

# The control of Asian rust by glyphosate in glyphosate-resistant soybeans

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## Abstract

**BACKGROUND:** Glyphosate is a widely used broad-spectrum herbicide. Recent studies in glyphosate-resistant (GR) crops have shown that, in addition to its herbicidal activity, glyphosate exhibits activity against fungi, thereby providing disease control benefits. In GR wheat, glyphosate has shown both preventive and curative activities against *Puccinia striiformis* f. sp. *tritici* (Erikss) CO Johnston and *Puccinia triticina* Erikss, which cause stripe and leaf rusts respectively.

**RESULTS:** Laboratory studies confirmed earlier observations that glyphosate has activity against *Phakopsora pachyrhizi* Syd & P Syd which causes Asian soybean rust (ASR) in GR soybeans. The results showed that glyphosate at rates between 0.84 and 1.68 kg ha<sup>-1</sup> delayed the onset of ASR in GR soybeans. However, field trials conducted in Argentina and Brazil under natural infestations showed variable ASR control from application of glyphosate in GR soybeans. Further field studies are ongoing to define the activity of glyphosate against ASR.

**CONCLUSIONS:** These results demonstrate the disease control activities of glyphosate against rust diseases in GR wheat and GR soybeans.

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**Keywords:** glyphosate-resistant; Asian soybean rust; *Phakopsora pachyrhizi*; rust control

## 1 INTRODUCTION

Glyphosate is a broad-spectrum herbicide that inhibits plant 5-enolpyruvyl shikimate 3-phosphate synthase (EPSPS), thereby blocking the synthesis of aromatic amino acids and numerous secondary metabolites derived from the phenylpropanoid pathway. EPSPS is also present in fungi and bacteria, but not in animals.<sup>1</sup> Assuming a glyphosate-sensitive EPSPS, fungi and bacteria may also be susceptible to the action of glyphosate. In pure culture, growth of many fungi was inhibited by glyphosate, but only at very high concentrations (100 to more than 1000 mg g<sup>-1</sup> of agar medium for ED<sub>50</sub>).<sup>2</sup> Glyphosate has been reported to inhibit the proliferation of mammalian pathogenic fungi<sup>3</sup> and was active against apicomplexan parasites which cause diseases such as malaria and toxoplasmosis.<sup>4</sup>

The fact that conventional crops are killed by glyphosate has complicated investigations on potential disease control activities of glyphosate. It has been reported that soil-applied glyphosate can protect plants against soil-borne fungi.<sup>5</sup> A recent report also described reduced *Fusarium* head blight in wheat from spray drift of glyphosate.<sup>6</sup> In contrast, glyphosate was shown to increase the growth of *Pyrenophora* sp.

and *Fusarium* sp. *in vitro*, and this was implicated in an increase of *Fusarium* head blight in conventional wheat.<sup>7</sup>

The development of glyphosate-resistant (GR) crops has enabled the evaluation of disease control effects of glyphosate in the absence of herbicidal crop injury. A recent review by Duke *et al.*<sup>8</sup> references reports of both enhanced and reduced disease severity in GR crops. Most published studies thus far have focused on GR soybeans and showed no increased incidence of *Fusarium*-mediated sudden death syndrome,<sup>9</sup> *Rhizoctonia* sp.-mediated root rot<sup>10</sup> or *Sclerotinia sclerotiorum* (Lib.) de Bary-mediated white mold.<sup>11</sup> Recent studies in GR wheat showed that glyphosate may have the beneficial effects of reducing incidences of rusts<sup>12,13</sup> and increasing yield in soil infested with *Rhizoctonia* sp. or *Gaeumannomyces graminicola* (Sacc) v Arx and J Olivier.<sup>14</sup>

The authors' studies of *Puccinia triticina* Erikss in GR wheat showed that glyphosate, at a typical weed control rate of 0.84 kg AE ha<sup>-1</sup>, effectively prevented and cured leaf rust.<sup>12</sup> Spray application of blank surfactant or water produced little rust control. The activity was dose dependent and was observed with glyphosate applied from 14 days before to 5 days after

