Plant-to-plant variation in New Zealand maize under No-Till management footprint

G.M. Pellow[1] and A.W. Holmes[2]

[1]Naturescapes; 49 Bates St, Orari, RD22, Geraldine, New Zealand

[2]Foundation for Arable Research, FAR Innovation Park, 185 Kirk Road, Templeton, Christchurch 8042, New Zealand

naturescapes@xtra.co.nz

Abstract

A three-year field study was undertaken in commercial maize crops in North Waikato, New Zealand to identify at what stage variability in plant growth first occurred and to quantify the variation in the development of individual maize plants, by measuring plant growth at key early growth stages V1–V5; silking, and cob length at harvest. Plant establishment performance in the paddock improved over the three years with higher numbers of plants establishing in each row and the plant spacing variability reducing. In Year 3 the standard deviation (SD) ranged from 1.57–3.68 cm and the coefficient of variation (CV) ranged from 12–26%. 100% of plots had a SD of less than 5.0 cm and a CV% of less than 33%. The regression of individual plant spacing by cob length for the three years showed that for each 1 cm increase in individual plant spacing, the cob length increased by 0.197±0.073 cm (statistically significant). Two crop establishment methods were used: Minimum tillage (MT) and no-till (NT). Across the three years in long-term no-till, a 1-day delay in reaching V5 or silking resulted in a reduction in cob length of 0.519±0.049 cm or 0.521±0.026 cm, respectively. Cob length was more strongly related to a delay to silking (R^2=0.50), than a delay to V5 (R^2=0.21). Our results show that variability in plant spacing affects cob length, however, at these levels, the variability in plant spacing did not result in shorter cobs under NT that season. Key findings in this study were: 1) Generally, once a delay occurred at any growth stage, the plant seldom caught up to its neighbours; resulting in the silks being late to emerge compared with other plants in the plot, and the plant was observed to be significantly smaller in size than its neighbours at silking; 2) plants reaching plant growth stage V5 and silking faster than other plants in the plot resulted in significantly longer cobs and 3) where there was a plant missing in a row, the resultant cob lengths are often only achieving partial compensatory growth of several centimetres of cob length, not full compensatory growth.

Additional keywords: cob length, crop establishment method, minimum tillage, no-till, plant growth stage, silking, *Zea mays* L.

Introduction

Several studies of plant-to-plant variation in different maize growing regions have artificially created variability in plant stands by delaying seeding, and artificially altering the seed spacing in South Central Ontario, Canada (Liu *et al.*, 2004) or thinning after emergence to obtain various plant spacings in Argentina (Andrade & Abbate, 2005) and the USA (Thompson, 2013; Lauer & Rankin, 2004). These studies removed some of the natural paddock factors such as poor planter performance, pest, and disease influences and did not examine plant growth throughout the development of the plant to explain the effect on yield responses. Martin *et al.* (2005), studied plants in the USA, Argentina, and Mexico, marking plants in each row at or before V8 growth stage, and recording ear details at harvest. However, this methodology gave no information on plant development before the V8 stage. At most sites plant spacing was measured and at some sites Normalized Difference Vegetative Index readings were also taken.

A commercial maize (*Zea mays* L.) silage and grain farmer in Waikato, New Zealand, identified plant variability within maize rows was leading to a reduction in yield. The grower followed good management systems including no-till (NT) management to minimize degradation of soil quality; the use of a well-maintained precision NT planter; a strong plant nutrient programme and careful selection of hybrids suitable for the site.

Observation of the crops identified that plant emergence from the soil occurred within a two to three-day window and that plant spacing was generally consistent, providing a "picket fence" like plant stand, with a high percentage and even establishment rates of plants. However, variability was evident from growth stages V3-5 onwards. At harvest, variability in maize cob diameter and length; and the absence of any ears on some plants was observed, with a consequential reduction in crop yield, and profitability. The significant implication of this variability in ear development is that crop potential has not been realised, and crop inputs such as fertilizer, agrichemicals, and natural resources of rain and sunshine have been under-utilised.

Some barren corn plants were observed, which may be due to genetic mutations, boron deficiency, or climatic related stress factors during pollination.

