Weed Technology

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Determining the critical period for grass control in high-yielding cotton using Japanese millet as a mimic weed

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Research Article

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Abstract

Field studies were conducted over five seasons from 2004 to 2015 to determine the critical period for weed control (CPWC) in high-yielding, irrigated cotton using a competitive mimic grass weed, Japanese millet. Japanese millet was planted with or after cotton emergence at densities of 10, 20, 50, 100, and 200 plants m^{-2}. Japanese millet was added and removed at approximately 0, 150, 300, 450, 600, 750, and 900 degree days of crop growth (GDD). Data were combined over years. Japanese millet competed strongly with cotton, with season-long interference resulting in an 84% reduction in cotton yield with 200 Japanese millet plants m^{-2}. The data were fit to extended Gompertz and logistic curves including weed density as a covariate, allowing a dynamic CPWC to be estimated for densities of 10 to 200 Japanese millet plants m^{-2}. Using a 1% yield-loss threshold, the CPWC commenced at 65 GDD, corresponding to 0 to 7 d after crop emergence (DAE), and ended at 803 GDD, 76 to 98 DAE with 10 Japanese millet plants m^{-2}, and 975 GDD, 90 to 115 DAE with 200 Japanese millet plants m^{-2}. These results highlight the high level of weed control required throughout the cropping season in high-yielding cotton to ensure crop losses do not exceed the cost of weed control.

Introduction

Glyphosate resistance is a problem in many grass and broadleaf weeds in Australia, with the first case of a glyphosate-resistant weed, rigid ryegrass (*Lolium rigidum* Gaudin), confirmed in 1996 (Preston 2019). Since then, glyphosate resistance has been confirmed in an additional nine grass and seven broadleaf weeds, with resistant weeds being troublesome in a range of situations, including cropping, fallows, fence lines, and roadways in Australia (Preston 2019). Many of these resistant weeds are difficult to control in the northern farming region of eastern Australia where the cotton industry is established.

Glyphosate-resistant junglerice [*Echinochloa colona* (L.) Link.] was first confirmed in a cotton field in Australia in 2009 (Werth et al. 2010). Glyphosate-resistant weeds have since become widespread throughout the cotton industry, with glyphosate-resistant junglerice, feather fingergrass (*Chloris virgata* Sw.), windmillgrass (*Chloris truncata* R. Br.), hairy fleabane (*Erigeron bonariensis* L.), rigid ryegrass, and annual sowthistle (*Sonchus oleraceus* L.) present in or surrounding many fields. Glyphosate-resistant liverseedgrass (*Urochloa panicoides* P. Beauv.) and sweet signalgrass [*Brachiaria eruciformis* (Sm.) Griseb.] are also present in the region where cotton is grown.

Managing glyphosate-resistant weeds is challenging for many cotton growers, especially where weeds have established on surrounding properties or irrigation infrastructures, providing a continuing source of reinfestation that may be outside the control of the cotton grower. In-field management of these weeds has become increasingly reliant on the use of alternative weed management tactics, such as herbicides with different modes of action, interrow cultivation, and hand hoeing, with the aim of preventing seed set of any weeds that survive a glyphosate application and driving the weed seedbank down over time (Thornby et al. 2013).

Before the development of glyphosate resistance, grass control had not been a major issue in the Australian cotton industry, as grass weeds were readily controlled using a range of herbicides, including glyphosate. Only junglerice was listed among the 15 most numerous weeds of cotton in 2001 (Charles et al. 2004) and again in 2010 (Werth et al. 2013). However, with the development of glyphosate resistance, grass weeds have become increasingly problematic in the Australian cotton-farming system (Thornby et al. 2013). Glyphosate-resistant junglerice and feather fingergrass were present in 23% and 26%, respectively, of cotton fields (Otto 2018). Over the last decade, these plants have been managed using a range of control tactics, with heavy reliance on the acetyl-coA carboxylase (ACCase)-inhibiting herbicides applied over the top of cotton and other broadleaf crops. Consequently, the incidence of resistance in junglerice and feather fingergrass to both glyphosate and the ACCase-inhibiting herbicides is increasing in the cotton system (Otto 2018; Tout 2012; A Jalaludin, Queensland Department of Agriculture and Fisheries, personal communication).

Rigid ryegrass, primarily a winter-growing weed, was not previously an issue in cotton, as it did not grow through the hotter part of the season in the cotton-growing regions. However, with cotton production expanding into cooler, more southerly areas of eastern Australia, cotton is now being grown in areas where rigid ryegrass with resistance to multiple modes of herbicidal action is present. In addition, some ecotypes of rigid ryegrass appear to be changing, and populations of this "winter" weed can now be found actively growing in cotton fields in midsummer and are spreading into the more northerly parts of the cotton-producing region, infesting 11% of cotton fields (Otto 2018). Anecdotally, plants have been found in cotton with resistance to all but one of the herbicidal modes of action currently registered for grass control in cotton in Australia.

Glyphosate-resistant feather fingergrass and windmillgrass are also becoming increasingly common in cotton fields, and it is likely to be only a matter of time before liverseedgrass and sweet signalgrass become problematic in cotton. With increasing reliance on alternative chemistries such as the ACCase-inhibiting herbicides to control these glyphosate-resistant grass weeds, it can be expected that populations of these and other commonly occurring grasses will also develop resistance to these alternative modes of herbicidal action in the near future.

