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**Corresponding author**:
Navdeep Godara, Graduate Assistant, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR 72704
Email: ngodara@uark.edu



# Response of quizalofop-resistant rice to sequential quizalofop applications under differential environmental conditions

Navdeep Godara[1], Jason K. Norsworthy[2], Thomas R. Butts[3], Trenton L. Roberts[4] and Edward E. Gbur[5]

[1]Graduate Assistant, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [2]Distinguished Professor and Elms Farming Chair of Weed Science, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [3]Assistant Professor and Extension Weed Scientist, Cooperative Extension Service, Lonoke, AR, USA; [4]Professor of Soil Fertility/Soil Testing, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA and [5]Professor, Agricultural Statistics Laboratory, University of Arkansas, Fayetteville, AR, USA

## Abstract

Quizalofop-resistant rice allows for over-the-top applications of quizalofop, a herbicide that inhibits acetyl-coenzyme A carboxylase. However, previous reports have indicated that quizalofop applied postemergence may cause significant injury to quizalofop-resistant rice. Therefore, field experiments were conducted to evaluate the response of quizalofop-resistant rice cultivars to quizalofop applications across different planting dates. Under controlled conditions, the effects of soil moisture content, air temperature, and light intensity on quizalofop-resistant rice sensitivity to quizalofop were investigated. In the planting date experiment, injury of more than 11 percentage points was observed on early-planted rice compared with late-planted rice at the 5-leaf stage, with higher injury observed under saturated soil conditions. However, quizalofop applications at the labeled rate caused ≤16% reduction in yield regardless of planting environment. Quizalofop-resistant cultivars exhibited more injury by at least 25 percentage points when soil was maintained at 90% or 100% of field capacity because rice cultivars 'PVL01', 'PVL02', and 'RTv7231 MA' exhibited ≥42%, 30%, and ≥54% injury, respectively, compared with ≤10%, ≤5%, and ≤22% injury, respectively, at 40% or 50% of field capacity, pooled over rating timing. Greater injury ranging from 18% to 31% was observed on quizalofop-resistant rice grown under low light intensity (600 μmol $m^{-2}s^{-1}$) compared with 5% to 14% injury under high light intensity (1,150 μmol $m^{-2}s^{-1}$). The injury persisted from 7 to 28 d after 5-leaf stage application (DAFT), averaged over quizalofop-resistant cultivars and air temperatures (20/15 C and 30/25 C day/night, respectively). At 7 DAFT, greater injury (by 5 to 21 percentage points) was observed on quizalofop-resistant cultivars; PVL01, PVL02, and RTv7231 MA exhibited 33%, 9%, and 58% injury, respectively, under 20/15 C temperature conditions compared with 13%, 4%, and 37% injury, respectively, under 30/25 C day/night conditions averaged over light intensities. Overall, quizalofop is likely to cause a greater risk for injury to quizalofop-resistant rice if it is applied under cool, cloudy, and moist soil conditions.

## Introduction

Quizalofop-resistant rice was developed to combat troublesome herbicide-resistant grass weed species, including barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and weedy rice (*Oryza sativa* L.; Lancaster et al. 2018; Roma-Burgos et al. 2021). A survey conducted in 2020 that represented 40% of the total planted rice hectares in Arkansas reported high concern with problematic herbicide-resistant weeds, and alternative herbicides were the second-most frequent strategy used to control herbicide-resistant weeds, including barnyardgrass, providing a suitable fit for quizalofop-resistant rice technology (Butts et al. 2022). Quizalofop-resistant rice is a non-genetically modified plant that allows for the postemergence application of quizalofop (Guice et al. 2015). Quizalofop (categorized by the Weed Science Society of America as a Group 1 herbicide) is a member of the aryloxyphenoxypropionate herbicide family and inhibits the acetyl-coenzyme A carboxylase (ACCase). Quizalofop use rates vary from 100 to 138 g ai $ha^{-1}$ for a single application. However, the maximum usage rate should not exceed 240 g ai $ha^{-1}$ annually in any quizalofop-resistant rice production system (Anonymous 2017). Sequential application of quizalofop at the 2-leaf rice stage followed by application at the 5-leaf growth stage is necessary for controlling troublesome grass weeds in a quizalofop-resistant rice system (Anonymous 2017, 2021b). A single dominant gene governs the target-site resistance mechanism in quizalofop-resistant rice, but the consistency of the expression of the resistance mechanism is line-specific and could vary depending on environmental conditions (Camacho et al. 2019, 2020).

Quizalofop at 120 g ai ha$^{-1}$ caused up to 26% injury to quizalofop-resistant rice lines (Camacho et al. 2020). Quizalofop-resistant rice sensitivity to quizalofop was inconsistent and required further investigation to evaluate the effect of environmental attributes.

'PVL01' (Horizon Ag. LLC, Memphis, TN) was the first quizalofop-resistant rice cultivar derived from crossing 'Cheniere', a long-grain conventional cultivar having japonica traits, and 'BASF1-5', a quizalofop-resistant donor line having indica traits. The cultivar exhibited moderate resistance to lodging, 7,500 kg ha$^{-1}$ yield potential, and long-grain rice quality parameters (Famoso et al. 2019). 'PVL02' (Horizon Ag. LLC) is a long-grain quizalofop-resistant rice cultivar developed by crossing the Cheniere and BASF1-5 lines. PVL02 has an increased yield potential compared with that of PVL01 and yields more than 8,095 kg ha$^{-1}$ (Famoso and Linscombe 2020). The BASF1-5 line encompasses a gene with mutagenized nucleic acid responsible for herbicide resistance, encoding a rice plastidic ACCase enzyme and substituting leucine amino acid residue with an isoleucine amino acid residue at the 1792 position in the rice ACCase amino acid sequence (Famoso and Linscombe 2020). The Provisia® (BASF Corporation, Research Triangle Park, NC) formulation of quizalofop is labeled for PVL01, PVL02, and 'PVL03' cultivars (Anonymous 2017). The 'RTv7231 MA' (RiceTec Inc., Alvin, TX) cultivar was developed using conventional breeding techniques; it contains a mutation at the G2096S position in the carboxyl transferase coding region of the ACCase gene, conferring quizalofop resistance (Hinga et al. 2013). The Highcard™ (ADAMA, Raleigh, NC) safened formulation of quizalofop is labeled for use on the RTv7231 MA cultivar (Anonymous 2021b). The RTv7231 MA cultivar produced rough rice yields greater than 10,000 kg ha$^{-1}$ when assessed in on-farm experiments in Arkansas (Frizzell et al. 2021). Safeners for aryloxyphenoxypropionate herbicides are derived from isoxadifen-ethyl, which improves rice tolerance to quizalofop (Shen et al. 2017). Quizalofop-resistant cultivars PVL01, PVL02, PVL03, and RTv7231 MA became commercially available to producers in 2018, 2020, 2022, and 2022, respectively (Anonymous 2021a; Bruce 2019; Hines 2018; McClure 2021).

Climatic factors influence the efficacy of aryloxyphenoxypropionate herbicides by affecting the physiochemical processes of target plants that involve herbicide absorption, translocation, and metabolism (Varanasi et al. 2015). More specifically, soil moisture, light intensity, and air temperature are all known to influence the efficacy of ACCase inhibitors (Varanasi et al. 2015). For example, diclofop efficacy was reduced on yellow foxtail [*Setaria lutescens* (Weigel) Hubb.], wild oat (*Avena fatua* L.), little-seed canarygrass (*Phalaris minor* Retz.), and barnyardgrass when applied postemergence under low soil moisture conditions (Dortenzio and Norris 1980). Similarly, reduced control of green foxtail [*Setaria viridis* (L.) Beauv.] was observed with labeled fenoxaprop, fluazifop, and haloxyfop rates when low soil moisture conditions persisted surrounding herbicide applications (Boydston 1990). Fluazifop also exhibited reduced control of quackgrass [*Agropyron repens* (L.) Beauv.] under moisture stress conditions (Kells et al. 1984).