Objective

This three-year field study was undertaken in commercial maize crops in North Waikato, New Zealand to identify at what stage variability in plant growth first occurred and to quantify the variation in the development of individual maize plants, by measuring plant growth at key early growth stages V1–V5; silking; and cob length at harvest.

Materials and Methods

The monitoring programme began in spring 2012 to assess crop growth and development, at specified growth stages, in a commercial NT maize paddock of 7.8 ha (37°18'54"S, 174°54'20"E). This paddock was managed under the NT system for seven years before the start of the trial. Crop history is detailed in Table 1.

The soil type was a Typic Orthic Brown Soil tending to a Typic Orthic Gley Soil of the Aroha Silt Loam series. Composite soil samples were taken from 0-15 cm depth in winter 2012, and a Basic Soil test was undertaken at Hill Laboratories, Hamilton. Crop management was undertaken to industry best practice standards

For the MT, two passes with a chisel plough and roller were undertaken. For NT, the planter was a John Deere 1750 vacuum with Precision Planting vSet meters and vDrive, Deltaforce, 2020 display, Keeton seed firmers, Martin floating row cleaners, RID gauge wheels, Martin spike closing wheels, and drag chains. Dry fertiliser was applied through JD single disc openers with heavy-duty downforce springs on 2 x 2 placement.

Table 2 records the seeding date and population as well as the germinated population for each paddock in both trials.

Table 1: Crop history for the paddock managed under NT system for seven years before the commencement of the trials.

Harvest Year	Variability Trial Paddock		Tillage Trial Paddock	
	Maize Crop	Cover crop following the maize crop	Maize crop	Cover crop following the maize crop
2012	Silage	Green oats	Grain	Mustard
2011	Silage	Triticale	Grain	Mustard
2010	Grain	No cover crop	Grain	Mustard
2009	Grain	No cover crop	Grain	Mustard
2008	Silage	Annual ryegrass	Grain	No cover crop
2007	Grain	No cover crop	Grain	No cover crop
2006	Silage	Annual ryegrass	Grain	No cover crop

Table 2: Seeding date, seeding population rate and germinated population per paddock during the two trials.

Planting Year	Seeding Population Rate	Germinated Population	Seeding Date
Crop Variability Trial			
2012	97,805	95,238	3/11/12
2013	100,000	96,154	16/10/13
2014	100,000	96,154	21/10/14
Tillage Comparison Trial			
2014: Minimum Tillage	115,000	102,041	25/10/14
2014: No-Till	115,000	106,383	25/10/14

Variability in Maize Growth Trial – (Trial 1)

Each year, for the three consecutive years, plots were marked approximately 30 m apart at VE stage, in a diagonal transect across the same paddock, which allowed eleven plots to be evaluated. Each plot consisted of 5.3 m of rows 4 and 5 (the centre rows of an 8-row planter run as these were not affected by soil compaction from the planter or tractor tyres). Headland rows were not included and the first plot was located approximately 10 m into the paddock. Each plant in the plot was marked with a stake labelled with the Plot and Row Number and the distance along the 5.3 m of the row to ensure each plant was monitored accurately throughout the growing season. Where the end of the plot fell between two plants, the next plant was marked as the last plant in the plot, and all information recorded throughout the crop life of that plant. Because the plots were defined by measurement, the number of plants per plot varied.

To eliminate planter related issues as the cause of the variation in plant growth, the eight rows of the planter run in Plot-1 were all monitored at the same growth stages as the 11-plot transect in that year allowing checking of the performance of each planter unit across the toolbar.

Plant growth was recorded as the number of days after planting that each labelled plant reached specified growth stages using the leaf collar method described by Ritchie *et al.* (1992). Silking was defined as a plant with 2 cm of silk emerged from the husk. Growth stages recorded each year are summarized in Table 3. If a plant died at or before V3, its value was removed prior to the regression analysis as the absence of this plant will have only had a small effect on its neighbours competing for resources of light, moisture, and nutrients. Any plant pest damage observed was recorded by type, level of damage, and any resultant growth effects. Researchers in the US (Douglas & Tooker, 2012) indicated that slugs can act as vectors for plant diseases in potatoes grown in the Mid-Atlantic region of the United States, but this has not been reported on other field crops, however slugs do feed on all plant parts including roots. New Zealand slug scientists have not reported these effects (M. Wilson, *pers. comm.*, 2019).

