Simulating maize growth and development grown using plastic mulch

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Abstract

Maize production in New Zealand has traditionally been centred around warmer North Island regions such as the Waikato and Bay of Plenty. However, recently maize silage production has increased in cooler, South Island, areas such as Canterbury. Maize yields in these regions are limited by slow canopy development, due to cool temperatures, and the risk of early autumn frosts, which limit the use of longer duration hybrids. Applying photodegradable plastic mulch to the soil, soon after sowing, is a technique that has been used to overcome these limitations. Unfortunately, previous experimental results with this technology have been site and season specific. This research used a mechanistic simulation model to evaluate the potential of plastic mulch for maize silage crops at three locations in the South Island of New Zealand. As a first step the model outputs were compared with an experiment at Lincoln to determine the effect of a plastic mulch treatment with an uncovered control treatment for an early and medium maturity maize hybrid. The model simulated leaf appearance, radiation interception and silage yield well. The model was then used with long-term weather data (1981 - 2001) to simulate average maize silage yields for early, medium and late maturing maize hybrids (Comparative relative maturities = 75 - 80, 90 - 95, 105 - 110) at Winchmore, Lincoln and Blenheim from three sowing dates (25 September, 20 October and 14 November) grown with or without plastic mulch. For a given combination of sowing date, hybrid and location, the plastic mulch treatments gave modest increases in silage yield, but resulted in maturity being 11 - 12 days earlier. The analysis showed that to fully realise the benefits of the plastic mulch it would need to be used with a longer maturity hybrid. The longer maturity hybrid coupled with plastic mulch reached silage maturity on a similar date to the early maturing hybrid without plastic mulch and gave silage yield increases of 0.9 - 2.0 t ha^{-1}, depending on sowing date and location. The largest differences were for the early sowing. Overall the highest yields were for the 25 September sown crop, of the late hybrid, grown at Blenheim using plastic mulch.

Additional keywords: Maize; plastic mulch; simulation modelling; soil temperature.

Introduction

Maize is a C_4 plant that requires temperatures of 20 - 30 °C for maximum growth rates (White *et al*., 1999). The base temperature for maize development is 8 °C (Muchow *et al*., 1990), and photosynthetic rates decrease markedly at temperatures below 20 °C. In New Zealand, maize production has historically been centred in the North Island in regions such as the Waikato and Bay of Plenty. For example, in the 1981 - 82 season a total of 18,750 ha of maize were grown in New Zealand, of which 64 % were in the Waikato and Bay of Plenty regions with only 150 ha grown in the South Island (Anon. 1983 cited by Bansal and Eagles, 1985). Maize crops are grown for both grain and silage production. With the recent increase in dairy production in the South Island production of maize for silage has begun to increase in this area. In 2002 3,400 ha of maize were grown for silage in the South Island mainly in Canterbury (2,400 ha) (Statistics-New-Zealand, 2002). The area around mid-south Canterbury is regarded as the southern limit of reliable maize production (Wilson *et al*., 1994), due to relatively cool within-season temperatures and a short, and variable, frost-free season.

Even in this environment maximum mid-summer maize growth rates can still be high (~30 g m^{-2} d^{-1}). In the South Island cool spring temperatures are close to the developmental base temperature and therefore maize canopy development is quite slow. Silking, the time of peak LAI, depends on sowing date and hybrid choice, but usually occurs in late January or early February in Canterbury. Using data from Hawke's Bay (39.47 °S, 176.64 °E), Sorenson *et al*. (2000) found that for each 10 day delay in peak LAI past the longest day, maize grain yield decreased by ~1.3 t ha^{-1}. Assuming a harvest index of 0.5, this equates to a loss of silage yield of 2.6 t ha^{-1} for each 10 day delay. Clearly, any management system that increases the canopy development rate and reduces the risk of the crop failing to mature before an early autumn frost is important. Traditionally, early sowing dates (mid October) and short maturity hybrids have been used in this region (Wilson *et al*., 1994). However, although short maturity hybrids are at less risk of autumn frosts, they are also shorter duration and hence lower yielding than later maturing hybrids (Sorensen and Stone, 1999).

