper with a chop length of 0.5–1 cm. The harvested fresh yield was weighed, and a subsample of 3 kg was taken. Samples were stored at 5 °C for a maximum of 1–2 days until further analysis.

Approximately 200 g of chopped maize yield was dried for 48 h at 100 °C in Helsinki, or for 3–4 days at 50 °C in Maaninka, and weighed to determine the DM content of the plant mass. Dry matter yield (DM Mg ha^{-1}) was calculated as (fresh yield [Mg ha^{-1}] + biomass of the plant sample from 1 m [Mg ha^{-1}]) × DM content (g kg^{-1}) / 1000. In Helsinki, an additional sample of 200 g of chopped mass was dried first for 1 h at 103 °C to avoid microbial growth, and then for 48 h at 50 °C. The samples from Helsinki and Maaninka dried at 50 °C were ground (Sako-mylly KT-3100, Koneteollisuus, Helsinki, Finland) into a fine powder (1 mm mesh size) and stored at room temperature for further analysis.

Forage quality analyses

Starch content was analysed from a ground forage maize sample (100 mg) with a commercial assay kit (Total Starch Assay Kit (AA/AMG), Megazyme, Wicklow, Ireland) according to Hall (2009) and the protocol supplied by the manufacturer, by using a spectrophotometer (Shimadzu UV-1800, Shimadzu, Kyoto, Japan). Water-soluble carbohydrate (WSC) content was determined spectrophotometrically according to Somogyi (1945). The N content of the yield was determined from a ground forage maize sample (200 mg) with the Dumas combustion method (Ebeling 1968) using a C/N analyser (FP828, LECO, St. Joseph, MI, USA). The N content was multiplied with a protein ratio of 6.25 to obtain the crude protein (CP) content of the yield. Neutral detergent fibre (NDF) content was analysed from a ground forage maize sample (100 mg) using an NDF analyser (in Helsinki: Fibretherm FT 12, Gerhardt, Königswinter, Germany; in Maaninka: Heraeus Thermicon T, Heraeus, Hanau, Germany) according to van Soest et al. (1991) with α-amylase and sodium-sulfate. The NDF was expressed without residual ash.

Statistical analyses

Statistical analyses were conducted with the SAS 9.4 (SAS/STAT Software, SAS Institute, Cary, NC, USA) using the MIXED procedure. Analysis of variance (ANOVA) was done separately for Helsinki and Maaninka. Two replicates of both mulch treatments were excluded from the statistical analysis of forage quality at the third harvest time in Helsinki in 2018 due to analysis failure. One replicate of mulch film treatment was excluded from all statistical analyses in Helsinki in 2020 due to the unauthorised picking of ears by the public from some of the plots. Also, outliers with a standard deviation of residual exceeding ±3 × residual mean were excluded from the analysis.

For the results from Helsinki (2018–2020), the ANOVA model included mulch treatment, harvest time, year, and their interactions (mulch × harvest time, mulch × year, harvest time × year, mulch × harvest time × year) as fixed factors. The random factor in the ANOVA model was replication within a year. In Maaninka, the ANOVA model included mulch treatment, year, and their interaction as fixed factors, and replication within a year as a random factor. The level of significance used in the ANOVA was $p < 0.05$. Pairwise comparisons were done according to the significant interactions. Pairwise comparisons were conducted using Tukey-Kramer's adjustment for multiple comparisons. Fisher's exact test was used to test differences in ear developmental stages between two mulch treatments for data from Helsinki, but not for data from Maaninka due to small frequencies. The highest standard errors of the mean (SEM) are presented for the results with variable annual sample sizes.

AGRICULTURAL AND FOOD SCIENCE
Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

Results

For forage maize DM yield, no significant interactions between mulch, harvest time or year were recorded in Helsinki (Fig. 1). Maize grown with mulch film produced a higher DM yield than crops grown without mulch (15.0 vs. 12.7 Mg ha^{-1}; $p < 0.001$). The DM yield increased between the first and second harvest times from 11.8 to 14.7 Mg ha^{-1} ($p < 0.001$), but not between the second and third harvest times. The DM yields recorded in Helsinki were lower in 2018 (11.8 Mg ha^{-1}) than in 2019 or 2020 (both 15.3 Mg ha^{-1}; $p < 0.001$). In Maaninka, no interaction between mulch and year was observed. The use of mulch film resulted in a higher DM yield (16.0 vs. 12.2 Mg ha^{-1}; $p = 0.007$; Fig. 2). Additionally, the DM yields recorded in Maaninka were higher in 2020 than in 2019 (17.2 vs. 11.0 Mg ha^{-1}; $p = 0.001$).