Tillage Comparison Trial – (Trial 2)

To determine whether the NT establishment method produced different results to minimum tillage (MT), in the third year we monitored a neighbouring paddock (5.9 ha) - a long-term commercial paddock comprising half the paddock being minimally tilled and the other half in long-term no-till. As shown in Table 3, more growth stages were monitored this year, and therefore the number of plots to be monitored was reduced to five plots in each cultivation system, with the eight rows in each of the first plots monitored to confirm the planter was performing correctly. Soil type, weather conditions, and planter details are the same as the other paddock. Crop rotation was slightly different as shown in Table 1.

Harvest Monitoring

For all plots in the two trials, at harvest, every ear was removed from the plant, numbered and the length of the cob with kernels present was measured to the nearest 0.5 cm. Plants that died since the silking stage were noted. Where there was bird damage to kernels on the cob, the length was taken as the length of the cob without bird damage.

Table 3: The growth stage monitoring undertaken each year, hybrids grown in those plots and crop end-use for the plots in each paddock.

Planting Year	Number of Plots	Tillage Method	Growth Stages Monitored	Maize hybrids[a] grown and monitored in paddock and end-use
Crop Variability Trial				
2012	11	Long-term No-Till	V1, V3, V5, Silking, Cob length	P0021, P0537 Grain
2013		Long-term No-Till	V1, V2, V3, V5, Silking, Cob length	P0021, P0537, P0216, P0891, P1253, XOSD486, P0439, XOSA147 Grain
2014	5 (Plots 4-8 inclusive)	Long-term No-Till	V1, V2, V3, V4, V5, Silking, Cob length	P0547, P0021 Silage
Tillage Comparison Trial				
2014	5	Long-term Minimum Tillage	V1, V2, V3, V4, V5, Silking, Cob length	P0891 Silage
	5	Long-term No-Till	V1, V2, V3, V4, V5, Silking, Cob length	P0891 Silage

[a]: Maize hybrids used = Genetic Technologies Limited hybrids

Photographs were taken of the cobs laid out on a white sheet in plant order, with a gap left for any dead plants, plants that produced cobs less than 5 cm long; or any plants that were alive but produced no ear. This provided a visual record of any compensatory effects.

Plant Spacing

The methodology for measuring plant spacing was based on Nielsen (2001). Plant spacing variability was measured as the distance between each plant in the plot row at the V1 growth stage. The SD of the plant spacing and the CV% of plant spacing was calculated from the measured distances between plants in each plot row. Plant spacing was calculated as the average of the distance from one plant to both its neighbouring plants in the row to the nearest 1 cm. 36 to 48 plants were measured in each plot, with the first and last plant values omitted for the plant spacing analysis.

Statistical Analysis

All variables (plant spacing, time to various growth stages, and cob length) were centred for each row in each plot in each year, by averaging the data for each row in each plot in each year and subtracting this mean value from each data value:

$$\textit{Centered variable} = \textit{Variable} - \textit{Mean (variable)}$$

This centering adjusted for spatial effects as well as differences among hybrids, cultivation, and years, and allowed a large amount of data to be examined as a single data set. Relationships between centred variables were then examined using regression correlation, with regression lines restricted to go through the origin.

Regression analyses were conducted for two variables in MS Excel with a single independent variable and were checked in GenStat as a gold standard comparison. Regression analyses were calculated according to Table 4.

The relationship between the two variables was tested for statistical significance using a 5% level test. Scatter graphs were drawn for the two variables and analysed for each year (Trial 1) and the two crop establishment treatments in Year 3 (Trial 2). The best fit trend-line was calculated for the data set (plots not shown) and results presented below.

Table 4: Regression analysis variables.

