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Corresponding author:
Graham W. Charles;
Email: graham.charles@dpi.nsw.gov.au

Assessing the impact of later emerging broadleaf weeds on the critical period for weed control in high-yielding cotton

Graham W. Charles[1] and Ian N. Taylor[2]

[1]Research Scientist, Weeds Research Unit, Invasive Species Biosecurity, New South Wales Department of Primary Industries and Regional Development, Australian Cotton Research Institute, Narrabri, NSW, Australia and [2]Formally New South Wales Department of Primary Industries, now Chief Executive Officer, Cotton Seed Distributors, Wee Waa, NSW, Australia

Abstract

The critical period for weed control (CPWC) has been used to define weed-control threshold triggers in many cropping systems. Using the CPWC to develop a weed-control threshold for broadleaf weeds that emerge later in the season would be valuable to cotton growers to enable them to schedule management of later emerging weeds to occur before crops suffer unacceptable yield losses. Field studies were conducted over two seasons from 2006 to 2008 to determine the CPWC for a broadleaf weed in cotton, using mungbean as a mimic weed. Mungbean was planted into cotton at densities of 1 to 50 plants m^{-2}, at up to 450 growing-degree days (GDD) after crop planting, and removed at successive 200 GDD intervals after introduction, or left to compete full season. The data were fit to logistic and Gompertz curves. More complex models were developed and tested that included the time of planting and removal, weed density, height and biomass in the relationships. The CPWC models were able to predict the yield loss from later emerging weeds and together with an understanding of the expected growth rates of the weeds, the functions could be used predictively to determine the likely impact of delaying a weed-control input. This predictive element will be of value to cotton growers needing to coordinate weed-control inputs with other farm activities.

Introduction

Weed management was greatly simplified for cotton growers in Australia with the introduction of varieties that were tolerant of glyphosate, allowing most weeds to be controlled inexpensively using over-the-top application of this herbicide (Werth et al. 2013). However, wide-scale use of glyphosate throughout the farming system has led to a shift in the weed spectrum with an increasing dominance of glyphosate-resistant and glyphosate-tolerant species (Charles et al. 2021). Cotton growers are managing these weeds using a mixture of cultivation, residual herbicides and contact herbicides in an increasingly complex system where some management tools are focused on specific problematic species (Koetz 2022). Examples of the use of these specific tools is the application of Group 1 herbicides in cotton crops to manage feather fingergrass (*Chloris virgata* Sw.), junglerice (*Echinochloa colona* [L.] Link), and windmillgrass (*C. truncata* R. Br.). This management is often on an ad hoc basis, increasing resistance pressure on these tools. Resistance to some of these alternative chemistries is already being reported (Chauhan and Mahajan 2023).

Coordinating and balancing the various inputs needed to grow a high-yielding cotton crop is a challenge faced by Australian cotton growers on a daily basis. Growers need to ensure that returns from inputs outweigh the costs of these inputs. Weeds need to be managed such that yield losses from weed competition do not exceed the cost of weed control, but also that inputs are delayed as long as practical to reduce the combined number of inputs required to manage weeds over the season (Taylor et al. 2004). Overlaying this balance is the need to ensure that weeds are controlled before they set seed, driving down the weed seedbank over time, an essential step in managing herbicide resistance (Korres and Norsworthy 2015).

Understanding weed competition and defining an economic threshold for controlling weeds in cotton is central to establishing economically rational weed management for the crop. However, this understanding is complicated by the changing sensitivity of cotton to weed competition throughout the growing season. Cotton is very sensitive to competition early in the season and becomes increasingly tolerant of competition as the crop grows and matures (Charles et al. 2021). The critical period for weed control (CPWC) can be a valuable tool for understanding the economic threshold for weed control as it incorporates the changing sensitivity of cotton to weed competition throughout the season (Charles et al. 2021). The CPWC is delineated by the critical timing for weed removal (CTWR) and the critical weed-free period (CWFP), the period at the start of the season during which the crop can tolerate competition before unacceptable yield loss occurs, and the minimum following period during which the crop needs to be maintained weed free to avoid unacceptable yield loss, respectively (Knezevic et al. 2002). The minimum acceptable yield-loss threshold (YLT) is determined from the value of the crop, the cost of the weed-control input to be used, and the level of acceptable risk (Knezevic and Datta 2015). Most studies apply a 5% YLT (Bukun 2004; Ghosheh et al. 1996, Korres and Norsworthy 2015; Price et al. 2018), but a 1% YLT better reflects the cost of control and crop value for high-yielding cotton in Australia (Charles et al. 2019).

The CTWR, CWFP and YLT combine to define the CPWC that can be used by a cotton grower to make economically rational decisions around weed management on the basis of an understanding of in-crop competition (Charles et al. 2021; Knezevic and Datta 2015; Korres and Norsworthy 2015).

The CPWC can be defined for any crop and weed combination, but the results are often seasonal, weed species-, and crop-specific, providing only general guidance for future weed management decisions. This inability to define relationships that can be applied more widely is due to the influence of a range of factors not incorporated in the CPWC, including weed species and density, and climatic conditions, with in-crop rainfall often an overwhelming influence on crop yields (Burkun 2004; Charles et al. 2019; Tingle et al. 2003; Tursun et al. 2015, 2016; Webster et al. 2009). However, in irrigated, high-yielding Australian cotton crops, where inputs are optimized to match crop needs as far as is possible, a multispecies CPWC model that was robust over seasons could be defined, including temperature, weed height, and weed biomass in the relationships (Charles et al. 2021). Temperature was included in the models by using growing-degree days (GDD) as the measure of time in the relationships. Weed height and weed biomass were included as additional terms in the logistic and Gompertz equations used to define the CPWC.

