Alternative Herbicides for Controlling Herbicide-Resistant Annual Bluegrass (*Poa annua* L.) in Turf

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Abstract: *Poa annua* is a cosmopolitan, cool-season grass species regarded as one of the most significant weeds of turfgrass. It is mainly controlled by herbicides; however, repeated use of herbicides in golf turf has resulted in the evolution of multiple-herbicide resistant *P. annua*. Four field experiments were performed in autumn and spring in golf turf to identify effective herbicide options to control multiple herbicide-resistant *P. annua*. In herbicide resistance screening, the trial site population (SA1) was found to be susceptible to amicarbazone and terbuthylazine, but resistant to simazine and metribuzin at the field rate of each herbicide. Consistent with the results of the pot study, the PSII-inhibiting herbicides amicarbazone and terbuthylazine provided the best control (80–100%) of *P. annua* in both autumn and spring trials with minimal damage to the turf. In contrast, the other two PSII-inhibiting herbicides, metribuzin and simazine, were relatively ineffective in controlling *P. annua* in the field. Indaziflam also performed well in both autumn trials and reduced *P. annua* occurrence by >75%. Pyroxasulfone and s-metolachlor only provided moderate weed control in both the autumn and spring trials, reducing *P. annua* occurrence by 50%. Among the nine different herbicides, amicarbazone and terbuthylazine were found to be most effective for spring and autumn application in turf. As resistance to some PSII-inhibiting herbicides has already evolved in this field population, the use of amicarbazone and terbuthylazine needs to be integrated with other herbicide modes of action and non-chemical tactics to delay the onset of resistance to them.

Keywords: *Poa annua* L.; annual bluegrass; amicarbazone; terbuthylazine; indaziflam; weed management

1. Introduction

Annual bluegrass (*Poa annua* L.) is one of the most problematic weeds in sports turf, particularly in temperate climates [1,2]. It reduces the turf quality for sport and creates an uneven surface that affects ball roll [3,4]. This weed also competes for water and nutrients with the desired turfgrass species and reduces turf growth. It often produces panicles below the turf cutting height, which reduces the effectiveness of mowing for weed control [3]. *P. annua* is a genetically diverse weed species that typically germinates in autumn, grows in winter, and produces seed in spring; however, some germination can occur in spring as well [5,6]. During summer *P. annua* senesces, resulting in dead, bare, and unsightly patches that reduce the aesthetic value of turf [7]. It is considered the most problematic weed of golf courses in Australia and other countries, such as the USA. One feature that makes it difficult to control *P. annua* is its large seed bank of up to 200,000 seed m⁻² [6] and potential for year-round germination [8].

Several alternative management strategies including manual, cultural, biological and chemical control are available for controlling *P. annua* [9,10]. However, chemical control tends to be most commonly used, because of the ease of application and reliability of weed control. Both PRE and POST herbicides are used to control *P. annua* in turf [11]. However, repeated use of herbicides has resulted in the evolution of herbicide resistant *P. annua*...
populations [12–14]. The loss of herbicides to resistance requires new weed management practices including additional herbicides to control *P. annua*.

Greenkeepers of the golf course used for this study had reported difficulty in controlling *P. annua* with several herbicides. Seeds were collected from the golf course trial site in October 2017 to screen for herbicide resistance. The population was confirmed resistant to four different herbicide modes of action HRAC (Herbicide Resistance Action Committee) group, 1, 2, 5 and 31 in initial research, with >9-fold resistance to HRAC group 1, 2 and 31 and >2-fold resistance to HRAC group 5. Therefore, alternate herbicides with different mode of action could be an option for controlling this population. Hence, four field trials were conducted at a golf course in spring and autumn seasons between 2018 and 2020. The treatments were selected based on some commonly used herbicides currently registered for controlling *P. annua* in golf turf in Australia and additional herbicides that are not currently registered for turf, but may be suitable for controlling *P. annua*. The objective of the study was to identify suitable herbicide options to control multiple herbicide-resistant *P. annua* in a bermuda grass (*Cynodon dactylon*) turf during autumn and spring.