Dependent variable	Independent variable
Relative cob length	Date plants reached each growth stage
Date plants reached each growth stage	Plant spacing
Cob length	Plant spacing

Results and Discussion

Plant Spacing

The plant spacing SD and CV% results by year are presented in Table 5. The percentage of establishment plant numbers below the recommended SD (of less than 5 cm) and CV% levels (of less than 0.33) (Nielsen, 2001; Doerge, *et. al.*, 2015) in the two experiments ranged from 94 - 100%. 100% of the plots in the NT treatment meet these two recommended criteria, whereas only 94% of the MT treatment plots meet the criteria. However, both the SD and the CV% of NT plant spacing was significantly higher than those of the MT ($p< 0.001$).

In the crop variability experiment, the SD and CV% results were reduced from Years 1 and 2 to Year 3. Each year the range for these figures across the plots reduced suggesting that plant establishment uniformity improved in the three years with higher numbers of plants establishing in each row and the plant spacing variability reducing. This was likely to have resulted from improvements in fine-tuning the planter, including planting into soil conditions that were closer to optimum, an increase in seed populations, seed depth may have increased and seed singulation improved. Also, pest control e.g. slug baiting and cutworm control was timelier. Authors, including Kumar *et. al.* (2012), have found it takes several years following the change from cultivation to NT for soils to stabilize, and increases in soil carbon, aggregate stability, and available water capacity taking time to occur. Weather conditions across the three years varied. The winter and spring in Year 1 were cool and wet resulting in a delayed planting date; while Years 2 and 3 experienced drier winter-spring conditions.

Table 5: Maize plant spacing variability measured at growth stage V1 for two long-term maize paddocks. Trial 1 covered 3 years of continuous NT. Trial 2 measured one year of a long-term tillage comparison between MT and NT. The table shows the ranges in SD and CV% among the eleven plots (two rows of 5.3 m per plot) in Trial 1 and five plots in Trial 2.

Year	SD range	% of plots with SD < 5cm	CV% range	% of plots with CV% < 0.33	% of plots meeting SD and CV% recommendation
Trial 1					
1	1.11 – 6.15	96%	8 –39	96%	96%
2	1.07 – 5.26	96%	8 – 33	96%	96%
3	1.57 – 5.26	100%	12 – 26	100%	100%
Trial 2					
Minimum Tillage	1.08 – 5.30	94%	9 – 33	94%	94%
No-Till	1.06 – 4.14	100%	9 – 31	100%	100%

[1] SD = standard deviation [2] CV% = coefficient of variation

Plant variability and cob length by plot

There is an industry belief that where there is a gap due to a missing plant in a row, the two plants either side will compensate for the gap utilising the available resources and producing larger ears so yield will only be minimally impacted. Assuming kernel depth remains the same, if a grower desired the average cob length to be at least 15 cm of harvestable kernels to provide a realistic return on inputs; then to have full compensatory growth the cob lengths of the two cobs either side of a missing plant would need to be:

$$\text{15cm harvestable kernels} + \frac{\text{15cm harvestable kernels of missing cob}}{2} = \text{22.5cm harvestable kernels}$$

Studying the cob lengths of the individual plot studies show that compensatory cob length was not always occurring in these commercial paddocks. Often there was partial compensatory growth of several extra centimetres of cob length by neighbouring plants but not full compensatory growth. The result of only partial compensation is a reduction in total cob length below expectations for the desired plant population. This is shown in Figure 1 (and photographs of cobs shown in Figure 2), for example - plants at 317–385 cm in the row. There are six plants all producing cobs less than 15 cm long, with the two smallest cobs only 9 cm long. The plants at 306 and 397 cm only produced 15 cm long cobs resulting in very little compensatory effect for the group of small cobs. The plant at 369 cm was noted as being very short at the V5 stage and these six plants had been slow to reach V3, V5, and silking growth stages.

