Biology and survival of broom corn millet (*Panicum miliaceum*) seed

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Abstract The wild type of broom corn millet (*Panicum miliaceum*) is a serious emerging weed, currently prevalent in New Zealand sweet corn (*Zea mays*) crops. This study shows its seed is nearly twice the weight of other common grass weeds and can germinate in the temperature range 16–34°C, with 50% germination at 26°C and greatest germination occurring at 31°C. At 15°C it took 8 days for seedlings to emerge but required only 4 days at 25°C. Seed was able to emerge from depths of up to 170 mm in a range of soils. Experiments showed that broom corn millet seed can persist in the soil for longer than 2 years in the field but is killed in silage stack and bales. Immersion in stock effluent for up to three months reduced seed germination to less than 40%. These characteristics are discussed in relation to herbicide and management control options for this weed.

Keywords *Panicum miliaceum*, broom corn millet, seed biology, wild proso-millet, seed longevity, germination

INTRODUCTION

Broom corn millet (*Panicum miliaceum*) is a grain crop widely grown through the northern hemisphere and known as proso-millet in USA and elsewhere. In 1970 a black seeded biotype of this species appeared in the Midwest of USA (Colosi & Schaal 1997). It quickly became weedy and was called wild proso-millet (Harvey 1979). The black seeded wild-type differed from the cultivated type in that it produced more dry matter and attained greater height in full sun and all levels of shade, as well as producing up to twice as much seed compared to the cultivated type (Eberlein et al. 1990). The seed of the wild-type germinates over a longer period of time (Carpenter & Hopen 1985; Colosi et al. 1988) and its black pigmentation gives the wild-type some weedy characteristics,

making it slower to imbibe moisture and thus greatly extending its persistence in the soil seed bank (Khan et al. 1996).

Since 1961 broom corn millet has undergone multiple entries into New Zealand, finally becoming widespread in sweetcorn crops in Hawke's Bay, Poverty Bay and Marlborough between 1995 and 2005 (James et al. 2010). The early incursions would have been of the cultivated type and apparently have not persisted. However, some of the later incursions were of the wild-type, which have established and been widely dispersed in sweet corn crops by harvesting machinery. Now widespread, this weed is reducing crop yields through competition and interfering with harvesting by clogging machinery.

Broom corn millet seed has no dormancy and is able to germinate within days of shattering under suitable conditions. However, the hard, black palea and lemma around this seed restrict imbibition of water so that germination is generally delayed until they are weakened or damaged (Khan et al. 1996). Broom corn millet has been noted to emerge within a few days of soil disturbance in the field. It appears to be readily controlled by a number of both pre- and post-emergence herbicides but being a C_4 plant, it has a tendency to germinate throughout the growing season when growing conditions are met (Shenk et al. 1990; Harvey & McNevin 1990; Kleppe & Harvey 1991). As a result it frequently escapes control in crops by germinating after the herbicides have dissipated below phytotoxic levels (Carpenter & Hopen 1985; Harvey et al. 1987). The aim of the work presented here was to determine some of the biological traits of broom corn millet seed under New Zealand conditions to assist in designing better control strategies for this weed.

MATERIALS AND METHODS

The broom corn millet seed used in the experiments reported here was produced from potted plants that were grown from seed collected from Hawke's Bay. The seed was stored under dry, ambient conditions in the laboratory and was between 6 and 18 months old when used. Six-month-old seed was tested for germination at 20°C for 16 h alternating with 30°C for 8 h (ISTA 2009) to determine any dormancy of the seed and to investigate how many seeds were required to be tested to obtain meaningful germination data.

Seed weight

Thousand seed weight for broom corn millet was determined by counting and weighing four replicate sets of 1000 seeds. For comparison, single replicates of 1000 seeds were also weighed and counted for seven other C_4 weedy grasses: yellow bristle grass (*Setaria pumila*), barnyard grass (*Echinochloa crus-galli*), rough bristle grass (*Setaria verticillata*), smooth witchgrass (*Panicum dichotomiflorum*), summer grass (*Digitaria*

sanguinalis), witchgrass (*Panicum capillare*) and knot-root bristle grass (*Setaria gracilis*).