2. Materials and Methods

2.1. Experimental Site and Field Trial Design

Field trials were conducted on a Bermuda grass (*Cynodon dactylon*) turf at a golf course (34.896°S 138.51°E) in spring and autumn between 2018 and 2020. The chosen site was a practice green, which received the same weed control measures as the remainder of the golf greens. The turf was well managed with regular mowing (twice a week) at a height of 9 mm and watered every third night depending on the weather conditions. The soil type of the trial site is sandy in texture with 1.48% organic matter (Table 1). Liquid fertilizer MP Brilliance (20-0-0 + 6Fe, 1Mg) was applied at 37 L ha\(^{-1}\) every 3-4 weeks to maintain the fertility of the golf course. Meteorological and soil properties of the experimental sites are presented in Tables 1 and 2.

Table 1. Calendar dates and environmental conditions during herbicide application in field trials in 2018–2020.

| Application Timing | Trial | Date | Air Temperature at Spraying (°C) | Average Maximum Temperature during Trial (°C) | Average Minimum Temperature during Trial (°C) | Total Rainfall during Trial (mm) |
|--------------------|-------|------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------|
| Spring             | Trial 1 | 24 October 2018 | 17.7 | 23.1 | 13.3 | 35.5 |
|                    | Trial 2 | 30 September 2019 | 21.7 | 23.4 | 11.8 | 15.6 |
| Autumn             | Trial 1 | 8 March 2019 | 23.7 | 25.6 | 15.5 | 9.0 |
|                    | Trial 2 | 24 March 2020 | 20.5 | 24.9 | 15.0 | 4.2 |

 Nine different herbicide treatments were applied in the spring trial established in October 2018 and repeated in September 2019 (Table 3). Similarly, a field trial with nine herbicide treatments was undertaken in the autumn at the same location in March 2019 and repeated in March 2020 (Table 3). Dates of herbicide application and weather conditions are presented in Table 1. The timing of herbicide application in these trials is consistent with the weed management programs used by local greenkeepers. A range of both PRE and POST herbicides were used in both spring and autumn trials as emergence of *P. annua* occurs over a long period. Therefore, some herbicides e.g., s-metolachlor, indaziflam, which are mainly recommended for PRE application, were applied in both autumn and spring trials to test for both PRE and POST herbicide activity. Additionally, herbicides not currently registered for *P. annua* control were tested in these field trials. The trial was established in a
randomised complete block design with four replications. The plot size was $5 \, \text{m} \times 2 \, \text{m}$ with a $0.25 \, \text{m}$ gap between plots. A non-treated check treatment was included in each trial. Herbicides were applied using a CO$_2$-pressurized boom sprayer with medium droplet size flat-fan nozzles (TT01 and LD110-015) delivering $100 \, \text{L ha}^{-1}$ volume at a pressure of $200 \, \text{kPa}$. The trials were assessed 28 DAT (days after treatment) and again 42 DAT.

Table 3. List of herbicides used in spring and autumn treatment.

