New Zealand Journal of Agricultural Research

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tnza20

Tolerance of plantain (*Plantago lanceolata*) to translocated herbicides wiped on flower stems

Nidhi Shrivastav, Kerry C. Harrington, Peter D. Kemp, Xiong Z. He & Hossein Ghanizadeh

To cite this article: Nidhi Shrivastav, Kerry C. Harrington, Peter D. Kemp, Xiong Z. He & Hossein Ghanizadeh (07 Jul 2024): Tolerance of plantain (*Plantago lanceolata*) to translocated herbicides wiped on flower stems, New Zealand Journal of Agricultural Research, DOI: 10.1080/00288233.2024.2373218

To link to this article: https://doi.org/10.1080/00288233.2024.2373218

Published online: 07 Jul 2024.

NEW ZEALAND JOURNAL OF AGRICULTURAL RESEARCH
https://doi.org/10.1080/00288233.2024.2373218

RESEARCH ARTICLE

Tolerance of plantain (*Plantago lanceolata*) to translocated herbicides wiped on flower stems

Nidhi Shrivastav, Kerry C. Harrington, Peter D. Kemp, Xiong Z. He and Hossein Ghanizadeh

School of Agriculture and Environment, Massey University, Palmerston North, New Zealand

ABSTRACT
Growing plantain (*Plantago lanceolata*) within pastures reduces nitrate leaching following grazing. Plantain is usually grown with grass and clover species, making selective weed control challenging. One strategy to selectively remove tall weeds in pastures with mixed species is to apply herbicides using weed wipers. However, for many months of the year, plantain has upright leafless flower stems that will intercept herbicide applied using wipers. To determine if this means plantain might be damaged by wipers used in such swards, two glasshouse experiments tested the tolerance of mature plantain plants to the application of herbicides suitable for use in weed wipers (glyphosate, clopyralid, aminopyralid, dicamba, metsulfuron, picloram and triclopyr) to the flower stems. Aminopyralid (0.075% ai solution) and a low rate of glyphosate (1.8% ai) caused the least decrease in plantain biomass and should be safe for weed wiping within swards containing plantain. A higher rate of glyphosate (7.2% ai) and a glyphosate/metsulfuron mix (0.9% + 0.01% ai, respectively) caused the most damage to plantain, particularly following simulated rainfall after application. Thus, applying some herbicides using wipers should be possible for selective weed control within plantain swards even if rain falls soon afterwards, though field trials are required to fine-tune recommendations.

ARTICLE HISTORY
Received 23 January 2024
Accepted 21 June 2024

KEYWORDS
Herbicide application; plantain; pasture; weed management; weed wipers

Introduction

Narrow-leaved plantain (*Plantago lanceolata* L., hereafter called plantain) is a perennial plant species, and although considered to be a weed in some situations, cultivars that have been bred to be more productive have gained popularity in several countries, such as Australia, Ireland and New Zealand, for pasture production (Nguyen et al. 2022), where it is sown either alone or in a mix with other pasture species (Dodd et al. 2019). High productivity and nutritional values and its potential to mitigate nitrogen (N) loss from dairy farm systems are the primary reasons for the wide adoption of plantain as a pasture species (Bryant et al. 2019). Inclusion of plantain in mixed swards can

CONTACT Kerry C. Harrington K.Harrington@massey.ac.nz

effectively decrease nitrogen excreted in urine from livestock production systems while maintaining similar herbage production to perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) mixes (Box et al. 2016; Box and Judson 2018; Navarrete et al. 2022), thus reducing the ecological impact of grazing animals.

Plantain can be planted into pasture swards with ryegrass and clovers either by sowing seeds of all three species into newly prepared seedbeds or by introducing plantain into established ryegrass/clover swards by oversowing (seed broadcast on to pasture) or undersowing (seed drilled into pasture) (Bryant et al. 2019). Plantain generally only lasts a few years when grown with ryegrass/clover swards so either needs to be resown back into swards or the pastures need to be managed to allow seeds produced by plantain plants to re-establish within the swards (Dodd et al. 2019). Plantain flowers are wind-pollinated and self-incompatible, with annual seed production from each plantain plant varying from only a few hundred seeds to 10,000 seeds, depending on competition exerted by neighbouring plants (Cavers et al. 1980).

When considered to be a weed, plantain is generally only removed selectively using herbicides from turf where pure grass is desired, in which case MCPA is adequate by itself, though control can also be obtained with 2,4-D, mecoprop or picloram (Harrington 2000). In pastures, weeds are a problem because they can reduce livestock grazing by limiting utilization and reduced production by competing with pasture swards for moisture, light, and nutrients (Ghanizadeh and Harrington 2019). Plantain that has not been bred for improved productivity has for many years been considered as a weed in pastures because once established, it prevents more productive species from occupying these areas within paddocks (Matthews 1975). Herbicides are useful tools for weed management and maintaining production in pastures; nevertheless, it can be quite a challenge to find herbicides that are suitable for mixed-species pastures in which productive cultivars of plantain are wanted, primarily because very few herbicides can control well established weeds selectively without harming some of the pasture species within a mixed sward (Gawn et al. 2012; Harrington et al. 2017; Ghanizadeh and Harrington 2019).