This CPWC model of Charles et al. (2021) was based on a CTWR relationship defined for weeds that emerged with the crop and were removed at incremental periods postemergence, and a CWFP for weeds that emerged after the crop and were allowed to compete with the crop for the remainder of the season, as has been the past approach with these relationships (Knezevic and Datta 2015; Korres and Norsworthy 2015). This approach is valuable for identifying the point early in the season when the yield loss from competition from weeds that emerge with the crop exceeds the yield-loss threshold, and the point later in the season, after which weeds that emerge will not grow sufficiently to cause damage to the crop exceeding the yield-loss threshold. These late-emerging weeds do not need to be controlled to prevent yield loss exceeding the yield-loss threshold, but may need to be controlled at some point to protect crop fiber quality and prevent a buildup of the weed seedbank (Charles and Taylor 2021; Korres and Norsworthy 2015). The period between these two points is the CPWC. Weeds present during the CPWC need to be controlled to prevent yield loss exceeding the yield-loss threshold. Weeds that emerge with the crop need to be controlled at the start of the CPWC and weeds that emerge at the end of the CPWC do not need to be controlled until the end of the season.

However, the traditional CPWC relationships give no information on the required timing for control of weeds that emerge during the CPWC, other than that these weeds will need to be controlled before the end of the cropping season. The models give no guidance as to when the competitive damage from these later emerging weeds exceeds the YLT. To address this issue, Charles and Taylor (2021) extended the CPWC approach by exploring the relationships with a series of CTWR curves, defined for a large broadleaf weed that emerged in cotton up to 458 GDD postemergence and were removed at incremental periods thereafter. This approach allowed the yield loss during the cropping season to be determined for these later emerging weeds, not just the yield loss at the end of the season, as is the case using the traditional approach to the CPWC. A combined CTWR relationship was derived from this data that included the time of weed emergence, time of weed removal and weed density (Charles and Taylor 2021). Using this relationship, Charles and Taylor (2021) were able to predict the point at which the competitive damage from a later emerging weed would exceed the YLT, and thus, determine the required timing for control of these weeds to ensure crop damage from competition does not exceed the YLT.

This approach, defining a series of CTWR curves for a large broadleaf weed, more closely follows the pattern of in-crop weed competition in cotton, where crops are planted into clean fields and weeds emerge at intervals postemergence with successive flushes of emergence generally triggered by rainfall or irrigation events. Emerged weeds are controlled by herbicide or cultivation inputs, with multiple emergence events and multiple control inputs occurring within a single cropping cycle. The ability to predict the optimal timing of control for these later emerging weeds using this approach adds great value to the CPWC.

Whereas it seems reasonable to assume that this extended approach to the application of the CPWC could be used with other weeds, this hypothesis has not been tested. The objective for our study was to determine the CPWC for later emerging medium-sized broadleaf weeds over a range of weed densities and develop extended CTWR models to describe the competition from these later emerging weeds, including the time of weed emergence and weed removal in the relationships. We tested whether the relationships could be further improved by including weed density and weed size as covariates in the models.

Materials and Methods

Experiments were conducted at the Australian Cotton Research Institute at Narrabri, NSW (30.12ºS, 149.36ºE; elevation 201 m) on a heavy alluvial clay soil (fine, thermic, smectitic, Typic Haplustert) over two seasons from 2006 to 2008. Cotton was grown according to normal commercial practices, on raised hills, 1-m apart, fertilized with 180 kg N ha^{-1}, applied before planting, and flood irrigated during the season as required. Cotton, cultivar 'Sicot 80 BRF', was planted on October 6, 2006, and October 8, 2007, with 15 seeds m row^{-1}. Mungbean, cultivar 'Berken', was planted with the crop or at predetermined periods after cotton emergence with target densities of 2, 5, 10, 20, and 50 plants m row^{-1}, in rows adjacent to and offset from the cotton rows by 100 mm. Trifluralin (TriflurX®, 480 g L^{-1}; Nufarm Australia, Melbourne, Victoria, Australia) was incorporated at 1.1kg ai ha^{-1} using a rolling cultivator before the crop was planted. Weeds were controlled postemergence using glyphosate (Roundup Ready® Herbicide, 690 g kg^{-1}; Monsanto Australia, Melbourne, Victoria, Australia) at 1 kg ai ha^{-1} after removal of the mungbean plants, or by hand hoeing as needed.

Experimental Design

The experiments used split plot designs within a randomized complete block, with four replications within each season. Main plots were times of planting and subplots were weed densities and times of weed removal. Plots were each 10 m long by 4 m (4 crop rows) wide, with a 2 m alley between each set of plots. Mungbean was planted with the crop, or targeted for planting 150, 300, or 450 GDD after the crop, and removed at 200, 400, 600, and 800 GDD after planting, or allowed to compete until harvest. Actual times of weed planting and removal were influenced by external factors including rainfall and irrigation events. Mungbean failed to establish at the 450 GDD planting in the 2006-2007 season and no data have been presented for this establishment time. Data from an additional planting time of 79 GDD post crop planting have been included for this season. Growing-degree days from planting were calculated using 15.5 C as the base temperature (Equation 1), defined as:

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

where t_{min} and t_{max} were the daily minimum and maximum air temperatures, respectively, and t_b was the base temperature (Bukun 2004).