Application of a photo-degradable plastic mulch to maize crops at sowing is a potential method for improving maize canopy development rates and yields that has been used overseas (e.g. Easson and Fearnehough, 2000; Kwabiah, 2003, 2005a, b) and more recently in New Zealand (Stone *et al*., 1999; Fletcher *et al*., 2008). The mulch increases soil temperature by ~5°C and therefore enhances both canopy and reproductive development. Experiments in Canada have found up to a 25 % increase in silage yield and silage maturity occurring up to 15 days earlier using plastic mulch (Kwabiah, 2003, 2005a, b). Experiments in Ireland have given similar results with a 15 - 30% increase in silage yield and ~13 days earlier silage maturity (Easson and Fearnehough, 2000). An experiment in Canterbury, New Zealand (Fletcher *et al*., 2008), found that use of plastic mulch did not significantly increase silage yield, but that it did advance silage maturity by 14 days. Each of these results is specific to site, season, hybrid and sowing date. Obviously, it is impractical to experimentally test this technology for each of these combinations. A viable alternative is to use a mechanistic crop simulation model with long-term daily weather data to analyze the probable maize yield and development responses to the use of plastic mulch.

The objective of this research was to use a mechanistic maize simulation model (Muchow *et al*., 1990; Wilson *et al*., 1995) to assess the potential yield and development of maize grown either with a plastic mulch or in bare soil in New Zealand's South Island. As a first step the outputs of the model were tested against experimental crops grown at Lincoln with either a plastic mulch or uncovered (Fletcher *et al*., 2008). The model was then used with weather data for 20 maize growing seasons (1981 - 2001), to run simulations for Winchmore, Lincoln and Blenheim, representing high, medium and low risks for maize production respectively. At each location simulations were run for three hybrids (early, medium and late maturity), and for three sowing dates. The three sowing dates were 25 September, 20 October and 14 November, representing early, mid and late season sowings at these locations.

Model testing

The data for testing the model simulations was taken from the experiment of Fletcher *et al*. (2008). Briefly, an early (Pioneer 39G12, CRM = 78) and a medium (Pioneer 38H20 CRM = 91) maturity maize hybrid were sown at Lincoln, New Zealand, on 24 October 2007. Plots were sown at 116,000 plants ha^{-1} using a Samco (Limerick, Ireland) 4 row seeder and plastic layer. Plots were sown either covered with a thin plastic mulch or not covered. Pest management, irrigation and fertiliser were applied so that they did not limit growth.

Immediately, after sowing 50 mm soil temperature probes were installed in each plot. These logged soil temperatures every 30 minutes. Daily measurements of minimum (T_{min}) and maximum (T_{max}) air temperature, and incident solar radiation (MJ m^{-2} d^{-1}) were observed approximately 200 m from the experimental site. Whole crop biomass was measured three times, twice at around silking and once at silage maturity. The number of fully expanded leaves and radiation interception were measured 7 times during canopy development. Further details of the experiment are in Fletcher *et al*. (2008).

The final silage yields and silage maturity dates are shown in Table 1. The early maturity hybrid was harvested 7 - 8 days earlier than the medium hybrid and produced ~2 t ha^{-1} less silage. The plastic mulch treatments reached silage maturity 13 - 14 days earlier than the uncovered treatments and produced ~1 t ha^{-1} more silage. However, the differences in silage yield between plastic treatments were not statistically significant.

Table 1: Observed silage harvest data for two maize hybrids grown with and without plastic mulch (Fletcher *et al*., 2008), and hybrid-specific model variables used to simulate these crops.