One way to achieve selective weed control in a pasture is by applying herbicides with a weed wiper. This is a technique used to selectively control upright weed species in pastures and low-growing crops (Harrington and Ghanizadeh 2017). The concept of a weed wiper applicator is like painting with a pad or roller where absorbent material is saturated with herbicide solution and used to wipe a translocated herbicide onto plant parts growing above the height of the pasture, so herbicide is applied only to the weed species (Royston et al. 2006). Weed wipers have been available for several decades but there is a limited understanding of factors affecting their use, and only limited information is available on the use of herbicides applied with wipers to control weeds of pastures (Moyo et al. 2016; Harrington and Ghanizadeh 2017).

In our earlier work, we found that a cultivar of plantain (i.e. Agritonic) can tolerate some selective herbicides in both glasshouse and field conditions when weeds typically found in new pastures and plantain are both young (Shrivastav 2023; Shrivastav et al. 2023). Once plantain-based pastures are well-established, many of these herbicides are ineffective on older weeds, e.g. herbicides such as bentazone and low rates of MCPB will not control species such as broad-leaved dock (*Rumex obtusifolius* L.) or even annual species such as redroot (*Amaranthus powellii* S. Watson) once past the seedling stage (Holden 2023). One possibility to control such weeds is to use a wiper applicator to apply herbicides such as glyphosate or aminopyralid to weed species such as Californian thistle (*Cirsium arvense* (L.) Scop.) or broad-leaved dock when they have grown taller than the surrounding sward. However, at many times of the year when these species are taller than the pasture, plantain has leafless flower stems that are also taller than the surrounding pasture. Although pastures are usually grazed prior to using a wiper applicator to increase the height differential between the unpalatable weeds and the sward, the plantain flower stems can often also remain ungrazed.

Wipers allow very effective, non-selective, systemic herbicides to be used as they are applied only to the weeds, but research is required to determine if application to plantain flower stems results in damage to the plants, either from herbicide translocation or subsequent redistribution by rainfall. Thus, the objective of the glasshouse experiments reported below was to test the tolerance of two cultivars of plantain, Agritonic and Tonic, to the application by wiping of some herbicides suitable for use in weed wipers (glyphosate, metsulfuron, clopyralid, aminopyralid, dicamba, picloram and triclopyr) to the flower stems, simulating potential contact during weed wiping of pasture weeds. Glasshouse experiments were used rather than field trials to reduce the variables that can affect results, though some treatments did involve simulated rainfall as this can result in herbicide damage to lower foliage after application (Harrington et al. 2016).

Materials and methods

Two plantain seeds were sown in each of 128 PB¾ planter bags (64 each for Agritonic and Tonic), each filled with 0.4 L of potting mix (Dalton Base mix, which was comprised of 50% Fines A grade *Pinus radiata* bark size 0–12 mm with added calcium ammonium nitrate, 30% coco fibre and 20% Pacific pumice 7 mm) with 500 g long-term Osmocote, 50 g Osmoform and 150 g dolomite per 100 L of potting mix, in a heated glasshouse with sub-irrigation. Plants were thinned to one plant per bag at the 2-leaf stage. When the plants had fully established and developed flower stems, the number and average height of flower stems were measured for each plant, and all the leaves were cut to 7 cm to have a uniform length (simulating grazing), though flower stems were not cut. Canes were used to tie the flower stems loosely upright so they did not bend over neighbouring plants.

A range of herbicides (Table 1) was applied to the flower stems of both cultivars, using concentrations recommended for wiper application to weeds (Table 2). A paper towel was moistened with each solution and wrapped around all parts of the flower stems above a height of 12 cm from the ground level for about 5 s, with care being taken to ensure no

Table 1. Trade names and formulation details of herbicides used.

Herbicide	Trade name	Formulations
glyphosate	Nufarm Weedmaster G360	360 g ai L^{-1} glyphosate (isopropylamine salt)
metsulfuron	Answer	200 g kg^{-1} metsulfuron (methyl ester)
clopyralid	Dow AgroSciences Versatill	300 g L^{-1} clopyralid (amine salt)
aminopyralid	Dow AgroSciences Tordon Max	30 g L^{-1} aminopyralid (trisopropylamine salt)
dicamba	Nufarm Kamba 500	500 g L^{-1} dicamba (dimethylamine salt)
triclopyr/picloram/aminopyralid	Tordon Brushkiller XT	300 g L^{-1} triclopyr (butoxyethyl ester) and 100 g L^{-1} picloram and 8 g L^{-1} aminopyralid as amine salts, also contains 367 g/L diethylene glycol

Table 2. List of treatments applied to the plantain flower stems.