Weed density was recorded on 1 m of row randomly selected from the plot and weed height and aboveground biomass were recorded on 10 mungbean plants from the selected metre where weeds were removed at the time of weed removal. Plants were dried at 70 C for at least 72 hours in a forced-air oven to determine dry biomass. After defoliation, cotton was mechanically harvested using a commercial picker modified to pick a single row, with seedcotton yield recorded from the central two rows of each plot. A single-saw gin was used to determine the cotton ginning percentage and lint yield, from a subsample of seedcotton taken from one row of cotton in each plot. Fiber quality was determined from the subsamples using high volume instrument testing recording fiber length, strength, micronaire, short fiber content and uniformity.

Data Analysis

Data were analyzed using R statistical software, version 4.1.1 (R Foundation for Statistical Computing, Vienna, Austria). Only statistically significant differences between treatments ($P < 0.05$) are discussed. Data were initially analyzed by ANOVA to evaluate treatment effects on actual and relative lint cotton yields (cotton yield as a percentage of the yield on weed-free treatments) before regression modelling to determine the CPWC. Significant year by density interactions occurred with both the actual and relative lint yield sets. Consequently, the results are presented separately for each year.

CPWC curves were fit to the relative lint yield using Gompertz (Equation 2) and logistic (Equation 3) functions as described by:

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

where y is the relative lint yield, a is the upper asymptote, b is a constant, c is the inflection point of the curve, and T_A is the time of weed addition. The upper asymptote was constrained to 100% relative yield where the model predicted an asymptote below 100%, or where the Akaike information criterion (AIC) indicated this model was the better fit, and:

$$y = a + \frac{b}{1 + exp^{c(T_R - d)}} \qquad [3]$$

where y is the relative lint yield, a is the lower asymptote, $a+b$ define the upper asymptote, c is a constant, T_R is the time of weed removal, and d is the inflection point of the curve. The upper asymptote was constrained to 100% relative yield where the model predicted an asymptote below 100%. Inclusion of the a parameter in the model allowed the lower asymptote of the curves to be above 0% relative yield. Models were fit with and without the additional a parameter and the model of best fit was chosen, as indicated by the AIC.

The Gompertz function (Equation 2) was extended to include the additional covariates; weed density, height, and biomass, and combinations of these covariates, in the combined models (Equation 4):

$$y = 100\ exp^{-exp^{b(T_A - c + dV1 + eV2T_A)}} \qquad [4]$$

where y is the relative lint yield, b, d and e are constants, c is the inflection point of the curve, T_A is the time of weed addition, and $V_1$and V_2 are additional covariates.

The logistic function was also extended by including the time of weed addition to allow the successive addition events to be included in a combined model (Charles and Taylor, 2021), and the additional covariates; weed density, height, and biomass, and combinations of these covariates (Equation 5):

$$y = a + bT_A + \frac{(c - bT_A)}{1 + exp^{d(T_R - e + fV1T_R + gV2 + hT_A)}} \qquad [5]$$

where y is the relative lint yield; a is the lower asymptote, $a+c$ define the upper asymptote, b, d, f, g, and h are constants; e is the inflection point of the curve; T_A is the time of weed addition; $V_1$and V_2 are additional covariates; and T_R is the time of weed removal. Models were fit with and without the additional terms and the model of best fit was chosen, as indicated by the AIC.

Results and Discussion

Weed Competition and Relative Lint Yield of Cotton in the 2006-2007 Season

Seedcotton yield averaged 5,979 kg ha^{-1} on the weed-free plots over the 2006-2007 season and 2,392 kg lint ha^{-1}, similar to the yields previously reported for irrigated Australian cotton (Charles and Taylor 2021; Charles et al. 2019, 2020). Mungbean competed strongly with the cotton, with mungbean plants at the times of removal ranging from 2- to 94-cm tall, with aboveground dry biomass of 1 to 940 g m^{-2}. Full-season competition from 50 mungbean plants m^{-2} caused a 59% reduction in relative lint yield (Figure 1A), similar to the yield reduction reported by Charles et al. (2020). The CPWC commenced at crop emergence, 42 GDD after planting, and continued until harvest, with the point of minimum yield loss of 28% from a single weed-control input (Webster et al. 2009), similar to the findings reported by Charles et al. (2020) for competition with 30 mungbean plants m^{-2}. Mungbean was less competitive when added later in the season, with a maximum 48% reduction in relative yield with 50 mungbean plants m^{-2} added 167 GDD after crop planting, with the CPWC starting 80 GDD after

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weed addition and a minimum yield loss of 19% from a single weed-control input (Figure 1A). These observations were comparable with those reported for 10 or fewer common sunflower m^{-2} (*Helianthus annuus* L.) competing with cotton (Charles and Taylor 2021). Mungbean established poorly from the later weed introductions at 245 GDD and the target weed density of 50 mungbean plants m^{-2} was not achieved from this planting in this season.