Fluazifop efficacy was reduced on green foxtail when air temperature increased from 18 to 30 C. The reduced efficacy was attributed to increased herbicide absorption and volatilization from leaf surfaces at higher temperatures (Smeda and Putnam 1990). Kells et al. (1984) indicated that quackgrass plants had 26% greater absorption and extensive distribution of $^{14}$C-fluazifop-butyl at 30 C compared with absorption and distribution at 20 C. Additionally, higher translocation of $^{14}$C-fluazifop-butyl was observed on quackgrass exposed to nonshaded compared to shaded conditions (Kells et al. 1984). Higher absorption and translocation of $^{14}$C-sethoxydim have been observed in common bermudagrass [*Cynodon dactylon* (L.) Pers.] at 35 C than at 18 C (Wills 1984). Cyclohexanedione herbicides caused higher phytotoxicity on oat (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) when applied under low ultraviolet conditions, specifically during late evening or dark hours (McMullan 1996). However, the effect of differential environmental conditions on quizalofop-resistant rice response to quizalofop remains unaddressed in the literature. Therefore, we conducted research to evaluate the effects of air temperature, soil moisture, light intensity, and planting environments on the sensitivity of quizalofop-resistant rice to quizalofop applications.

## Materials and Methods

### *Planting Date Experiment*

Field experiments were conducted to determine the amount of injury caused by sequential quizalofop applications to quizalofop-resistant rice cultivars across different planting dates. Experiments were conducted in 2020 and 2021 at the Rice Research and Extension Center, Stuttgart, AR, on a Dewitt silt-loam soil (Fine, smectitic, thermic Typic Albaqualfs) with 27% sand, 54% silt, and 19% clay; pH 5.9; and 1.9% organic matter. The experiment was implemented as a randomized complete block with a split-split plot layout with the whole plot factor being site years (2020 and 2021); the split-plot factor being the planting date as early (mid-April timing) or late (early June timing); and the split-split plot factors being a factorial treatment structure of quizalofop-resistant rice cultivars PVL01, PVL02, and RTv7231 MA; and sequential quizalofop application rate as none, 1×, and 2×, with four replications. Quizalofop (Provisia® herbicide) was sequentially applied at the 1× rate (120 g ai ha$^{-1}$), and 2× rate (240 g ai ha$^{-1}$) in combination with 1% vol/vol crop oil concentrate (Agri-Dex®; Helena Chemical Company, Collierville, TN). However, overlap that occurs during commercial quizalofop applications in a grower's field will deliver a 2× rate of quizalofop along with 2% vol/vol crop oil concentrate. Highcard™ herbicide, now labeled for the RTv7231 MA cultivar, was not available in the 2020 growing season; therefore, quizalofop in the form of Provisia® was the formulated product applied.

PVL01 and PVL02 were planted at 72 seeds m$^{-1}$ row, while RTv7231 MA was planted at 52 seeds m$^{-1}$ row. Rice was planted at a 1.3-cm depth into 5.2-m-long by 1.8-m-wide plots, and each plot consisted of nine drill-seeded rows on 19-cm centers. Rice was planted on April 11, 2020, and April 14, 2021, for the early planting date and on June 3, 2020, and June 1, 2021, for the late planting date. Experiments were maintained weed-free with clomazone (Command™ herbicide; FMC Corporation, Philadelphia, PA) applied preemergence at 336 g ai ha$^{-1}$, and quinclorac (Facet L™ herbicide; BASF Corporation, Raleigh, NC) applied early postemergence at 280 g ai ha$^{-1}$ plus some hand weeding. At the rate mentioned above, quinclorac was applied at the 4-leaf growth stage of rice. Quizalofop was sequentially applied at the 2-leaf and 5-leaf growth stages of rice. Quizalofop at the 2-leaf growth stage was applied on May 12, 2020, and May 12, 2021, for the early planting date and on June 16, 2020, and June 16, 2021, for the late planting date. Quizalofop was applied at the 5-leaf growth stage on May 21, 2020, and May 31, 2021, for the early planting date and on June 27, 2020, and June 28, 2021, for the late planting date. Weather data, including air temperature, rainfall, and solar radiation, were assessed for a 7-d interval that spanned from 3 d before and 3 d after each quizalofop application using a weather station (Davis Instrument Corporation, Hayward, CA) at the experimental site. All herbicides were applied with a $CO_2$-pressurized backpack sprayer calibrated to deliver 140 L $ha^{-1}$ of spray solution at 276 kPa with a hand boom equipped with four Air Induction Extended Range 110015 spray nozzles (TeeJet® Technologies, Wheaton, IL). All plots were maintained using standard cultural practices and fertilized with 130 kg N $ha^{-1}$ as urea (46-0-0) at 24 h after the 5-leaf stage of quizalofop application, prior to the establishment of permanent flood (Hardke et al. 2022).

Percent injury was visually evaluated on a scale of 0% to 100%, with 0% representing no injury and 100% representing plant death. Visual injury evaluations were taken at the 5-leaf stage application, 14 d after 5-leaf stage application (14 DAFT), and 28 d after 5-leaf stage application (28 DAFT). Photographs of each plot were taken with a DJI Phantom quadcopter small unmanned aerial system (DJI, Shenzhen, China) at the 5-leaf stage application, 14 DAFT, and 28 DAFT. Images were analyzed using Field Analyzer (Green Research Services, LLC, Fayetteville, AR) to determine the proportion of green pixels in each photograph to assess the amount of groundcover. Dates were noted for each plot when rice reached the 50% heading stage. All plots were drained 2 wk before harvesting, rice was harvested with a small-plot combine to quantify grain yield, and rice yields were adjusted to 12% moisture. All data were subjected to ANOVA as a randomized complete block with a split-split plot using the GLIMMIX procedure in SAS software (version 9.4; SAS Institute Inc., Cary, NC). The main effects and interaction of year, planting date, cultivar, and quizalofop rate were considered fixed effects. Block nested within year and planting date nested within year were considered random effects (Gbur et al. 2012). Visual evaluation of rice injury was analyzed using beta distribution, while gamma distribution was used for relative groundcover and relative yield. Normal distribution was assumed for relative heading. Means were separated using Fisher's protected LSD ($P = 0.05$). Analysis of variance results for all the evaluated response variables in the planting date experiment is shown in Supplementary Table S1.

## Soil Moisture Experiment

Greenhouse experiments were conducted at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, AR, in fall 2021 to evaluate the effect of soil moisture levels on the tolerance of quizalofop-resistant rice to quizalofop applications. Two experimental runs were conducted. Each experiment was implemented as a completely randomized, two-factor treatment structure with three replications. The factors consisted of soil moisture levels (40%, 50%, 60%, 70%, 80%, 90%, and 100% of pore space filled with water) and quizalofop-resistant rice variety (PVL01, PVL02, and RTv7231 MA). The greenhouse was maintained at a temperature of 30 C and 25 C day and night, respectively, under a 14-h photoperiod throughout the experiments.

The soil was a leaf silt loam (fine, mixed, active, thermic Typic, Albaqualts) with 21% sand, 65% silt, 14% clay; pH 6.4, and 2.3% organic matter. The soil was sieved and dried until it reached 0% moisture. Dried soil weighing 8,000 g was transferred into 9.1-L buckets (24.2-cm diameter by 23.5-cm height; Lowe's Companies, Inc., Mooresville, NC). Soil-Plant-Air-Water hydrology software (U.S. Department of Agriculture–Agricultural Research Service, Washington DC) was used to determine the soil bulk density (1.4 g $cm^{-3}$) and volumetric field capacity (29.75%). The amount of water required to achieve the desired moisture level was calculated using the following equation:

$$W_w = FC \div BD \times ML \times W_s \quad [1]$$

where $W_w$ is the amount of water in grams or milliliters added to each bucket to attain the designated moisture level (ML), FC is the volumetric field capacity, BD is the matric bulk density of soil, and $W_s$ is the weight of dried soil in grams placed in each bucket. Designated soil moisture levels were maintained every day by weighing the total weight of each bucket after germination until flooding. Quizalofop was applied sequentially at the recommended use rate, 120 g ai $ha^{-1}$, in combination with 1% vol/vol crop oil concentrate (Agri-Dex®) at the 2-leaf stage, followed by a subsequent application at the 5-leaf stage. Moisture levels were maintained until a permanent flood at a depth of 6 cm was established in each bucket at 24 h after the 5-leaf stage application.