The initial response of many farmers to a spray failure is to increase the rate of the herbicide or to apply an alternative herbicide, often with the same herbicidal mode of action. However, extensive experience from within Australia and around the world has shown that continuous reliance on herbicides from a single mode-of-action group leads to more failures and promotes further resistance (Powles 2008). Thornby et al. (2013) have shown that by adopting an integrated approach to weed management, the development of herbicide resistance in weeds in cotton can be delayed for many years. To achieve this, it is essential that weeds are controlled before they set seed and that any survivors of a weed management input are controlled using an alternative input, driving down the weed seedbank over time (Thornby et al. 2013).

The timing of weed control inputs can be challenging with species such as junglerice, for which a main flush of emergence may occur at planting, but successive germination flushes typically occur throughout the season. Consequently, these weeds often need to be controlled on multiple occasions throughout the season, after rainfall or irrigation events that trigger weed germinations. Ideally, weed control activities are triggered by the growth stage of the weeds, ensuring weeds are controlled before they set seed, or before this point, triggered by an economic threshold. The adoption of a control threshold ensures weeds are managed before they suppress crop growth and cause economic loss that exceeds the cost of control. Additionally, the control threshold needs to be dynamic, responding to the stage of crop growth, as previous research has shown that crops are more sensitive to early-season weed competition than late-season competition (Charles et al. 2019a; Korres and Norsworthy 2015; Webster et al. 2009).

Establishing a dynamic economic threshold for weed control can be done using the critical period for weed control (CPWC), which identifies the period during crop development when the crop is sensitive to weed competition, such that the damage caused by weed competition exceeds the cost of controlling the weeds (Fast et al. 2009; Korres and Norsworthy 2015; Webster et al. 2009). The CPWC is determined by identifying the critical time for weed removal (CTWR), the critical weed-free period (CWFP), and the yield-loss threshold. The CTWR is the period after crop emergence during which weeds can be allowed to compete with the crop without causing a yield loss exceeding the yield-loss threshold. The CWFP is the minimum period after crop emergence during which the crop must be maintained weed-free to prevent a yield loss exceeding the threshold. The combination of the CTWR and the CWFP with the yield-loss threshold defines the CPWC (Charles et al. 2019a; Korres and Norsworthy 2015).

The CPWC has been established for a range of weeds in cotton, but generally in lower-yielding cotton crops. Charles et al. (2019a) used common sunflower (*Helianthus annuus* L.) as a large, mimic broadleaf weed at densities of 1 to 50 plants m^{-2} and found that at the highest weed density, the CPWC extended to almost the full season in high-yielding cotton (averaging 2,040 kg lint ha^{-1} on weed-free plots), much longer than had been observed in previous studies on lower-yielding crops (Bukun 2004; Cardoso et al. 2011; Korres and Norsworthy 2015).

As an alternative to undertaking experiments using naturally occurring weeds, a range of mimic weeds have been used in competition experiments, as they have the advantages of greater experimental controllability and repeatability, with better control over weed density and more uniform weed emergence (Charles et al. 2019b). Mimic grass weeds used in competition experiments have included barley (*Hordeum vulgare* L.) (Strydhorst et al. 2008), Japanese millet (Wu et al. 2010), oats (*Avena sativa* L.) (Brain et al. 1999), perennial ryegrass (*Lolium perenne* L.) (Afifi and Swanton 2012), and winter wheat (*Triticum aestivum* L.) (Cerrudo et al. 2012). A mimic weed is generally chosen that has morphological characteristics similar to those of the real weed for which it is being substituted and is often of the same genus as the real weed. Charles et al. (2019b) compared the competitive effects of junglerice and the mimic weed Japanese millet in irrigated cotton and found that although both real and mimic weeds had similar morphological characteristics (plant height, leaf number per plant, leaf area per plant, and dry weight per plant), junglerice was more competitive with cotton, causing a greater reduction in cotton lint yield than did Japanese millet at the highest observed density of 100 plants m^{-1} of crop row. No differences were found at 50 and 10 weeds m^{-1}. These findings demonstrated that while Japanese millet was not a perfect substitute for junglerice, experimental results from competition experiments using Japanese millet as a mimic weed can give valuable insight into the effect of a competitive grass weed such as junglerice in cotton.

The impact of a competitive grass weed on high-yielding cotton has not previously been reported. However, earlier work has shown that grasses can be very competitive in lower-yielding cotton crops. Bridges and Chandler (1987) recorded reductions of seed cotton yield approaching 100% from season-long competition with johnsongrass [*Sorghum halepense* (L.) Pers.] in cotton yielding approximately 1,400 to 3,300 kg seed cotton ha^{-1}, with the level of yield reduction increasing with increasing johnsongrass density. Similarly, Keeley and Thullen (1991a) reported seed-cotton yield reductions of up to 100% from season-long competition with barnyardgrass [*Echinochloa crus-galli* (L.) Beauv]. Brown et al. (1985)

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observed seed-cotton yield reductions of up to 80% from high densities of bermudagrass [*Cynodon dactylon* (L.) Pers.], although lesser reductions in yield were noted by Keeley and Thullen (1991b) and Vencill et al. (1993).

The objective of this study was to determine the CPWC for a competitive grass weed in high-yielding, irrigated cotton over a series of seasons, using Japanese millet as a mimic weed, and to evaluate the impact of Japanese millet density on the CPWC.