The data for the CTWR curves for 50 mungbean plants m^{-2} (Figure 1A), was combined and described using an extended logistic function (Equation 4) including the time of weed addition in the function (Figure 1B), as was done with a large broadleaf weed (Charles and Taylor 2021). This model described the change in the CPWC with delayed weed emergence, more closely emulating the situation commonly occurring in cotton fields, where a flush of weed germination occurs soon after the crop is planted and is normally controlled soon after crop emergence, followed by successive flushes of germinating weeds during the season triggered by rainfall or irrigation events. The function describes the competition from a flush of 50 mungbean plants m^{-2} occurring at any time from 0 GDD to 167 GDD post crop planting, with curves for 0, 79, and 167 GDD shown as examples (Figure 1B).

Full-season competition with 20 mungbean plants m^{-2} caused a 50% reduction in relative lint yield (Figure 1C), 9% less reduction in relative lint yield compared with the 59% yield reduction observed with the higher density of 50 mungbean plants m^{-2} (Figure 1A). The CPWC commenced at crop emergence, 48 GDD after planting, and continuing until harvest, with the point of minimum yield loss of 23% from a single weed-control input. Mungbean was less competitive when added later in the season, with a maximum 30% reduction in relative yield with 20 mungbean plants m^{-2} added 245 GDD post crop planting, and a minimum yield loss of 13% from a single weed-control input (Figure 1C). Full-season yield loss predicted by the combined CTWR curves with 20 mungbean plants m^{-2} reduced from 50% to 35% with weeds added 0 and 245 GDD after crop planting, respectively (Figure 1D).

The level of weed competition generally declined with lower weed densities and with later weed additions (Figure 1, and 2), as was reported by Charles and Taylor (2021). The reductions in cotton yield from 10, 5, and 2 mungbean plants m^{-2} followed the trends of the higher densities, with maximum reductions in relative lint yield of 44%, 60% and 25%, respectively (Figure 1E, 2A, and 2C). The CPWC commenced at emergence or up to 88 GDD postemergence (Figure 2A), and continued until harvest for 10 and 2 mungbean plants m^{-2}, but ended 960 GDD post crop-planting with 5 mungbean plants m^{-2}. The point of minimum yield loss from a single weed-control measure decreased from 22% yield loss with 10 mungbean plants m^{-2} added 79 GDD after crop planting, to 8% yield loss with 5 mungbean plants m^{-2} added 245 GDD after crop planting. Mungbean was less competitive when added later in the season, with a maximum 20% reduction in relative yield with 2 mungbean plants m^{-2} added 245 GDD after crop planting (Figure 2C).

Yield loss predicted by the combined CTWR curves with 10, 5, and 2 mungbean plants m^{-2} mirrored the trends of the individual curves, declining from a maximum of 63% yield loss with 5 mungbean plants m^{-2} emerging with the crop, to 20% yield loss with 5 mungbean plants m^{-2} added 245 GDD after crop planting (Figure 2B).

The quality of the cotton fiber was unaffected by weed competition, with no differences in ginning percentage, fiber length, strength, micronaire, short fiber content or fiber uniformity related to weed density or the timing of weed addition or removal (data not presented).

Combining Data Sets for the 2006-2007 Season

Data sets from all weed densities in the 2006-2007 season were combined and fit to extended Gompertz and logistic equations (Equations 3 and 4) with weed density, height, biomass, and combinations of these included as additional covariates in the equations (Figure 3). The models were able to describe the data, with the times of weed addition and weed removal together with the covariate explaining 77% to 89% of the variability in the data (r^2=0.6 to 0.8). The models of best fit included times of weed addition and removal, weed density, and weed height. Of the three covariates, weed density best described the competition models with r^2 values of 0.8 and 0.63, respectively, for the CWFP and CTWR relationships (Figure 3A). The models that included weed height gave a statistically satisfactory fit but were of limited practical application as there was little separation in the models related to height, such that the times of weed addition and weed removal had far more influence on the curves than did weed height per se. (Figure 3B). The model including weed biomass gave a satisfactory fit (Figure 3C), although a statistically inferior fit when compared with using weed density as a covariate (Figure 3A). However, the CTWR curve for the model including weed biomass failed to asymptote at 100% relative yield at 0 GDD, commencing with a 5% loss of relative yield, even when weeds were present at only 1 g m^{-2} (Figure 3C). One of the assumptions fundamental to these models is that there will be no loss of yield if weeds are removed at 0 GDD. Hence, although these CTWR curves provide a useful description of the yield loss caused by weed biomass later in the season, the poor fit (5% yield loss) at 0 GDD limits their practical application, making this model an inferior descriptor of weed competition.

In the field, the use of each of these covariates to define the CPWC has advantages and issues. Weed density is relatively easily estimated in the field and the equations incorporate some component of weed size through the inclusion of the T_A (time of weed addition) term in the CTWR curves (Figure 3A). However, the use of weed density does not easily allow for the assessment of successive germinations of weeds. To use weed density to determine the CPWC where successive germinations occur, it would be necessary to estimate the density of each cohort of weeds and integrate these densities into the relationships. This is beyond the scope of the current relationships.