## Air Temperature and Light Intensity Experiment

Experiments were conducted in a growth chamber (Conviron; Controlled Environments Inc., Pembina, ND) at the Crop Science Research Center, Fayetteville, AR, in fall 2021 and spring 2022 to assess the influence of air temperature and light intensity on the tolerance of quizalofop-resistant rice cultivars to sequential quizalofop applications. The experimental design was a completely randomized, split-split plot arrangement with three spatial replications and two temporal replications. The whole-plot factor was air temperature during the 14-h photoperiod as low (20 C) and high (30 C); the split-plot factor was light intensity as low (600 μmol $m^{-2}$ $s^{-1}$) and high (1,150 μmol $m^{-2}$ $s^{-1}$); and split-split plot factor was quizalofop-resistant rice cultivars PVL01, PVL02, and RTv7231 MA. The low and high light intensities were selected based on photosynthetic photon flux density observed during the early growth stages of the crop in the rice production acreage.

The growth chamber was separated into two sections with a curtain to alter the light levels on each side to achieve the designated light levels. The growth chamber was programmed to a 14-h photoperiod with 20/15 C and 30/25 C day/night temperature, respectively, for conducting two experimental runs for each air temperature level. Field soil identified as a leaf silt loam, previously described for soil moisture level experiments, was sieved and dried until a 0% moisture level was achieved. Air-dried soil totaling 8,000 g was placed in 9.1-L buckets. Quizalofop was applied sequentially at 120 g ai $ha^{-1}$ at the 2-leaf stage, followed by an application at the 5-leaf stage. A 1% vol/vol crop oil concentrate was added to each quizalofop application. All treatments were maintained every day at 100% field capacity after germination until all treatments were flooded at 24 h after the 5-leaf stage application.

## Methods Common to Both Controlled Condition Experiments

Quizalofop-resistant cultivars were planted at a 1.3-cm depth with eight seeds per treatment and later thinned to six plants per bucket after emergence. All treatments were maintained weed-free through hand weeding and were fertilized with 130 kg N $ha^{-1}$ at the 5-leaf growth stage before permanent flood establishment. Provisia® formulation of quizalofop was used for PVL01 and PVL02 varieties, whereas Highcard™ formulation of quizalofop was used for the RTv7231 MA cultivar. All quizalofop applications were made using a research track sprayer equipped with two flatfan 1100067 spray nozzles (TeeJet® Technologies) calibrated to deliver 187 L $ha^{-1}$ at 276 kPa with a speed of 1.61 km $h^{-1}$.

Visual evaluation of injury began at 7 d after the 2-leaf stage initial treatment (7 DAIT), at the 5-leaf stage application, and continued for 7, 14, 21, and 28 d after the 5-leaf stage application (DAFT) on a scale of 0% to 100%, with 0% indicating no injury and 100% indicating plant death. Plant height was measured at the 5-leaf growth stage and 28 DAFT. Photographs were taken at the 5-leaf rice stage and 28 DAFT, and were analyzed using Field Analyzer (Green Research Services, LLC) to determine the groundcover. Aboveground biomass was harvested 28 d after the 5-leaf stage application and oven-dried for 5 d to constant mass to evaluate the differences in biomass accumulation among treatments.

### Data Analysis for Controlled Condition Experiments

Response variables, including plant height, groundcover, and dry biomass data for each treatment, were expressed as a percentage of the nontreated control. For the soil moisture level experiment, the main effects of the soil moisture level and cultivar and their interaction were fixed effects. For the growth chamber experiment, air temperature, light intensity, and cultivar main effects and their interactions were considered fixed effects. The temporal run was considered a random effect for both experiments. Beta distribution was used for rice visual evaluation of injury, whereas relative groundcover, height, and biomass were analyzed with a gamma distribution. All data were subjected to ANOVA using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute, Cary, NC), and means were separated using Fisher's protected LSD test ($\alpha = 0.05$). For the visual injury response variable, rating timing was considered a repeated-measure variable that allowed for comparisons across ratings and included as a fixed effect in the treatment structure. Correlations across ratings for the fixed effects and residuals were modeled using an independence covariance structure, because no correlation among ratings was observed when residuals were evaluated qualitatively (Gbur et al. 2012).

## Results and Discussion

### Planting Date Experiment

Overall, greater injury by 8 and 30 percentage points was observed on PVL01 and RTv7231 MA cultivars in 2021 compared with 2020; however, injury ratings for PVL02 did not differ between 2020 and 2021, averaged over quizalofop rates and planting dates when evaluated at the 5-leaf stage (Table 1). Greater injury to quizalofop-resistant cultivars could be attributed to higher rainfall and cloud cover during the 2-leaf quizalofop application in 2021 (Table 2). Xie et al. (1996) also reported that fenoxaprop was more phototoxic to wild oat under low light intensity because aboveground biomass was reduced more under low than high light intensity. Additionally, rice planted early exhibited more injury by 11 percentage points than late planting when pooled over quizalofop-resistant cultivars, years, and quizalofop application rates at the 5-leaf stage (Table 1). More rainfall occurred during quizalofop applications at the 2-leaf stage when planted early compared with no rainfall surrounding the 2-leaf stage application when planted late, possibly resulting in greater injury at the 5-leaf stage (Table 2). Low soil moisture before and after applications of fenoxaprop, fluazifop, haloxyfop, and sethoxydim reduced the control of green foxtail [*Setaria viridis* (L.) Beauv.] compared to herbicides applied under saturated soil conditions (Boydston 1990).

At 14 DAFT, RTv7231 MA (56% injury) exhibited greater injury by 50 percentage points than PVL01 and PVL02 cultivars, both of which exhibited 6% injury, averaged over the years, planting dates, and sequential quizalofop rates (Table 1). The higher sensitivity of RTv7231 MA to quizalofop resulted in greater visual injury than other quizalofop-resistant cultivars, when the Provisia® formulation (unsafened) was used for over-the-top applications. At 14 DAFT, with data pooled over cultivars and sequential quizalofop application rates, early-planted rice had 20% injury in 2021 compared with 7% injury in 2020, which could be attributed to higher rainfall in 2021 (Tables 1 and 2). Similarly, pooled over planting dates and quizalofop-resistant cultivars, sequential quizalofop applications at the 1× rate caused greater injury by 10 percentage points in 2021 at 14 DAFT. More rainfall occurred close to the quizalofop applications in 2021 than in 2020; however, no differences were observed at 2× sequential quizalofop rates between 2020 and 2021 at 14 DAFT (Tables 1 and 2).

Rice that was planted late exhibited more injury, ranging from 22 to 25 percentage points, at the 2× sequential application rate compared to rice that was planted early, averaged over years and quizalofop-resistant cultivars, with injury persisting from 14 to 28 DAFT (Table 1). At 28 DAFT, RTv7231 MA exhibited 68% injury from the 2× rate of sequential application in 2020 compared with 44% injury in 2021 averaged over planting dates, which might be credited to the crop remaining unaffected at differential environmental conditions when quizalofop was applied at higher than the labeled use rate (Table 1). One way to overcome the negative effect of environmental conditions on the efficacy of an aryloxyphenoxypropionate herbicide is to increase the use rate (Dortenzio and Norris 1980; Kells et al. 1984).

Overall, PVL01 and PVL02 exhibited a high level of tolerance to quizalofop because no differences in injury were observed between 1× and 2× sequential application rates; however, RTv7231 MA exhibited greater injury at the 2× rate compared to the 1× sequential rate, averaged over planting dates when evaluated at 28 DAFT (Table 1). In 2020, PVL01 and RTv7231 MA was injured more when planted early than late, which was attributed to low solar radiation and wet soil conditions that persisted during the 5-leaf stage quizalofop application timing, averaged over sequential application rates at 28 DAFT (Tables 1 and 2).