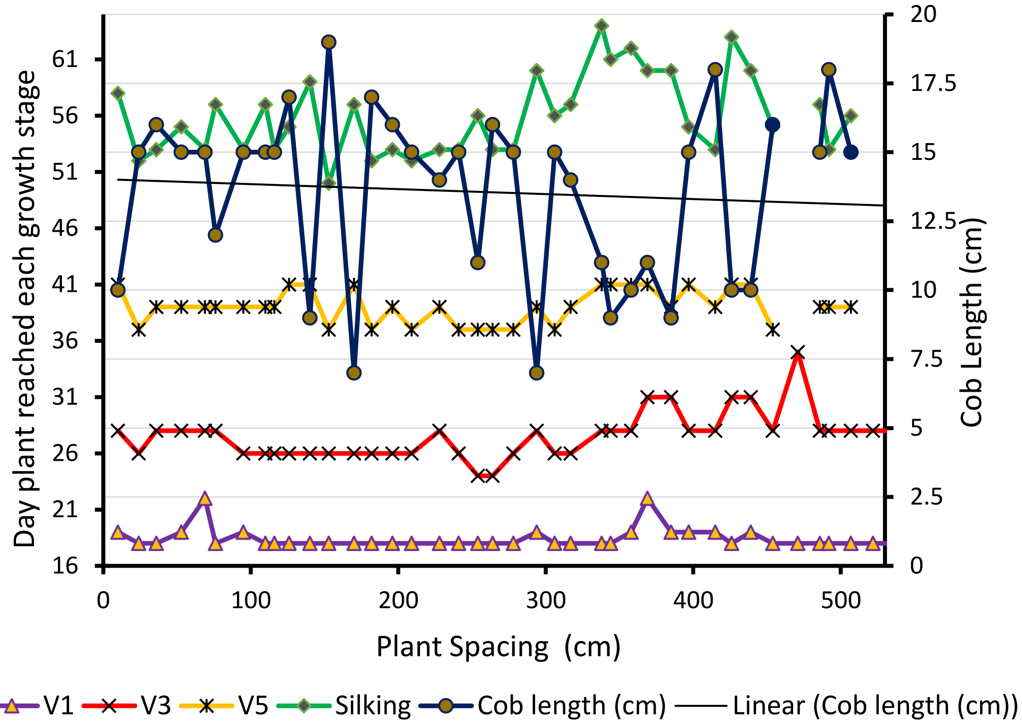

Figure 1: The date individual plants reached each growth stage (from seeding date) and the measured cob length (shown in dark blue, with the average cob length for the plot in black) in Year 1, at Plot 4/4 down the 5.3m length of the row.

Figure 2: Photographs of the consecutive ears harvested in Year One from Plot 4/4, down the 5.3 m length of the row, showing the variation in cob length within the row. Background lines are at 5 cm intervals.

In the plot with the highest total cob length, one plant died before harvest. This plant was the last plant to reach V1 in the plot, and at V2 was observed to have yellowed leaves. It continued to be the last plant in the plot to reach each growth stage and died between silking and harvest. There was only partial compensation of cob length by the plants on either side of this poor performing plant; one cob reached 19 cm but the other was only 15 cm long so very little compensation was achieved.

In the plot that produced the second-longest cobs, four plants had slug damage at V1 or V2 stage, resulting in three cobs achieving only 8-12.5 cm cob length and one cob reached 14 cm long. 14 plants suffered minor slug damage with six of the resultant cobs being 5-12.5 cm long and eight 13-16.5 cm long. Ten of these slug damaged plants were observed to be shorter plants in the plot at the V5 growth stage and one was very small and late reaching the silking stage producing only a 5 cm long cob. It is possible that slug damage could be confounding the results. The ten shortest cobs in the plot (5-12.5 cm long) all reached silking at least four days later than the first plant in this plot and of these nine had minor or major slug damage and nine were observed to be shorter than the other plants in the plot. The plot average cob length was 15.47 cm; with a SD of 3.35 and a CV of 22%. The SD of plant spacing for this plot was 2.20 and the CV was 18%.

Andrade and Abbate (2005). in their thinned plant spacing experiments observed a curvilinear response in average grain yield per plant to vegetative biomass per plant for maize. They suggested that the yield-per-plant increments of dominant plants do not compensate for decreases in yield of dominated plants, so the yield loss of late-emerging plants is not compensated for by a yield increase in the early emerging plants. The team of Liu *et al.* (2004), also manipulated emergence timing and plant spacing and concluded that maize is more responsive to variability in plant emergence than plant spacing resulting in a yield reduction. A two-leaf stage delay in emergence resulted in a cob length reduction of 4% and a four-leaf stage delay in emergence, an 8% reduction in cob length. Future work on this topic will measure grain yield as well as cob length.