| Herbicide                  | Trade Name       | HRAC Group [15] | Registered for Turf in Australia | Recommended Application Time | Used in Which Trial | Rate (g a.i. ha$^{-1}$) Used in Experiment | Company                     |
|----------------------------|------------------|-----------------|----------------------------------|------------------------------|---------------------|---------------------------------------------|-----------------------------|
| Pendimethalin              | Rifle® 440       | 3               | Yes                              | PRE                          | Autumn              | 1496                                        | Nufarm                      |
| Propyzamide (Pronamide)    | Kerb® 500 SC     | 3               | Yes                              | PRE, EPOST                   | Spring Autumn       | 600                                         | Corteva Agrisci.             |
| Metribuzin                 | Mentor® WG       | 5               | No                               | PRE, POST                    | Spring Autumn       | 210                                         | Adama                       |
| Simazine                   | Gesatop® 600 SC  | 5               | No                               | PRE, EPOST                   | Spring Autumn       | 1200                                        | Syngenta                    |
| Terbuthylazine             | Terbyne® Xtreme® 875 WG | 5 | No                               | PRE, POST                    | Spring Autumn       | 875                                         | Sipcam Pacific              |
| Amicarbazone               | Amitron® 700 WG  | 5               | Yes                              | PRE, POST                    | Spring Autumn       | 700                                         | Arysta LifeScience Australia Pty Ltd. |
| Pyroxasulfone              | Sakura® 850 WG   | 15              | No                               | PRE                          | Spring Autumn       | 100.3                                       | Bayer                       |
| S-Metolachlor              | Pennmag®         | 15              | Yes                              | PRE                          | Spring Autumn       | 1920                                        | Syngenta                    |
| Indaziflam                 | Specticle®       | 29              | Yes                              | PRE, EPOST                   | Spring Autumn       | 50                                          | Bayer                       |
| Endothall                  | Poachek®         | 31              | Yes                              | EPOST, POST                  | Spring              | 262.5                                       | Campbell Chemicals          |

2.2. Pot Trial Methodology

As most of the PRE herbicides applied in the trial were ineffective, a follow-up pot study was undertaken with the PRE herbicides (Table 4) to determine the resistance status of the $P. \text{annua}$ population from the trial site (hereafter referred to as SA1). The $P. \text{annua}$ population (SA1) used in this study was collected from the trial site during October 2018. One susceptible population collected from a non-golf course area was used as the susceptible control. Seed bulking was performed in 2019 and the pot trial conducted during July 2019 and repeated in June 2020 at the University of Adelaide following the method used by Barua, et al. [16]. Approximately 100 seeds were measured by volume (0.2 mL), placed onto the surface of standard potting mix [17] and herbicide applied directly onto the seed. Herbicides (Table 4) were applied using a laboratory moving boom sprayer equipped with a twin nozzle (Tee-jet 110° flat fan Spraying Systems, Wheaton, IL, USA) delivering an output of 118 L ha$^{-1}$ at a pressure of 250 kPa and speed of 1 m s$^{-1}$. Immediately after herbicide application, the seeds were covered with 5 mm of potting mix. The pots were placed outside and watered as required. The experiment was assessed for seedling emergence 28 DAT (days after herbicide treatment). Plants that emerged and grew to the two-leaf stage were considered resistant to the herbicide treatment. The experiment was repeated.

In order to further investigate resistance in $P. \text{annua}$ to PSII inhibiting herbicides, an additional pot trial was undertaken. In this dose-response pot trial herbicide rates used were the following: amicarbazone (0, 26.3, 52.5, 105, 210, 420, 840 and 1680 g a.i ha$^{-1}$), terbuthylazine (0, 32.8, 65.6, 131.3, 262.5, 525, 1050 and 2100 g a.i ha$^{-1}$), simazine (0, 26.3, 52.5, 105, 210, 420, 840 and 1680 g a.i ha$^{-1}$) and metribuzin (0, 13.1, 26.3, 52.5, 105, 210 and 420 g a.i ha$^{-1}$). The methodology used was the same as Barua et al. [16]. The susceptible population mentioned above was used as the susceptible control. Seeds were sown in trays
(330 by 200 by 50 mm) located outdoors. One to two leaf seedlings were transplanted into punnet pots (95 by 85 by 95 mm) containing the already described standard potting mix, with 5 plants per pot and replicated three times. At the 2-3 leaf stage, plants were treated with the herbicides using the laboratory moving boom sprayer mentioned above. Plants actively growing with new leaves after 28 days were classified as survivors, while plants with severe stunting or dead were considered susceptible [19]. The experiment was repeated.