At the 5-leaf stage of rice, PVL02 had ≤28% relative groundcover when rice was planted early in 2021; however, PVL02 planted late in 2021 exhibited no reduction in groundcover, regardless of sequential quizalofop rates (Table 3). At the 5-leaf stage, RTv7231 MA planted early had 11% relative groundcover compared with 62% relative groundcover when planted late in 2021 at the 1× rate of quizalofop (Table 3). Overall, greater injury to quizalofop-resistant cultivars planted early resulted in a greater reduction in the relative groundcover of the crop when compared to late planting in 2021, evaluated at the 5-leaf stage. At 14 DAFT, quizalofop-resistant cultivars planted late had 63% relative groundcover compared with 89% relative groundcover of early planted rice when quizalofop was applied at a 2× rate (Table 3). Higher rates of quizalofop might overcome the effect of environmental conditions on crop tolerance to the herbicide. Pooled over quizalofop-resistant cultivars, quizalofop rates, and planting dates, a reduction in the relative groundcover of rice was observed, ranging from 22 to 13 percentage points in 2021 compared to 2020, when groundcover was assessed at 14 and 28 DAFT (Table 3). At 28 DAFT, RTv7231 MA had 84% relative groundcover compared to that of PVL01

**Table 1.** Injury to quizalofop-resistant rice cultivars caused by sequential quizalofop applications over different planting dates.[a,b,c]

| Factor | Year | Planting | Cultivar | Rate | Injury | | |
|---|---|---|---|---|---|---|---|
| | | | | | 5-Leaf stage | 14 DAFT | 28 DAFT |
| | | | | g ai ha$^{-1}$ | | % | |
| Year × Planting × Cultivar | 2020 | Early | PVL01 | | 13 | 3 | 4 ef |
| | | | PVL02 | | 7 | 3 | 17 c |
| | | | RTv7231 MA | | 12 | 36 | 15 cd |
| | | Late | PVL01 | | 2 | 7 | 18 c |
| | | | PVL02 | | 1 | 8 | 10 cde |
| | | | RTv7231 MA | | 1 | 73 | 69 a |
| | 2021 | Early | PVL01 | | 17 | 10 | 4 ef |
| | | | PVL02 | | 8 | 7 | 2 f |
| | | | RTv7231 MA | | 56 | 65 | 38 b |
| | | Late | PVL01 | | 10 | 7 | 5 def |
| | | | PVL02 | | 4 | 11 | 5 def |
| | | | RTv7231 MA | | 17 | 46 | 31 b |
| Year × Cultivar × Rate | 2020 | | PVL01 | 120 | 4 | 2 | 8 ef |
| | | | PVL01 | 240 | 6 | 11 | 9 ef |
| | | | PVL02 | 120 | 2 | 2 | 5 f |
| | | | PVL02 | 240 | 4 | 17 | 9 ef |
| | | | RTv7231 MA | 120 | 3 | 30 | 16 de |
| | | | RTv7231 MA | 240 | 4 | 78 | 68 a |
| | 2021 | | PVL01 | 120 | 8 | 5 | 2 f |
| | | | PVL01 | 240 | 21 | 16 | 9 ef |
| | | | PVL02 | 120 | 6 | 8 | 3 f |
| | | | PVL02 | 240 | 6 | 9 | 3 f |
| | | | RTv7231 MA | 120 | 32 | 47 | 26 cd |
| | | | RTv7231 MA | 240 | 36 | 64 | 44 b |
| Year × Cultivar | 2020 | | PVL01 | | 5 c | 4 | 9 |
| | | | PVL02 | | 3 c | 5 | 13 |
| | | | RTv7231 MA | | 4 c | 55 | 39 |
| | 2021 | | PVL01 | | 13 b | 9 | 5 |
| | | | PVL02 | | 6 c | 9 | 3 |
| | | | RTv7231 MA | | 34 a | 55 | 34 |
| Planting × Rate | | Early | | 120 | 12 | 8 c | 7 b |
| | | | | 240 | 18 | 18 b | 10 b |
| | | Late | | 120 | 3 | 7 c | 7 b |
| | | | | 240 | 4 | 40 a | 35 a |
| Year × Rate | 2020 | | | 120 | 3 | 4 c | 9 |
| | | | | 240 | 5 | 31 a | 30 |
| | 2021 | | | 120 | 12 | 14 b | 6 |
| | | | | 240 | 17 | 24 a | 11 |
| Year × Planting | 2020 | Early | | | 10 | 7 b | 10 |
| | | Late | | | 1 | 21 a | 28 |
| | 2021 | Early | | | 22 | 20 a | 7 |
| | | Late | | | 9 | 17 a | 10 |
| Cultivar | | | PVL01 | | 8 | 6 b | 6 |
| | | | PVL02 | | 4 | 6 b | 6 |
| | | | RTv7231 MA | | 12 | 56 a | 37 |
| Planting | | Early | | | 15 a | 12 | 8 |
| | | Late | | | 4 b | 18 | 17 |

[a]Abbreviation: DAFT, days after final treatment at the 5-leaf stage.
[b]Means followed by the same letter within the same column are not different based on Fisher's protected LSD at $\alpha = 0.05$.
[c]Experiments were carried out at the Rice Research and Extension Center, Stuttgart, Arkansas.

and PVL02, which had ≥97% relative groundcover averaged over years, planting dates, and sequential quizalofop rates; therefore, RTv7231 MA was observed to be more sensitive to the Provisia® formulation than PVL01 and PVL02 (Table 3).

After quizalofop applications at a 2× rate, there was a 2-d delay before PVL02 recached the 50% heading stage when planted late compared to early, averaged over years (Table 4). A delay of 2 and 7 d was observed before RTv7231 MA reached the 50% heading stage after quizalofop was applied at 1× and 2× rates, respectively, when rice was planted late (Table 4). As a result, RTv7231 MA planted late had 37% relative yield in 2020 compared with 96% relative yield in 2021, after quizalofop was applied at the 2× rate. At 28 DAFT, increased injury observed in 2020 to RTv7231 MA planted late, regardless of quizalofop rate, resulted in a reduction in yield potential in 2020 (Tables 1 and 4). Similarly, PVL02 exhibited a 70% relative yield at the 2× rate of quizalofop when rice was planted late in 2021 (Table 4). In 2020, PVL01 and RTv7231 MA planted late exhibited 77% and 37% relative yield, respectively, compared with ≥87% relative yield of cultivars planted early when quizalofop was applied at a 2× rate (Table 4). Overall, ≥84% relative yield of quizalofop-resistant cultivars was observed when quizalofop was applied sequentially at the labeled rate, regardless of planting date and year (Table 4). Research findings provide insight into the potential effects of soil moisture and solar radiation on the tolerance of quizalofop-resistant rice cultivars to quizalofop applications. The greater injury was observed under cloudy and wet soil

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**Table 2.** Air temperature, rainfall, and solar radiation data near the experiment site.[a,b]

| Year | Planting date | Application timing | Air temperature | | | Rainfall | | Solar radiation | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Average | Average minimum | Average maximum | Average day$^{-1}$ | Total | Average day$^{-1}$ | Total |
| | | | ——— C ——— | | | — cm — | | — W m$^{-2}$ — | |
| 2020 | Early | 2-leaf | 17 | 12 | 22 | 0.19 | 1.35 | 236 | 1,649 |
| | | 5-leaf | 21 | 16 | 26 | 0.36 | 2.54 | 263 | 1,841 |
| | Late | 2-leaf | 25 | 19 | 31 | 0 | 0 | 328 | 2,296 |
| | | 5-leaf | 25 | 22 | 29 | 0.38 | 2.67 | 206 | 1,442 |
| 2021 | Early | 2-leaf | 17 | 12 | 22 | 0.31 | 2.16 | 221 | 1,548 |
| | | 5-leaf | 20 | 16 | 25 | 0.85 | 5.94 | 231 | 1,617 |
| | Late | 2-leaf | 28 | 23 | 33 | 0 | 0 | 307 | 2,150 |
| | | 5-leaf | 28 | 23 | 33 | 0 | 0.02 | 283 | 1,981 |

[a]Weather data were recorded for a 7-d interval from 3 d prior to each application to 3 d past each quizalofop application.
[b]Experiments were carried out at the Rice Research and Extension Center, Stuttgart, Arkansas.