Materials and Methods

Field studies were conducted over five seasons at the Australian Cotton Research Institute, Narrabri (30.12°S, 149.36°E, elevation 201 m) using commercial cotton cultivars 'Sicot 289 BR' in 2004 to 2005; 'Sicot 80 BRF' in 2005 to 2006, 2006 to 2007, and 2007 to 2008; and 'Sicot 71 BRF' in 2015 to 2016. The soil was a heavy alluvial clay soil (fine, thermic, smectitic, Typic Haplustert). Cotton was planted at 15 seeds m^{-2} on October 4, 2004; October 19, 2005; October 6, 2006; October 8, 2007; and October 21, 2015. The cotton was grown on raised hills, 1 m apart, in fully irrigated fields using furrow irrigation and fertilized with 180 kg N ha^{-1}, in line with commercial practices. Irrigation was scheduled according to computer modeling of the crop's requirements. Japanese millet 'Shirohie' was planted at the specified densities and times in rows adjacent to and offset from the cotton rows by 100 mm. Plots were otherwise maintained weed-free. Glyphosate (Roundup Ready® herbicide, 690 g kg^{-1}; Monsanto Australia, Melbourne, VIC, Australia) at 1 kg ai ha^{-1} was applied POST as necessary over plots that were weed-free, and hand hoeing was performed as needed.

Experimental Design

The experiments used a split-plot design within a randomized, complete block with four replications. Main plots were times of weed planting, and subplots were times of weed removal and weed densities. Subplots were 4 rows wide (4 m) by 10 m long. Japanese millet was sown to achieve 0, 10, 20, 50, 100, and 200 plants m^{-2}, planted with the crop or at predetermined POST periods. Times of weed planting and removal were measured in growing degree days (GDD), using 15.5C as the base temperature (Bukun 2004). Time (T) was defined as:

$$T = \sum \frac{(t_{\min} + t_{\max})}{2} - t_{\mathrm{b}} \qquad [1]$$

where $t_{\min}$ and $t_{\max}$ are the daily minimum and maximum air temperatures, respectively, and t_{b} is the base temperature.

Times of weed planting and removal were targeted to occur at around 150, 300, 450, 600, 750, and 900 GDD, but actual times were influenced by factors such as rainfall and irrigation scheduling. Not all weed densities and times of weed planting and removal occurred in all seasons, with weed emergence sometimes delayed by inadequate surface soil moisture at the time of planting, and not all target weed densities were achieved in all seasons.

The density of established weeds was recorded on 1 m of row in each plot at the time of weed removal. Plant height and aboveground biomass were recorded on 10 cotton and weed plants at the time of weed removal. Plants were weighed after drying at 70 C for at least 72 h in a forced-air oven. The values used for statistical analysis were averages of the data from these 10 plants. Cotton was harvested at the end of each season using a modified commercial harvester with a single picking head, recording seed-cotton yield from the central two rows of each plot. Subsamples from one row were ginned using a single-saw gin to determine ginning percentage and lint yield.

Statistical Analysis

Data were analyzed by ANOVA with replicate, year, time of weed interference and removal, weed density, and cotton variety as factors using R v. 3.4.2 statistical software (R Foundation for Statistical Computing, Vienna, Austria) with a significance level of $P < 0.05$. Analysis indicated no significant year or cotton variety effect or interactions on relative lint yield (lint yield relative to the weed-free control in each season), allowing the data sets from the five seasons to be combined. Relative lint yield was significantly ($P < 0.001$) related to time of weed removal and interference and weed density. Accordingly, data were grouped into density categories, such that the average density of each group equated as closely as possible to the nominal density of 10, 20, 50, 100, or 200 Japanese millet plants m^{-2}. Relative lint yield was regressed as a function of the time of weed removal or interference within each nominal weed density.

The effect of weed interference at each nominal weed density was modeled using the Gompertz function (Korres and Norsworthy 2015):

$$y = a \exp^{-\exp^{b(T-c)}} \qquad [2]$$

where y is the yield as a percentage of the weed-free control, a is the upper asymptote (constrained to 100%), b and c are constants, and T is the cumulative degree days since planting.

The exponential curve:

$$y = a + b \exp^{cT} \qquad [3]$$

was applied where the shape of the curve did not allow the Gompertz function to be fit.

The effect of weed removals at each nominal weed density was modeled using the logistic function:

$$y = \frac{a}{1 + \exp^{b(T-c)}} \qquad [4]$$

where y is the yield as a percentage of the weed-free control, a is the upper asymptote, b and c are constants, and T is the cumulative degree days since planting.

These functions were extended to include actual weed density as a covariate. The extended Gompertz function was:

$$y = a \exp^{-\exp^{b(T-c+dW)}} \qquad [5]$$

where d is an additional constant, and W is the observed weed density. The interaction term TW was not included, as it did not improve the fit of the relationship, as indicated by the Akaike information criterion (AIC).

The extended logistic function was:

$$y = \frac{a}{1 + \exp^{b(T-c+dTW)}} \qquad [6]$$

where d is an additional constant, and W is the observed weed density. The interaction term TW was used, as it gave a better fit, as indicated by the AIC.

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The extended exponential curve was:

$$y = a + b\exp^{(cT + dTW)} \quad [7]$$

with the interaction term TW again giving a better fit, as indicated by the AIC.

Data for weed and crop height and weed biomass were analyzed using ANOVA with replicate, year, time of weed removal and weed density as factors, using a significance level of $P < 0.05$. Analysis indicated all year effects and year interactions were fully accounted for by the time of weed removal, allowing the data sets from the five seasons to be combined. Data were grouped into density categories and modeled using the Gompertz function (Equation 2) and the exponential model (Equation 3), and the AIC was used to determine the model of best fit for the data. The extended Gompertz (Equation 5) and exponential model (Equation 7) were fit to the data, including actual weed density as a covariate in the calculations, and the model of best fit was determined using the AIC.

Results and Discussion

Cotton Lint Yield and Weed Density

Cotton yields averaged 5,190 kg seed cotton ha^{-1} and 2,070 kg lint ha^{-1} for the weed-free plots over the five seasons, similar to the average Australian yield for these years and well above the yields reported for most previous competition studies in cotton (Barnett and Steckel 2013; Bukun 2004; Cardoso et al. 2011; Fast et al. 2009; Korres and Norsworthy 2015).