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rust inoculation. Activity was maintained even if the inoculated leaf was shielded from glyphosate spray, indicating that the activity was derived from systemic glyphosate that was translocated into the inoculated leaf from the plant. Using  $^{14}\text{C}$ -glyphosate, it was shown that rust control was achieved with leaf systemic concentrations of glyphosate at  $<5$  ppm, which was much more active than that measured by *in vitro* assays.<sup>2</sup> It was also observed that rust control activity of glyphosate was not mediated through induction of four common pathogenesis-related markers for systemic acquired resistance.

Laboratory studies showed that glyphosate also has similar activity on *Puccinia striiformis* f. sp. *tritici* (Erikss) CO Johnston which causes stripe rust in GR wheat.<sup>12</sup> A field test under a heavy, natural infestation of stripe rust showed that glyphosate ( $0.42\text{--}0.84$  kg  $\text{ha}^{-1}$ ) effectively reduced rust when applied from 36 days before to 5 days after initial rust sighting in GR wheat. Based on conservation of key amino acids, available fungal EPSPS enzymes are predicted to be glyphosate sensitive. The authors' hypothesis is that glyphosate is acting directly on the rust fungi via inhibition of fungal EPSPS.

*Phakopsora pachyrhizi* Syd & P Syd is also an obligate pathogen that causes Asian soybean rust (ASR) resulting in severe yield loss in soybean crops. ASR is endemic in Asia; it was first detected in South America in 2001<sup>15</sup> and in the USA in 2004.<sup>16</sup> Feng *et al.*<sup>12</sup> reported preliminary data on the activity of glyphosate against ASR in GR soybeans. Further evidence from laboratory and field studies on the activity of glyphosate against ASR in GR soybeans will now be presented.

## 2 MATERIALS AND METHODS

### 2.1 Materials

GR soybeans in various germplasms all contained the Roundup Ready<sup>®</sup> trait which conferred resistance to glyphosate via a glyphosate-insensitive CP4-EPSPS gene. The experiments utilized commercially available glyphosate formulations belonging to the family of Roundup<sup>®</sup> herbicides which may contain different glyphosate salts or surfactant systems. MON 0818, a common cationic surfactant in some glyphosate formulations, was obtained from Monsanto Co. The following commercially available fungicides were also utilized: carbendazim 125/flusilazole 250 g  $\text{L}^{-1}$  SC (Punch C<sup>®</sup>; DuPont Co., South Africa), tebuconazole 250 g  $\text{L}^{-1}$  EC (Folicur<sup>®</sup>; BayerCropscience, South Africa) and pyraclostrobin 133/epoxiconazole 50 g  $\text{L}^{-1}$  SE (Opera<sup>®</sup>; BASF Corp., Brazil).

### 2.2 Plant production

GR soybean seeds (Roundup Ready<sup>®</sup> AG5601 and AG5409R) were planted into plastic seedling sleeves ( $3.5 \times 3.5 \times 10$  cm) in artificial soil mixture. The sleeves were placed into plastic containers ( $22 \times 16 \times 7$  cm) and subjected to daily overhead irrigation

after planting and to twice-a-week subirrigation after emergence. Plants were grown in a growth chamber at  $17\text{--}25^\circ\text{C}$  and 60% RH, with a 14 h day length at a light intensity of  $650 \mu\text{E m}^{-2} \text{s}^{-1}$ .