Table 4. Rate of herbicides used and survival (%) of the field population SA1 to herbicides at PRE application in a pot study.

| Chemical Name       | HRAC Group | Rate (g a.i. ha\(^{-1}\)) Used in Study | % Survival | Resistance Status * |
|---------------------|------------|----------------------------------------|------------|---------------------|
| Pendimethalin       | 3          | 1496                                   | 10         | S                   |
| Propyzamide (Pronamide) | 3          | 600                                    | 15         | S                   |
| Metribuzin          | 5          | 210                                    | 30         | R                   |
| Simazine            | 5          | 1200                                   | 34         | R                   |
| Amicabazone         | 5          | 700                                    | 0          | S                   |
| Terbuthylazine      | 5          | 875                                    | 19         | S                   |
| Pyroxasulfone       | 15         | 100.3                                  | 0          | S                   |
| S-Metolachlor       | 15         | 1920                                   | 14         | S                   |
| Indaziflam          | 29         | 50                                     | 0          | S                   |

* R—Resistant: More than 20% survival compared to the untreated control is considered as resistant [18], S—Susceptible.

2.3. Data Collection and Analysis

Prior to herbicide treatment, a low density of \(P.\) annua was present on the site in the autumn trials, but a much larger number of \(P.\) annua plants were uniformly distributed at the trial site in spring trials. The occurrence of \(P.\) annua in the trials after treatment was determined with the use of a 1 by 1 m grid divided into four hundred 50 by 50 mm squares. The grid was placed in the centre of each plot at three random locations and the number of squares containing \(P.\) annua plants counted to determine the % occurrence. The treatments were visually assessed for turf phytotoxicity at 7 DAT, 28 DAT and 42 DAT using a scale of 0–100 where 0 = no visual injury and 100 = no green tissue [20].

The data of percent occurrence of \(P.\) annua were subjected to two way analysis of variance (ANOVA) with GenStat version 19 (VSN International Ltd. Hemel Hempstead, UK) with herbicide and experiment run treated as variables. As there was a significant variation between experimental runs \((p < 0.05)\), the data of each run is presented separately. The data were square-root transformed before statistical analysis to normalize the distribution of the residuals. Where treatment differences were significant, the means of the transformed data were compared using Fisher’s Protected LSD at \(p = 0.05\). As there were no significant differences in turf quality between the two runs, the data were pooled for statistical analysis.

Dose response trials were set up as a completely randomized design and repeated. Data was subjected to three way ANOVA for each herbicide with population, rate and run as variables. For every herbicide there was a significant effect of rate \((p < 0.0001)\) and population \((p < 0.0001)\), but not for run. Therefore, data for each herbicide were pooled across experiments. Survival at each rate was converted to mortality and the data analyzed using PriProbit (1.63) [21] with the \(LD_{50}\) with 95% confidence intervals (CI) determined and resistance ratios calculated as \(LD_{50}\) Resistant/\(LD_{50}\) Susceptible. Population responses to the herbicides were considered different if confidence intervals of the \(LD_{50}\) did not overlap.

3. Results

3.1. Spring Trial Assessment

The occurrence of \(P.\) annua in the non-treated control for the two spring field trials varied between 86 and 100% of grids (Table 5), which indicates a relatively uniform spatial distribution at the site. In both spring trials, amicarbazone (2% occurrence) and terbutylazin...
Lazine (15–20% occurrence) provided the greatest control. The remaining treatments were less effective, particularly endothall, which was ineffective in both spring trials due to herbicide resistance confirmed previously at this site Barua, et al. [16]. These less effective treatments showed inconsistency in weed control over the two years.

Table 5. Effect of spring herbicide treatments on % occurrence of *P. annua* in golf turf in 2018 and 2019 after 28 DAT.

| Treatment                  | 2018   | 2019  |
|----------------------------|--------|-------|
| Propyzamide (Pronamide)    | 62.4 d | 64.3 ef|
| Metribuzin                 | 60.4 d | 49.8 d|
| Simazine                   | 66.3 d | 57.7 e|
| Terbutylazine              | 14.6 b | 19.6 b|
| Amicarbazone               | 1.9 a  | 1.6 a |
| Pyroxasulfone              | 50.4 c | 39.4 c|
| S-Metolachlor              | 55.5 cd| 41.1 c|
| Indaziflam                 | 59.6 d | 39.9 c|
| Endothall                  | 81.4 e | 67.2 f|
| Non-treated                | 99.5 f | 86.3 g|

*a* values with different letters within each column are significantly different.