Japanese millet competed strongly with the cotton, with season-long interference resulting in an 84% lint yield reduction with 200 Japanese millet plants m^{-2} (Figure 1E). This yield reduction was less than the 97% loss reported by Keeley and Thullen (1991a) for season-long competition with barnyardgrass with densities of 180 and 287 plants m^{-2}, and the 100% yield loss reported for large crabgrass [*Digitaria sanguinalis* (L.) Scop.] in the row at midseason densities of 250 plants m^{-2}, but greater than was reported for bermudagrass in cotton (Brown et al. 1985; Keeley and Thullen 1991b; Vencill et al. 1993). Even at the lowest density of 10 plants m^{-2}, Japanese millet in the current study competed strongly with cotton, with season-long interference reducing cotton lint yield by 49% (Figure 1A).

Comparison of the weed removal and weed interference (CTWR and CWFP) curves over increasing weed density suggests the level of weed competition increased with increasing weed density, with the maximum observed yield losses increasing. In addition, there was a decline in the point of minimum yield loss from a single weed control measure (the intersection point of the weed removal and weed interference curves) with increasing weed density (Webster et al. 2009). The point of minimum yield loss declined from 10% yield loss with 10 Japanese millet plants m^{-2} (Figure 1A) to 26% yield loss with 200 Japanese millet plants m^{-2} (Figure 1E).

An arbitrary 5% lint yield-loss threshold was applied (Ghosheh et al. 1996), such that the CPWC was defined by the upper intersection of the CTWR and CWFP curves with the 5% threshold for each weed density (Figure 1A–E). The critical periods so derived extended from 87 to 275 GDD with 10 Japanese millet plants m^{-2} through 96 to 668 GDD with 200 Japanese millet plants m^{-2} (Figure 1A and E). Thus, there was an increasing trend in the upper limit of the critical period with increasing weed density, but no consistent trend in the effect of weed density on the lower limit of the critical periods.

This lack of consistent response in the lower limit of the CPWC relationships to weed density was also observed by Charles et al. (2019a) with sunflower used as a mimic weed competing in high-yielding cotton. Charles et al. (2019a) concluded the lack of response reflected two components. First, the sensitivity of the derived CPWC to the shape of the fitted curves, with the shape of the curves as they approach the yield-loss threshold changing with increasing weed density, leading to anomalous results when the curves intersect the threshold at or soon after crop emergence. This issue with the shape of the curves changing with changes in weed density was exaggerated in our data, as we were unable to fit logistic curves to the data for 10 and 20 weeds m^{-2}, with exponential curves replacing the logistic curves at these lower weed densities. This change in curve type changed the shapes of the curves as they approached the yield-loss threshold.

Second, Charles et al. (2019a) observed that the competitive effect of the weeds was not directly proportional to the density of weeds, due to increasing intraspecific competition with increasing weed density. Thus, at high weed densities, increasing weed density made proportionally less difference to the level of weed competition experienced by the crop, as shown by the effect of increasing weed density on cotton biomass in our data, where at the end of the season (1,600 GDD), the presence of 10 Japanese millet plants m^{-2} reduced the crop biomass by 22% compared with the weed-free control from 1,110 to 857 g m^{-2} respectively (Figure 2D). Increasing the weed density an additional 20-fold to 200 Japanese millet plants m^{-2} only reduced the crop biomass by an additional 18% to 608 g m^{-2}. At higher weed densities, increases in weed density resulted in relatively small changes in the competitive effect on the crop, and these effects became increasingly difficult to separate from the background variation.

Plant Height and Biomass

Increasing weed density caused a small reduction in weed height, with a 20-fold increase in weed density from 10 to 200 Japanese millet plants m^{-2} reducing weed height at midseason (800 GDD) by 19%, from 131 to 106 cm, respectively (Figure 2A). This reduction in weed height is similar to the findings of Charles et al. (2019a), who observed up to a 24% reduction in midseason weed height with increasing densities of common sunflower in a high-yielding cotton crop. A reduction in weed height with increasing weed density was not observed with tropic croton (*Croton glandulosus* L. var. *septentrionalis* Muell. Arg.) (Askew and Wilcut 2001). Those authors reported that a tropic croton density of 3.5 plants m^{-1} of crop row reduced crop yield by 46% and crop height by 5 cm, but increasing density of tropic croton did not reduce the weed's height. Similarly, Scott et al. (2000) observed a reduction in crop yield and crop height, but reported no response in weed height with increasing densities of jimsonweed (*Datura stramonium* L.) in cotton. Askew and Wilcut (2002) also observed no impact on weed or cotton height from increasing densities of ladysthumb (*Persicaria maculosa* Gray). They proposed this lack of response was due to the slow early-season growth rate of ladysthumb, which was shorter than the crop until approximately 70 d after planting (DAP). Similarly, Bryson (1987) found no effect of increasing hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] density on either crop or weed height, but again the hemp sesbania was shorter than the crop until approximately 55 DAP. This was not the case in our data, where the Japanese millet emerged with