### 2.3 Chemical spray application

Plants were treated with commercial fungicide or glyphosate formulations applied via an overhead sprayer. The spray apparatus contained an overhead fixed flat-fan spray nozzle with a rotating circular platform (120 cm diameter). Fifteen plants per treatment were placed in a circle on the periphery of the platform directly below the nozzle, which was adjusted to 50 cm from the top of the plant canopy. The formulation was pressurized and forced through the nozzle as the platform rotated. Plants were sprayed only once, with each rotation taking 8 s. An empty pot was placed at the beginning and end of the cycle to prevent any spray overlap. The sprayer delivered 0.45 mL of formulation per pot area (15 cm diameter), which translated to a spray volume of  $250 \text{ L ha}^{-1}$ . Thereafter, plants were transferred to a growth chamber set at  $20\text{--}24^\circ\text{C}$  with 70% RH at a light intensity of  $650 \mu\text{E m}^{-2} \text{s}^{-1}$ .

Two commercially available fungicides used for the control of Asian soybean rust were tested at their labeled rates. These were carbendazim + flusilazole (Punch C<sup>®</sup>) and tebuconazole (Folicur<sup>®</sup>). The Roundup<sup>®</sup> formulation contained glyphosate isopropylamine salt at 360 g acid equivalent (AE)  $\text{L}^{-1}$ . MON0818, the surfactant in the formulation, was tested at a concentration of  $1 \text{ g L}^{-1}$ . Chemical formulations were applied at either days before rust inoculation (DBI) or days after rust inoculation (DAI) to assess preventive or curative activities.

### 2.4 Rust inoculation

ASR is endemic in regions of South Africa, and urediospores were collected from naturally infected soybean plants maintained in the greenhouse. Urediospores were collected immediately prior to inoculation using a fine paint brush and suspended in distilled water. Urediospore concentration was determined using a hemocytometer and adjusted to about  $8000 \text{ spores mL}^{-1}$  with  $1 \text{ g L}^{-1}$  Tween<sup>®</sup> 20 as a dispersant.

An air sprayer<sup>17</sup> was used to apply an even coat of urediospores to the abaxial surface of the central leaf of the second youngest trifoliolate in V3-4 plants (3-4-trifoliolate growth stage). Each treatment used 15 replicate plants. After inoculation, plants were placed in a dew chamber ( $24^\circ\text{C}$ , 98% RH, in the dark) for 36 h to facilitate spore germination and infection. Thereafter, plants were transferred to a growth chamber ( $21\text{--}22^\circ\text{C}$ , 87-90% RH) with a 12 h day length. Rust incidence (0-100%) on individual plants was visually rated on the basis of the number of pustules per area on the abaxial surface of the inoculated leaf. Averages and standard errors (SEs)

of disease incidence were calculated from 15 replicate plants.

### 2.5 Laboratory experiment design

The laboratory experiments were reproduced in AG5601 and AG5409R GR soybean germplasm. Preventive studies involved spray application of chemicals before rust inoculation. GR soybean plants (15 replicates per treatment, V3 or three-trifoliolate stage) were sprayed with glyphosate (0.84 or 1.68 kg ha<sup>-1</sup>, 1× or 2× rates) at 14, 7 or 1 DBI. The 1 DBI treatments also included water, surfactant (1 g L<sup>-1</sup> MON0818), carbendazim + flusilazole (Punch C<sup>®</sup>) and tebuconazole (Folicur<sup>®</sup>). Plants were inoculated on the same day, and rust ratings were recorded at 7, 17, 20 and 25 DAI.

Curative studies involved spray application of chemicals after rust inoculation. GR soybean plants (15 replicates per treatment, V3 stage) were inoculated on the same day and incubated in a high-humidity chamber to induce infection, followed by chemical spray treatments with glyphosate, water, surfactant (1 g L<sup>-1</sup> MON0818) or carbendazim + flusilazole. Treatment variables included glyphosate rate (0.42, 0.84 or 1.68 kg ha<sup>-1</sup>) and spray timing (1, 3 or 6 DAI). Rust ratings were recorded at 20, 27, 34 and 40 DAI.