Herbicides	Ratio of herbicide product to water	Herbicide concentration (g ai L^{-1})
untreated control	–	–
glyphosate (low rate)	1:20	18
glyphosate/metsulfuron	1:40 (+ 0.5 g L^{-1})	9 + 0.1
glyphosate (high rate)	1:5	72
clopyralid	1:40	7.5
aminopyralid	1:40	0.75
dicamba	1:40	12.5
triclopyr/picloram/aminopyralid	1:40	7.5 + 2.5 + 0.2

dripping occurred on to leaves of the plants. The herbicide was applied using paper towels rather than a wiper partly to ensure plenty of herbicide was applied to each stem and partly to avoid cross-contamination of herbicides between treatments if wipers had been used (which are very difficult to clean). The plants were spread out after applying herbicides to allow the herbicide to dry without dripping from the stems. After 24 hours, half of the treated plants were exposed to overhead irrigation for 8 minutes to simulate 2 mm of rainfall. As the plants had been in small planter bags for 6 months, Osmocote Pro (3-4 months-controlled release) fertilizer granules were applied at 1.6 g per bag 3 weeks after herbicide treatment to provide additional nutrition to the plants.

The experiment was conducted using a randomized complete block design with four replicates of two cultivars (i.e. Agritonic and Tonic), eight different herbicidal treatments, and two rainfall scenarios (with and without overhead irrigation). As the plants varied quite substantially in the number of stems present at treatment, the block design allowed plants to be allocated to replicates depending on the number of flower stems so that replicates varied in flower stem number. Stems varied in their stage of development, though those that were old and brown were removed and not counted. The daily maximum and minimum temperatures during the 2 weeks after spraying averaged 23.5°C and 17.0°C, respectively. Two months after herbicide treatment, all plants had leaves cut to a height of 7 cm, and the cut leaf material was oven dried at 70°C for 48 hours and weighed. Stems were also cut to 7 cm at this time to make it easier to harvest the new leaf growth, and the stem material was then discarded. Two other dry weight assessments were done for each plant, using the same method, at 3 and 4 months after herbicide treatment, so that for treatments where there was an initial check in growth, it could be determined if and when plants recovered from this decrease in production. This experiment (First Wiping Experiment) was repeated 1 year later (Second Wiping Experiment), using the same procedure as described above. For each of the two experiments, plants were sown in winter and treated in early summer, with no supplemental lighting.

Statistical analysis

All data were analysed using SAS v.9.13 software (SAS Institute, Cary, NC, USA) with $\alpha = 0.05$. A general linear model (GLM Procedure) was applied to determine if the dry weight of plantain was affected by block, cultivar, rainfall and herbicide, to quantify any interactions of cultivar, rainfall, herbicide, block and time of harvest, as well as the interactions of cultivar, rainfall, and herbicide with time. Data on the total dry weight of plantain regrowth for the three harvests across both cultivars affected by different herbicides were analysed using ANOVA (GLM Procedure) with a least significant difference (LSD) for multiple comparisons between treatments.

Results

First wiping experiment

The herbicide treatments differed significantly in their effect on the total dry weight of plantain (Table 3, Figure 1). The 1.8% glyphosate treatment caused almost no reduction in total dry weight compared with the untreated control, whereas all other herbicide treatments did cause a marked reduction in dry weight. The most damaging was the 7.2% glyphosate treatment, though only one plant had died from any of the treatments by the final harvest 4 months after application, which occurred for a plant treated with triclopyr, picloram and aminopyralid then subjected to simulated rainfall (data not shown).

There was a significant effect of cultivar on dry weight of plantain plants within the experiment (Table 3), with the Agritonic plants consistently out-performing the Tonic plants. The average final dry weight of new growth following treatment for the Agritonic plants was 6.15 g, compared with 4.64 g for Tonic plants. However, there was no significant interaction between cultivar and effects of herbicides, so none of these herbicides appeared to affect Tonic plants more than Agritonic plants. Thus, results from the two cultivars were averaged for Figure 1.

Despite the equivalent of 2 mm of rainfall being applied to some of the plants 24 hours after treatment, the overall effect of rainfall on dry matter results for Experiment 1 was not significant, though the interaction between rainfall and herbicide effects was significant (Table 3). As can be seen in Figure 1, the 7.2% glyphosate treatment appeared to be less damaging to the plantain after rainfall, whereas the triple mixture of triclopyr, picloram and aminopyralid was significantly more damaging following the rainfall.

The only significant interaction between the dry weight measured at each harvest ('time') and the treatments was for the herbicides applied (Table 4). As can be seen in Figure 1, some herbicide treatments such as dicamba and aminopyralid appeared to be boosting the plant dry weight at the first harvest compared with the untreated control and the least affected treatment, the 1.8% glyphosate. By the third harvest, there was much less dry weight being produced by plants treated with dicamba and aminopyralid than the untreated control plants, though plants treated by all herbicides were still producing new growth for all three harvests.

Table 3. ANOVA table for test of between-subjects effects (cultivar, rainfall and herbicides) on plantain dry weight for first wiping experiment.