Germination temperature range

A Grant Temperature Gradient Plate (Grant Instruments Limited, Cambridge, United Kingdom) was used to determine the temperature range required for seed germination. The temperature gradient plate was set to run a one-way gradient, using a temperature range of 5°C to 34°C. A single layer of K-22 Kimpak (Anchor Paper Company, St. Paul, Minnesota) that had been soaked in water was placed on the plate surface and two layers of steel blue seed germination blotters, also soaked in water, placed on top. The plate was located in a laboratory and received natural light. The plate was split into four replicates and 45 seeds per replicate were placed at even increments up the plate with each increment representing a 1°C change in temperature. Germination on the plate was scored at radicle emergence. Germinated seeds were left on the plate until normal development of the emerging seedling could be assessed. Seed was left on the plate for 64 days when the plate was turned off and remaining seed allowed to germinate at ambient temperature.

The base germination temperature was calculated according to Coolbear et al. (1984) where T_{50} is defined as the time taken from sowing for the median seed to germinate and a plot of $1/T_{50}$ against germination temperature will give a straight line relationship with the x-intercept equal to the base temperature for germination (T_b). Because neither the germination nor the time to 50% germination data was normally distributed, the data were analysed using the Kruskal-Wallis test in SAS (version 9.2, SAS Institute Inc., Cary, NC, USA).

Emergence and growth at different temperatures

Nine broom corn millet seeds were placed at 50 mm depth in each of 16 5-litre pots filled with commercial potting mix (Daltons). Four replicate pots were then placed in constant temperature water baths at 10°C, 15°C, 20°C or

25°C in two separate glasshouses. Commencing on 23 December 2009 the experiment ran for 7 weeks. Supplemental lighting (400 W Na vapour lamps) was used during early morning to provide a photoperiod of 16 h for the duration of the experiment. Each day the pots were inspected for germination and on completion of the experiment both height and dry matter of individual plants were recorded.

Depth of emergence

This experiment was conducted using 16 different cropping soils from various North Island (14 soils) and northern South Island (2 soils) locations. The soils ranged in organic matter content from 3.1 to 10.8%, in bulk density from 0.73 to 0.93 kg/litre and in pH from 4.6 to 7.0. Several 30 mm lengths of 100 mm diameter polyvinyl chloride (PVC) pipe were filled with the test soils and 10 broom corn millet seeds were placed on the soil surface. Extra tubes were then placed on top and packed with the same soil type to give duplicate depths of 30 to 170 mm. The assembled tubes were maintained in a glasshouse at average temperatures between 25°C (day) and 15°C (night). All tubes were watered regularly and each set-up was maintained for 40 days. All broom corn millet seedlings were recorded on emergence. After 40 days the tubes were disassembled and remaining seed examined for viability using the Unimbibed Seed Crush Test (Sawma & Mohler 2002). Regression analyses were carried out between the greatest depth of seedling emergence and soil pH, organic matter and bulk density.

Persistence in the soil seed bank

Eight seed burial sites were located at various locations across New Zealand from Northland to Canterbury. Approximately 200 seeds of broom corn millet (0.855 g) were weighed into a fine mesh bag. For each site 30 lengths (250 mm) of perforated, 60 mm diameter plastic drainpipe were packed with soil and a bag of seed placed at 50 mm from each end. During the winter of 2008, these tubes were buried vertically with their tops flush with the soil surface. This resulted in one bundle of seed being buried 50 mm from the

soil surface and the other at 200 mm. At 1 and 2 years after burial, five tubes from each site were collected and the bags of seed retrieved, noting whether they were from the 50 or 200 mm depth. Each seed bag was opened and the contents mixed evenly through 1 kg of seed raising mix and spread out in trays. These were maintained at ambient temperatures in the glasshouse and watered as required. After 4–6 weeks the emerged seedlings were counted.

Persistence in silage, baleage and effluent

Bags of broom corn millet seed similar to those used for the seed bank study were prepared for this experiment. Ten bags were placed in each of two silage stacks (one grass, the other maize) at the time the stacks were laid down. Five bags were placed deep in the centre of each stack and the other five were placed half way up the side and next to the polythene liner. Similarly, five bags were placed in the centre and five at the edge in each of two polythene-wrapped pasture silage bales (baleage) within 12 h of them being prepared. Tinytag® temperature recorders were also inserted into the baleage, near the centre and adjacent to the wrapping with the seed bags. Fifteen bags of seed were also placed in a dairy farm effluent pond attached to a weighted line to hold them at a depth of about 30 cm. The seed bags were retrieved from the silage and baleage after 3 months while five bags were retrieved from the effluent pond at 1, 2 and 3 months after placement. After retrieval the contents of the bags were evaluated for seed germination in the same manner as for the soil seed bank study.