Weed height is more easily estimated in the field than is weed density, but its use in the field suffers from the same limitations as weed density of not readily integrating findings over a range of weed heights, and our relationships were relatively insensitive to weed height (Figure 3B). The use of weed biomass to determine the CPWC in the field has the advantage of being able to integrate across successive germinations of weeds, but biomass is more difficult to accurately determine in the field. The combination of weed height and density gave the best fit of the relationships we tested (Figure 3D), although there was only a small improvement over the simpler model including only weed density, and it suffers from the limitations of both the height and density models.

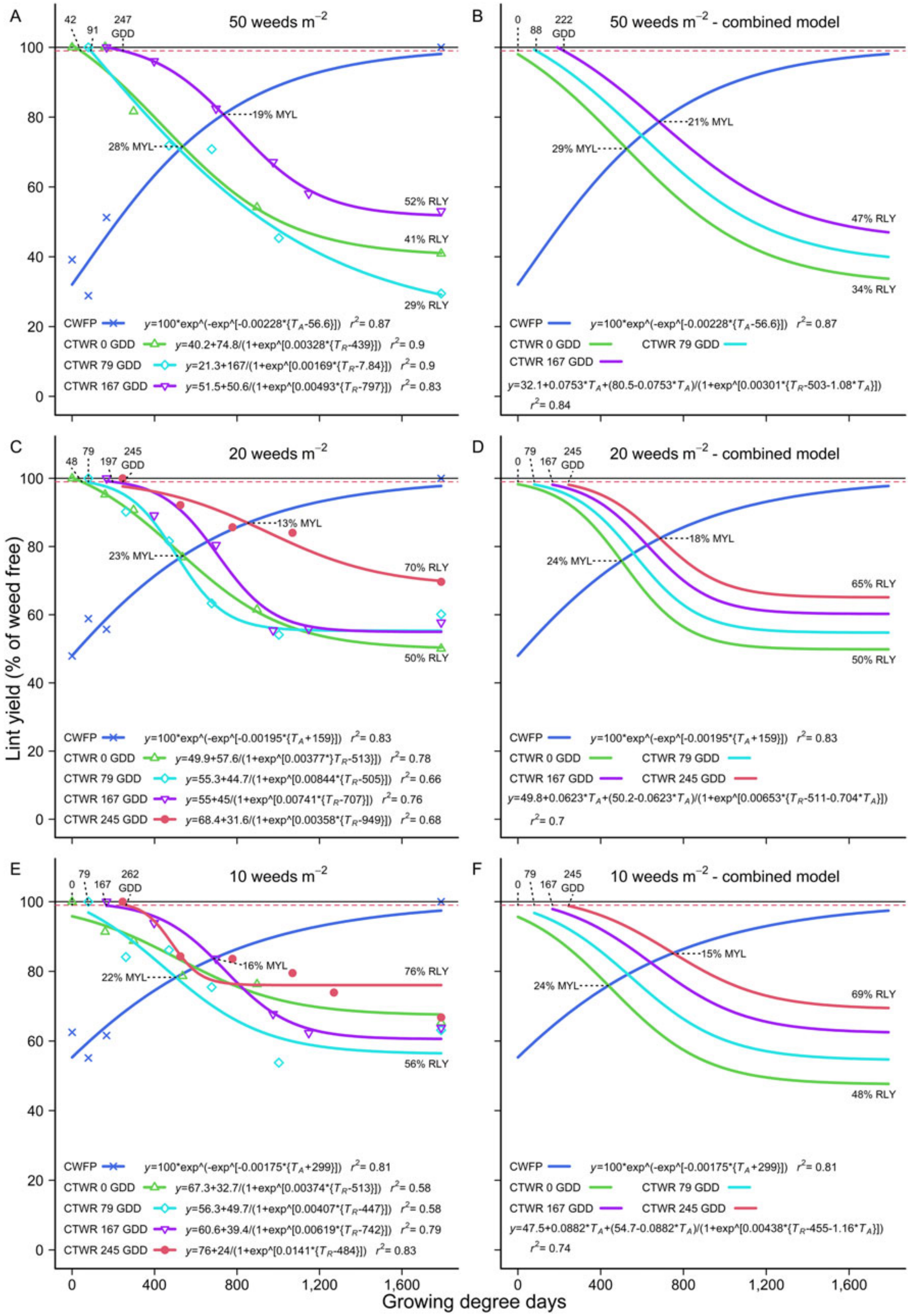

Figure 1. Critical period for weed control (CPWC) for 50, 20, and 10 mungbean plants m^{-2} competing with cotton in the 2006-2007 season. Mungbean was added at: 0, 79, 167, and 245 growing-degree days (GDD) after cotton. Actual data and example curves from models combining the data are shown for each weed density. Data points are treatment means. Horizontal black and dashed red lines indicate the weed-free yield and 1% yield-loss threshold, respectively. The intersections of the critical time for weed removal (CTWR) and critical weed-free period (CWFP) lines with the yield-reduction threshold defines the CPWC for each time of weed introduction. Numbers above the weed-free yield indicate the start of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, and T_R is time of weed removal.