**Table 3.** Rice relative groundcover compared with the nontreated control after sequential quizalofop applications.[a,b,c]

| Factor | Year | Planting | Cultivar | Rate | Relative groundcover | | |
|---|---|---|---|---|---|---|---|
| | | | | | 5-Leaf stage | 14 DAFT | 28 DAFT |
| | | | | g ai ha$^{-1}$ | ——— % ——— | | |
| Year × Planting × Cultivar × Rate | 2020 | Early | PVL01 | 120 | 106 ab | 107 | 110 |
| | | | PVL01 | 240 | 100 ab | 110 | 106 |
| | | | PVL02 | 120 | 105 ab | 116 | 101 |
| | | | PVL02 | 240 | 54 bcd | 113 | 105 |
| | | | RTv7231 MA | 120 | 90 abc | 106 | 99 |
| | | | RTv7231 MA | 240 | 47 bcd | 76 | 94 |
| | | Late | PVL01 | 120 | 118 a | 116 | 108 |
| | | | PVL01 | 240 | 85 abc | 103 | 103 |
| | | | PVL02 | 120 | 99 ab | 88 | 105 |
| | | | PVL02 | 240 | 86 abc | 96 | 104 |
| | | | RTv7231 MA | 120 | 80 abc | 81 | 113 |
| | | | RTv7231 MA | 240 | 53 bcd | 42 | 70 |
| | 2021 | Early | PVL01 | 120 | 96 ab | 83 | 97 |
| | | | PVL01 | 240 | 61 bc | 90 | 97 |
| | | | PVL02 | 120 | 28 cde | 75 | 73 |
| | | | PVL02 | 240 | 11 e | 89 | 95 |
| | | | RTv7231 MA | 120 | 11 e | 76 | 81 |
| | | | RTv7231 MA | 240 | 12 e | 64 | 74 |
| | | Late | PVL01 | 120 | 91 abc | 78 | 106 |
| | | | PVL01 | 240 | 67 bc | 67 | 89 |
| | | | PVL02 | 120 | 104 ab | 76 | 99 |
| | | | PVL02 | 240 | 104 ab | 73 | 101 |
| | | | RTv7231 MA | 120 | 62 bc | 79 | 80 |
| | | | RTv7231 MA | 240 | 18 de | 31 | 73 |
| Cultivar × Rate | | | PVL01 | 120 | 114 | 95 a | 105 |
| | | | | 240 | 77 | 91 a | 98 |
| | | | PVL02 | 120 | 74 | 87 a | 94 |
| | | | | 240 | 48 | 91 a | 101 |
| | | | RTv7231 MA | 120 | 37 | 85 a | 92 |
| | | | | 240 | 27 | 50 b | 77 |
| Planting × Rate | | Early | | 120 | 52 | 92 a | 93 |
| | | | | 240 | 36 | 89 a | 95 |
| | | Late | | 120 | 90 | 85 a | 101 |
| | | | | 240 | 60 | 63 b | 89 |
| Cultivar | | | PVL01 | | 93 | 93 | 102 a |
| | | | PVL02 | | 60 | 89 | 97 a |
| | | | RTv7231 MA | | 32 | 65 | 84 b |
| Year | 2020 | | | | 82 | 93 a | 101 a |
| | 2021 | | | | 39 | 71 b | 88 b |

[a]Abbreviation: DAFT, days after final treatment at 5-leaf stage.
[b]Means followed by the same letter within the same column are not different based on Fisher's protected LSD at $\alpha = 0.05$.
[c]Experiments were carried out at the Rice Research and Extension Center, Stuttgart, Arkansas.

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**Table 4.** Relative heading and relative yield of quizalofop-resistant rice compared with the nontreated control for the planting date experiments.[a,b]

| Factor | Year | Planting | Cultivar | Rate | Relative heading[c] | Relative yield[d] |
|---|---|---|---|---|---|---|
| | | | | g ai ha$^{-1}$ | days | % |
| Year × Planting × Cultivar × Rate | 2020 | Early | PVL01 | 120 | 2 | 103 a-d |
| | | | PVL01 | 240 | 1 | 113 abc |
| | | | PVL02 | 120 | 0 | 104 a-d |
| | | | PVL02 | 240 | 2 | 96 a-e |
| | | | RTv7231 MA | 120 | 0 | 98 a-e |
| | | | RTv7231 MA | 240 | 2 | 87 b-e |
| | | Late | PVL01 | 120 | 0 | 84 cde |
| | | | PVL01 | 240 | 1 | 77 de |
| | | | PVL02 | 120 | 0 | 95 a-e |
| | | | PVL02 | 240 | 1 | 109 a-d |
| | | | RTv7231 MA | 120 | 2 | 89 b-e |
| | | | RTv7231 MA | 240 | 8 | 37 f |
| | 2021 | Early | PVL01 | 120 | 0 | 94 a-e |
| | | | PVL01 | 240 | 1 | 99 a-e |
| | | | PVL02 | 120 | -1 | 134 a |
| | | | PVL02 | 240 | -1 | 122 abc |
| | | | RTv7231 MA | 120 | -1 | 100 a-e |
| | | | RTv7231 MA | 240 | -1 | 103 a-d |
| | | Late | PVL01 | 120 | 0 | 112 a-d |
| | | | PVL01 | 240 | 2 | 91 b-e |
| | | | PVL02 | 120 | 2 | 124 ab |
| | | | PVL02 | 240 | 3 | 70 e |
| | | | RTv7231 MA | 120 | 1 | 103 a-d |
| | | | RTv7231 MA | 240 | 7 | 96 a-e |
| Planting × Cultivar × Rate | | Early | PVL01 | 120 | 1 bcd | 99 |
| | | | PVL01 | 240 | 1 bcd | 106 |
| | | | PVL02 | 120 | −1 d | 118 |
| | | | PVL02 | 240 | 0 cd | 108 |
| | | | RTv7231 MA | 120 | −1 d | 99 |
| | | | RTv7231 MA | 240 | 1 bcd | 94 |
| | | Late | PVL01 | 120 | 0 cd | 97 |
| | | | PVL01 | 240 | 1 bcd | 84 |
| | | | PVL02 | 120 | 1 bcd | 109 |
| | | | PVL02 | 240 | 2 b | 88 |
| | | | RTv7231 MA | 120 | 2 b | 96 |
| | | | RTv7231 MA | 240 | 7 a | 59 |

[a]Means followed by the same letter within the same column are not different based on Fisher's protected LSD at $\alpha = 0.05$.
[b]Experiments were carried out at the Rice Research and Extension Center, Stuttgart, Arkansas.
[c]Days delay to 50% heading stage compared with the nontreated control.
[d]PVL01, PVL02, and RTv7231 MA yielded 8,929 kg ha$^{-1}$, 9,054 kg ha$^{-1}$, and 11,882 kg ha$^{-1}$, respectively, in early planting interval in 2020; PVL01, PVL02, and RTv7231 MA yielded 4,970 kg ha$^{-1}$, 5,447 kg ha$^{-1}$, and 11,068 kg ha$^{-1}$, respectively, in late planting interval in 2020. PVL01, PVL02, and RTv7231 MA yielded 7,676 kg ha$^{-1}$, 7,139 kg ha$^{-1}$, and 7,344 kg ha$^{-1}$, respectively, in early planting interval in 2021; PVL01, PVL02, and RTv7231 MA yielded 7,862 kg ha$^{-1}$, 6,851 kg ha$^{-1}$, and 7,986 kg ha$^{-1}$, respectively, in late planting interval in 2021.

conditions. However, quizalofop-resistant cultivars recovered from injury caused by sequential quizalofop applications under differential planting environments, because a ≤16% reduction in relative yield was observed when the labeled rate of quizalofop was applied to the crop.

### Soil Moisture Experiment

A significant interaction between cultivar and soil moisture level was observed for all the evaluated response variables (Supplementary Table S2). Additionally, the interaction of cultivar by rating timing was significant for the visual injury response variable (Supplementary Table S2). In general, greater injury to quizalofop-resistant cultivars was observed at 7 and 14 DAFT, averaged over soil moisture levels (Table 5). After the 5-leaf stage quizalofop application, the greatest injury was observed on RTv7231 MA, followed by PVL01 and PVL02, regardless of rating timings, averaged over soil moisture levels (Table 5). Differences in visual injury among quizalofop-resistant cultivars were not observed at the 5-leaf stage (Table 5), because quizalofop takes 1 to 3 wk after application to cause chlorotic and necrotic symptomology (Shaner 2014). PVL01, PVL02, and RTv7231 MA exhibited ≥42%, 30%, and ≥54% injury, respectively, after sequential quizalofop applications when the cultivars were maintained at 90% or 100% of field capacity (Table 6). However, PVL01, PVL02, and RTv7231 MA exhibited ≤10%, ≤5%, and ≤22% injury, respectively, when quizalofop was applied sequentially to the cultivars maintained at 40% or 50% of field capacity (Table 6).