From the 46 plots Martin *et al.* (2005), studied they found that the plant-to-plant variation in maize grain yield averaged 2765 kg/ha yet the two sites with the highest average maize grain yield had very different average plant-to-plant variations in yield of 4211 kg/ha and 2926 kg/ha. They also determined that as the average grain yield increased, so did the SD of the yields within each row, but they could not conclusively identify the cause of the variation in yields. Lauer and Rankin (2004) thinned maize plants at V5-6 to a population of 74,000 plants/ha and a range of plant spacings, determining that when the plant spacing variation increased above 12 cm, relative grain yield decreased 1.06% per cm for every 1cm SD above 12 cm. Relative grain yield reduced by up to 18% when plant spacing became more “hill-like” in patterns of two, four and eight-plants separated by a gap. They recommended planters are tuned pre-planting season to ensure plant spacings are correct, although they suggest plants will compensate if plant density in the field is adequate. Plant density in commercial fields has increased since this paper (Lauer & Rankin, 2004) was published.

Plant growth rates

Figure 1 tracks the days (from planting) when each plant in a plot reached growth stages V1, V3, V5, silking, and the resultant length of cob harvested from that plant. Plants reaching a specific growth stage faster or slower than other plants in that row were readily identified. The strongest correlation was between delays in plants reaching silking (peaks in the top line) and smaller cobs (lower points in the cob length line). Analysing the length of cob produced by each plant on the plot graphs showed that delays in reaching growth stages V3 or later often resulted in a shorter cob length. Generally, once a delay occurred at any growth stage, the plant seldom caught up to its neighbours; resulting in the silks being late to emerge compared with other plants in the plot and the plant being observed to be significantly smaller in size than its neighbours at silking. Many of these plants produced small cobs, 10–12 cm in length, and often less than 10 cm in length, compared with full-size cobs of at least 15 cm.

The cumulative regression statistics for Years 1 to 3 are reported in Table 6. This shows that the relationship between cob length and a delay in reaching each growth stage was significant, with 21% of the variance in cob length explained by a delay in reaching the V5 growth stage and 50% of the variance in cob length explained by a delay in the plant reaching silking. The adjusted r^2 values for cob length and reaching plant growth stages V1 – V3 inclusive were lower, explaining 5–20% in the variation in cob lengths.

For a one-day delay in reaching the V5 growth stage, cob length decreased by 0.519±0.049 cm in Years 1 to 3. The results were very similar between the two tillage treatments with the cob length tending to decrease by 0.448±0.074 cm for each 1-day delay in reaching V5 in the MT treatment and 0.429±0.065 cm in the NT treatment.

For each one-day delay in silking, cob length decreased by -0.521±0.026 cm in Years 1 to 3. The results for silking and cob length regression were again very similar in the two tillage treatments with the decrease in cob length for each one day delay to silking in the MT tending to be -0.446±0.043 cm and for the NT -0.419±0.035 cm.

For each one-day delay in silking, cob length decreased by -0.521±0.026 cm in Years 1 to 3. The results for silking and cob length regression were again very similar in the two tillage treatments with the decrease in cob length for each one-day delay to silking in the MT tending to be -0.446±0.043 cm and for the NT -0.419±0.035 cm.

In the tillage comparison, the proportion of the variance for a one-day delay in reaching growth stage V1 or V2 and cob length in the NT was approximately double that in the MT treatment. A one-day delay in reaching growth stage V2 in the MT treatment resulted in cob length tending to decrease by -0.748±0.189 cm and for the NT -1.118±0.172 cm. A one-day delay in reaching growth stage V3 in the MT treatment resulted in cob length tending to decrease by -0.654±0.115 cm and for the NT -0.811±0.155 cm. By growth stage V4 the relationships were very similar for the two treatments and remained similar for the relationship between V5 and silking.

The regression of individual plant space by cob length for Years 1 to 3 showed that for each 1 cm increase in individual plant space, the cob length increased by 0.197 ±0.073 cm. In both treatments, there was a positive but not statistically significant correlation between cob length and plant spacing.