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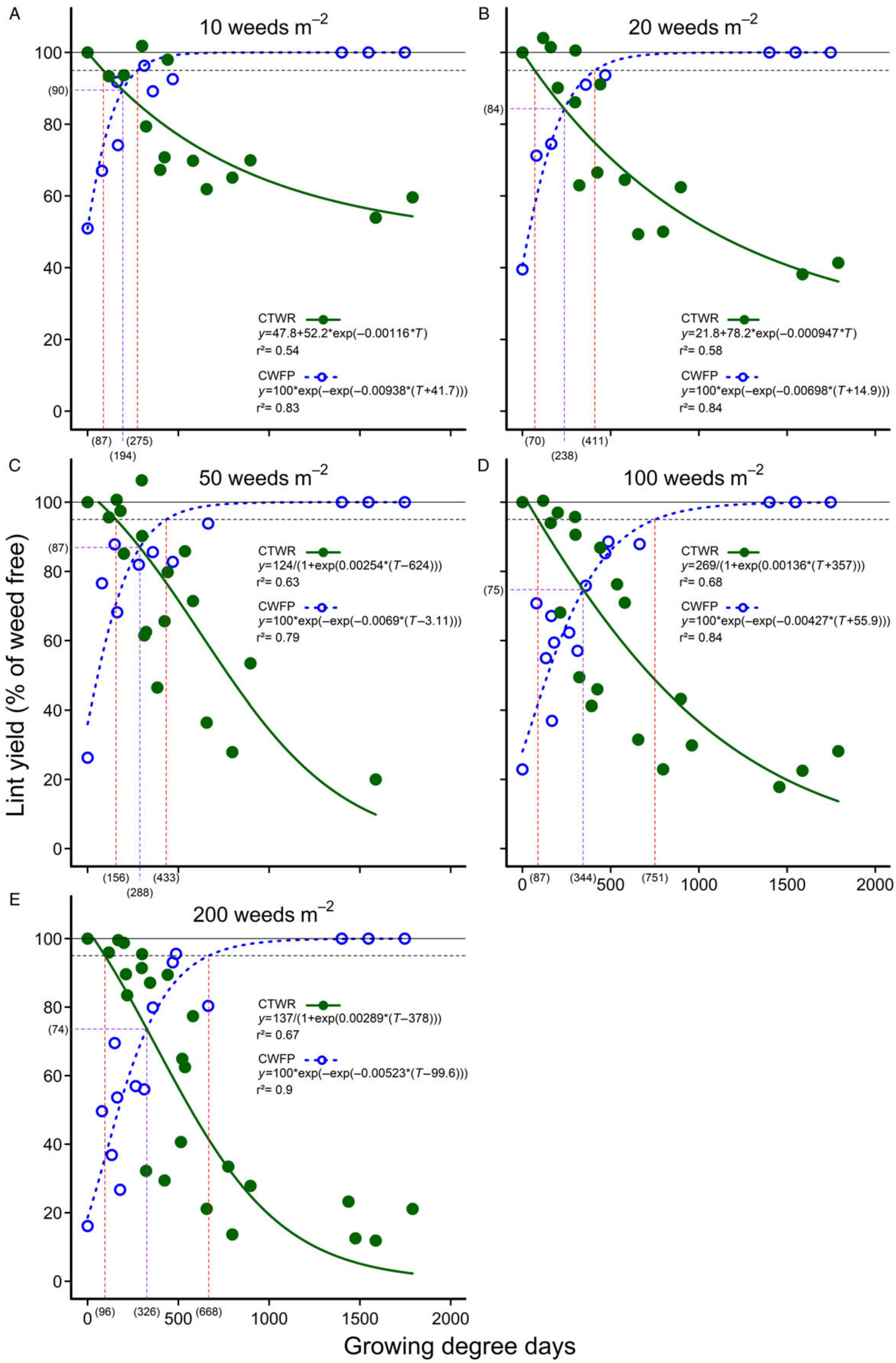

Figure 1. The influence of Japanese millet interference durations—critical time for weed removal (CTWR; green lines) and critical weed-free period (CWFP; blue lines)—on the relative cotton lint yield reduction. Parameters of the exponential and Gompertz (CTWR) and logistic (CWFP) functions are shown within the figures, where *y* is the lint yield and *T* the cumulative growing degree days since planting. Data points for the relationships are treatment means. The horizontal solid lines indicate the weed-free yield and the horizontal dashed lines give a nominal 5% yield-reduction threshold. The critical period for weed control (CPWC) is defined by the upper intersection of the CTWR and CWFP lines with the threshold. The limits of the derived CPWC curves are shown by the vertical dashed red lines and values bracketed below the *x* axis. The point of minimum yield loss is indicated by the dashed purple lines and bracketed values.