	Observed harvest data		Hybrid specific model variables	
Treatment	Date	Silage yield (t DM ha^{-1})	Final leaf number, (n)	Area of largest leaf, A_{max} (cm^2)
Early + plastic	18 Mar	26.9	16	660
Early - plastic	31 Mar	25.3	16	660
Medium + plastic	25 Mar	28.4	18	720
Medium - plastic	8 Apr	27.8	18	720

The crops were simulated using the simulation model of Wilson *et al*. (1995). This model is based on that of Muchow *et al*. (1990), except that it includes a number of modifications to deal with maize crops grown under cool temperatures. The most important of these is that it uses soil temperature to drive development before there are 8 fully expanded leaves. In the original Wilson *et al*. (1995) model this was achieved by increasing air temperature by 3 °C. However, in this test of the model actual soil temperature data were used. Other changes included using a broken stick approach for calculating thermal time (Tt) at low temperatures; stopping simulations when a frost (T_{min} < -1°C) occurred; altering the leaf appearance rate of the first 7 leaves; and reducing RUE from 1.6 g MJ^{-1} at T_{mean} = 16 °C to 0 g MJ^{-1} at T_{mean} = 8 °C.

The model requires hybrid-specific parameters for final main stem leaf number (FLN), the area of the largest leaf (A_{max}), Tt from sowing to emergence and Tt from silking to the start of grain fill. The latter two were set to 100 °Cd and 90 °Cd respectively for both hybrids. The FLN was set to 16 for the early hybrid and 18 for the medium hybrid regardless of whether plastic mulch treatment was used or not. These values were experimentally observed. The equation of Birch *et al*. (1998) relating A_{max} to FLN was used to estimate an A_{max} of 660 cm^2 for the early hybrid and 720 cm^2 for the medium hybrid (Table 1).

The simulations of the time courses of fully expanded leaf number, solar radiation interception and biomass accumulation were compared with the observed data. Using the observed soil temperature data the model successfully simulated the key aspects of crop growth and development affected by the plastic mulch treatment (Figure 1).