In one experiment, plants were subjected to simulated rainfall to remove leaf-surface residues of glyphosate prior to rust inoculation. Glyphosate was applied at 1 DBI, and plants ( $n = 15$ ) were manually washed with 2 × 10 L of water at 3 h post glyphosate spray; plants were inoculated the following day. In another experiment, the trifoliolate targeted for rust inoculation was shielded from glyphosate spray. The second trifoliolate of the V3 plant ( $n = 15$ ) was placed in a small plastic bag so as to prevent spray interception during glyphosate application. Plants were allowed to dry prior to removing the plastic covering; the shielded trifoliolate was inoculated the following day.

### 2.6 Field experiment design

Field trials were conducted in Itin and Saenz Pena in northern Argentina, and in Morrinhos and Sorriso in Brazil, using various GR soybean lines (Roundup Ready<sup>®</sup> M-soy 8000, M-soy 8045, M-soy 8248, M-soy 8585, Nidera 9000 and Dalia 500). Field studies relied upon natural infestations of rust which varied depending on environmental conditions. Because of unpredictable timing of infestation, glyphosate was applied repeatedly at multiple growth stages.

In Argentina, glyphosate (Roundup<sup>®</sup> Max, 0.84 or 1.64 kg AE ha<sup>-1</sup>, 1× or 2×) was repeatedly applied at reproductive stages from flowering to pod formation (R1, R2 and R3) within a 24 day period. The labeled rate of pyraclostrobin + epoxiconazole (Opera<sup>®</sup>), commonly used to control Asian soybean rust, was applied at R3 growth stage upon rust detection, and rust ratings were taken at 11 days after the treatment. For each treatment, 120 leaves (eight

plants × five trifoliate) were collected and classified on the basis of the number of pustules per leaf into low (0–5 pustules), moderate (6–20 pustules) or severe (>20 pustules) incidences. Percentages of leaves in each incidence category were calculated.

The Brazilian field trials used a similar treatment protocol with repeat applications of glyphosate at 1× or 2× rates. In some studies, glyphosate spray commenced at the V3 stage and was repeated every 14 days for a total of 5–6 applications. The labeled rate of pyraclostrobin + epoxiconazole was sprayed at rust detection. Rust incidence (0–100%) was assessed visually on the basis of pustule number per area at various times to generate area under disease progress curves (AUDPCs) that were analyzed by the Tukey test for significance at  $P < 0.05$ .

## 3 RESULTS

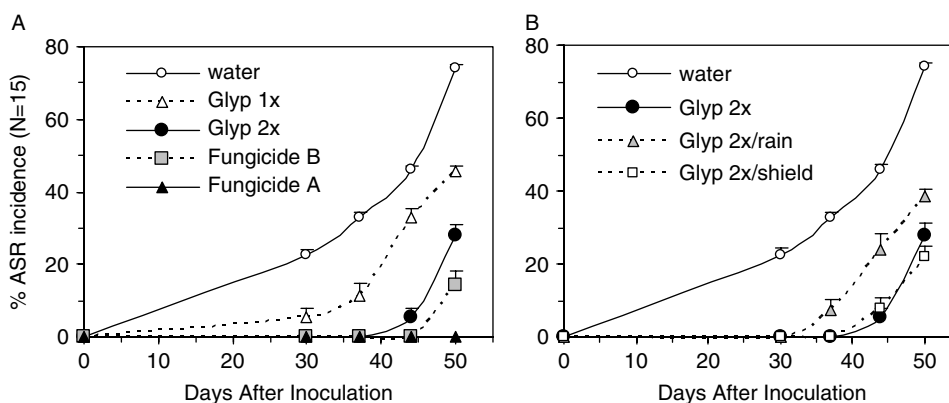
The present work began with laboratory studies in South Africa to confirm the activity of glyphosate against ASR under controlled environmental conditions and constant disease pressure. An attempt was then made to translate the laboratory data to the fields in Argentina and Brazil under natural ASR infestations.