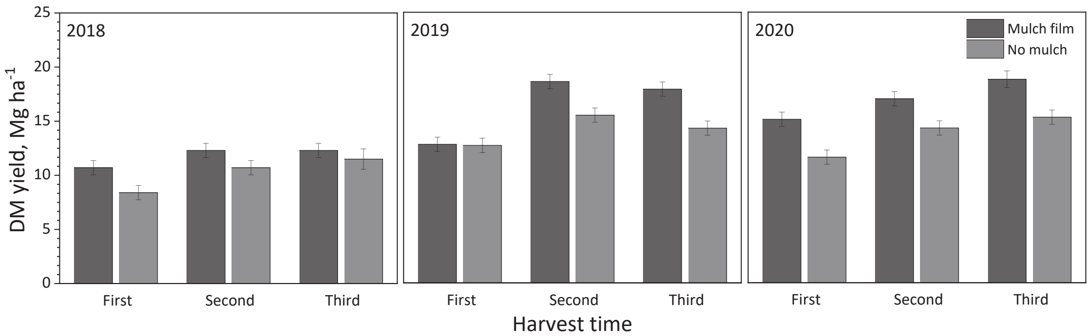

Fig. 1. Whole crop dry matter (DM) yield of forage maize with mulch film (darker bars) or without mulch (lighter bars) harvested at three different times in Helsinki (2018–2020). Data shown are means ± standard error of the mean.

A significant interaction between mulch, harvest time, and year in Helsinki (Table 4) indicated that the effect of mulch film on DM content differed between years and harvest times. In 2019, the use of mulch film increased DM content only at the third harvest time, whereas in 2018, the increase was observed at the first two harvest times, and in 2020 on all harvest times. The observed increase in the DM content due to mulch film use varied from 16 to 43 g kg^{-1} DM. The DM content increased between the first and third harvest times, approximately from 200 to 300 g kg^{-1} (Table 4). However, in 2018, the DM content of mulch film treatment did not increase after the second harvest time, hence underscoring the interaction between mulch, harvest time, and year. The DM contents recorded in Helsinki were lower in 2020 than in 2018 ($p < 0.001$) and 2019 ($p < 0.001$). In Maaninka, the DM content was not affected by mulch, but the DM contents recorded were lower in 2019 than in 2020 (Table 5).

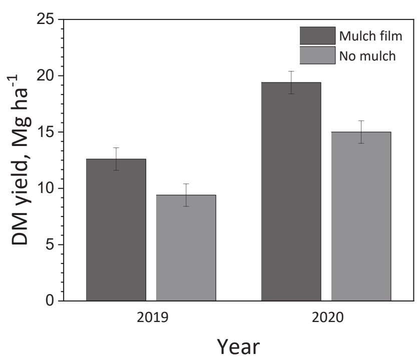

Fig. 2. Whole crop dry matter (DM) yield of forage maize with mulch film (darker bars) or without mulch (lighter bars) in Maaninka (2019–2020). Data shown are means ± standard error of the mean.

The use of mulch film increased the starch content significantly, at the first harvest time by 27 g kg^{-1} DM and at the second harvest time by 61 g kg^{-1} DM, as indicated by the interaction between mulch and harvest time in Helsinki (Table 4). However, the mulch film did not affect the starch content in 2019, as indicated by the interaction between mulch and year. The starch content increased constantly between the first, second, and third harvest

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

times, but the magnitude of increase between the harvest times varied within the years. Annual differences in starch content were observed, as the starch contents were higher in 2018 than in 2020 (p < 0.001) and 2019 (p < 0.001), and also higher in 2019 than in 2020 (p < 0.001).

Forage WSC content decreased following the use of mulch film by 27 g kg^{-1} DM in Helsinki (Table 4). Additionally, the WSC content decreased until the last harvest time. However, the magnitude of decrease in the WSC content varied between the years, as indicated by the interaction between harvest time and year. Overall, the WSC contents recorded were higher in 2020 than in 2019.

Table 4. Quality of forage maize with mulch film or without mulch harvested at three different times in Helsinki (2018–2020). Data shown are means.