The regression of plants reaching any of the growth stages and individual plant space in each year and the two tillage treatments, showed only weak correlations. Given the large data set, we can be confident that there was a weak correlation between the date a plant reaches any given growth stage and the individual plant space. The adjusted r^2 values are less than 2%, so offer very little explanation as to why plants are slow to reach a given growth stage. The only statistically significant results were V1 and plant spacing in the MT treatment; where for each 1 cm increase in individual plant space, the plants were slower reaching V1 by 0.050±0.042 days. In Year 1, the relationship between silking and plant spacing was statistically significant with a 1 cm increase in plant spacing resulting in plants tending to reach silking date faster by 0.242±0.123 days.

Table 6: Regression statistics analysis for Years 1-3, Trial 1. Percent of variation in y variable explained by x variable.

Variables Years 1-3: X	Y	% variation in y variable explained by x variable	P-value	95 % Confidence Interval for the slope of the trend line
Plant Spacing centred	Delay reaching first V1 date centred	-0.04	0.75	For each 1cm increase in plant spacing, plants reached the first V1 date faster, by 0.003±0.021 days
Plant Spacing centred	Delay reaching first V2 date centred	0.05	0.21	For each 1cm increase in plant spacing, plants reached the first V2 date slower, by 0.032±0.05 days
Plant Spacing centred	Delay reaching first V3 date centred	-0.04	0.71	0.027 ± 0.146
Plant Spacing centred	Delay reaching first V5 date centred	-0.03	0.58	0.016 ± 0.056
Plant Spacing centred	Delay reaching first silking date centred	0.26	0.01	-0.122 ± 0.096
Plant Spacing centred	Cob length centred (cm)	1.69	<0.0001	0.197 ± 0.073
Delay reaching first V1 date centred	Cob length centred (cm)	9.15	<0.0001	-0.935 ± 0.146
Delay reaching first V2 date centred	Cob length centred (cm)	20.24	<0.0001	-0.541 ± 0.076
Delay reaching first V3 date centred	Cob length centred (cm)	4.94	<0.0001	-0.089 ± 0.019
Delay reaching first V5 date centred	Cob length centred (cm)	21.34	<0.0001	-0.519 ± 0.049
Delay reaching first silking date centred	Cob length centred (cm)	50.07	<0.0001	-0.521 ± 0.026

Boomsma, *et al.* (2010), measured plant height and plant height variability at four and eight weeks after emergence in a 14-year study examining the effect of crop rotation (maize – soybean (*Glycine max* L. Merr.) and continuous maize) and the tillage system (No-Till and mouldboard plough). In several years, they found the continuous maize – NT system had reduced actual and relative grain yields and lower plant heights at the four- and eight-week stages compared to other system combinations. However, the actual and relative four and eight-week plant height variability was rarely greatest for this system, and only in a few years were the actual and/or relative plant densities lowest. Boomsma, *et al.* (2010), reported the single–factor regression analysis for a reduction in grain yield was strongest with an increase in relative four-week plant height variability. When ua multi-factor regression analysis of relative yield, four-week plant height variability, and weather parameters was calculated Boomsma, *et al.* (2010), suggested there are two critical periods: 1) pre-plant conditions of cool and wet or warm and dry which can result in non-uniform germination, emergence, and early seedling growth; 2) conditions at rapid stem elongation when low precipitation and/or high temperatures can result in intra-specific competition between dominant and dominated plants. However, this study did not measure maize plant height or rate of growth to allow it to be considered in relation to the findings of Boomsma, *et al.* (2010).

Conclusions

Results from the three years crop monitoring demonstrated a significant correlation between delay in a plant reaching a particular growth stage and decrease in cob length. The strongest detrimental effect on cob length was shown to be a delay in reaching growth stage V5 or silking. There was a weak relationship between growth stages and plant spacing, as well as between plant spacing and cob length. Where there was a plant missing in a row the resultant cob lengths of neighbouring plants are often only achieving partial compensatory growth of several centimetres of cob length, not full compensatory growth. Measurement of the actual grain weight produced by the plots, thereby allowing actual yield to be calculated, would have made the results of this work more relatable.