### 3.1 Laboratory preventive studies

ASR control by glyphosate or two fungicide formulations was measured following application at 1 DBI in GR soybeans (AG5601). Results in Fig. 1A showed that plants treated with carbendazim + flusilazole (fungicide A) remained rust free at 50 DAI, whereas a low incidence (14%) developed with tebuconazole (fungicide B). Glyphosate 2× remained rust free at 37 DAI, whereas the 1× dose developed a low incidence (5%) by 30 DAI. These results demonstrated that glyphosate application delayed the onset of ASR, but the duration of activity was less than that of fungicide standards. The effect of glyphosate was also dose dependent, with the 2× rate providing longer-lasting control than the 1× rate.

The performance of glyphosate 2× applied at 1 DBI was further examined (Fig. 1B). ASR control was reduced when plants were washed with a simulated rainfall at 3 h post glyphosate spray and before rust inoculation. Studies have shown that leaf-surface glyphosate is effectively removed by washing.<sup>18</sup> The results showed that the wash reduced but did not eliminate ASR control, and this is indicative that leaf-surface glyphosate contributed little to the activity. The reduced ASR activity can be explained by the loss of leaf-surface glyphosate, resulting in lower plant absorption.

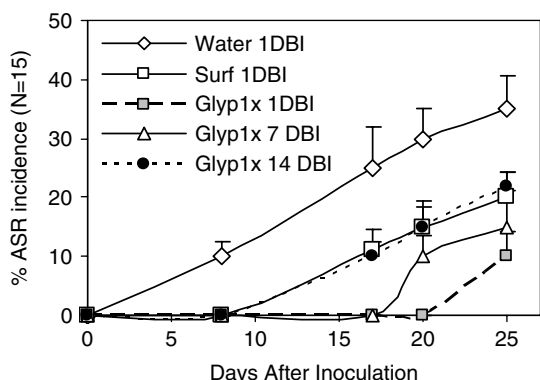
In another treatment (Fig. 1B), the trifoliolate leaf targeted for rust inoculation was shielded from glyphosate spray. Since the inoculated leaf never contacted the spray, the only source of glyphosate in the leaf was translocated from the rest of the plant. The results showed comparable rust control



**Figure 1.** (A) Preventive activity against Asian rust in GR soybeans of spray applications 1 day before inoculation (1 DBI) of water, glyphosate (Glyp, 1× or 2×, 0.84 or 1.68 kg AE ha<sup>-1</sup>), fungicide A (carbendazim + flusilazole) or fungicide B (tebuconazole). (B) Preventive activity of glyphosate (2×) at 1 DBI with a rain-wash of plants at 3 h after spray and before rust inoculation or with the inoculated leaf shielded from glyphosate spray.

when the inoculated leaf was or was not shielded from the glyphosate spray. Identical experiments conducted with the second GR soybean line (AG5409R) produced similar results. These results indicated that ASR control was derived from systemic glyphosate that required absorption and translocation in the plant. Similar results had been observed for rust control in GR wheat.<sup>12</sup>

The timing of glyphosate spray in ASR control in GR soybean (AG5409R) is shown in Fig. 2. Application of water 1 DBI produced a linear increase in rust incidence (10–35% from 8–25 DAI). Application of surfactant (1 g L<sup>-1</sup> MON 0818) 1 DBI delayed the onset of rust; however, pustules appeared by 8 DAI and increased linearly at a rate similar to that of the water control. MON 0818 is known to cause cell necrosis<sup>19</sup> and may have transiently inhibited spore germination or growth. Glyphosate 1× at 1 DBI delayed ASR for 20 days; however, when sprayed at 7 or 14 DBI, ASR was delayed for only 17 or 7 days respectively. These results showed that glyphosate was most effective when applied just before ASR inoculation, and the preventive window diminished with longer delays between glyphosate application and ASR inoculation. Identical experiments conducted



**Figure 2.** Preventive activity against Asian rust in GR soybeans of spray applications of glyphosate (Glyp, 1× at 0.84 kg AE ha<sup>-1</sup>) at 1, 7 or 14 days before inoculation (DBI), water or surfactant control (1 g L<sup>-1</sup> MON 0818) at 1 DBI.

with the second GR soybean line (AG5601) produced similar results. The diminishing preventive activity with time was also observed with rust control in GR wheat<sup>12</sup> and was due to declining glyphosate concentration in plant tissues from translocation and plant growth.