The greater injury observed on quizalofop-resistant cultivars at higher moisture levels resulted in more reduction in relative groundcover and crop height than cultivars maintained under low moisture levels. At 28 DAFT, a reduction in relative groundcover of ≥28, ≥20, and ≥25 percentage points of PVL01, PVL02, and RTv7231 MA, respectively, was observed at 90% or 100% of field capacity when compared with 40% or 50% of field capacity level (Table 6). At the 5-leaf rice stage, PVL01, PVL02, RTv7231 MA exhibited a reduction of at least 20, 24, and 13 percentage points in relative height when maintained at 90% or 100% of field capacity compared to cultivars that were maintained at 40% or 50% of field capacity (Table 6). However, PVL01, PVL02, and RTv7231 MA exhibited a reduction of 24, 12, and 30 percentage points or greater in relative height when maintained at 90% or 100% of field

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**Table 5.** Injury to quizalofop-resistant cultivars after sequential quizalofop applications at different rating timings averaged over soil moisture levels after the greenhouse study.[a,b,c]

| | Injury | | | | | |
|---|---|---|---|---|---|---|
| Cultivar | 7 DAIT | 5-Leaf stage | 7 DAFT | 14 DAFT | 21 DAFT | 28 DAFT |
| | % | | | | | |
| PVL01 | 12 jk | 13 jk | 40 e | 42 de | 34 f | 29 g |
| PVL02 | 6 l | 11 k | 23 h | 23 h | 18 i | 14 j |
| RTv7231 MA | 12 jk | 13 jk | 49 bc | 54 a | 51 ab | 46 cd |

[a]Abbreviations: DAIT, days after initial treatment at the 2-leaf stage; DAFT, days after final treatment at the 5-leaf stage.
[b]Means followed by the same letter are not different based on Fisher's protected LSD test at α = 0.05.
[c]Experiments were carried out at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, Arkansas, in fall 2021.

**Table 6.** Rice injury, relative groundcover, relative height, and relative biomass of quizalofop-resistant cultivars at differing moisture levels following sequential quizalofop applications from the greenhouse experiments.[a,b,c]

| Cultivar | Soil moisture | Injury[d] | RGC 5-leaf stage | RGC 28 DAFT | RH 5-leaf stage | RH 28 DAFT | Relative biomass |
|---|---|---|---|---|---|---|---|
| | % | | | | | | |
| PVL01 | | | | | | | |
| | 40 | 10 ij | 83 b-g | 72 abc | 89 bcd | 97 abc | 50 bcd |
| | 50 | 6 jk | 108 a | 90 ab | 99 ab | 100 ab | 73 abc |
| | 60 | 23 fg | 91 a-d | 65 bcd | 78 efg | 96 a-d | 34 def |
| | 70 | 36 cde | 58 h | 45 def | 72 f-i | 87 a-e | 16 hij |
| | 80 | 38 cde | 67 d-h | 53 cde | 76 e-h | 81 c-f | 26 e-h |
| | 90 | 42 bc | 62 fgh | 44 def | 69 h-k | 73 f | 19 ghi |
| | 100 | 54 ab | 58 h | 30 fg | 63 jk | 55 g | 9 k |
| PVL02 | | | | | | | |
| | 40 | 5 k | 96 abc | 89 ab | 98 ab | 99 ab | 81 ab |
| | 50 | 4 k | 102 ab | 97 a | 102 a | 101 a | 89 a |
| | 60 | 17 gh | 63 e-h | 67 abc | 70 g-j | 96 abc | 41 de |
| | 70 | 18 gh | 83 b-g | 72 abc | 84 cde | 99 ab | 42 cde |
| | 80 | 22 fg | 73 c-h | 74 abc | 76 e-h | 91 a-e | 50 bcd |
| | 90 | 30 def | 81 b-h | 62 bcd | 74 f-i | 83 b-f | 34 def |
| | 100 | 30 ef | 87 b-f | 69 abc | 68 h-k | 87 a-f | 44 cde |
| RTv7231 MA | | | | | | | |
| | 40 | 12 hi | 89 a-e | 63 bcd | 94 abc | 96 a-d | 43 cde |
| | 50 | 22 fg | 68 c-h | 51 cde | 82 def | 89 a-e | 31 d-g |
| | 60 | 30 def | 71 c-h | 39 efg | 79 d-g | 80 def | 23 fgh |
| | 70 | 37 cde | 62 gh | 58 cd | 67 ijk | 87 a-f | 23 fgh |
| | 80 | 41 cd | 60 gh | 38 efg | 72 ghi | 78 ef | 17 hi |
| | 90 | 54 ab | 66 d-h | 26 g | 69 h-k | 59 g | 12 ijk |
| | 100 | 57 a | 64 e-h | 17 h | 62 k | 52 g | 9 jk |

[a]Abbreviations: DAIT, days after initial treatment at the 2-leaf stage; DAFT, days after final treatment at the 5-leaf stage; RGC, relative groundcover compared with the nontreated control; RH, relative height compared with the nontreated control.
[b]Experiments were carried out at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, Arkansas, in fall 2021.
[c]Means followed by same letter within a column are not different based on Fisher's protected LSD test at α = 0.05.
[d]Injury to quizalofop-resistant cultivars averaged over rating timings (7 DAIT, 5-leaf stage, 7 DAFT, 14 DAFT, 21 DAFT, and 28 DAFT).

capacity than at 40% or 50% of field capacity, evaluated at 28 DAFT (Table 6).

PVL01, PVL02, and RTv7231 MA exhibited ≥50%, ≥81%, and ≥31% relative biomass, respectively, at the 40% or 50% moisture level, whereas relative biomass was reduced to ≤19%, ≤44%, and ≤12%, respectively, when quizalofop-resistant cultivars were maintained at 90% or 100% soil moisture level (Table 6). Sequential quizalofop applications caused greater injury and biomass reduction of quizalofop-resistant cultivars under high moisture soils (90% or 100% of field capacity) than low moisture content soils (40% or 50% of field capacity). Furthermore, a significant reduction in relative groundcover and relative height of quizalofop-resistant cultivars was reported after quizalofop applications when rice was maintained at 90% or 100% of field capacity than 40% or 50% of field capacity levels. Diclofop efficacy was similarly reduced on yellow foxtail, wild oat, littleseed canarygrass (*Phalaris minor* Retz.), and barnyardgrass in other research under low soil moisture conditions and could be attributed to an alteration in metabolism within the plant (Dortenzio and Norris 1980). Similarly, fluazifop, another aryloxyphenoxyprioponate herbicide, caused greater phytotoxicity on quackgrass when applied to plants maintained under adequate moisture levels than moisture-stressed plants; however, no differences in absorption and translocation were observed in quackgrass at either moisture level (Kells et al. 1984). Overall, research demonstrated that high soil moisture contents that persisted around the time of quizalofop applications exacerbated injury to quizalofop-resistant rice, and the severity of damage to the crop could be reduced by avoiding quizalofop applications during wet soil conditions.

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**Table 7.** Injury to quizalofop-resistant rice cultivars at different rating timings and temperature levels after sequential quizalofop applications pooled over light intensity levels.[a–d]

| | | Injury | | | | | |
|---|---|---|---|---|---|---|---|
| Temperature | Cultivar | 7 DAIT | 5-Leaf stage | 7 DAFT | 14 DAFT | 21 DAFT | 28 DAFT |
| | | % | | | | | |
| 20 C | PVL01 | 13 ghi | 24 def | 33 c | 32 cd | 26 cde | 20 efg |
| | PVL02 | 6 j-m | 7 jkl | 9 hij | 8 ijk | 6 j-m | 4 lmn |
| | RTv7231 MA | 17 efg | 37 bc | 58 a | 62 a | 50 b | 44 b |
| 30 C | PVL01 | 4 k-n | 7 jkl | 13 ghi | 13 ghi | 5 j-m | 3 mn |
| | PVL02 | 2 n | 3 mn | 4 k-n | 6 j-m | 3 lmn | 3 mn |
| | RTv7231 MA | 15 fgh | 21 d-g | 37 bc | 38 bc | 21 d-g | 16 efg |

[a]Abbreviations: DAIT, days after initial treatment at the 2-leaf stage; DAFT, days after final treatment at the 5-leaf stage.
[b]Means followed by same letter are not different based on Fisher's protected LSD test at $\alpha = 0.05$.
[c]Experiments were conducted at the Crop Science Research Center, Fayetteville, Arkansas.
[d]Light intensity levels were 600 and 1,150 µmol $m^{-2}$ $s^{-1}$.