RESULTS

Seed weight

The thousand seed weight for broom corn millet was 4.269 g (± 0.048 g), which was nearly twice as heavy as the next heaviest seed, yellow bristle grass (2.487 g) and barnyard grass (2.204 g), with the remainder of the grasses tested being far lighter: rough bristle grass (1.280 g); smooth witchgrass (0.897 g); summer grass (0.664); witchgrass (0.493 g) and knot-root bristle grass (0.091 g).

Germination temperature range

More than a third ($37 \pm 2.4\%$) of the seed had germinated in the first 4 days and most of the seed that would germinate had done so within the first week ($83 \pm 5.4\%$). After 21 days only 14% of seed remained ungerminated, of which most (11%) still appeared healthy and viable while 3% was dead.

The minimum temperature at which any germination (1%) was observed was 13°C while maximum germination was 88%, which occurred at 31°C (Figure 1). Although the experiment was left to run on the temperature gradient plate for 64 days, germination on the plate at any temperature had effectively ceased after 5–7 days.

Figure 1 Germination (%) of broom corn millet seed after 64 days at different germination temperatures (error bars are the standard error of the mean).

The time taken to 50% germination was quickest at 34°C ($T_{50} = 46$ h), although this time did not differ significantly between 28°C and 34°C. Regression of $1/T_{50}$ against germination temperature resulted in a regression line that gave a calculated base temperature of 7.4°C (Figure 2).

Emergence and growth at different temperatures

Broom corn millet took more than twice as long to germinate at the lowest temperature of 10°C compared to 25°C (Table 1). As expected, the

Figure 2 Rate of germination ($1/T_{50}$) on the temperature gradient plate at different temperatures.

growth of broom corn millet was also strongly related to temperature (Table 1). The growth of seedlings at the lowest temperature (10°C) was more horizontal than vertical, with more tillers produced compared to other temperatures. Generally, plants grew more in height with increasing temperatures and the highest individual plant height was observed at 20°C. It was noted that in the 20°C and 25°C treatments the broom corn millet plants developed much more extensive root systems, making them more difficult to uproot from the substrate.

Table 1 Mean day of first seedling emergence and growth of broom corn millet after 7 weeks at various temperatures.

Temp. (°C)	Day of first seedling emergence	Average number of tillers/plant	Average height (cm±SD)
10	9	6	65±13.2
15	8	5	88±23.2
20	6	4	100±15.9
25	4	4	75±16.0

Similar to germination results, emergence rate was more than twice as fast at 25°C than at 10°C by 50 days after sowing (Table 2).

Table 2 Number of broom corn millet seeds emerged at different temperatures from a total of 36 seeds planted in pots.

Temperature (°C)	Cumulative number of seeds germinated by Day				
	10	20	30	40	50
10	1	5	7	8	8
15	5	7	7	7	7
20	16	17	17	17	18
25	16	25	27	27	27

Depth of emergence

Broom corn millet was able to emerge in all the soils investigated up to a depth of 120 mm. At this depth between 10 and 90% of the sown seed emerged. Emergence was reduced at the 150 mm depth with seedlings emerging in only 7 of the 16 soils and with a reduced maximum of 60%. At 170 mm depth, emergence occurred in only 6 soils with a maximum of 40%. There was also a clear relationship observed with depth of emergence and plant vigour at the greater depths to such an extent that several of the seedlings from 150 and 170 mm depths died soon after emergence. In addition, there was a clear relationship between depth and time to emergence, with seedlings emerging within 5 days at the shallow depths but taking up to 14 days at the greater depths. Seedling emergence did not appear to be related to any particular soil characteristic.