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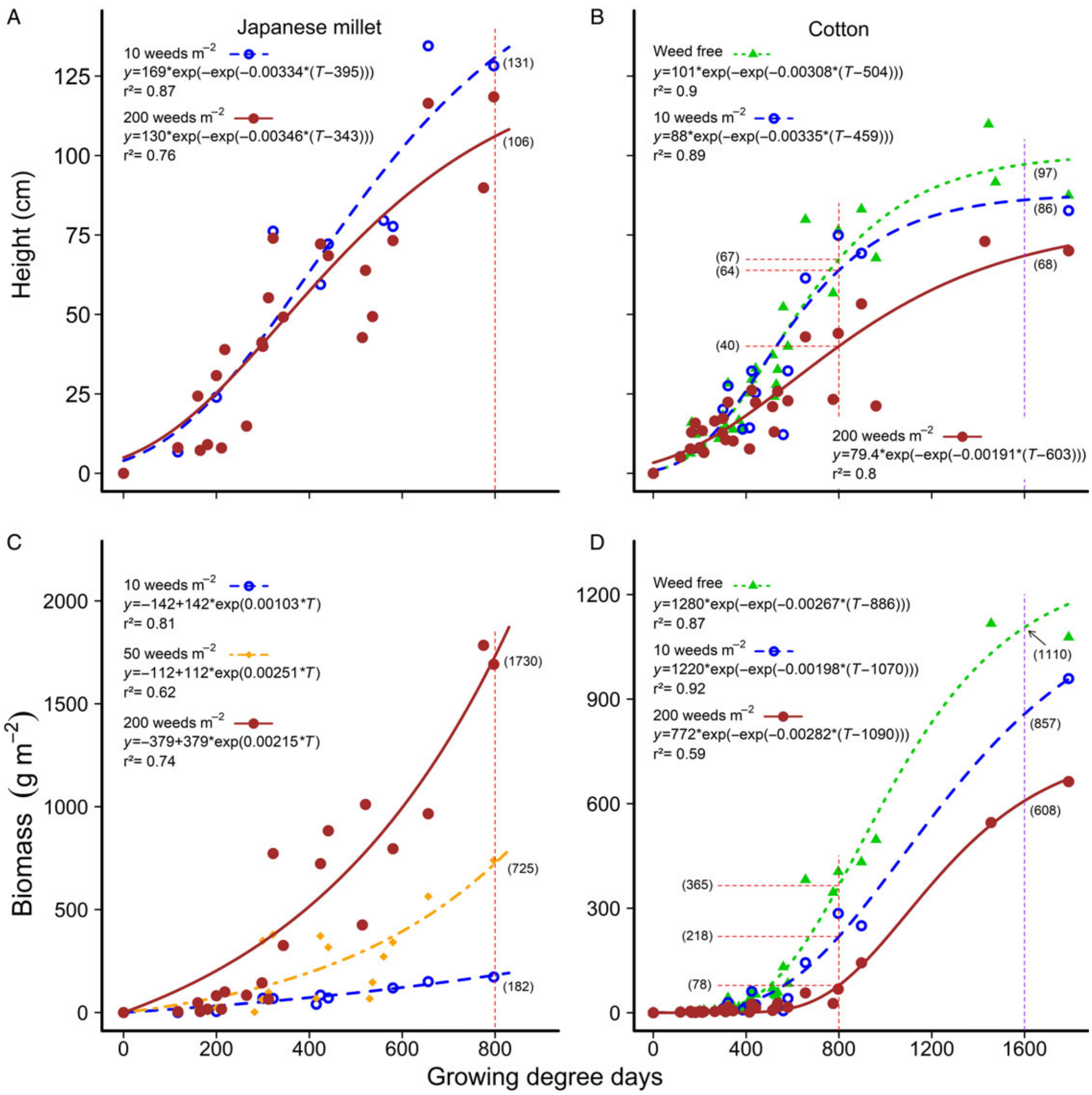

Figure 2. Changes in Japanese millet and cotton height and dry, aboveground biomass over time for densities of 0 (weed-free), 10, and 200 m^{-2}. Data points for the relationships are treatment means. Values at midseason (800 growing degree days since planting [GDD]) are indicated by the dashed red lines and bracketed values.

the crop and grew more rapidly than the crop, exceeding the height of the cotton throughout the season (Figure 2A and B). Thus, we conclude that the effect of increasing weed density on weed height relates to the dominance in height of the weed over the crop throughout the first half of the season. Where the weed is dominant throughout the season, increasing weed density results in a reduction in both crop and weed height, as we observed in our data.

Japanese millet was taller than the crop throughout the season, and around double the height of the cotton midseason, with Japanese millet 131 cm in height with 10 plants m^{-2} at 800 GDD, compared with weed-free cotton at 67 cm in height, declining to 40 cm where cotton competed with 200 Japanese millet plants m^{-2} (Figure 2B).

Crop height was reduced by increasing Japanese millet density, with weed-free cotton 27-cm taller at midseason than cotton competing with 200 Japanese millet plants m^{-2} (Figure 2B). Similarly, other studies have shown cotton height decreased in response to increasing levels of weed competition (Barnett and Steckel 2013; Charles et al. 2019a; Robinson 1976; Scott et al. 1999), although in some studies the response was only observed in some seasons or on some sites or varied with weed species (Buchanan and Burns 1971a, 1971b; Chandler 1977). Ma et al. (2016) reported a reduction in cotton height with increasing velvetleaf (*Abutilon theophrasti* Medik.) densities, but at the same time observed an increase in velvetleaf height. These varying results suggest that species differ in their height response to increasing levels of competition, and the responses may be affected by seasonal variation. The height of corn (*Zea mays* L.), for example, rose with increasing levels of intraspecific competition to 10 plants m^{-2}, but decreased at higher densities (Abuzar et al. 2011)

Weed biomass increased with increasing weed density, but the rate of increase in biomass was less than the rate of increase in density. Midseason weed biomass increased 10-fold from 182 g to 1,730 g m^{-2} as weed density increased 20-fold from 10 to 200 Japanese millet plants m^{-2} (Figure 2C). This response was similar to the response in weed biomass with increasing densities of johnsongrass (Bridges and Chandler 1987), common sunflower (Charles et al. 2019a), and velvetleaf (Ma et al. 2016).

Crop biomass was reduced by increasing Japanese millet density, but again the response was not directly proportional to the increase in Japanese millet density. Midseason cotton biomass per meter of row was reduced by 40% by the presence of

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Table 1. The start and end of the critical period for weed control (CPWC) using a 1% yield-loss threshold.

Weed density	CPWC start	CPWC end
No. m^{-2}	Growing degree days since planting	
10	39	449
20	57	644
50	81	670
100	42	1,130
200	46	979

10 Japanese millet plants m^{-2} and 79% by 200 Japanese millet plants m^{-2} (Figure 2D). By crop harvest, the reduction in crop biomass had lessened to 22% with 10 weeds m^{-2} and 45% with 200 Japanese millet plants m^{-2}.