In 2018, amicarbazone provided the highest level of control by reducing *P. annua* occurrence to 2% followed by terbutylazine that reduced *P. annua* occurrence to 14% (Table 5). However, the other two PSII-inhibiting herbicides (simazine and metribuzin) provided moderate control and reduced the occurrence of *P. annua* between 60 to 66% (Table 5). Other mode of action herbicides, such as indaziflam and propyzamide, also reduced occurrence to 60 to 62% (Table 5).

Amicarbazone and terbutylazine were also the most effective weed control treatments in the 2019 spring trial, followed by pyroxasulfone, indaziflam and s-metolachlor. Amicarbazone reduced the occurrence of *P. annua* to 2% followed by terbutylazine to 20% (Table 5). Simazine and metribuzin provided moderate control of *P. annua* similar to the results obtained in 2018. The next most effective treatments were pyroxasulfone and indaziflam that reduced *P. annua* occurrence to 39% followed by s-metolachlor to 41% (Table 5).

3.2. Autumn Trial Assessment

The occurrence of *P. annua* was high (>96%) in untreated plots for both 2019 and 2020 autumn trials (Table 6). Amicarbazone was once again the most effective herbicide in autumn 2019, followed by terbutylazine, indaziflam, pyroxasulfone, and s-metolachlor. In contrast, pendimethalin, propyzamide and simazine were less effective treatments in both autumn trials. The occurrence of *P. annua* was reduced to 0% by amicarbazone, 6% by terbutylazine, 22% by indaziflam, 43% by pyroxasulfone, and 45% by s-metolachlor (Table 6).

Table 6. Effect of autumn herbicide treatments on % occurrence of *P. annua* in golf turf in 2019 and 2020 after 28 DAT.

| Treatment                  | 2019   | 2020  |
|----------------------------|--------|-------|
| Pendimethalin              | 83.5 f | 80.5 g|
| Propyzamide (Pronamide)    | 84.9 f | 56.1 e|
| Metribuzin                 | 55.8 e | 59.2 ef|
| Simazine                   | 89.8 fg| 68.4 f|
| Terbutylazine              | 6.2 b  | 8.0 b |
| Amicarbazone               | 0.0 a  | 1.4 a |
| Pyroxasulfone              | 43.2 d | 40.6 d|
| S-Metolachlor              | 44.9 de| 55.0 e|
| Indaziflam                 | 22.6 c | 26.3 c|
| Non-treated                | 99.9 g | 96.4 h|

*a* values with different letters within each column are significantly different.
In 2020, amicarbazone was again the best treatment and reduced *P. annua* occurrence to below 2% (Table 6). Terbutylazine was the second best treatment and reduced *P. annua* occurrence to 8%, followed by indaziflam to 26%, pyroxasulfone to 40%, and s-metolachlor to 55% (Table 6). Consistent with the spring trials, simazine and metribuzin were less effective than amicarbazone or terbutylazine.

A difference in the performance of two herbicides (propyzamide and simazine) was observed in the two autumn trials (Table 6). As the soil type at the study site is sandy in texture (Table 2), higher rainfall in 2019 (Table 1) may have moved these herbicides through the soil profile reducing their performance in that year.