Source	df	Mean Square	F	Sig.
Block	3	13.8	4.25	0.0074
Cultivar	1	72.4	22.3	<0.001
Rainfall	1	0.038	0.01	0.914
Herbicides	7	68.9	21.2	<0.001
Cultivar * Rainfall	1	0.14	0.13	0.708
Cultivar * Herbicides	7	4.17	1.29	0.265
Rainfall * Herbicides	7	7.50	2.31	0.032
Cultivar * Rainfall * Herbicides	7	1.66	0.51	0.824
Error	93	3.24		

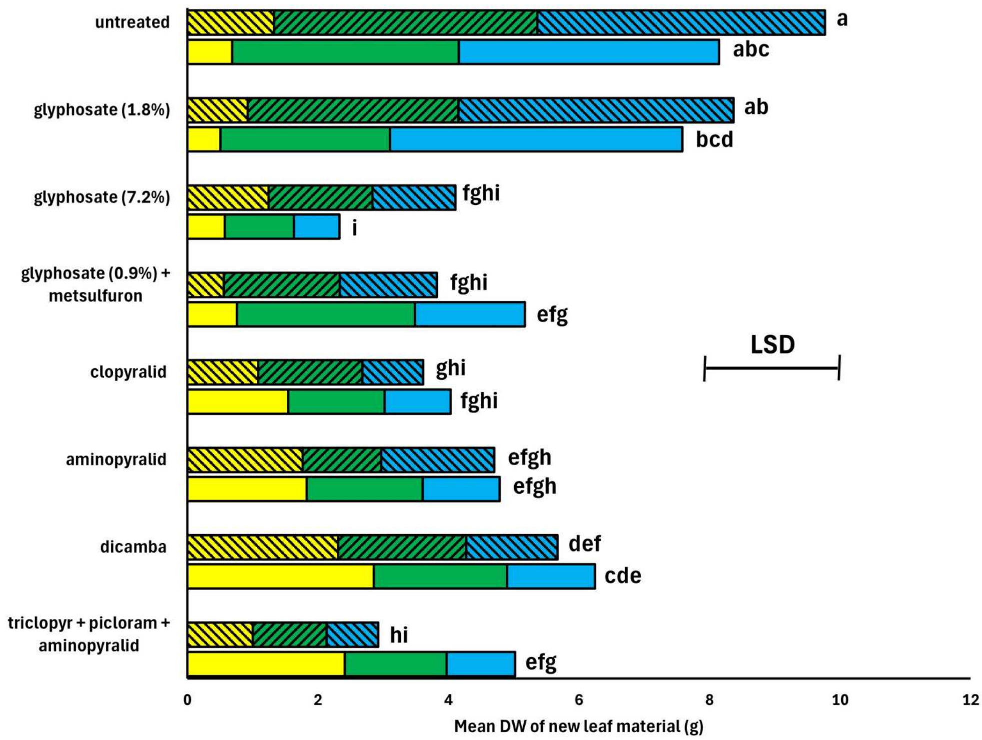

Figure 1. The effect of herbicide treatments in Experiment 1 on dry weight of plantain regrowth for Harvest 1 (yellow), Harvest 2 (green) and Harvest 3 (blue) averaged across both cultivars, with separate bars for when rainfall was simulated after treatment (cross-hatched) and for no rainfall (plain). The least significant difference (LSD) bar is for total dry weight at $p = 0.05$. Treatments that share the same letter had no significant difference in total dry weight at $p = 0.05$.

Second wiping experiment

Herbicide treatments also had a significant effect on the dry weight of plantain in the second experiment (Table 5, Figure 2). However, results differed in some ways from those obtained in the first wiping experiment. Although there was little impact of 1.8% glyphosate on plantain again in the second experiment, there was also much less of an adverse effect of aminopyralid, the triclopyr/picloram/aminopyralid mixture or

Table 4. ANOVA table for tests of within-subjects effects (time) with cultivar, rainfall and herbicides on dry weight for the first wiping experiment.

Source	df	Mean Square	F	Sig.
Block	4	314.0	481.1	<0.001
Time	2	21.5	32.9	<0.001
Time * Cultivar	3	8.8	13.5	<0.001
Time * Rainfall	3	0.19	0.29	0.833
Time * Herbicides	21	17.4	26.7	<0.001
Time * Cultivar * Rainfall	3	0.72	1.10	0.348
Time * Cultivar * Herbicides	21	0.82	1.25	0.207
Time * Rainfall * Herbicides	21	1.19	1.82	0.017
Time * Cultivar * Rainfall * Herbicides	21	0.33	0.50	0.966
Error	285	0.65		

Table 5. ANOVA table for test of between-subjects effects (cultivar, rainfall and herbicides) on plantain dry weight for second wiping experiment.