		DM content		Starch		WSC		CP		NDF	
		g kg^{-1}		g kg^{-1} DM							
Year	Harvest time	Mulch film	No mulch	Mulch film	No mulch	Mulch film	No mulch	Mulch film	No mulch	Mulch film	No mulch
2018	First	210^{Ab}	194^{Aa}	70^{Ab}	35^{Aa}	ND	ND	101^{B}	104^{B}	487^{Ca}	467^{Cb}
	Second	329^{Bb}	284^{Ba}	245^{Bb}	168^{Ba}	ND	ND	76^{A}	82^{A}	383^{Aa}	405^{Ab}
	Third	319^{B}	312^{C}	303^{C}	272^{C}	ND	ND	84^{AB}	86^{AB}	419^{Ba}	440^{Bb}
2019	First	212^{A}	207^{A}	41^{A}	14^{A}	216^{Ca}	242^{Cb}	81	80	481^{Ba}	491^{Bb}
	Second	273^{B}	263^{B}	201^{B}	173^{B}	106^{Ba}	136^{Bb}	74	73	407^{Aa}	431^{Ab}
	Third	351^{Cb}	325^{Ca}	220^{C}	236^{C}	33^{Aa}	57^{Ab}	77	77	471^{Ba}	463^{Bb}
2020	First	191^{Ab}	171^{Aa}	24^{Ab}	5^{Aa}	257^{Ca}	265^{Cb}	58	65	511^{Ba}	535^{Bb}
	Second	227^{Bb}	203^{Ba}	116^{Bb}	38^{Ba}	166^{Ba}	216^{Bb}	56	61	481^{Aa}	504^{Ab}
	Third	274^{Cb}	243^{Ca}	201^{C}	145^{C}	98^{Aa}	122^{Ab}	53	61	474^{Aa}	475^{Ab}
p-value (SEM)	Mulch (M)	<0.001 (1.8)		<0.001 (4.0)		<0.001 (12.6)		0.003 (1.1)		0.016 (3.1)	
	Harvest time (H)	<0.001 (2.2)		<0.001 (5.0)		<0.001 (12.6)		<0.001 (1.3)		<0.001 (4.1)	
	Year (Y)	<0.001 (2.5)		<0.001 (4.3)		0.001 (12.6)		<0.001 (1.8)		<0.001 (4.3)	
	M × H	0.146 (3.1)		0.004 (7.3)		0.958 (12.6)		0.010 (1.6)		0.688 (5.9)	
	M × Y	0.078 (3.3)		0.005 (6.8)		0.226 (12.6)		0.998 (2.1)		0.123 (6.3)	
	H × Y	<0.001 (4.0)		<0.001 (8.5)		0.019 (12.6)		<0.001 (2.6)		<0.001 (8.6)	
	M × H × Y	0.006 (6.0)		0.087 (14.0)		0.403 (12.6)		0.886 (3.3)		0.206 (12.0)	

DM = dry matter; WSC = water soluble carbohydrates; CP = crude protein; NDF = neutral detergent fiber; ND = not determined; SEM = standard error of the mean. Means of harvest times marked with different uppercase letters (A, B, C) differ significantly (p < 0.05) from each other within a year. Means of mulch treatments marked with different lowercase letters (a, b) differ significantly (p < 0.05) from each other within a harvest time and a year.

Forage CP content had a significant interaction between mulch and harvest time in Helsinki, but the pairwise comparison showed no significant differences between the mulch treatments at any harvest time (Table 4). The use of mulch film decreased the NDF content, but only marginally (11 g kg^{-1} DM). Both CP and NDF contents decreased between the first and second harvest times, although the CP content responded to harvest time only in 2018, as indicated by a significant interaction between harvest time and year. The CP contents recorded were higher in 2018 than in 2019 (p = 0.002) and 2020 (p < 0.001), and higher in 2019 than in 2020 (p < 0.001). On the contrary, the NDF contents recorded were higher in 2020 than in 2018 (p < 0.001) and 2019 (p < 0.001), and also higher in 2019 than in 2018 (p < 0.001).

In Maaninka, use of mulch film increased the starch content in 2020 by 67 g kg^{-1} DM, whereas in 2019, no increase was recorded, as indicated by the significant interaction between mulch and year (Table 5). The NDF content was 39 g kg^{-1} DM lower with the use of mulch film. The WSC and CP contents were unaffected by mulch. Annual variance in the quality was recorded in Maaninka; as in 2020, the starch contents were higher and NDF contents were lower than in 2019.

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

Table 5. Quality of forage maize with mulch film or without mulch in Maaninka (2019–2020). Data shown are means.