In all four trials, amicarbazone was the most effective treatment; however, it produced mild turf grass injury (data were not shown). This persisted for four weeks after herbicide application, followed by complete recovery of the turf at six weeks. No other treatments were phytotoxic to the turf. Perry, et al. [22] reported that amicarbazone provided superior control of *P. annua* through foliar and root uptake at 371 g ha$^{-1}$ as compared to atrazine at 2025 g ha$^{-1}$. Another study suggested that amicarbazone is more active than other PSII inhibitors such as atrazine Dayan, et al. [23]. Amicarbazone has been recently registered for turf in Australia at 210 g ha$^{-1}$[24], a much lower rate than 700 g ha$^{-1}$ used in our field trials that were initiated prior to the registration of amicarbazone. It is possible the lower rate on the label will provide less effective control of *P. annua* than observed in this trial and in other studies [22,23]. The efficacy of amicarbazone at lower rates on *P. annua* needs to be validated. Of all the herbicide treatments investigated, terbutylazine consistently resulted in good turf quality followed by indaziflam, propyzamide and amicarbazone at six weeks after herbicide application. In both the autumn and the spring trials there was rapid recovery of turf grass and no difference in turfgrass density (data not shown here) at 6 weeks after herbicide application. However, terbutylazine, which was the second most effective herbicide in these trials, is not registered for use in turf in Australia. Indaziflam was the next most effective herbicide for PRE application in autumn and is registered for use in Australia [25]. Two other herbicides, pyroxasulfone and s-metolachlor, provided similar levels of control (40–55%) in all the trials. S-metolachlor is registered in turf for *P. annua* control during the autumn season. Pyroxasulfone should be considered as an option for use in turf and would increase the range of herbicide options for *P. annua*. The use of herbicide rotations can help to slow the evolution of resistance in weeds.

### 3.3. Pot Trial Screening

To investigate why some PRE herbicides were not effective in the autumn field trial, a pot study was conducted with the trial site population (SA1) using these herbicides. Moderate levels of resistance (30 to 34% survival) were detected to metribuzin and simazine (Table 3), which could explain the poor efficacy of these two herbicides in the field. However, SA1 was susceptible to the other herbicides used in the field trials (Table 3). Therefore, other factors, such as weed growth stage, weed competition and environmental conditions appear to be responsible for the poor control of *P. annua* by these herbicides.

### 3.4. Dose-Response Trial

To further investigate the extent of resistance to the PSII inhibiting herbicides used in the trial, dose response experiments were conducted on SA1. Compared to the S population, SA1 had 2.6-fold resistance to metribuzin and 2.2-fold to terbutylazine. The LD$_{50}$ of SA1 population to metribuzin was 1.5-fold higher than the S population and for amicarbazone was 1.2-fold higher (Table 7). Low-level resistance does not always result in a failure of the herbicide in the field. Terbutylazine controlled the S population well below the field rate, so this herbicide was effective despite the low-level resistance present. In contrast, metribuzin at the field rate only controlled the S population, so the increase in tolerance of SA1 is the likely cause of poor performance in the field. The dose response study confirmed the SA1 population exhibited greater resistance to simazine and lower resistance to terbutylazine, but little resistance to amicarbazone.
Table 7. The dose required for 50% mortality (LD$_{50}$) of susceptible (S) and trial site population (SA1) to various PSII inhibiting herbicides with 95% confidence intervals (CI) in parentheses. R/S is the ratio of LD$_{50}$ of resistant and susceptible populations.

| Herbicides       | Population | S             | SA1            | R/S |
|------------------|------------|---------------|----------------|-----|
|                  |            | LD$_{50}$ g a.i. ha$^{-1}$ |               |     |
| Simazine         |            | 249.1 (193.9, 319.6) | 638.4 (500.6, 818.6) | 2.6 |
| Amicarbazone     | R/S        | 284.0 (227.8, 353.9) | 354.5 (284.7, 442.2) | 1.2 |
| Metribuzin       | R/S        | 72.8 (57.6, 91.9)  | 109.0 (86.3, 137.1) | 1.5 |
| Terbuthylazine   | R/S        | 258.2 (194.3, 342.9) | 575.2 (440.3, 751.8) | 2.2 |

4. Discussion

Resistance to 10 herbicide modes of action has been reported in *P. annua* worldwide [12], which restricts the number of herbicide options available for its control in turf. Most of the herbicides used in the autumn trial exhibited poor control of *P. annua* in the field (Table 6), despite resistance not being confirmed in pot studies (Table 3). This indicates that factors other than herbicide resistance were responsible for the poor performance, such as high seed bank, herbicide application timing relative to weed emergence, soil type, thatch layer, and environmental conditions [10,26].