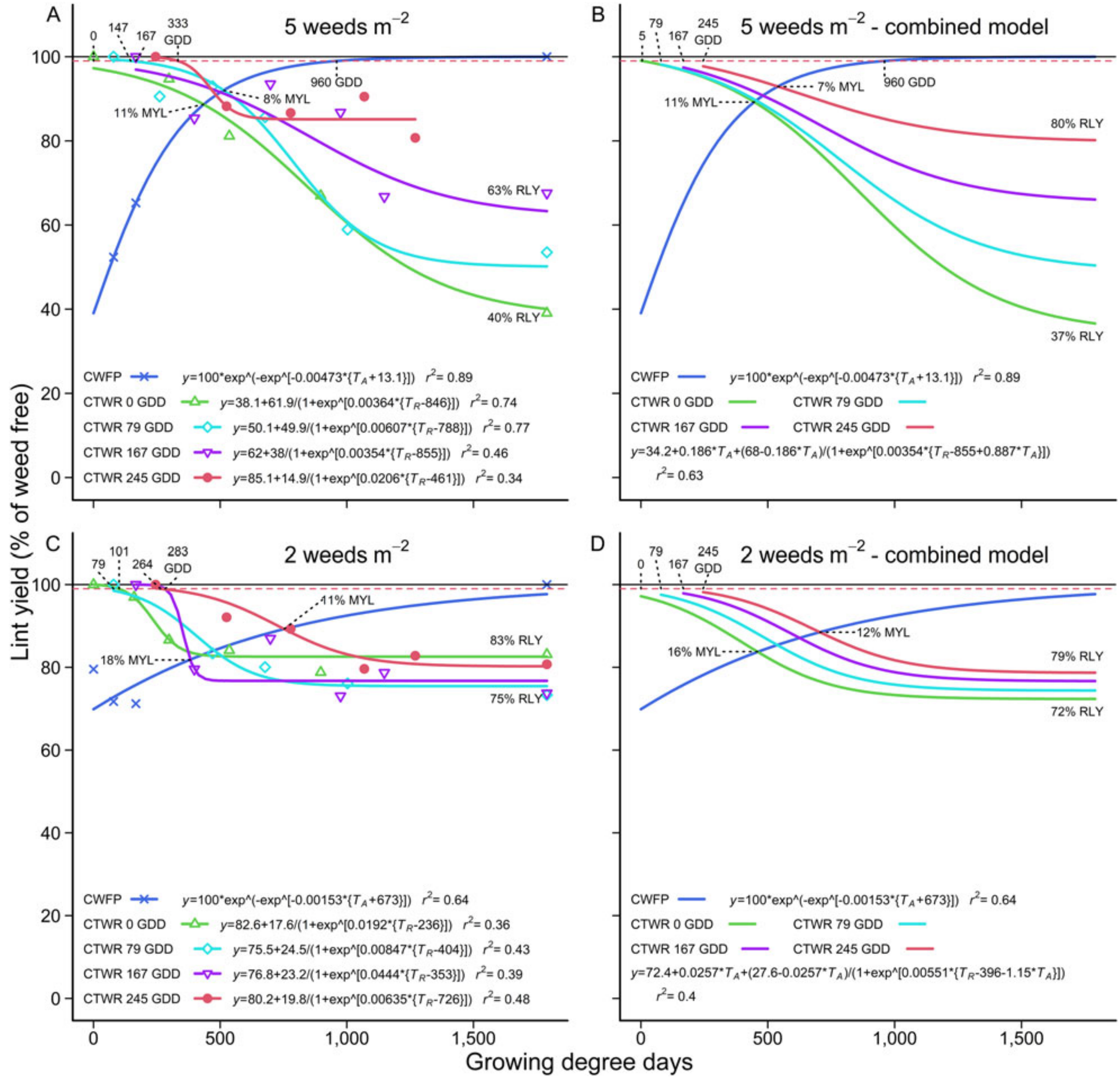

Figure 2. Critical period for weed control (CPWC) for 5, and 2 mungbean plants m^{-2} competing with cotton in the 2006-2007 season. Mungbean was added at: 0, 79, 167, and 245 growing-degree days (GDD) after cotton. Actual data and example curves from models combining the data are shown for each weed density. Data points are treatment means. Horizontal black and dashed red lines indicate the weed-free yield and 1% yield-loss threshold, respectively. The intersections of the critical time for weed removal (CTWR) and critical weed-free period (CWFP) lines with the yield-reduction threshold defines the CPWC for each time of weed introduction. Numbers above the weed-free yield indicate the start of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, and T_R is time of weed removal.

Weed Competition and Relative Lint Yield of Cotton in the 2007-2008 Season

Seedcotton yield averaged 5,938 kg ha^{-1} on the weed-free plots over the 2007-2008 season and 2,371 kg lint ha^{-1}, similar to the yields from the previous season of 5,979 and 2,392 kg ha^{-1}, respectively. Mungbean established poorly when introduced at the time of cotton planting in the 2007-2008 season, but the mungbean plants were larger and competed more strongly with cotton than was observed in the previous season (Figure 4, and 5 compared with Figure 1, and 2, respectively). A comparison of mungbean biomass (aboveground dry weight per m^2) from the first postemergence weed introduction in the two seasons showed weed biomass 1.5 times to 1.8 times greater in the 2007-2008 season (Figure 6B) compared with the 2006-2007 season for weed densities of 5 to 50 plants m^{-2}, respectively (Figure 6A), even though the yield cotton on the control plots was similar for the two seasons. Seasonal differences in the growth rates of the mungbean plants were apparent beyond 400 GDD, with biomass increasing rapidly beyond 400 GDD at most weed densities in the 2007-2008 season (Figure 6B), but the corresponding increase in biomass was not apparent at most weed densities until beyond 600 GDD in the 2006-2007 season (Figure 6A).