Source	df	Mean Square	F	Sig.
Block	3	32.3	2.97	0.036
Cultivar	1	96.8	8.91	0.004
Rainfall	1	168.5	15.5	<0.001
Herbicides	7	157.0	14.5	<0.001
Cultivar * Rainfall	1	1.72	0.16	0.692
Cultivar * Herbicides	7	12.5	1.15	0.337
Rainfall * Herbicides	7	17.2	1.59	0.149
Cultivar * Rainfall * Herbicides	7	3.6	0.34	0.936
Error	93	10.9		

clopyralid compared with the first experiment. The 7.2% glyphosate treatment was again the most damaging treatment, but the metsulfuron/glyphosate mixture was just as damaging.

Another difference between the two experiments was that rainfall had a highly significant impact on damage caused by herbicides in the second experiment, though the interaction with herbicides was not significant in the second experiment (Table 5). This time, rainfall consistently resulted in increased damage from herbicides, with marked differences especially for dicamba and the metsulfuron/glyphosate mixture between treatments where no rain fell after treatment compared with 2 mm of rain simulated 24 hours after treatment.

Consistent with Experiment 1, there was a significant effect caused by cultivars but no significant interaction with herbicides or rainfall (Table 5), allowing data to be averaged for Figure 2. Agritonic plants out-performed Tonic plants again, with the average final dry weight of new growth following treatment for the Agritonic plants being 10.02 g, compared with 8.28 g for Tonic plants. The greater production in the second experiment was probably caused by increased fertiliser application as nutrients appeared to be lacking in the first experiment.

Only one plant died in Experiment 1 yet nine died in Experiment 2, with similar numbers of Tonic and Agritonic plants affected (data not shown). Once plants from the two cultivars were combined for analysis, this gave eight plants for each treatment combination of herbicide and rainfall. In Experiment 2, three plants died that were treated with 7.2% glyphosate, of which one had no rain treatment and the other two were exposed to simulated rainfall. All the remaining plants that died had been exposed to simulated rainfall after herbicide application, with five of these treated with the glyphosate/metsulfuron mix and the other treated with dicamba. All plants that died were from replicates that had high numbers of flower stems when treated. This was consistent with the significant block effect for both experiments, with more flower stems at treatment resulting in more damage caused by applied herbicides.

As with the first experiment, there was a significant interaction between the dry weight measured at each harvest and the herbicides applied (Table 6). Although the effect was not as marked as in the first experiment, once again some of the hormone herbicide treatments such as clopyralid, aminopyralid and the triclopyr/picloram/aminopyralid treatments appeared to have grown better than other treatments by the first harvest but not by later harvests.

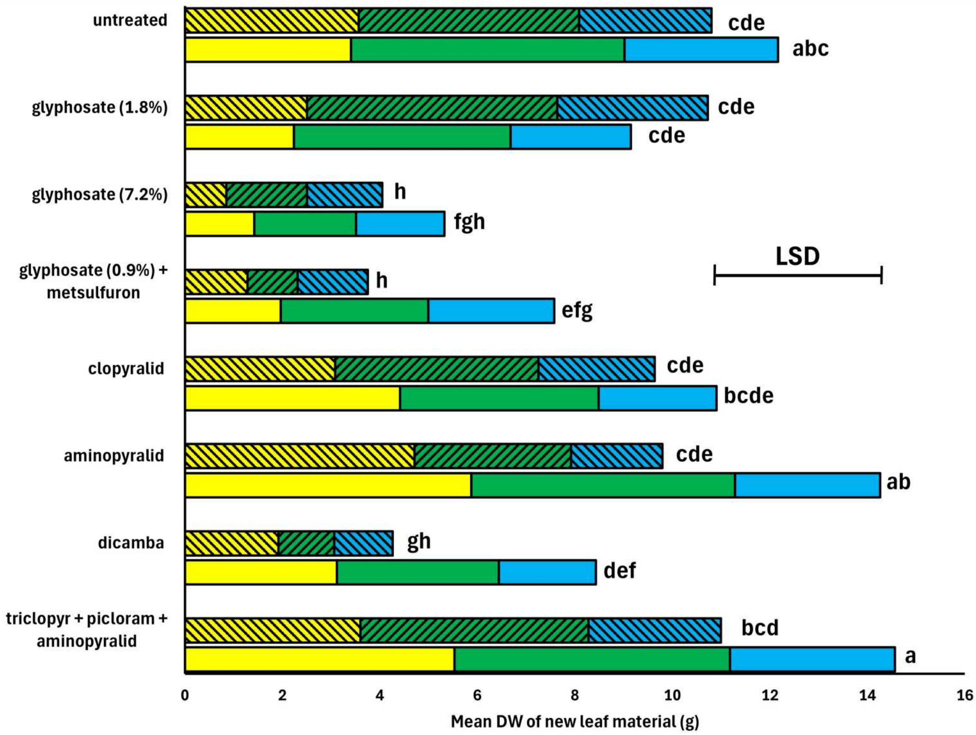

Figure 2. The effect of herbicide treatments in Experiment 2 on dry weight of plantain regrowth for Harvest 1 (yellow), Harvest 2 (green) and Harvest 3 (blue) averaged across both cultivars, with separate bars for when rainfall was simulated after treatment (cross-hatched) and for no rainfall (plain). The least significant difference (LSD) bar is for total dry weight at $p = 0.05$. Treatments that share the same letter had no significant difference in total dry weight at $p = 0.05$.