Year		DM content	Starch	WSC	CP	NDF
		g kg^{-1}	g kg^{-1} DM			
2019	Mulch film	197	24	200	81	531^{a}
	No mulch	187	6	176	83	564^{b}
2020	Mulch film	227	98^{b}	193	88	456^{a}
	No mulch	215	31^{a}	243	86	502^{b}
p-value (SEM)	Mulch (M)	0.060 (3.6)	0.003 (6.5)	0.487 (13.3)	0.905 (2.4)	0.013 (7.9)
	Year (Y)	0.002 (3.9)	0.002 (6.9)	0.178 (14.1)	0.266 (2.7)	<0.001 (7.9)
	M × Y	0.796 (5.1)	0.030 (9.2)	0.077 (18.8)	0.462 (3.5)	0.553 (11.2)

DM = dry matter; WSC = water soluble carbohydrates; CP = crude protein; NDF = neutral detergent fiber; SEM = standard error of the means. Means of mulch treatments marked with different letters (a, b) differ significantly ($p < 0.05$) from each other within a year.

Plant height had a significant interaction between mulch and harvest time in Helsinki, but the plant height did not show a response to mulch treatment at any harvest time in the pairwise comparisons (Table 6). Generally, the plants were taller in 2020 than in 2019 ($p < 0.001$) and 2018 ($p < 0.001$), and also taller in 2019 than in 2018 ($p = 0.037$). In Maaninka, plant height remained unaffected by the use of mulch film, but the plants were clearly taller in 2020 than in 2019 (Table 7).

Table 6. Plant height, ear proportion of dry matter (DM) yield, and ear DM content of forage maize with mulch film or without mulch harvested at three different times in Helsinki (2018–2020). Data shown are means.

Year	Harvest time	Plant height, cm		Ear proportion, % of DM yield		Ear DM content, g kg^{-1}	
		Mulch film	No mulch	Mulch film	No mulch	Mulch film	No mulch
2018	First	263^{B}	261^{B}	26^{A}	24^{A}	ND	ND
	Second	243^{A}	217^{A}	52^{Bb}	48^{Ba}	ND	ND
	Third	239^{A}	200^{A}	60^{C}	53^{C}	ND	ND
2019	First	261	260	23^{A}	25^{A}	204^{A}	181^{A}
	Second	256	258	55^{Bb}	50^{Ba}	414^{B}	390^{B}
	Third	274	264	58^{B}	57^{B}	444^{Cb}	411^{Ba}
2020	First	341	339	22^{A}	12^{A}	204^{Ab}	126^{Aa}
	Second	343	348	44^{Bb}	31^{Ba}	395^{Bb}	281^{Ba}
	Third	341	347	52^{C}	47^{C}	472^{Cb}	438^{Ca}
p-value (SEM)	Mulch (M)	0.019 (3.8)		<0.001 (0.7)		<0.001 (5.6)	
	Harvest time (H)	0.017 (4.2)		<0.001 (0.8)		<0.001 (6.5)	
	Year (Y)	0.001 (6.1)		<0.001 (0.8)		0.067 (7.9)	
	M × H	0.005 (5.1)		0.004 (1.3)		<0.001 (8.7)	
	M × Y	0.217 (6.7)		0.166 (1.3)		0.076 (8.1)	
	H × Y	<0.001 (7.4)		0.027 (1.5)		<0.001 (9.5)	
	M × H × Y	0.201 (8.5)		0.320 (2.7)		0.018 (11.5)	

ND = not determined; SEM = standard error of the means. Harvest times marked with different uppercase letters (A, B, C) differ significantly ($p < 0.05$) from each other within a year. Mulch treatments marked with different lowercase letters (a, b) differ significantly ($p < 0.05$) from each other within a harvest time and a year.

In Helsinki, the ear proportion of DM yield increased due to the use of mulch film, but only at the second harvest time, as indicated by the interaction between mulch and harvest time (Table 6). Ear DM content was 60 g kg^{-1} DM higher due to the use of mulch film in 2020, whereas in 2019, the effect was not observed on all harvest times. Both ear proportion of DM yield and ear DM content increased the later the harvest time was. At the third harvest time, ear proportion of DM yield averaged 55 %, and ear DM content was above 400 g kg^{-1} DM. The visually defined ear developmental stages (R stages) were parallel for the two mulch treatments, but different for the three harvest times (Appendix Table A3). In 2018, the average ear developmental stage was R4 at the first harvest time,

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

and R5 at the second and third harvest times. In 2019 and 2020, the average ear developmental stages were R3 at the first harvest time, R4 at the second harvest time, and R5 at the third harvest time (Fig. 3).

Table 7. Plant height, ear proportion of dry matter yield (DM), and ear DM content of forage maize with mulch film or without mulch in Maaninka (2019–2020). Data shown are means.