Persistence in the soil seed bank

With a single exception, persistence of broom corn millet seed was strongly related to burial depth. At seven of the eight sites, seed viability after 2 years ranged from 1–10% when buried at 50 mm but remained at 18–50% at 200 mm depth. The exception was a sandy soil in Bay of Plenty where seed survival was similar (about 40%) at both burial depths after 2 years. At all sites, the viability of seed after 2 years at both burial depths was similar to that after 1 year, suggesting that most of the loss was in the first year after burial. At the shallow depth this was probably mostly due to seed death after germination as at many sites seedling broom corn millet plants were observed in the test areas. Loss of viable seed from the greater 200 mm depth could also

be from germination as the depth of emergence study revealed much suicidal germination (those that died before they emerged) at the greater depths.

Persistence in silage, baleage and effluent

Of the total of 8000 broom corn millet seeds placed in silage and baleage for 3 months, not one seed was found to be viable, irrespective of the seed being placed near the centre or at the edge. The data loggers showed that temperatures in the wrapped baleage never exceeded 40°C with a 10–15°C day/night differential. This indicates that there was little internal heating from fermentation. It is therefore unlikely that temperature alone killed the seed. However, holding broom corn millet seed in dairy effluent for up to 3 months only partially devitalised the seed. On removal from the effluent pond after 1, 2 and 3 months, 76, 62 and 38% of the seed germinated respectively.

DISCUSSION

Eberlein et al. (1990) found that cultivated proso millet seed was heavier (5.8–5.9 mg/seed) than the wild-type seed (3.8–4.0 mg/seed) while Moore & Cavers (1985) found seed of the wild-type ranged in weight from 3.7–6.0 mg/seed. Seed in the present study was slightly heavier than the former but well within the range found by the latter.

The base temperature for germination of 7.4°C calculated in this study is similar to the 6.9°C reported by Wiese & Binning (1987). However, in this study no germination was observed below 13°C and only 1% germination was observed at that temperature after 65 days. In comparison Wiese & Binning (1987) found that

germination occurred at 8°C at or within 21 days. The much slower germination rate and higher minimum germination temperature in the seed lot of *P. miliaceum* evaluated in the present study compared to those reported by Wiese & Binning (1987) may reflect the different development environments of the two seed lots.

The ability of broom corn millet to emerge quickly as well as from deep within the soil is due to its large seed size. James et al. (2002) have previously shown the relationship between seed size and depths from which they can emerge.

The black seed of wild-proso millet has been demonstrated to persist for 4 years or more in a range of soils but greater germination in free-draining soils depleted the seed bank earlier than in poorly drained soils (Colosi et al. 1988). This is in contrast to the results presented here, where seed survival at 5 cm depth was greatest in the free-draining sandy soil.

There has been a large amount of research on the devitalisation of weed seeds in silage but none could be found on broom corn millet. Generally the seed of weedy grasses was much more susceptible to devitalisation than broadleaf weed species (Zahnley & Fitch 1934; Blackshaw & Rode 1991). The results from the effluent pond study are in keeping with that of other researchers (e.g. Humphreys et al. 1997).

The results presented here on some aspects of the biology of broom corn millet seed give good insights into why this weed is so difficult to manage. Maize planting in New Zealand begins when soil temperatures reach 10–12°C. Optimal soil temperatures for planting sweet corn are 20–22°C but planting can begin at the same time as maize, although emergence can take 16–18 days (Reid 2007). As this study has shown that broom corn millet emergence is below 50% at these temperatures, the early planted crop (cooler temperatures) is more likely to get established before broom corn millet emerges. However, for crops planted late, the broom corn millet will emerge at the same time as the crop. Thus with early plantings the crop is more likely to get a competitive edge. However, the broom corn millet plants that emerge later in the season

when temperatures increase, are less likely to be controlled by pre-emergence herbicides due to their efficacy decreasing with time. Late emerging plants could also be difficult to control with post-emergence applications if the crop becomes too tall. If both the crop and weed emerge simultaneously then pre-emergence herbicides are likely to have better efficacy. However, as planting or application of the pre-emergence herbicide often take place a few days after the final cultivation, the rapid emergence (3–4 days) of broom corn millet could enable it to emerge and establish before the herbicide is applied and/or activated.

The ability of broom corn millet to emerge from depths of up to 170 mm means that ploughing to bury the seed and reduce emergence is not a viable option because the seed cannot be buried deep enough by normal equipment. As the deeply buried seed has greater persistence it will simply be returned to the top few cm depth with the next ploughing.