**Table 8.** Rice injury at different rating timings and light intensity levels after sequential quizalofop applications, averaged over air temperature levels for quizalofop-resistant cultivars PVL01, PVL02, and RTv7231 MA.[a–e]

| | Injury | | | | | |
|---|---|---|---|---|---|---|
| Light intensity | 7 DAIT | 5-Leaf stage | 7 DAFT | 14 DAFT | 21 DAFT | 28 DAFT |
| | % | | | | | |
| Low | 9 def | 15 bc | 29 a | 31 a | 21 b | 18 bc |
| High | 6 fg | 10 cde | 14 bcd | 14 bcd | 7 ef | 5 g |

[a]Abbreviations: DAIT, days after initial treatment at the 2-leaf stage; DAFT, days after final treatment at the 5-leaf stage.
[b]Means followed by the same letter are not different based on Fisher's protected LSD test at $\alpha = 0.05$.
[c]Light intensity levels were 600 and 1,150 µmol $m^{-2}$ $s^{-1}$.
[d]Air temperatures were 20/15 C and 30/25 C day/night, respectively.
[e]Experiments were conducted at the Crop Science Research Center, Fayetteville, Arkansas.

### Air Temperature and Light Intensity Experiment

Rice injury from quizalofop applications was affected by air temperature and light intensity (Supplementary Table S3). When averaged over light intensity levels, the greater injury was observed on PVL01 (ranging from 20% to 33%) and RTv7231 MA (ranging from 37% to 62%) under low temperature when compared to cultivars maintained under high temperature. PVL01 and RTv7231 MA rice exhibited injury ranging from 3% to 13% and 16% to 38%, respectively, when assessed after 5-leaf-stage quizalofop application to 28 DAFT (Table 7). Pooled over light intensity, PVL02 exhibited greater injury under low temperature (ranging from 6% to 9% injury) than under high temperature (2% to 4% injury), and it persisted until 7 DAFT. However, PVL02 recovered from transient injury, and no differences in visual injury were observed at either temperature level after 7 DAFT (Table 7). Xie and others (1996) documented that fenoxaprop phytotoxicity to wild oat was reduced under high temperatures than under low temperatures. No differences in fenoxaprop absorption and translocation were observed; however, lower phytotoxicity to wild oat might be caused by enhanced metabolic degradation within plants at a high temperature (Xie et al. 1996). The greatest injury to quizalofop-resistant cultivars from quizalofop was observed at 7 and 14 DAFT at either temperature, regardless of light intensity levels (Table 7).

Likewise, no differences in terms of visual injury were observed between quizalofop-resistant rice grown under differential light intensity conditions before 7 DAFT, and the greatest injury to rice was reported at 7 and 14 DAFT, averaged over quizalofop-resistant cultivars and air temperatures (Table 8). When pooled over quizalofop-resistant cultivars and air temperature levels, greater injury to rice ranging from 18% to 31% was observed under low light intensity compared to high light intensity (5% to 14% injury), and greater injury persisted from 7 DAFT to 28 DAFT (Table 8). Previous research also reported that high light intensity maintained for 4 wk after fluazifop application caused lower phytotoxicity to couch grass (*Elymus repens* L.) than low light intensity, which could be attributed to enhanced metabolism under brighter conditions (Coupland 1986).

When averaged over temperature levels, the relative groundcover of PVL01 (77%) and RTv7231 MA (38%) was reduced under low light compared to high light, under which PVL01 and RTv7231 MA exhibited 99% and 82% relative groundcover, respectively, at 28 DAFT (Table 9). Furthermore, RTv7231 MA exhibited a reduction of 37 percentage points in relative groundcover under low temperature compared to high temperature, averaged over light intensity levels, when assessed at 28 DAFT (Table 9). The relative height of RTv7231 MA was reduced to 15 percentage points under low light compared to high light conditions when evaluated at the 5-leaf stage and pooled over temperature levels (Table 9). Similarly, the relative height of RTv7231 MA was reduced to 55 percentage points under low light and low temperature combinations compared to the high light and low temperature conditions at 28 DAFT. No differences were observed in relative height at either light intensity level under high temperature conditions (Table 9).

No differences in relative biomass of quizalofop-resistant cultivars were observed at either light intensity level when maintained under high temperature conditions (Table 9). However, PVL01

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**Table 9.** Quizalofop-resistant rice cultivars relative groundcover, relative height, and relative biomass compared with the nontreated control following sequential quizalofop applications under different temperature and light regimes.[a–e]

| Factor | Temperature | Light | Cultivar | RGC 5-leaf stage | RGC 28 DAFT | RH 5-leaf stage | RH 28 DAFT | Relative biomass |
|---|---|---|---|---|---|---|---|---|
| | | | | % | | | | |
| Temperature × Light × Cultivar | 20 C | Low | PVL01 | 46 | 64 | 71 | 78 ab | 26 d |
| | | | PVL02 | 91 | 87 | 91 | 95 ab | 76 ab |
| | | | RTv7231 MA | 34 | 23 | 56 | 43 c | 4 e |
| | | High | PVL01 | 68 | 95 | 91 | 99 ab | 68 abc |
| | | | PVL02 | 92 | 92 | 97 | 102 a | 91 a |
| | | | RTv7231 MA | 74 | 72 | 70 | 98 ab | 44 bcd |
| | 30 C | Low | PVL01 | 82 | 93 | 85 | 98 ab | 84 ab |
| | | | PVL02 | 102 | 98 | 104 | 99 ab | 95 a |
| | | | RTv7231 MA | 56 | 63 | 64 | 69 b | 34 cd |
| | | High | PVL01 | 88 | 103 | 92 | 96 ab | 88 ab |
| | | | PVL02 | 81 | 97 | 95 | 101 ab | 95 a |
| | | | RTv7231 MA | 83 | 94 | 79 | 98 ab | 76 abc |
| Light × Cultivar | | Low | PVL01 | 62 c | 77 b | 78 bc | 87 | 47 |
| | | | PVL02 | 115 a | 92 ab | 97 a | 97 | 85 |
| | | | RTv7231 MA | 44 d | 38 c | 59 d | 54 | 12 |
| | | High | PVL01 | 77 bc | 99 a | 92 ab | 97 | 78 |
| | | | PVL02 | 86 b | 95 ab | 96 a | 101 | 93 |
| | | | RTv7231 MA | 78 bc | 82 ab | 74 c | 98 | 58 |
| Temperature × Cultivar | 20 C | | PVL01 | 56 | 78 ab | 80 | 88 | 42 |
| | | | PVL02 | 91 | 89 ab | 94 | 98 | 83 |
| | | | RTv7231 MA | 50 | 40 c | 62 | 64 | 13 |
| | 30 C | | PVL01 | 85 | 98 a | 88 | 97 | 86 |
| | | | PVL02 | 118 | 97 a | 99 | 100 | 95 |
| | | | RTv7231 MA | 68 | 77 b | 71 | 82 | 52 |

[a]Abbreviations: DAFT, days after final treatment at the 5-leaf stage; RGC, relative groundcover compared with the nontreated control; RH, relative height compared with the nontreated control.
[b]Means within the same column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$.
[c]Light intensity levels were 600 and 1,150 µmol $m^{-2}$ $s^{-1}$.
[d]Air temperatures were 20/15 C and 30/25 C day/night, respectively.
[e]Experiments were conducted at the Crop Science Research Center, Fayetteville, Arkansas.

and RTv7231 MA exhibited a reduction of 42 and 40 percentage points in relative biomass under low light intensity compared to high light intensity, when maintained under low temperature conditions (Table 9). Likewise, no differences in relative biomass of quizalofop-resistant cultivars were observed between low and high temperatures when maintained under high light intensity (Table 9). The risk of injury to quizalofop-resistant rice from quizalofop applications escalated if low air temperature and low solar radiation persisted at the timing of herbicide applications; however, rice recovered from transient injury if cold and cloudy conditions did not prevail simultaneously. At low light intensity, the relative biomass of PVL01 and RTv7231 MA reduced from 84% to 26% and 34% to 4%, respectively, from high- to low-temperature conditions (Table 9). Quizalofop metabolism in quizalofop-resistant wheat (CoAXium™ wheat) was reduced under low temperature compared to high temperature; however, quizalofop absorption and de-esterification of quizalofop pro-herbicide to quizalofop-p-acid was not reduced under low temperature (Bough et al. 2022) Overall, lower temperature and prolonged cloudy conditions increased the severity of damage to quizalofop-resistant cultivars from postemergence quizalofop applications. Clethodim efficacy on barley or oat was increased when applied in the dark or evening hours due to the absence of ultraviolet light compared to full sunlight, attributed to the susceptibility of cyclohexanedione herbicides to photodegradation by ultraviolet light during daytime (McMullan 1996).