		Plant height, cm	Ear proportion, % of DM yield	Ear DM content, g kg^{-1}
Mulch treatment	Mulch film	288	40	273
	No mulch	297	30	214
Year	2019	261	24	204
	2020	324	46	282
p-value (SEM)	Mulch (M)	0.423 (8.0)	0.019 (3.5)	0.001 (14.5)
	Year (Y)	<0.001 (8.0)	0.013 (4.4)	0.030 (19.3)
	M × Y	0.659 (11.3)	0.195 (5.0)	0.238 (20.5)

SEM = standard error of the mean

In Maaninka, use of mulch film increased ear proportion by 10 % of DM yield and ear DM content by 59 g kg^{-1} DM (Table 7). However, mulch did not affect the ear developmental stage (Appendix Table A4). The average ear developmental stages at harvest were R2 in 2019 and R3 in 2020.

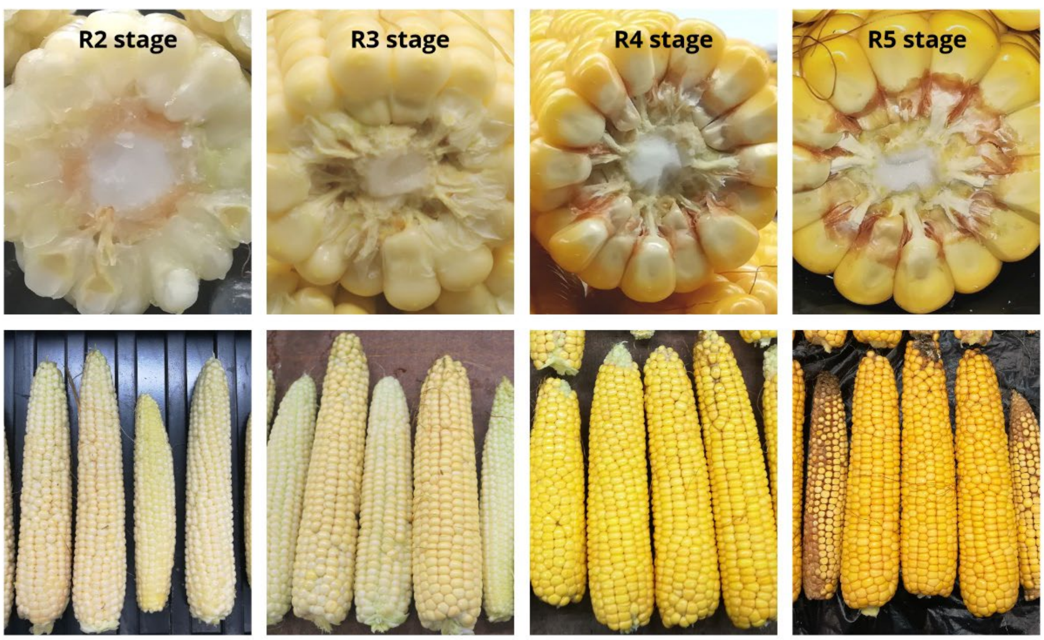

Fig. 3. Maize ears at different developmental stages (R stages) in the field experiments in Helsinki (2018–2020). R stages were defined according to Brown (2017).

Discussion

The use of mulch film increased the DM yield on average by 2.3 Mg ha^{-1} in Helsinki and 3.8 Mg ha^{-1} in Maaninka. The observed yield increase is in accordance with the previous studies conducted in Western Europe (van der Werf 1993, Easson and Fearnehough 2000, Keane et al. 2003, Farrell and Gilliland 2011), and is likely related to the higher soil temperature and moisture under the mulch compared with bare soil at the beginning of the growing season (Easson and Fearnehough 2000, Keane et al. 2003, Tofanelli and Wortman 2020). Improved temperature and moisture conditions under the mulch film enhance the emergence, growth of seedlings and roots, and establishment of the canopy (van der Werf 1993, Kwabiah 2003, Wang et al. 2018). As a response to enhanced growth, maize plants with mulch film often grow taller and have more leaves and leaf area compared with plants without mulch (van der Werf 1993, Easson and Fearnehough 2000, Deng et al. 2019).

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

The higher DM yield with mulch film than without mulch in Helsinki indicates that the whole plant biomass accumulation was enhanced in plants grown with mulch film. Nevertheless, ear developmental stages were similar with mulch film and without mulch in Helsinki, and yield DM content, ear DM content, and proportion of ears in DM yield did not have a consistent pattern across years and harvest times. Therefore, the effect of mulch use on ear development remained unclear in Helsinki. Overall, the increase in DM yield in Helsinki was more related to an increase in total plant biomass than ear development. However, in Maaninka, the ear proportion of DM yield increased by 33% and the ear DM content increased by 26% as a result of the mulch film use. Thus, the use of mulch film advanced ear development in Maaninka, as also reported by Easson and Fearnehough (2000). The different responses of ear development to mulch use in Helsinki and Maaninka could be related to the effective temperature sum accumulation between sowing and the last harvest time, which was markedly lower in Maaninka (at or below 700 °Cd) than in Helsinki (above 850 °Cd). Hence, the mulch film may have had a greater effect on the growth and development of maize under the more northern conditions in Maaninka.