Therefore attention to uniform plant spacing is important, but there is a greater impact on cob length (and therefore yield) from factors that cause a plant to be slow to reach a given growth stage, especially V5 or silking. Also, once a delay has occurred during early growth stages the plants seldom caught up to their neighbours resulting in the silks being late to emerge compared to other plants in the plot and the plants being smaller in size than their neighbours at silking.

Regression analysis of the one-year comparison between MT and NT indicated there was a similar correlation between growth stages V1 and cob length in both crop establishment treatments but that there was twice the variability of data (r^2) explained in the NT treatment than there was in the MT treatment. By growth stages V4, V5 and silking, regression analysis on cob length showed very similar results between the two crop establishment treatments. The correlations between plant spacing and growth stage for the two crop establishment treatments were very similar. Measurement of these crop establishment treatments over at least three years would be required for more conclusive results.

We have shown plant-to-plant variability begins at the V1 growth stage, with delays in reaching growth stages resulting in delays to silking, and shorter cob length. Further study of the interacting factors is required to understand exactly how to minimise this variability in maize cropping systems in New Zealand to assist growers to improve commercial crop yields.

Acknowledgements

Chris Pellow, Pellow's Produce Ltd for raising the issue of variability in his maize crops, provided the commercial maize crops for this study and assisted with some of the crop monitoring. David Densley, Consulting Manager, Intelact Ltd encouraged the development of this project. Dave Saville, Biometrician, Saville Statistical Consulting Ltd provided invaluable assistance with the statistical analysis of the data set. FAR NZ provided funding to publish this paper. Dr. Jim Camberato, Purdue University for peer-reviewing the paper.

References

Andrade, F.H.; Abbate, P.E. 2005. Response of maize and soybean to variability in stand uniformity. *Agronomy Journal 97*: 1263-1269.

Boomsma, C.R.; Santini, J.B.; West, T.D.; Brewer, J.C.; McIntyre, L.M.; Vyn, T.J. 2010. Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment. *Soil and Tillage Research 106*: 227-240.

Doerge, T.; Jeschke, M.; Carter, P. 2015. Planting Outcome Effects on Corn Yield. Crop Insights Vol 25 No1. Retrieved 12 Dec 2018 from https://www.pioneer.com/us/agronomy/corn_planting_outcome_effects.html /

Douglas, M.R.; Tooker, J.F. 2012. Slug (Mollusca: Agriolimacidae, Arionidae) ecology and management in no-till field crops, with an emphasis on the mid-Atlantic region. *Journal of Integrated Pest Management 3*: C1-C9. Retrieved 3 Dec 2012 from https://www.researchgate.net/publication/230652200

Kumar, S.; Kadono, A.; Lal, R. Dick, W. 2012. Long-term no-till impacts on organic carbon and properties of two contrasting soils and corn yields in Ohio. *Soil Science. Society of America. Journal 76*: 1798-1809.

Lauer, J.G.; Rankin, M. 2004. Corn response to within row plant spacing variation. *Agronomy Journal 96*: 1464-1468.

Liu, W.; Tollenaar, M.; Stewart, G.; Deen, W. 2004. Crop ecology, management and quality. *Crop Science 44*: 847-854.

Martin, K.L.; Hodgen, P.J.; Freeman, K.W.; Melchiori, R.; Arnall, D.B.; Teal, R.K.; Mullen, R.W.; Desta, K.; Phillips, S.B.; Solie, J.B.; Stone, M.L.; Caviglia, O.; Solari, F.; Bianchini, A.; Francis, D.D.; Schepers, J.S.; Hatfield, J.L.; Raun, W.R. 2005. Plant-to-plant variability in corn production. *Agronomy Journal 97*: 1603-1611.

Nielsen, R.L. 2001. Stand Establishment Variability in Corn. Dept. of Agronomy publication AGRY-91-01. Retrieved 12 Dec 2018 from http://www.agry.purdue.edu/ext/pubs/AGRY-91-01_v5.pdf

Ritchie, S.W.; Hanway, J.J.; Benson, G.O. 1992. How a Corn Plant Develops. Sp. Rpt. #48. Iowa State University of Science and Technology. Cooperative Extension Service. Ames, IA

Thompson, T.A. 2013. Within-row spacing effect on individual corn plant yield. MSCS Thesis, University of Illinois, Urbana-Champaign, Illinois.