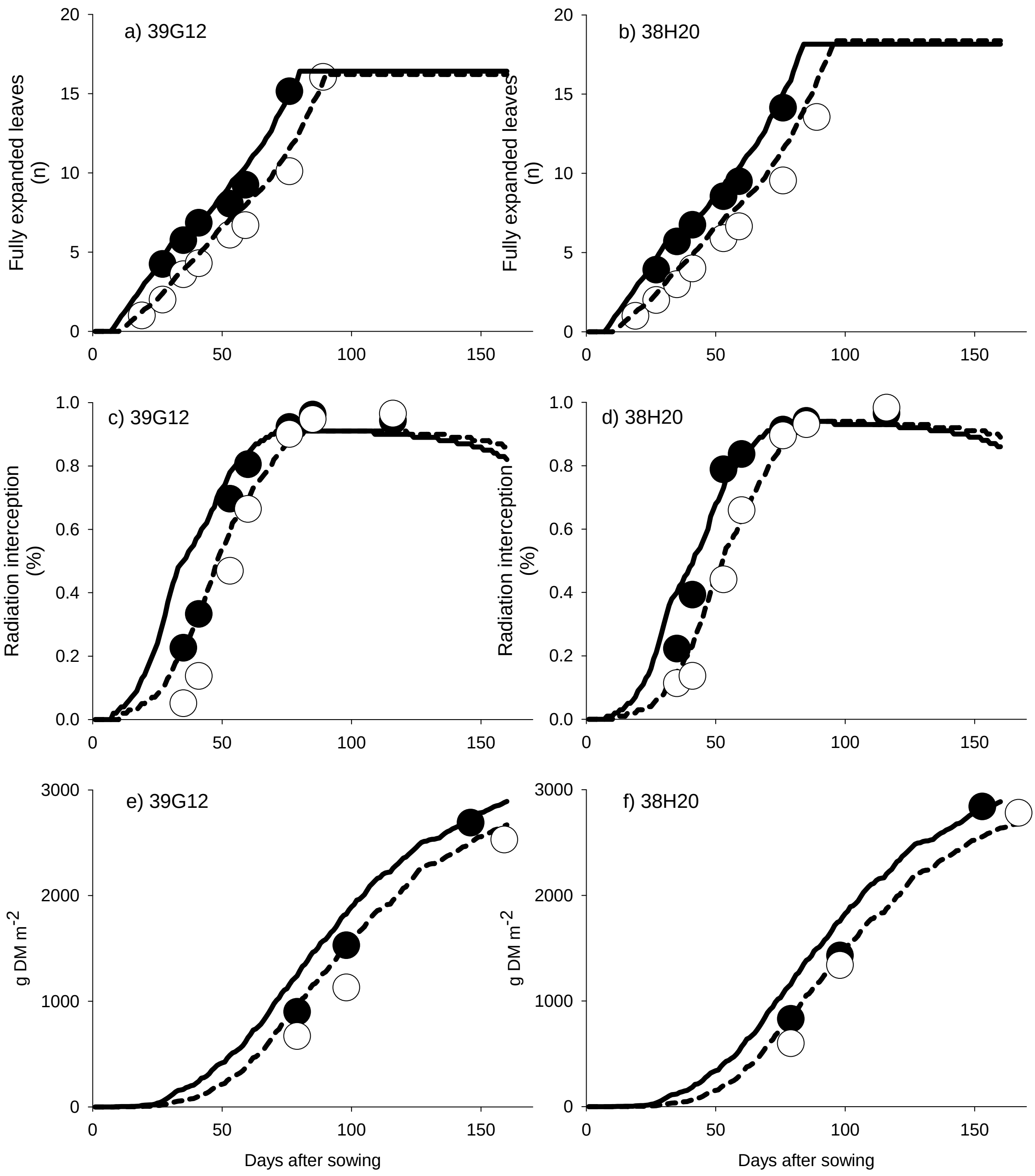

Figure 1: Time courses of simulated (lines) and observed (symbols) fully expanded leaf numbers (a and b), solar radiation interception (c and d), and crop dry matter (e and f) for an early (a, c and e) and a medium (b, d and f) maturity maize hybrid grown at Lincoln with (filled symbols and solid lines) or without (open symbols and dashed lines) plastic mulch.

For both hybrids the model closely simulated the number of fully expanded leaves plant^{-1} (Figure 1a, b). During canopy development the plastic mulch treatments had 2 - 5 more fully expanded leaves than the uncovered treatments and these differences were simulated well by the model. The model also closely tracked the solar radiation interception of both hybrids with and without plastic (Figure 1 c, d). However, it tended to slightly over predict solar radiation interception early in crop development (0 - 50 DAS), especially for the early maturity hybrid grown with plastic. The model also gave accurate predictions of crop biomass for both hybrids grown with or without plastic (Figure 1e, d, f). The plastic mulch treatments gave the same or a slightly increased silage yield than the uncovered treatment. However, these yields were achieved approximately two weeks earlier than the uncovered crops and the model was able to simulate these differences in crop growth and duration. This indicated that the model was suitable for long-term simulation analysis.

Long-term simulation analysis

A long-term simulation analysis for maize production with and without plastic mulch was run for the combinations of three hybrids (early, medium and late maturing), three sowing dates (early, mid and late season) and three locations in the South Island of New Zealand. The three sowing dates were 25 September, 20 October, and 14 November. The three locations were Blenheim (41.52 °S, 173.95 °E), Lincoln (43.63 °S, 172.45 °E) and Winchmore (43.83 °S, 171.72 °E). Blenheim is the most northerly and has the warmest mean temperatures and the longest season of the three locations. Lincoln is further south and has cooler mean temperatures and a shorter frost-free season. Winchmore is slightly further south again but is further inland than Lincoln and therefore has the coolest mean temperatures and the shortest frost-free season.

The three hybrids had 16, 18, and 20 final main stem leaves for the early, medium and late maturing hybrid. This represents approximate silage CRMs of 75 - 80, 90 - 95 and 105 - 110 (Table 2). Using the equation of Birch *et al.* (1998) it was estimated that these hybrids had an A_{max} of 660, 720 and 790 cm^2, respectively. It was assumed that the Tt from sowing to emergence was 100 °Cd and from silking to the start of grain filling it was 90 °Cd. In each simulation the plant population was 110,000 plants ha^{-1}, which is a typical sowing rate for maize silage crops.

Table 2: Simulation model input variables for the early, medium and late maturing maize hybrids.