Dynamic Relationships for Cotton Lint Yield

Clearly, high-yielding cotton crops are sensitive to competition from a competitive grass weed such as Japanese millet, with the duration of the CPWC extending to midseason for densities of 100 weeds m^{-2} or more, using a 5% yield-loss threshold (Figure 1D and E). However, where the target weed is susceptible to glyphosate in a glyphosate-tolerant cotton crop, a cost-based yield-loss threshold of less than 1% could be applied to the analysis, on the basis of Australian 2019 commodity prices. A 1% threshold extended the CPWC to 449 GDD with 10 weeds m^{-2}, and 979 GDD with 200 weeds m^{-2}, but the issue in our data of an inconsistent trend in the lower limit of the CPWC remained (Table 1).

To address this issue of lack of consistent trend in the lower limit of the CPWC, Charles et al. (2019a) fit the relative lint yield data to extended Gompertz and logistic curves that included weed density as a covariate in the equations, allowing a dynamic CPWC to be calculated. Using this approach with our data, the CPWC estimated by these curves for a 1% yield-reduction threshold increased to be from 65 to 803 GDD with 10 Japanese millet plants m^{-2}, and 31 to 975 GDD with 200 Japanese millet plants m^{-2} (Figure 3).

The lower limit of the dynamic CPWC corresponded to before crop emergence for 200 Japanese millet plants m^{-2}, to 1 to 7 d post–crop emergence (DAE) for 10 Japanese millet plants m^{-2}, in line with the results reported by Charles et al. (2019a) for common sunflower competing in high-yielding cotton, and Bukun (2004) for a mixed weed population using a 2.5% threshold, but earlier than most other previous studies on lower-yielding crops at 3 to 5 wk POST (Cardoso et al. 2011; Fast et al. 2009; Keeley and Thullen 1991a; Korres and Norsworthy 2015; Papamichail et al. 2002). This difference from earlier work does not appear to relate to weed size, as the earliest start of the lower limit coincides with weed emergence, but rather to greater sensitivity of higher-yielding cotton to early weed competition in combination with the low threshold adopted. Increased sensitivity to early weed competition in high-yielding cotton crops could be related to the high levels of early fruit retention of these crops (Bange et al. 2008) and consequently reduced compensatory ability. However, Wilson et al. (2003) showed that although high-yielding crops had a high level of early fruit retention, first position retention rarely exceeded 60%, and plants were still able to compensate for early-season damage. Hence, it is difficult to explain why the lower limit of the CPWC is at crop emergence in our data.

The upper limit of the dynamic CPWC corresponded to 76 to 98 DAE for 10 Japanese millet plants m^{-2}, and 90 to 115 DAE for

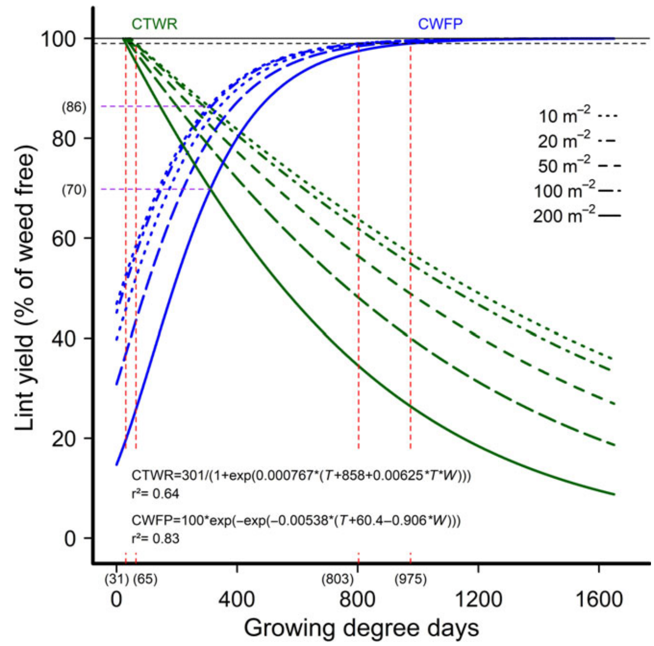

Figure 3. Dynamic relationships showing the influence of Japanese millet interference durations—critical timing for weed removal (CTWR; green lines) and critical weed-free periods (CWFP; blue lines)—on the relative cotton lint yield, using extended Gompertz (CTWR) and logistic (CWFP) functions including weed density as a covariate. Parameters of the models are shown within the figures, where *y* is relative lint yield, *T* the cumulative degree days since planting, and *W* the weed density. The derived relationships for the Japanese millet densities of 10, 20, 50, 100, and 200 m^{-2} are presented as examples. The horizontal solid line indicates the weed-free yield, and the horizontal dashed line shows a 1% yield-reduction threshold. The critical period for weed control (CPWC) is defined by the upper intersection of the CTWR and CWFP lines with the threshold. The limits of the derived CPWC curves for 10 and 200 Japanese millet plants m^{-2} are shown by dashed red lines and values bracketed below the *x* axis. The points of minimum yield loss from a single weed control input at 10 and 200 weeds m^{-2} are shown by the dashed purple lines and bracketed values.

200 Japanese millet plants m^{-2}, longer than the 44 to 52 DAP reported by Korres and Norsworthy (2015) on lower-yielding cotton, or the 55 to 60 DAE observed by Tursun et al. (2015), but in line with the results of others, such as Keeley and Thullen (1991a) for barnyardgrass densities of up to 300 plants m^{-1} of row, and Bukun (2004), Cardoso et al. (2011), and Papamichail et al. (2002), all with naturally occurring mixed weed populations. The point of minimum yield loss where a single weed control input was made during the season increased from 14% for 10 weeds m^{-2} to 30% for 200 weeds m^{-2}, far exceeding the 1% yield-loss threshold (Figure 3).