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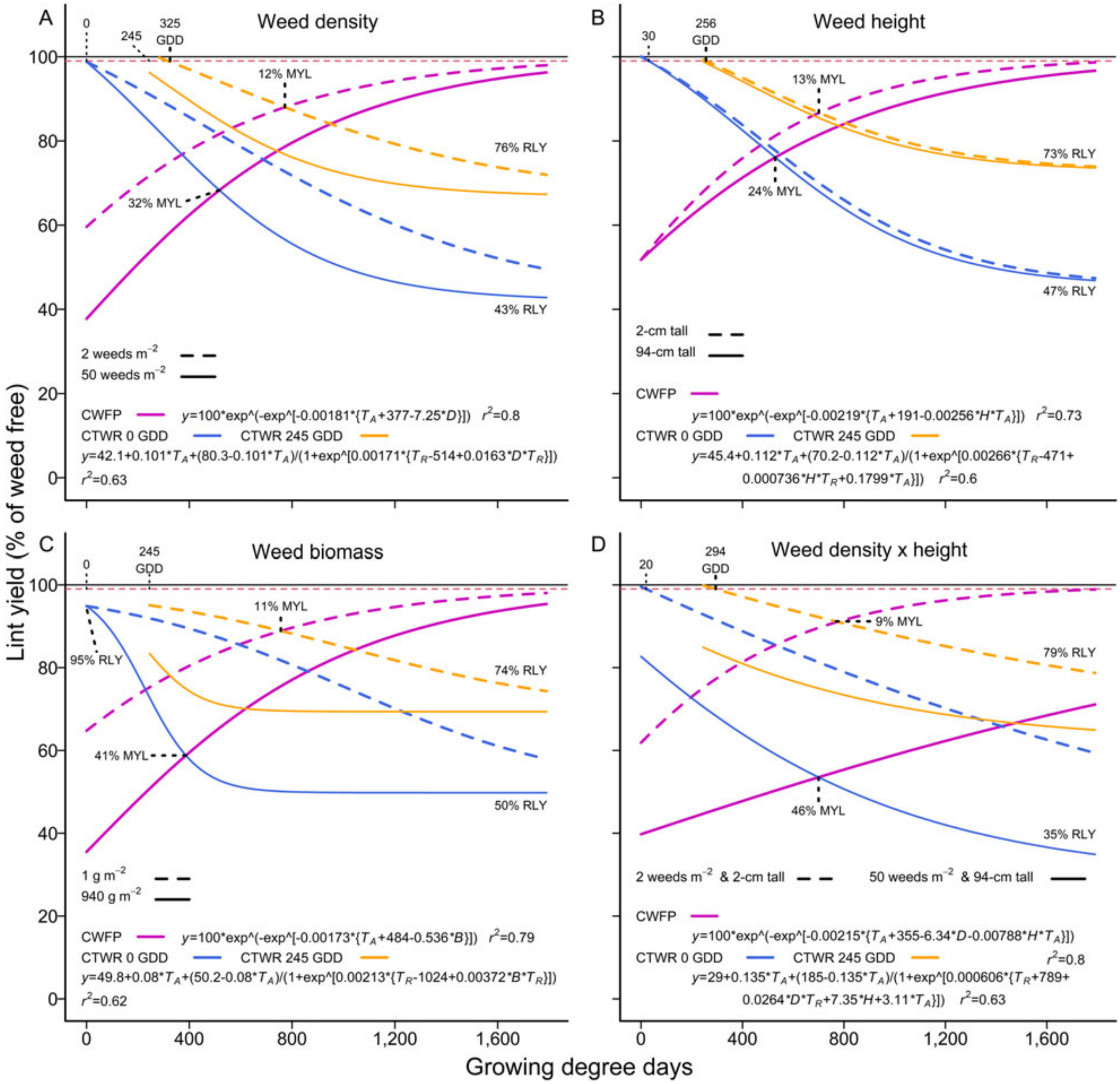

Figure 3. Critical period for weed control (CPWC) for mungbean competing with cotton over a range of times of weed addition and removal and weed densities in the 2006-2007 season. Models include weed density (A), weed height (B), weed biomass (C), and both weed density and height (D) as covariates. The derived curves for mungbean added 0, and 245 growing-degree days (GDD) after crop planting are presented as examples for the critical timing for weed removal (CTWR) and critical weed-free period (CWFP) relationships. Horizontal black and dashed red lines indicate the weed-free yield (WFY) and 1% yield-loss threshold (YLT), respectively. The intersections of the CTWR and CWFP lines with the YLT defines the CPWC for each time of weed introduction. Numbers above the WFY indicate the start of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, T_R is time of weed removal, and *D*, *H*, and *B* are weed density, height and biomass, respectively.

A comparison of plant height between the two seasons (Figure 7) shows similar trends to that of plant biomass (Figure 6). The mungbean plants grew to similar heights in both seasons but the acceleration in height began more than 200 GDD earlier in 2007-2008 compared with the previous season. The plants achieved their maximum height at approximately 1,000 GDD in 2007-2008, whereas plants did not achieve their maximum height until the end of the season at 1600 GDD in 2006-2007 (Figure 7).