Hybrid	Approximate silage CRM	Final leaf number	Area of largest leaf, A_{max} (cm^2)
Early	75 - 80	16	660
Medium	90 - 95	18	720
Late	105 - 110	20	790

To simulate the effects of using plastic mulch or leaving the soil uncovered, soil temperature was calculated from air temperature. In the original Wilson *et al.* (1995) model soil temperature was taken as air temperature plus 3 °C. This modification was retained in this analysis for the uncovered treatments. It was necessary to use this approximation as appropriate soil temperatures were not measured at any site. The plastic treatment increased soil temperature by a further 5 °C for the first 32 days after sowing (Fletcher *et al.*, 2008). Therefore, for the simulated plastic mulch treatments soil temperature was taken as air temperature plus 8 °C for the first 32 days after sowing. After this it was assumed that the effect of the plastic mulch disappeared and soil temperature was again taken as air temperature plus 3 °C. Simulations were run using each of these combinations of sowing date, hybrid, location and mulch treatment for 20 seasons of long-term weather data (sowing years 1981 - 2000).

Results and Discussion

The long-term simulation analysis showed that for a given hybrid, sowing date and location combination applying the plastic mulch treatment moderately increased silage yield (Figures 2 - 4). The yield increases were between 0 and 2.1 t ha^{-1} at Lincoln and Winchmore and 0 and 1.4 t ha^{-1} at Blenheim. The moderate yield increases were the result of more rapid canopy development. However, at the same time the plastic mulch treatment resulted in silage maturing 11 - 12 days earlier. Therefore, there was less total solar radiation incident on these crops. For example, for a short maturity hybrid sown at Winchmore on 14 November the mean silage yield was 20.4 t ha^{-1} harvested on the 22 April for the uncovered treatment, but 21.7 t ha^{-1} harvested on the 9 April for the plastic mulch treatment (Figure 2).

With longer duration hybrids, regardless of plastic treatment, mean simulated yields increased for the sowings of 25 September and 20 October but had little effect on the 14 November sowing (Figures 2 - 4). For example, at Blenheim long and short maturity hybrids sown without plastic mulch on 25 September had mean silage yields of 29.1 and 28.0 t ha^{-1}, respectively. But for a 14 November sowing these same treatments both had mean yields of 25.0 t ha^{-1}. The plastic treatment seemed to give greater increases for the long maturity hybrid than the short maturity hybrid. The higher yield for the longer maturity hybrids was because there was more solar radiation incident on these crops and the crops were able to intercept a greater proportion of that radiation (Sorensen and Stone, 1999). These simulation results are consistent with the experimental results of Wilson *et al*. (1994). However, the longer maturity hybrids were at significant risk of being killed prematurely by an early autumn frost, particularly in the later sowings. These results were also found in the modelling analysis in the current research (data not shown). For example, at Lincoln, for a 25 September sowing without plastic mulch none of the crops were simulated to have been frosted before they reached silage maturity. However, for a 14 November sowing without plastic mulch 40 % of the long maturity crops were prematurely frosted compared with only 10 % of the short maturity crops. This demonstrates why short and medium maturity hybrids are generally favoured in the cool climate of Canterbury.

The long-term simulation analysis demonstrated that for a given sowing date plastic mulch treatment coupled with a long maturity hybrid produced a higher silage yield and could be harvested on a similar date to a short maturity hybrid without plastic mulch. For example, at Winchmore a short maturity hybrid sown on 25 September without plastic mulch reached silage maturity on 12 March and yielded 24.2 t ha^{-1}. By comparison, a long maturity hybrid sown with plastic mulch on the same day reached silage maturity on 14 March and gave a silage yield of 25.5 t ha^{-1} (Figure 2).

Conclusion

The influence of a plastic mulch treatment on maize growth, development and yield was accurately simulated using the Wilson *et al*. (1995) model. Long-term simulation analysis demonstrated that plastic mulch treatment alone is unlikely to produce large increases in maize silage yield. To realise the full benefits of the plastic mulch it would need to be combined with an earlier sowing date and a longer maturity hybrid (CRM 105 - 110) in these locations. This combination would mature at approximately the same time as a short maturity hybrid (CRM 75 - 80) but with a considerably increased silage yield.