Response of quizalofop-resistant cultivars to quizalofop was observed to be affected by several environmental factors, including soil moisture content, light intensity, and air temperature. Quizalofop applications need to be avoided under cold and cloudy conditions. Furthermore, quizalofop applications onto rice under saturated soil conditions will exacerbate the severity of damage to quizalofop-resistant cultivars more than if dry conditions existed surrounding the application timings. Quizalofop-resistant rice recovered from transient injury caused by quizalofop applications under differential planting environments, because a ≤16% reduction in relative yield occurred after quizalofop was applied at the labeled rate. PVL03, a new Provisia cultivar, will be commercially available to rice producers in the growing season of 2022 with an increased yield and milling advantage along with blast [*Magnaporthe grisea* (TT Hebert) Barr.] and *Cercospora* resistance over the previously available Provisia cultivars (McClure 2021).

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Producers need to consider environmental conditions for alleviating the risk of injury to quizalofop-resistant cultivars from quizalofop applications.

**Supplementary material.** To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2022.95

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## References


Anonymous (2017) Provisia™ herbicide product label. BASF Corporation Publication No. 2017-04-522-0004. Research Triangle Park, NC: BASF Corporation. 12 p

Anonymous (2021a) Max-Ace herbicide tolerance technology for rice approved by EPA. https://www.adama.com/us/en/news-and-media/max-ace-herbicide-tolerance-technology-for-rice-approved-by-epa. Accessed: January 19, 2022

Anonymous (2021b) Highcard™ herbicide product label. ADAMA. EPA Reg No. 66222-289. Raleigh, NC: ADAMA Agan, Ltd. 17 p

Bough RA, Gaines TA, Dayan FE (2022) Low temperature delays metabolism of quizalofop in resistant winter wheat and three annual grass weed species. Front Agron 3:800731

Boydston R (1990) Soil water content affects the activity of four herbicides on green foxtail (*Setaria viridis*). Weed Sci 38:578–582

Bruce S (2019) New Provisia rice variety approved for release. https://www.lsuagcenter.com/profiles/rbogren/articles/page1558706996237. Accessed: January 19, 2022

Butts TR, Kouame KB-J, Norsworthy JK, Barber LT (2022) Arkansas Rice: Herbicide Resistance Concerns, Production Practices, and Weed Management Costs. Front Agron 4:881667

Camacho JR, Linscombe SD, Sanabria Y, Mosquera PA, Oard JH (2019) Inheritance of Provisia™ rice resistance to quizalofop-*p*-ethyl under laboratory and greenhouse environments. Euphytica 215:83

Camacho J, Linscombe S, Webster E, Oard J (2020) Inheritance of resistance and response of Provisia™ rice to quizalofop-p-ethyl under US field conditions. Weed Technol 34:357–361

Coupland D (1986) The effects of environmental factors on the performance of fluazifop-butyl against *Elymus repens*. Ann Appl Biol 108:353–363

Dortenzio W, Norris R (1980) The influence of soil moisture on the foliar activity of diclofop. Weed Sci 28:534–539

Famoso AN, Harrell DL, Groth DE, Webster EP, Oard JH, Zaunbrecher RE, Bearb KF, Conner CA, Guidry GJ, Angira B, White LM, Linscombe SD (2019) Registration of 'PVL01' rice. J Plant Regist 13:330–333

Famoso A, Linscombe SD, inventors; Louisiana State University (2020) Rice cultivar designated 'PVL02'. World Intellectual Property Organization WO 2020/219346 A1. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2020219346. Accessed: December 28, 2021

Frizzell TD, Hardke JT, Amos LR, Frizzell DL, Hale KF, Castaneda-Gonzalez E, Clayton TL, Wamishe Y (2021) Pages 221–238 *in* Utilization of on-farm testing to evaluate rice cultivars. B R Wells Arkansas Rice Research Studies 2020. Little Rock: University of Arkansas System Division of Agriculture

Gbur EE, Stroup WW, McCarter KS, Durham S, Young LJ, Christman M, West M, Kramer M (2012) Analysis of generalized linear mixed models in the agricultural and natural resources sciences. Madison, WI: American Society of Agronomy, Soil Science Society of America, Crop Science Society of America. 283 p

Guice J, Youmans C, Rhodes A, Schultz J, Bowe S, Armel G, Harden J (2015) Provisia rice system; weed management strategies for rice. Proc South Weed Sci Soc 68:197

Hardke JT, Barber T, Bateman N, Butts TR, Hamilton M, Henry C, Mazzanti R, Norsworthy JK, Roberts TL, Wamishe Y (2022) Pages 3–26 *in* 2022 Rice Management Guide. Little Rock: University of Arkansas System Division of Agriculture

Hines O (2018) BASF releases Provisia rice system for the 2018 season. https://www.basf.com/us/en/media/news-releases/2018/05/P-US-18-058.html. Accessed: January 19, 2022

Hinga M, Griffin S, Moon MS, Rasmussen RD, Cuevas F, inventors (2013) Methods and compositions to produce rice resistant to ACCase inhibitors. US patent 20130023416A1. https://patents.google.com/patent/US9370149B2/en. Accessed: January 28, 2022

Kells J, Meggitt W, Penner D (1984) Absorption, translocation, and activity of fluazifop-butyl as influenced by plant growth stage and environment. Weed Sci 32:143–149

Lancaster ZD, Norsworthy JK, Scott RC (2018) Evaluation of quizalofop-resistant rice for Arkansas rice production systems. Int J Ag. DOI 10.1155/2018/6315865

McClure S (2021) PVL03 takes the Provisia rice system to the next level. https://www.horizonseed.com/horizon/content/news/ProvisiaRicePVL03Sept202021. Accessed: March 7, 2022

McMullan P (1996) Grass herbicide efficacy as influenced by adjuvant, spray solution pH, and ultraviolet light. Weed Technol 10:72–77

Roma-Burgos N, Butts TR, Werle I, Bottoms S, Mauromoustakos A (2021) Weedy rice update in Arkansas, USA, and adjacent locales. Weed Sci 69:514–525

Shaner DL, ed (2014) Pages 243–245 *in* Herbicide handbook. 10th Edition. Lawrence, KS: Weed Science Society of America

Shen C, Tang W, Zeng D, Xu H, Su W, Wu R (2017) Isoxadifen-ethyl derivatives protect rice from fenoxaprop-p-ethyl–associated injury during the control of weedy rice. Weed Sci 65:579–587

Smeda R, Putnam A (1990) Influence of temperature, rainfall, grass species, and growth stage on efficacy of fluazifop. Weed Technol 4:349–355

Varanasi A, Prasad PV, Jugulam M (2015) Impact of climate change factors on weeds and herbicide efficacy. Adv Ag 135:107–146

Wills G (1984) Toxicity and translocation of sethoxydim in bermudagrass (*Cynodon dactylon*) as affected by environment. Weed Sci 32:20–24

Xie HS, Hsiao AI, Quick WA (1996) Influence of temperature and light intensity on absorption, translocation, and phytotoxicity of fenoxaprop-ethyl and imazamethabenz-methyl in *Avena fatua*. J Plant Growth Regul 15:57–62