The DM yield increased from the first to the second harvest time regardless of mulch use in Helsinki. The highest DM yield of approximately 14.7 Mg ha^{-1} was obtained when the ear developmental stage was R4 (dough) or R5 (dent), when the yield DM content was approximately 260 g kg^{-1}, and when the accumulated effective temperature sum was above 850 °Cd in Helsinki. Previously, in Sweden, Hetta et al. (2012) observed that the DM yield was highest at the ear developmental stage of R5 when the DM content was 370 g kg^{-1}. Also, in Serbia, Mandić et al. (2020) showed that DM yield increased until the DM content was 450 g kg^{-1}. Compared with those previous studies (Hetta et al. 2012, Mandić et al. 2020), the accumulation of DM yield ceased relatively early in this study. The early cessation of DM yield increment was most likely related to leaf senescence and harvest losses. However, the ears continued maturing, and the DM content of the yield increased even when the DM yield accumulation had stagnated.

Annual differences in DM yield were marked in both study sites. In Helsinki, the 23% lower DM yield in 2018 in comparison to years 2019 and 2020 was mostly related to low precipitation and hence, reduced vegetative biomass accumulation. In May–August 2018, the monthly precipitation sums were clearly below the long-term average. The limited vegetative growth may be reflected in plant height, as in 2018, the plants were on average 11% shorter than in 2019, and 45% shorter than in 2020 in Helsinki. In addition to weather conditions, also harvest losses and unintended picking of ears may have influenced the relatively low DM yield in 2018. In Maaninka, the approximately 56% higher DM yield in 2020 than in 2019 was related to weather conditions, and thus, to vegetative growth and ear development. The monthly mean temperature and precipitation sum during the vegetative growth period in June–July were higher in 2020 than in 2019. Therefore, the vegetative growth was enhanced, and the plants grew on average 24% taller in 2020 than in 2019. Also, the night frosts occurred before the harvest in 2019, which may have caused leaf senescence, and thus, harvest losses. Another reason for the high DM yield in 2020 was enhanced DM accumulation, and thus, further ear development stage in comparison to 2019 due to a clearly higher effective temperature sum.

The forage quality response to mulch film use had different patterns of change between the locations, years, and harvest times. The WSC content decreased as a response to mulch film use, but only in Helsinki. Mulch film increased starch content at the first and second harvest times in Helsinki, but only in 2018 and 2020, and the effect was not observed in Maaninka in either of the study years. Hence, the effect of mulch film on starch content was not consistent. The lack of consistent response of the starch content to mulch film conflicts with previous studies (Easson and Fearnehough 2000, Farrell and Gilliland 2011), which indicated that forage starch content was approximately 37% higher for plants grown under film in comparison to plants grown without film. In Helsinki, starch content increased by an average of 31% following mulch film use, but only on four out of nine samplings. This indicates the unclear effect of mulch film on ear development and the variance of results due to fluctuating weather conditions. Also, the unintended picking of the ears by the public may have caused variance in the starch content results. In Maaninka, the starch content remained very marginal regardless of mulch film due to the limited effective temperature sum. To summarise, the previously recorded increase in starch content following the use of mulch film in Western Europe was not observed in the cool climate and fluctuating weather conditions in Northern Europe.

The quality of harvested forage yield improved from the first until the third harvest time in October, when the accumulated effective temperature sum had exceeded 850 °Cd and the ears had reached the R5 stage (dent) in Helsinki. The most important factor of forage maize quality – starch content – increased clearly with delayed harvest time, similar to previous studies in Northern Europe (Mussadiq 2012, Seleiman et al. 2017, Kumar et al. 2022). The increase in starch content is a result of ear development, and thus, increase in the ear proportion of

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

the yield. After maize pollination, storage carbohydrates are translocated from vegetative plant parts to kernels, where the carbohydrates provide carbon for starch synthesis (Struik 1983, Mäkelä et al. 2005, Ning et al. 2018). The accumulation of starch into kernels was indicated by the ear proportion of DM yield and the ear DM content, which both increased 2–3-fold between the first and third harvest times.