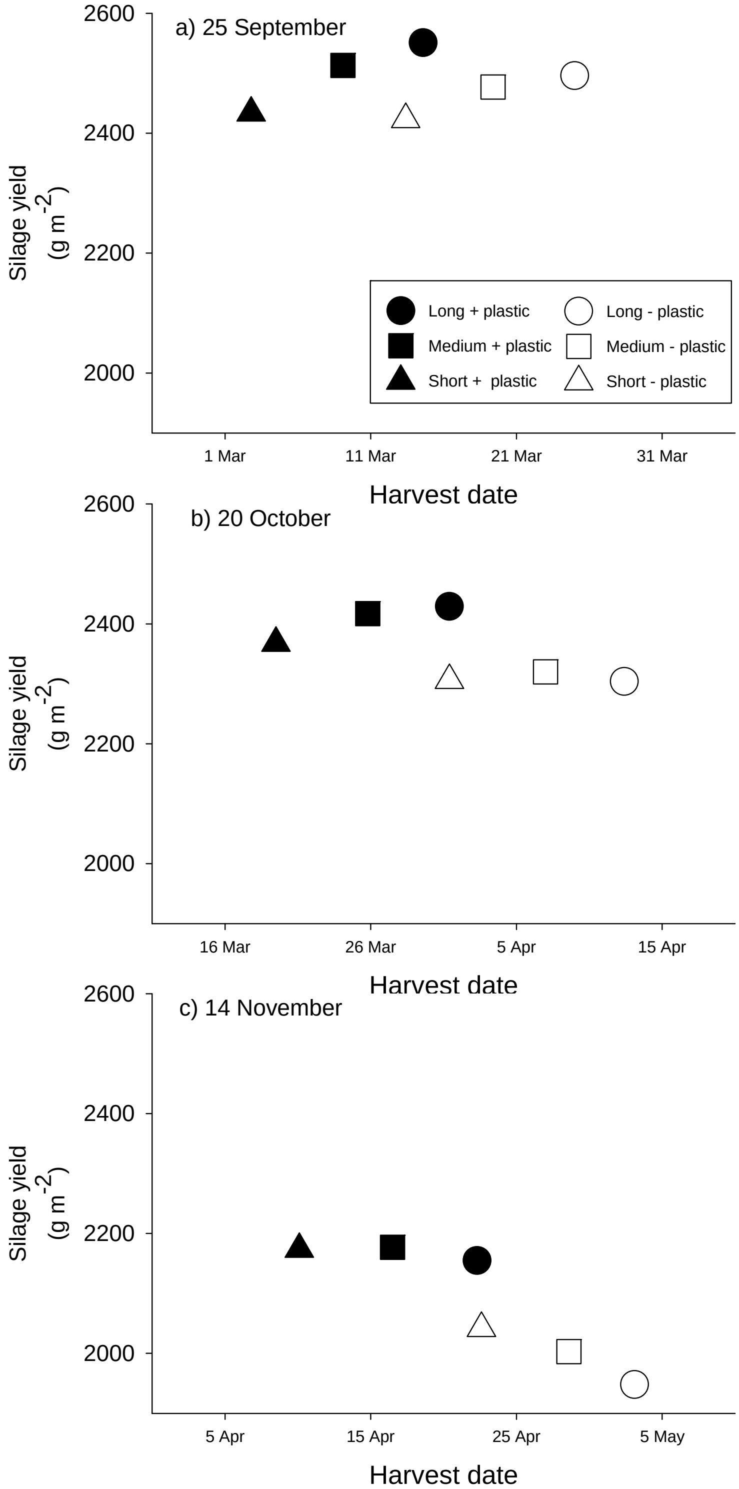

Figure 2: Mean simulated (1981 - 2000) harvest date and silage yield of early, medium and late maize hybrids sown with or without plastic mulch at Winchmore, on 25 September (a), 20 October (b) or 14 November (c).