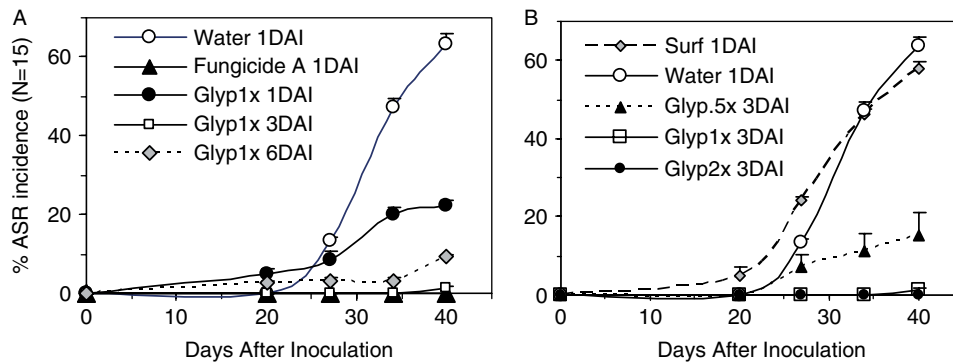
### 3.2 Laboratory curative studies

Spray application of water at 1 DAI produced a steady increase in rust incidence (0–64% from 0–40 DAI), which was completely controlled by carbendazim + flusilazole (fungicide A) in GR soybean AG5409R (Fig. 3A). Application of glyphosate 1× at 1 or 6 DAI reduced rust incidence (23 or 9% at 40 DAI); however, optimal rust control (1% at 40 DAI) was achieved with the 3 DAI application.

The effect of glyphosate dose applied at 3 DAI is shown in Fig. 3B. Relative to that of water or surfactant, modest rust control was achieved with glyphosate 0.5× (15% at 40 DAI); however, complete rust control was achieved with glyphosate 1× or 2×. Identical experiments conducted with the second GR soybean line (AG5601) produced similar results and confirmed the dose-dependent curative activity of glyphosate on ASR. The overall laboratory data indicate that glyphosate 1–2× was needed for ASR control in GR soybeans.

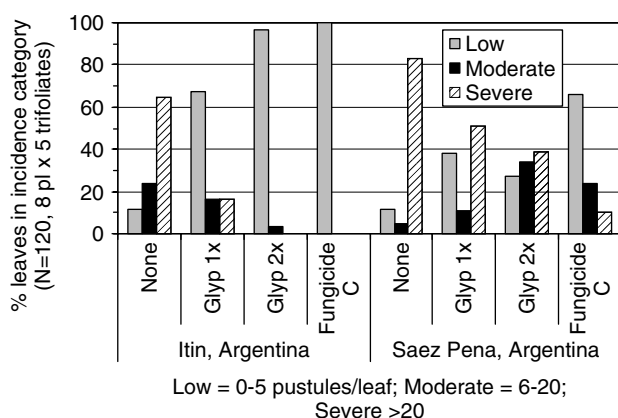
### 3.3 Field studies

Environmental conditions such as temperature and humidity play a major role in timing and severity of natural rust infestation. During the summer of 2005, weather conditions in Itin and Saenz Pena, Argentina, were dry, with little rain and low humidity, resulting in late manifestation of ASR in GR soybeans. As the timing of rust infection was unpredictable, glyphosate (1× or 2×) was applied repeatedly at reproductive growth stages (R1, R2 and R3) within a 24 day period. Pyraclostrobin + epoxiconazole (fungicide C) was applied at R3 growth stage upon rust detection. ASR incidence was rated 11 days later on the basis of the number of pustules per leaf.