Discussion

The herbicide treatment that consistently caused the least damage to plantain when applied to flower stems of the plants was the 1.8% glyphosate solution, which equates to a 1:20 mix of 360 g ai L^{-1} glyphosate products mixed with water. This concentration has been shown elsewhere to give effective control of troublesome pasture weeds such as *Cirsium arvense* (Rotowiper 2004; Moyo et al. 2022).

Table 6. ANOVA table for tests of within-subjects effects (time) with cultivar, rainfall and herbicides on plantain dry weight for second wiping experiment.

Source	df	Mean Square	F	Sig.
Block	3	10.8	5.41	0.0012
Time	2	57.6	29.0	<0.001
Time * Cultivar	3	14.6	7.34	<0.001
Time * Rainfall	3	20.3	10.2	<0.001
Time * Herbicides	21	23.3	11.7	<0.001
Time * Cultivar * Rainfall	3	0.76	0.38	0.766
Time * Cultivar * Herbicides	21	1.85	0.93	0.552
Time * Rainfall * Herbicides	21	2.78	1.40	0.117
Time * Cultivar * Rainfall * Herbicides	21	0.90	0.45	0.982
Error	285	1.99		

We had assumed that wiping systemic herbicide on the upper part of leafless stems of plantain would not damage the plants too badly as photosynthesising cells present in these stems should send sugars they produce to the nearest sink, which would be the flower head with developing seeds (Grekul et al. 2005; Wilson et al. 2006). However, these experiments were needed to test this hypothesis, and to also investigate whether simulated rainfall soon after application might wash herbicide down to plantain leaves below the stems. There was no evidence in either experiment of rainfall washing down herbicide being a problem for the 1.8% glyphosate solution.

If the herbicide was mainly moving into the developing seeds of the plantain plants, the probability is high that the viability of these seeds would have been affected. This was not investigated with our experiments as the emphasis of the work was to determine whether the productivity of the plantain plants would be affected as sources of fodder for livestock. Removing the flower stem at the first harvest made it easier to cut the foliage at 7 cm height at each harvest, simulating defoliation by livestock. Loss of viability of the seeds might cause problems if continued persistence of plantain in pastures relies on re-establishment of plants from fallen seeds once swards begin to thin out (Dodd et al. 2019). However, plantain produces a large number of flower stems throughout each season (Cavers et al. 1980) so affected plants might be expected to have produced seeds earlier or later in the season than when the herbicide treatment occurred.

Although applying the herbicide using soaked paper towels was not directly equivalent to applying it using a traditional wiper such as the Rotowiper, this was done to reduce the variability that usually occurs when applying herbicide from a passing wiper. It has to be assumed that much more herbicide would be applied by wrapping a paper towel soaked with herbicide solution around both sides of all stem material above 12 cm height for 5 s compared with a rapid touching of a wiper from one side in field applications. Thus, this was a very rigorous test of the crop safety of the herbicides, applying more than is likely to occur normally. For the 1.8% glyphosate solution to cause almost negligible damage from this application, and from having 2 mm of simulated rainfall within 24 hours of application (more than would typically be expected so soon after application) suggests strongly that this treatment will be safe to use in the field.

The greater level of damage that occurred for plants that had the most flower stems implies this was due to higher doses of herbicide being applied to these plants. If we assume a similar amount of herbicide was applied to each treated flowering stem, then the amount of herbicide applied to each plant would have been proportional to the number of stems treated, which explains why those plants which died usually had more stems than plants that did not die. This plant death would probably also occur in field applications with a wiper, but if less herbicide is applied using a wiper than with moist paper towels wrapped around all sides of the stem for a longer contact time, death might be less likely in the field. The average length of green stem material treated with herbicide in Experiment 1 was 284 cm plant^{-1}, compared with 339 cm plant^{-1} in Experiment 2. This is only a 19% increase on average, and there was much variability in treated stem length within each experiment, but this greater stem length is one possible reason for increased deaths in Experiment 2.

Although the 7.2% glyphosate solution caused significant levels of damage in both experiments, it was four times more concentrated than the 1.8% solution that appeared to be safe to use. Also, the rigorous application method discussed above may have resulted in it causing more damage than might occur from normal wiper application. The main reason for including this treatment was to test whether a higher concentration of glyphosate might be less safe to use. On many herbicide labels, the suggested application rate for wiping 360 g ai L^{-1} formulations of glyphosate to weeds is one part herbicide product to two parts water, as opposed to the 1:20 ratio we found to be safe. This very strong concentration of glyphosate was originally put on herbicide labels for the earliest ropewick applicators which applied much less solution to weeds than modern wipers (Harrington and Ghanizadeh 2017). With trial results showing the improved applicators such as the Rotowiper with much larger wiping surfaces give good weed control using the 1:20 ratio (Moyo et al. 2022), these stronger concentrations are not needed for adequate weed control and the results in our current work show that crop damage is more likely if stronger concentrations are used.