Broom corn millet has the ability to set seed in a very short time if under stress. Normally it would grow into a multi-tillered plant producing thousands of seeds but it was found in both glasshouse and field that when under stress or late germinating (autumn) it is able to set seed within 5 weeks of emergence, much quicker than other *C₄* grass weeds. This makes it very difficult to manage because a small number of plants escaping control are able to replenish the weed seed bank for the following season.

ACKNOWLEDGEMENTS

Funding for these studies was provided by MAF Sustainable Farming Fund, HortNZ and the Foundation for Arable Research.

REFERENCES

- Blackshaw RE, Rode LM 1991. Effect of ensiling and rumen digestion by cattle on weed seed viability. *Weed Science* 39: 104–108.
- Carpenter JL, Hopen 1985. A comparison of the biology of wild and cultivated proso millet (*Panicum miliaceum*). *Weed Science* 33: 795–799.

- Colosi JP, Cavers PE, Bough MA 1988. Dormancy and survival in buried seeds of proso millet (*Panicum miliaceum*). Canadian Journal of Botany 66:161-168.
- Colosi JC, Schaal BA 1997. Wild proso millet (*Panicum miliaceum*) is genetically variable and distinct from crop varieties of proso millet. Weed Science 45: 509-518.
- Coolbear P, Francis A, Grierson D 1984. The effect of low temperature pre-sowing treatment on the germination performance and membrane integrity of artificially aged tomato seeds. Journal of Experimental Botany 35: 1609-1617.
- Eberlein V, Lurvey EL, Miller TL, Michael JL 1990. Growth and development of wild-proso millet (*Panicum miliaceum*) biotypes. Weed Technology 4: 415-419.
- Harvey RG 1979. Serious new weed threat: wild-proso millet. Crops & Soils Magazine 31(2): 10-13.
- Harvey RG, Dekker JH, Fawcett RS, Roeth FW, Wilson RG 1987. Enhanced biodegradation of herbicides in soil and effects on weed control. Weed Technology 1: 341-349.
- Harvey RG, McNevin GR 1990. Combining cultural practices and herbicides to control wild-proso millet (*Panicum miliaceum*). Weed Technology 4: 433-439.
- Humphreys J, Culleton N, Jansen T, O'Riordan EG, Storey T 1997. Aspects of the role of cattle slurry in dispersal and seedling establishment of *Rumex obtusifolius* seed in grassland. Irish Journal of Agriculture and Food Research 36: 39-49.
- ISTA 2009. International rules for seed testing edition 2009. The International Seed Testing Association, Bassersdorf, Switzerland.
- James TK, Rahman A, Webster T, Waller J 2002. Emergence of weeds as affected by vertical seed distribution in arable soils. New Zealand Plant Protection 55: 213-217.
- James TK, Rahman A, Trivedi PD 2010. Broom corn millet (*Panicum miliaceum*): a new menace for maize and sweetcorn growers in New Zealand. In: Zydenbos S ed. Proceedings of the 17th Australasian Weeds conference, Christchurch, New Zealand. Pp. 32-34.
- Khan M, Cavers PB, Kane M, Thompson K 1996. Role of pigmented seed coat of proso millet (*Panicum miliaceum* L.) in imbibition, germination and seed persistence. Seed Science Research 7: 21-25.
- Kleppe CD, Harvey RG 1991. Postemergence-directed herbicides control wild-proso millet (*Panicum miliaceum*). Weed Technology 5: 746-752.
- Moore DRJ, Cavers PB 1991. A comparison of seedling vigour in crop and weed biotypes of proso millet (*Panicum miliaceum*). Canadian Journal of Botany 63: 1659-1663.
- Reid JB 2007. Sweet corn toolkit manual. Crop & Food Research, Hastings New Zealand.
- Sawma JT, Mohler CL 2002. Evaluating seed viability by an unimbibed seed crush test in comparison with the tetrazolium test. Weed Technology 16: 781-786.
- Shenk MD, Braunworth WS, Fernandez RJ, Curtis DW, McGrath D, William RD 1990. Wild-proso millet (*Panicum miliaceum*) control in sweet corn (*Zea mays*). Weed Technology 4: 440-445.
- Wiese AM, Binning LK 1987. Calculating the threshold temperature of development for weeds. Weed Science 35: 177-179.
- Zahnley JW, Fitch JB 1934. Effect of ensiling on the viability of weed seeds. Journal of the American Society of Agronomy 26: 816-822.