The timing of a herbicide application is important to maximise PRE herbicide effectiveness [11]. In the current study, herbicide timings were similar to those used by local greenkeepers. In our field study, the performance of indaziflam was greater in the autumn trial than the spring trial. Brosnan, et al. [27] reported that soil application of indaziflam was more effective than foliar application to control *D. ischaemum* and *P. annua*. They concluded that indaziflam needs to be absorbed by the roots to maximise POST control. Therefore, time of application is important for the success of indaziflam. It is likely that when this herbicide was applied in autumn some *P. annua* had already germinated, thus reducing the efficacy of the indaziflam. In previous research, indaziflam was shown to be more effective when used PRE and EPOST (early POST) [28], which could explain why it was less effective in our spring trials where weeds were established. Greenkeepers often reapply the same herbicide during the season to maximise activity on subsequent germinations, which was not done in these field trials. Multiple applications may be more effective than a single application. Thus, a follow-up application timing study is needed to determine the difference between a single and multiple applications of this herbicide.

Pronamide has been shown to provide good control *P. annua* with PRE and POST treatments [29]. However, in our study performance of pronamide only provided moderate efficacy (Tables 5 and 6). In a previous study, poor efficacy of pronamide used POST on *P. annua* in Georgia, USA was associated with reduced absorption and translocation [30]. Others have also claimed that unsuitable application timing (when plants are too large) can lead to the poor efficacy of pronamide [31].

Factors which influence the efficacy of PRE herbicides include solubility in soil solution, binding to organic matter and the half-life in soil [32]. Uptake of herbicides by the root occurs more readily when the herbicide is in soil solution. Out of the herbicides tested in the autumn trials, amicarbazone had the highest solubility in water [33] and was found to have the greatest efficacy. In contrast, terbuthylazine and indaziflam have lower water solubility that could account for their lower activity.

Soil organic matter content can also play an important role in PRE herbicide activity [34]. In our study, some of the PRE herbicides were unsuccessful for controlling *P. annua*...
in the autumn trial, even though no herbicide resistance was detected. The soil at the trial site was sandy with 1.48% soil organic matter content (Table 2). Soil low in organic matter (low cation exchange capacity) has a lower tendency to bind herbicides and allows greater herbicide availability for uptake by weeds. However, heavy rainfall or frequent irrigation can move the herbicides through the soil profile before the compound has a chance to bind to the soil colloids and organic matter [32]. Since most P. annua seeds germinate in the top layer of soil [10,35], leaching of herbicides to lower layers of soil could result in reduced weed control.

Another factor that may have reduced the performance of PRE herbicides is the thatch layer, which is primarily organic matter (stems, stolons, roots), in turf that develops between the turf and soil surface [36]. This limits the movement of air, water and nutrition into the soil [37]. The thatch layer can also bind PRE herbicides, thereby reducing their effectiveness [38,39].

In conclusion, amicarbazone was the most effective herbicide for the reduction of P. annua occurrence (98–100%) followed by terbuthlazine (>80%), indazaflam (>63%) and pyroxasulfone (>57%) in both autumn and spring trials. Indaziflam performance was greater in the autumn trial than the spring trial indicating that indazaflam could be a good option for autumn application. The availability of multiple herbicides with different modes of action allows rotating herbicides in an herbicide management program, which is important to reduce the risk of resistance. Pyroxasulfone, although not currently registered in turf, could be a viable option for P. annua control. Amicarbazone and terbuthylazine controlled the trial site population (SA1) in pots indicating it was susceptible to both herbicides (Table 3). In contrast, simazine and metribuzin were less effective (Table 3). Terbuthylazine could be a potential candidate for P. annua control in turf. Given the extensive presence of herbicide resistance, it would be invaluable for the greenkeepers to test their populations for resistance status, so they can make informed choices of herbicides for P. annua control. The currently effective herbicides need to be used with care otherwise, they could also lose their effectiveness due to resistance.

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