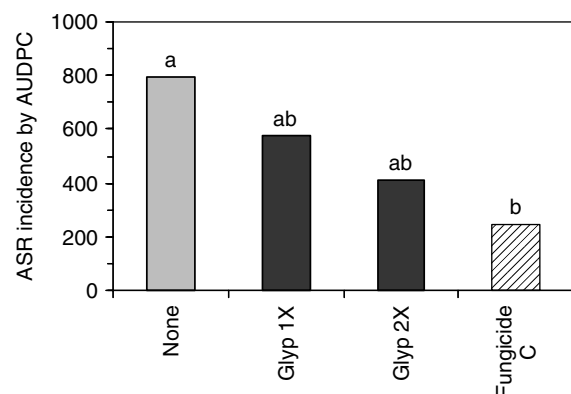
**Figure 3.** (A) Curative activity for Asian rust in GR soybeans of spray applications of glyphosate (Glyp, 1× at 0.84 kg AE ha<sup>-1</sup>) at 1, 3 or 6 days after inoculation (DAI), water and fungicide A (carbendazim + flusilazole) at 1 DAI. (B) Curative activity as a function of glyphosate dose (0.5×, 1× or 2×) from spray application at 3 DAI, surfactant (1 g L<sup>-1</sup> MON 0818) or water alone at 1 DAI.

The percentages of leaves ( $n = 120$ ) categorized as low (0–5 pustules leaf<sup>-1</sup>), moderate (6–20 pustules leaf<sup>-1</sup>) or severe (>20 pustules leaf<sup>-1</sup>) incidences are shown in Fig. 4. With the untreated plants in Itin, severe and moderate incidences were recorded in 65 and 24% of the leaves respectively. In comparison, application of 1× glyphosate resulted in mostly low (67%) incidence. Application of 2× glyphosate produced 96% low incidence, which was nearly equivalent to that of pyraclostrobin + epoxiconazole. Plants sprayed with glyphosate or the fungicide also showed a reduction in the defoliation that is a typical symptom of ASR infection. The results from the Itin site showed good translation of laboratory data to the field. In contrast, the results from the Saenz Pena site showed a similar trend but with overall less control across all treatments including that of the fungicide standard. ASR incidence was reduced with application of glyphosate 1× or 2×; however, neither the fungicide nor glyphosate provided complete ASR control.



**Figure 4.** Percentage of leaves with low, moderate or severe incidences of Asian rust in GR soybeans from field trials in Itin and Saenz Pena, Argentina. Glyphosate (Glyp, 1× or 2×, 0.84 or 1.68 kg AE ha<sup>-1</sup>) was applied repeatedly at reproductive (R1, R2 and R3) growth stages. Asian soybean rust was detected at R3, and fungicide C (pyraclostrobin + epoxiconazole) was applied upon rust detection. Leaves ( $n = 120$ , five trifoliates × eight plants) were harvested at 11 days after the fungicide spray and categorized as low (0–5 pustules leaf<sup>-1</sup>), moderate (6–20 pustules leaf<sup>-1</sup>) or severe (>20 pustules leaf<sup>-1</sup>) incidences.

A total of six trials were conducted in Brazil, where plants were repeatedly sprayed with glyphosate at 14 day intervals starting at the V3 growth stage; pyraclostrobin + epoxiconazole (fungicide C) was sprayed at rust sighting. Disease incidence, based on area under disease progress curve (AUDPC), showed that none of the treatments provided effective rust control; however, the fungicide did provide statistically significant ( $P < 0.05$ , Tukey test) reduction in five out of six trials relative to that of untreated plots. In comparison, glyphosate 2× or 1× provided statistically significant reduction in two trials and one trial respectively. Representative results from the Sorriso site where ASR was detected 7 days after the last glyphosate spray are shown in Fig. 5. Application of glyphosate 1× or 2× reduced ASR incidence relative to that of the unsprayed control, but only with the fungicide was a statistically significant reduction obtained. The Brazilian trials showed that neither glyphosate nor the fungicide provided effective ASR control; however, overall greater ASR reduction was observed with the fungicide than with glyphosate.