Overall, the target starch content of 300 g kg^{-1} DM (Phipps et al. 2000) was only reached in Helsinki in 2018 when the effective temperature was clearly higher than in the other study years exceeding 950 °Cd already at the second harvest time. Therefore, the ear development stages at the first two harvest times were more advanced in 2018 than in 2019 and 2020, and thus, conversion of WSC into starch was correspondingly further at the third harvest time. In 2019 and 2020, when the effective temperature accumulation was moderate, the starch contents remained under the target starch content, similar to the previous studies conducted in Finland (Seleiman et al. 2017, Liimatainen et al. 2022). The lower starch accumulation in 2020 than in 2019 was a result of relatively tall plants, and thus, a low ear proportion of the DM yield in 2020. Also, different temperature patterns during the late growing season may have affected starch accumulation. In 2020, the late growing season temperatures were higher than usually, and the accumulation of effective temperature sum continued markedly until the third harvest time unlike in 2018 and 2019. Regardless of the relatively high temperature at the late growing season in 2020, the decreased solar radiation, and shortened days may have limited the starch accumulation to ears. In Maaninka, the starch contents remained below 100 g kg^{-1} DM, which is clearly below the target starch content. The low starch accumulation was related to the low effective temperature sum accumulation, and thus, restrained ear development. In both locations, the main factor causing restricted starch accumulation was the cool climate, as starch contents exceeding 300 g kg^{-1} DM have been recorded regularly in Southern Sweden (Hetta et al. 2012, Mussadiq 2012, Kumar et al. 2022), where the effective temperature sum accumulation is markedly higher than in Finland. The very low starch accumulation in Maaninka indicated that forage maize quality remains especially low in Central Finland, more specifically in Northern Savo, which is one of the most important milk production regions in Finland (Virkajärvi et al. 2015).

Forage WSC content decreased drastically with delayed harvest time, similar to the results previously reported by Seleiman et al. (2017) in Finland, Kumar et al. (2022) in Sweden and Lynch et al. (2012, 2013) in Ireland. The decrease in WSC content relates to the unloading of carbohydrate storages from the vegetative plant parts during ear development (Struik 1983, Mäkelä et al. 2005). During the ear filling, the water-soluble carbohydrates are translocated from leaves and stem to kernels via phloem, where they are hydrolysed and used in starch synthesis (Mäkelä et al. 2005, Ning et al. 2018). In Helsinki, the WSC contents were lower by approximately 42% in 2019 than in 2020, which was opposite to starch contents, which were 67% lower in 2020 than in 2019. The difference in the ratio of WSC and starch contents was related to the ear proportion of the yield. Even though ear DM contents and ear development stages were similar in 2019 and 2020, the markedly high vegetative biomass accumulation in 2020 diluted the proportion of ears in DM yield, and thus, also WSC and starch contents in the whole crop biomass.

Forage NDF content in Helsinki decreased between the first and second harvest times, but not between the second and third harvest times, as also found by Khan et al. (2014) who indicated that the decrease in NDF is the steepest when forage DM content increases from <250 g kg^{-1} to 250–290 g kg^{-1}. In general, the NDF content tends to decrease as ears mature and gain weight, because the NDF content of ears is lower compared with vegetative plant parts (Wiersma et al. 1993, Johnson et al. 1999, Lynch et al. 2012, Lynch et al. 2013). This effect was present in this study, since the NDF content decreased as the ear proportion of DM yield doubled between the first two harvest times. In Helsinki, the NDF content was highest in 2020 due to enhanced vegetative growth, and thus, a low proportion of ears in the DM yield. Correspondingly, in Maaninka, the NDF content was lower in 2020 than in 2019, because the ear proportion of DM yield was almost 2-fold in 2020 in comparison to 2019.

The CP content had no marked response to harvest time, unlike in the earlier studies (Wiersma et al. 1993, Johnson et al. 1999, Lynch et al. 2013, Khan et al. 2014) which indicated a clear decline in CP content due to delayed harvest time. Usually, the CP content declines as plant photosynthesis continue while the N uptake is ceased, leading to the utilization of plant storage proteins (Wiersma et al. 1993). However, in this study, a marked decline in CP content was not observed, probably due to the limited photosynthesis during the late growing season. Annual differences recorded in CP content were observed in Helsinki, where the average CP content was 50% higher in 2018 than in 2020. In 2020, the relatively low CP content at or below 65 g kg^{-1} DM was explained by the low ear proportion, and respectively, high vegetative biomass proportion of yield, as vegetative biomass has lower CP content in comparison to ear biomass (Hetta et al. 2012, Lynch et al. 2013).