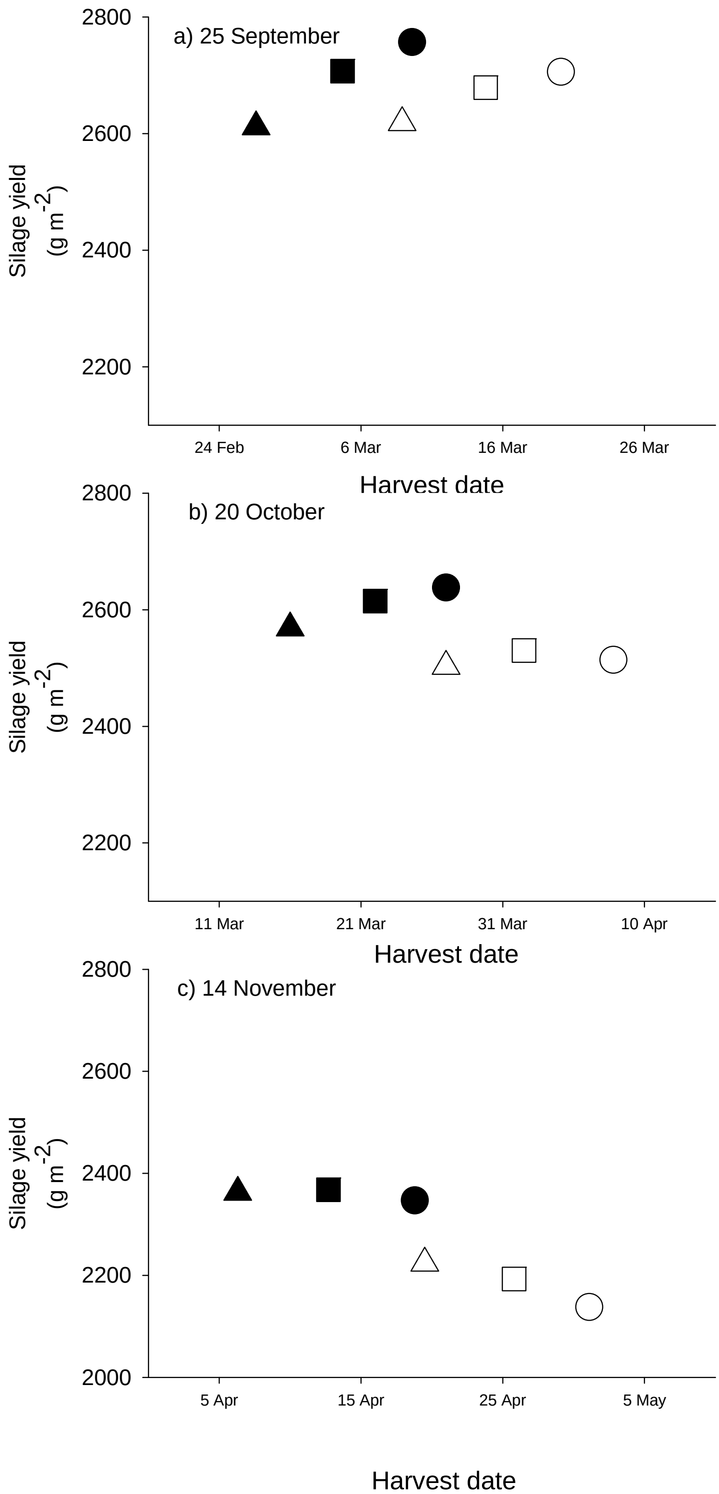

Figure 3: Mean simulated (1981 - 2000) harvest date and silage yield of early, medium and late maize hybrids sown with or without plastic mulch at Lincoln, on 25 September (a), 20 October (b) or 14 November (c). Symbols as in Figure 2.