**Figure 5.** Incidence of Asian rust in GR soybeans, based on area under disease progress curve (AUDPC), from field trials in Sorriso, Brazil. Glyphosate (Glyp, 1× or 2×, 0.84 or 1.68 kg AE ha<sup>-1</sup>) was sprayed at 14 day intervals (5–6 total sprays), and rust was sighted at 7 days after the last spray. Fungicide C (pyraclostrobin + epoxiconazole) was sprayed upon rust sighting, and ratings were collected from 7 to 15 days after the spray. Statistical significance was analyzed relative to unsprayed controls (similar letters in labels represent no difference at  $P < 0.05$ , Tukey test).

#### 4 DISCUSSION

The laboratory studies provided strong evidence that glyphosate is active against ASR. A glyphosate use rate of 0.84–1.68 kg ha<sup>-1</sup> produced consistent control that approached that of standard fungicides including carbendazim + flusilazole and tebuconazole. As in the case of wheat rusts,<sup>12</sup> ASR activity was attributed to systemic glyphosate that required absorption and translocation in the plant. The field results were more variable, and ASR control by glyphosate ranged from good to moderate in locations in Argentina and Brazil. The performance of pyraclostrobin + epoxiconazole was similarly variable, resulting in incomplete ASR control in many locations. The field data suggest that ASR control by glyphosate or fungicides is impacted upon by many environmental variables including the possibility of different races of *P. pachyrhizi* that may differ in glyphosate sensitivity. Further studies are ongoing to identify the factors that impact upon the activity of glyphosate on ASR.

The present results showed that ASR control in GR soybeans required a higher rate (1–2×) of glyphosate than rust control in GR wheat (0.5–1×).<sup>12</sup> One obvious explanation is the differential sensitivity of *P. pachyrhizi* vs *Puccinia* species to glyphosate; however, the plant half-life of glyphosate may also be a factor. Soybeans are known to degrade glyphosate, albeit slowly, to aminomethyl phosphonic acid.<sup>20,21</sup> Since rust control is attributed to glyphosate, its degradation is expected to reduce the activity. This has been implicated in glufosinate-resistant crops. Glufosinate, a herbicide that inhibits glutamine synthetase, has also shown disease control activities against *Rhizoctonia*, *Sclerotinia* and *Pythium*.<sup>22–24</sup> In glufosinate-resistant bentgrass,<sup>24</sup> glufosinate provided only a 2–3 day disease control window which was much shorter than that of glyphosate.<sup>12</sup> One explanation is that glufosinate-resistant plants are engineered with the phosphinothricin acetyl transferase (PAT) gene for efficient degradation of glufosinate.

Current commercial GR crops, with the exception of GR canola, are all engineered with a glyphosate-insensitive CP4-EPSPS gene which conserves glyphosate in the plant.<sup>25</sup> This is expected to change with the development of GR crops based on glyphosate degradation genes such as glyphosate acetyl transferase (GAT)<sup>26,27</sup> and glyphosate decarboxylase (GDC).<sup>28</sup> While these GR crops may exhibit adequate glyphosate resistance, the disease control benefits are expected to differ, depending on the gene of interest.

The herbicidal properties of glyphosate will no doubt continue to drive its use. The present studies demonstrate that glyphosate may offer additional benefits of rust control in GR wheat and soybean, and preliminary data have shown activity against other diseases in GR corn, cotton, pea and onion (unpublished results). Further laboratory and field studies are ongoing to define the utility of glyphosate in disease management in GR crops.

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