The approach of Charles et al. (2019a) to develop a dynamic CPWC can also be applied to the weed and crop height and biomass data of Figure 2. In each case, a dynamic model including weed density improved the fit of the data, as indicated by the AIC. These dynamic models (Figure 4) allow weed and crop height and biomass to be determined for any weed density in the observed range of 10 to 200 Japanese millet plants m^{-2}. With these dynamic models, it may be possible to develop a more generalized, multispecies competition model, using weed biomass and height as the measures of weed competitiveness, as suggested by Charles et al. (2019b).

We conclude that where grass weeds are present at densities of 10 m^{-2} or more, a high level of weed control must be maintained throughout the first half of the cropping season in high-yielding cotton to ensure crop losses do not exceed the cost of weed control.

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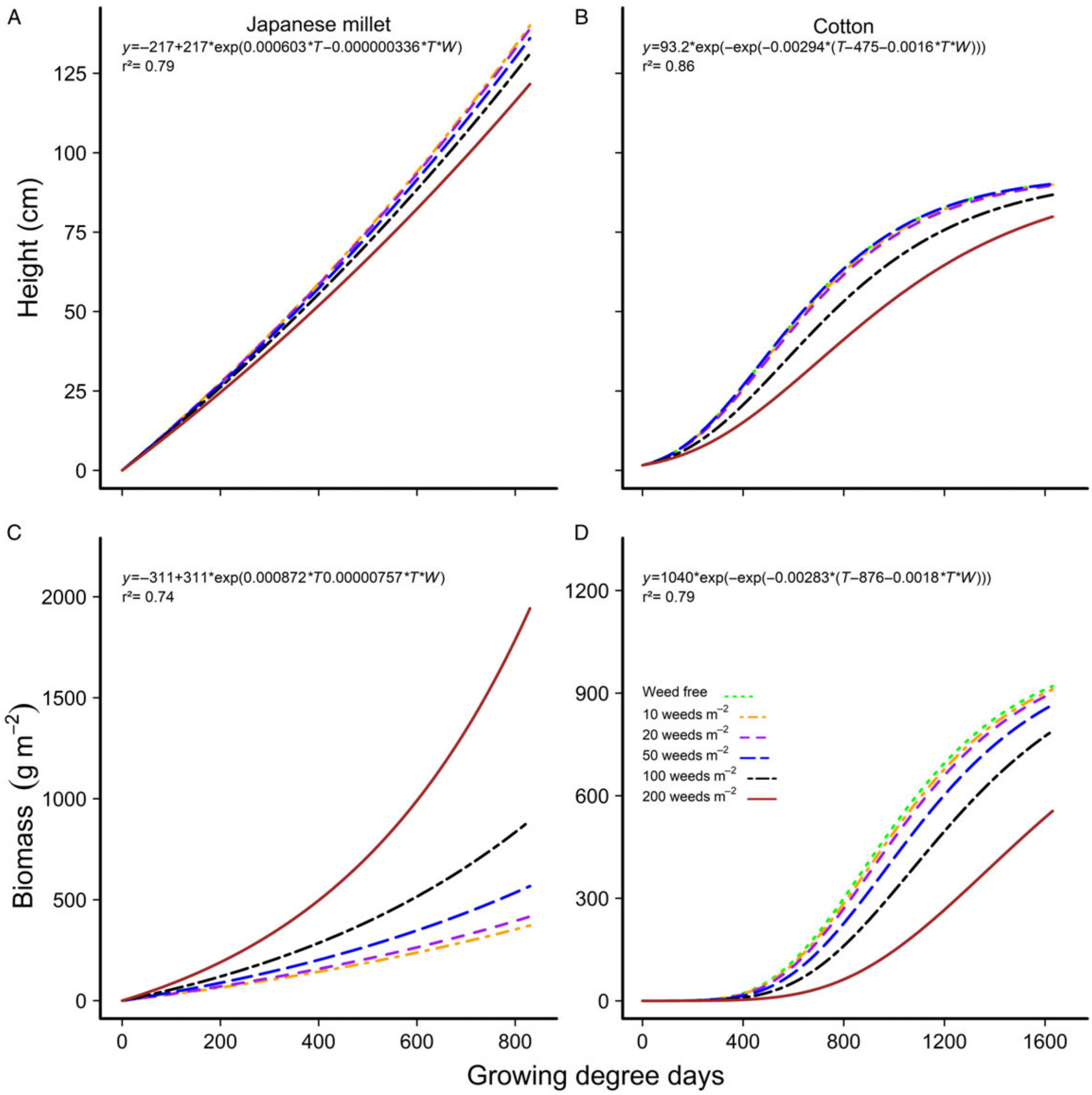

Figure 4. Dynamic relationships showing the Japanese millet and cotton height and dry, aboveground biomass over time using extended exponential and Gompertz functions including weed density as a covariate. Parameters of the models are shown within the figures, where *y* is plant height or biomass, *T* the cumulative degree days since planting, and *W* the weed density. The derived relationships for the Japanese millet densities of 0 (weed-free), 10, 20, 50, 100, and 200 m^{-2} are shown as examples.

In addition, weeds present at low densities will still need to be controlled before they set seed to protect lint quality, to avoid difficulties at harvest, and to drive down the weed seedbank over time and help manage herbicide resistance (Korres and Norsworthy 2015; Thornby et al. 2013).

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