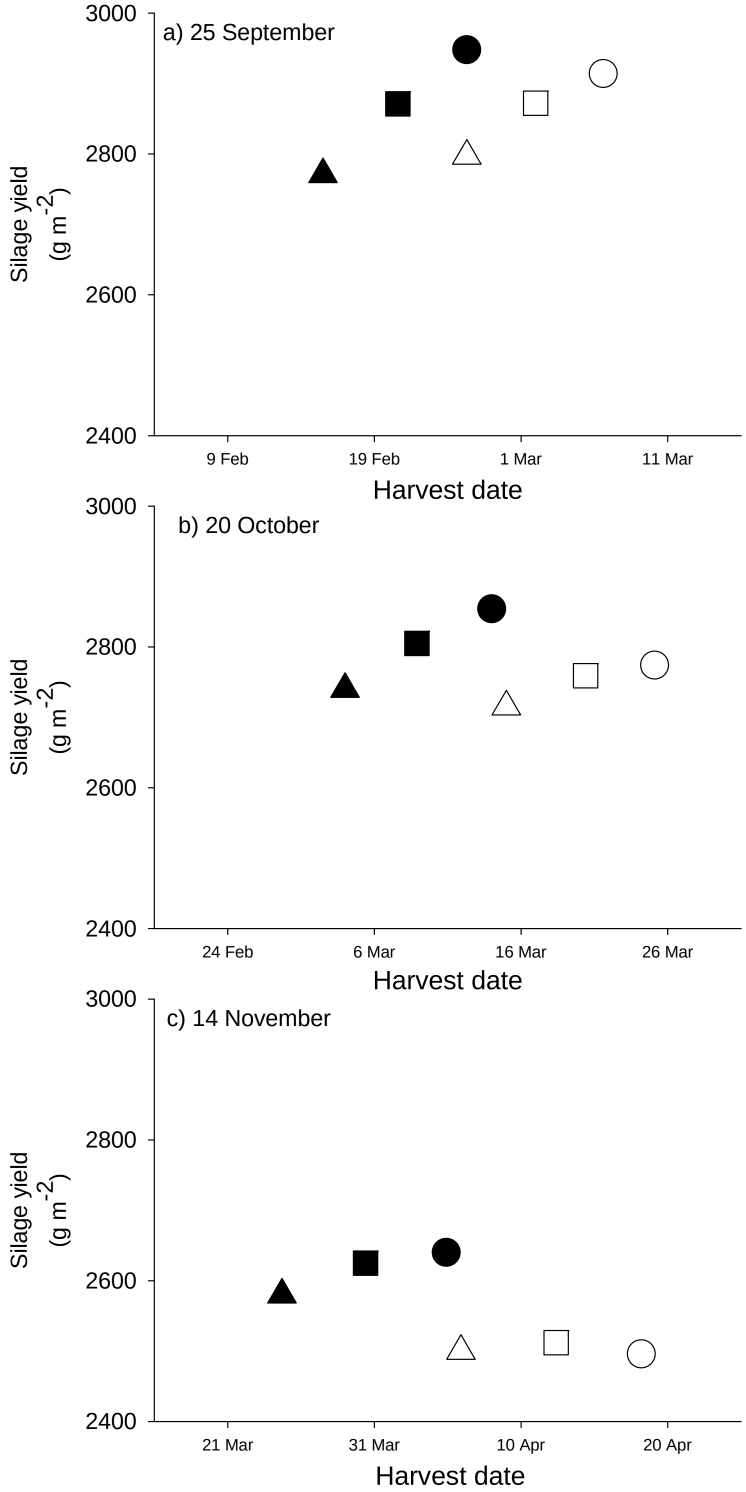

Figure 4: Mean simulated (1981 - 2000) harvest date and silage yield of early, medium and late maize hybrids sown with or without plastic mulch at Blenheim, on 25 September (a), 20 October (b) or 14 November (c). Symbols as in Figure 2.

The highest mean silage yield (29.5 t ha^{-1}) came from using the earliest sowing date (25 September), the longest maturity hybrid (20 leaves; CRM 105 - 110) and plastic mulch at the northernmost location (Blenheim).

Acknowledgements

The research was funded by the New Zealand Foundation for Research, Science and Technology through their Pastoral21 feed program. Samco Agricultural Manufacturing (Limerick, Ireland) made their drill available and Grant Matthews (Genetic Technologies Ltd) supplied the maize seed. The excellent technical assistance of Shane Maley in completing the experimental work is gratefully acknowledged.

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