Agricultural and Food Science (2023) 32: xx–xx
https://doi.org/10.23986/afsci.125326

Mulch film can be used to increase forage maize DM yield, although the use of oxo-(bio)degradable films, such as the mulch film used in this study, became banned in the European Union (EU) countries starting from 2021 (Directive (EU) 2019/904). The ban of oxo-degradable plastics is related to environmental risks, as oxo-biodegradable and other biodegradable plastics, in general, are associated with chemical pollution (Markowicz and Szymánska-Pulikowska 2019) and the release of micro-plastics into the environment (Markowicz and Szymánska -Pulikowska 2019, Serrano-Ruiz et al. 2021). However, the use of all other mulch film materials is still allowed, including, for example synthetic, plant oil-based, and starch-based films, as well as paper mulches. The yield impact of mulch film does not seem to be related to the mulch material (Tofanelli and Wortman 2020). Hence, other film materials besides oxo-biodegradable plastic could result in a similar increase in forage maize DM yield, as observed in this study and previous studies (e.g. van der Werf 1993, Keane et al. 2003, Easson and Fearnehough 2000, Farrell and Gilliland 2011).

Conclusions

The use of mulch film increased forage maize DM yield in Northern European climate conditions. However, the use of mulch film improved forage quality only marginally, and it did not enhance earlier harvest time. The highest DM yield was achieved at ear developmental stage R4 (dough), although the yield starch content increased markedly until the R5 stage (dent). However, the effective temperature sum limits ear development, hence starch accumulation to ears particularly in Central Finland, which is an important milk production region within Finland. Therefore, the nutritional value of forage maize fluctuates regardless of the mulch film use under the climate conditions of Finland. Future research could be conducted to assess the soil dynamics related to the use of mulch film in Northern European climate conditions. Also, the economic implications of the mulch film use in forage maize production would require further attention.

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Agricultural and Food Science (2023) 32: xx–xx
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Appendix

Table A1. Topsoil (0–25 cm) properties of the experimental areas in Helsinki (2018–2020) and Maaninka (2019–2020)

	Helsinki			Maaninka	
	2018	2019	2020	2019	2020
pH	6.0	6.1	6.1	6.4	6.4
SOM, %	9	9	10	4	4
P, mg l^{-1}	11	11	6	64	22
K, mg l^{-1}	240	180	260	160	210

SOM = soil organic matter; P = phosphorus, K = potassium

Table A2. Herbicide applications of forage maize stand in Helsinki (2018–2020)

Year		Herbicide application			
		First	Second		Third
2018	Timing	at sowing	18 DAS	18 DAS	31 DAS
	Active ingredient	pendimethalin[1]	thifensulfurol-methyl[2]	rimsulfuron[3]	rimsulfuron[3]
	Application rate	5 l ha^{-1}	15 g ha^{-1}	30 g ha^{-1}	20 g ha^{-1}
2019	Timing	at sowing	26 DAS	26 DAS	-
	Active ingredient	pendimethalin[1]	thifensulfurol-methyl[2]	rimsulfuron[3]	-
	Application rate	5 l ha^{-1}	15 g ha^{-1}	30 g ha^{-1}	-
2020	Timing	at sowing	17 DAS	17 DAS	-
	Active ingredient	pendimethalin[1]	thifensulfurol-methyl[2]	rimsulfuron[3]	-
	Application rate	5 l ha^{-1}	10 g ha^{-1}	50 g ha^{-1}	-

a.i. = active ingredient; DAS = days after sowing
Used herbidice products: [1] Stomp, a.i. 400 g L^{-1}; BASF, Ludwigshafen, Germany ; [2] Harmony 50SX, a.i. 500 g kg^{-1}; DuPont, Wilmington, USA; [3] Titus WBS, a.i. 250 g kg^{-1}; DuPont, Wilmington, USA

Table A3. Ear developmental stages (R stages) of forage maize with mulch film or without mulch in Helsinki (2018–2020). Data shown are frequencies and percentages of R stage observations averaged over three years and three harvest times.

	Mulch treatment	R stage				
		R2	R3	R4	R5	Total
Frequency (column %)	Mulch film	0 (0%)	10 (48%)	7 (64%)	18 (53%)	35 (49%)
	No mulch	5 (100%)	11 (53%)	4 (36%)	16 (47%)	36 (51%)

Fisher's exact test, $p = 0.1223$

Table A4. Ear developmental stages (R stages) of forage maize with mulch film or without mulch in Maaninka (2019–2020). Data shown are frequencies and percentages of R stage observations averaged over two years.

	Mulch treatment	R stage			
		R1	R2	R3	Total
Frequency	Mulch film	0 (0%)	4 (48%)	4 (50%)	8 (50%)
(column %)	No mulch	1 (100%)	3 (53%)	4 (50%)	8 (50%)

Statistical test was not conducted due to small frequencies.