One of the more common weed species found in pastures containing plantain are docks such as broad-leaved dock. The 1:20 concentration of glyphosate is known to give poor control of docks due to a partial tolerance of these species to low rates of glyphosate, with the most effective treatment if using a wiper being the glyphosate/metsulfuron mixture included in our experiments (Rotowiper 2004). Unfortunately, the inclusion of metsulfuron to glyphosate appeared to be one of the most damaging treatments we assessed, causing some plant death in the second experiment. Even in the treatments with no rainfall, there was some damage recorded, suggesting that there may have been movement down to the leaves other than from rainfall, perhaps from translocation or dripping after application.

Other herbicides known to control dock species when applied using conventional spraying equipment are dicamba, aminopyralid and the triclopyr/picloram/aminopyralid mixture (Holden 2023). All of these are translocated herbicides suitable for use in weed wipers. Dicamba and aminopyralid are both herbicides known to have such minimal effects on plantain that some formulations are registered in New Zealand for controlling weeds selectively in pure plantain crops when applied at lower concentrations by conventional spray equipment (Holden 2023). Despite this, dicamba appeared to be rather damaging to plantain in the two experiments, especially after rainfall in the second experiment. However, there has been little use of dicamba in wiper applicators so the concentration selected for this trial was a 1:40 ratio with water as recommended for aminopyralid and some triclopyr/picloram products (Holden 2023). This dicamba concentration was shown by these experiments to be too concentrated to be used safely, especially when so much was applied using the paper towels. Field trials would be needed to determine if dicamba can be used safely to control docks in plantain-based pastures.

The safety of treatments such as aminopyralid and the triple mix of triclopyr, picloram and aminopyralid are difficult to determine based on the two experiments, because they appear fairly safe in Experiment 2 but resulted in significantly reduced dry matter of plantain in Experiment 1. As with dicamba, aminopyralid is known to have little effect on plantain when applied using spray application to the foliage of plantain, so the decrease in dry matter production following application only to the flower stems using the recommended rate for use in a weed wiper suggested too much was applied in Experiment 1. As less herbicide would be applied using a standard wiper than the moistened paper technique used in the experiments, presumably results such as those shown in Experiment 2 with almost no negative effect on plantain are the more likely results that will be obtained in the field.

These experiments only examined the effect on plantain production. Plantain is often grown in combination with clovers in pasture swards (Dodd et al. 2019). Work that has been conducted in the field with wipers by Moyo et al. (2022) showed that for herbicides wiped on to *Cirsium arvense* plants growing above clover, damage was severe to clovers from metsulfuron, clopyralid or a triclopyr/picloram mixture, but not from a 1.8% glyphosate treatment. This was assumed to be caused by rainfall washing herbicide down to the clover, and that white clover tolerates low rates of glyphosate but is very sensitive to the other herbicides. Aminopyralid is also very damaging to clovers (Holden 2023). In addition to being tolerated best by the plantain in both experiments, the 1.8% glyphosate treatment would also be a safer treatment for clovers growing with plantain.

Conclusion

Despite some variability in results and the probability that much more herbicide was applied using the paper towels than a wiper, the treatment that appears safest for weed wiping in plantain-based pastures where plantain flower stems are present is the 1.8% glyphosate solution, obtained by using a 1:20 ratio of 360 g ai L^{-1} glyphosate products with water. This should be safe to use without field testing, but only if this concentration is not exceeded and no metsulfuron is added. For weeds that are not well controlled by this treatment such as docks, we have identified other herbicides that could be assessed in field trials which are probably safe for plantain if applied using traditional roller wiping equipment, with aminopyralid likely to be the safest for plantain, though these are unlikely to be as safe for clovers as the 1.8% glyphosate mixture. Rain falling soon after application could increase the risk of damage from these other herbicides.

Acknowledgement

The authors wish to thank Lesley Taylor, Su Liu and Sunil Sapkota (technicians at Massey University's Plant Growth Unit) for assistance with growing the plants used in this work, and the peer reviewers of the manuscript for their helpful comments.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Financial support for the chief author was provided by a New Zealand Aid Programme Scholarship from the New Zealand Ministry of Foreign Affairs and Trade.

ORCID

Nidhi Shrivastav http://orcid.org/0009-0007-0741-5670
Kerry C. Harrington http://orcid.org/0000-0003-2238-516X
Peter D. Kemp http://orcid.org/0000-0002-2239-2012
Xiong Z. He http://orcid.org/0000-0003-3956-4498
Hossein Ghanizadeh http://orcid.org/0000-0001-5381-7880

References

Box LA, Edwards GR, Bryant RH. 2016. Milk production and urinary nitrogen excretion of dairy cows grazing perennial ryegrass-white clover and pure plantain pastures. Proceedings of the New Zealand Society of Animal Production. 76:18–21.

Box LA, Judson AG. 2018. The concentration of bioactive compounds in *Plantago lanceolata* is genotype specific. Journal of New Zealand Grasslands. 80:113–118.

Bryant RH, Dodd MB, Moorhead AJE, Edwards P, Pinxterhuis IJB. 2019. Effectiveness of strategies used to establish plantain in existing pastures. Journal of New Zealand Grasslands. 81:131–138. doi: 10.33584/jnzg.2019.81.406.

Cavers PB, Bassett IJ, Crompton CW. 1980. The biology of Canadian weeds. 47. Plantago lanceolata L. Canadian Journal of Plant Science. 60:1269–1282. doi: 10.4141/cjps80-180.

Dodd MB, Moss RA, Pinxterhuis IJB. 2019. A paddock survey of on-farm plantain use. Journal of New Zealand Grasslands. 81:125–130. doi: 10.33584/jnzg.2019.81.408.

Gawn TL, Harrington KC, Matthew C. 2012. Weed control in establishing mixed swards of clover, plantain and chicory. New Zeal Plant Prot. 65:59–63.

Ghanizadeh H, Harrington KC. 2019. Weed management in New Zealand pastures. Agronomy. 9 (8):448. doi: 10.3390/agronomy9080448.

Grekul CW, Cole DE, Bork EW. 2005. Canada thistle (*Cirsium arvense*) and pasture forage responses to wiping with various herbicides. Weed Technology. 19:298–306. doi: 10.1614/WT-03-272R1.

Harrington KC. 2000. Weeds of lawns and sport turf – identification and control. Palmerston North, New Zealand: NZ Sports Turf Institute.

Harrington KC, Ghanizadeh H. 2017. Herbicide application using wiper applicators - A review. Crop Protection. 102:56–62. doi: 10.1016/j.cropro.2017.08.009.

Harrington KC, Ghanizadeh H, Moyo C, Kemp P, Eerens H. 2016. Are root exudation or rainfall on treated plants likely causes of pasture damage after wiper application of herbicides? Proceedings of the Australasian Weeds Conference. 20:72–75.

Harrington KC, Ghanizadeh H, Moyo C, Kemp PD, Eerens JPJ. 2017. Pasture damage from spot-sprayed herbicides. New Zealand Plant Protein. 70:1–7.

Holden P. 2023. New Zealand Novachem agrichemical manual – 2024/2025. Christchurch, New Zealand: AgriMedia Ltd.

Matthews LJ. 1975. Weed control by chemical methods. Wellington, New Zealand: A R Shearer.

Moyo C, Harrington KC, Ghanizadeh H, Kemp PD, Eerens JPJ. 2016. Spectrophotometric technique for measuring herbicide deposition from wiper applicators. New Zealand Journal of Agricultural Research. 59(4):412–421. doi: 10.1080/00288233.2016.1229681.

Moyo C, Harrington KC, Kemp P, Eerens J, Ghanizadeh H. 2022. Wiper application of herbicides to *Cirsium arvense*. Agronomy. 12:2262. doi: 10.3390/agronomy12102262.

Navarrete S, Rodriguez M, Horne D, Hanly J, Hedley M, Kemp P. 2022. Nitrogen excretion by dairy cows grazing plantain (*Plantago lanceolata*) based pastures during the lactating season. Animals. 12:469. doi: 10.3390/ani12040469.

Nguyen TT, Navarrete S, Horne DJ, Donaghy DJ, Kemp PD. 2022. Forage plantain (*Plantago lanceolata* L.): meta-analysis quantifying the decrease in nitrogen excretion, the increase in milk production, and the changes in milk composition of dairy cows grazing pastures containing plantain. Animal Feed Science and Technology. 285:115244. doi: 10.1016/j.anifeedsci.2022.115244.

Rotowiper. 2004. Rotowiper - assembly and operators manual. http://www.rotowiper.com/uploads/1/2/0/5/120501768/full_nz_operators_manual_1.8_to_3.2_-_tr[884].pdf.

Royston T, Christian C, Maddock J. 2006. Weedswiper - a unique, non-drip, non-drift, supply on demand weed wiper. Aspects of Applied Biology. 77(2):461.

Shrivastav N. 2023. Improving weed control options for ryegrass/clover pastures that contain plantain (Plantago lanceolata) [PhD thesis]. Palmerston North: Massey University. https://mro.massey.ac.nz/handle/10179/69261.

Shrivastav N, Harrington KC, Kemp PD, Ghanizadeh H. 2023. An assessment of resistance of two plantain (*Plantago lanceolata*) cultivars to phenoxy herbicides. New Zealand Journal of Agricultural Research. 1–12. doi: 10.1080/00288233.2023.2260774.

Wilson RG, Martin AR, Kachman SD. 2006. Seasonal changes in carbohydrates in the root of Canada thistle (*Cirsium arvense*) and the disruption of these changes by herbicides. Weed Technology. 20(1):242–248. doi: 10.1614/WT-05-052R1.1.