The difference in mungbean growth between the two seasons can be related to differences in temperatures and rainfall between the two seasons (Figure 8). The 2007-2008 season was milder, with lower average maximum temperatures, but the cumulative GDD for the two seasons were similar for the first half of the season (first 800 GDD). The 2007-2008 season had much lower average minimum temperatures for the second half of the season, and the crop was harvested after only 1,450 GDD (200 days after planting [DAP]), compared with harvest at 1,790 GDD in the 2006-2007 season (185 DAP). The 2007-2008 season was also much wetter, with 173 mm of early-season rain (first 500 GDD), compared with 62 mm in 2006-2007, and 383 mm of rain in the first 1000 GDD of the season, compared with 90 mm in 2006-2007. In addition to

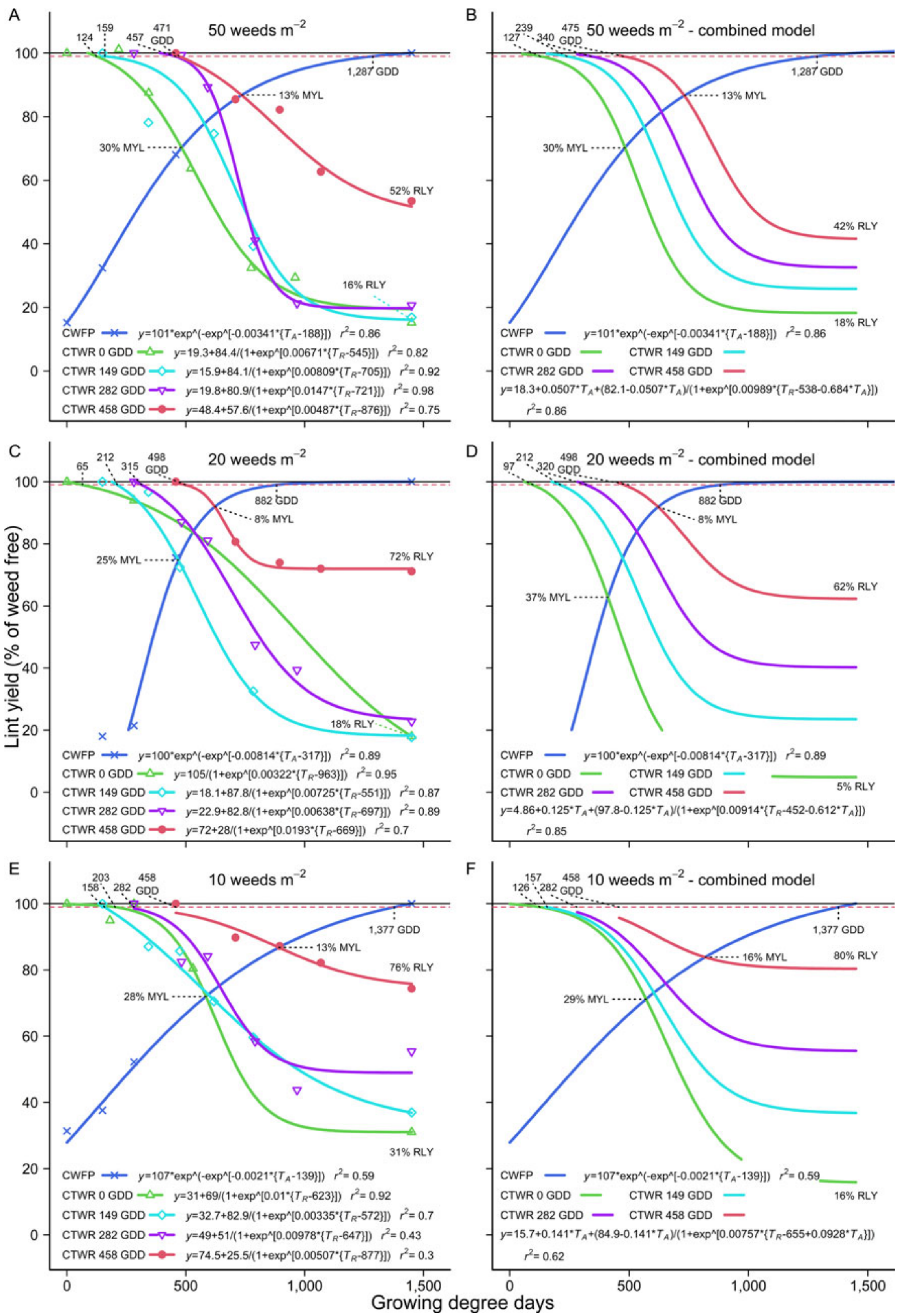

Figure 4. Critical period for weed control (CPWC) for 50, 20, and 10 mungbean plants m^{-2} competing with cotton in the 2007-2008 season. Mungbean was added at: 0, 149, 282, and 458 growing-degree days (GDD) after cotton. Actual data and example curves from models combining the data are shown for each weed density. Data points are treatment means. Horizontal black and dashed red lines indicate the weed-free yield and 1% yield-loss threshold, respectively. The intersections of the critical time for weed removal (CTWR) and critical weed-free period (CWFP) lines with the yield-reduction threshold defines the CPWC for each time of weed introduction. Numbers above the weed-free yield indicate the start of the CPWC and numbers below the line indicate the end of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, and T_R is time of weed removal.

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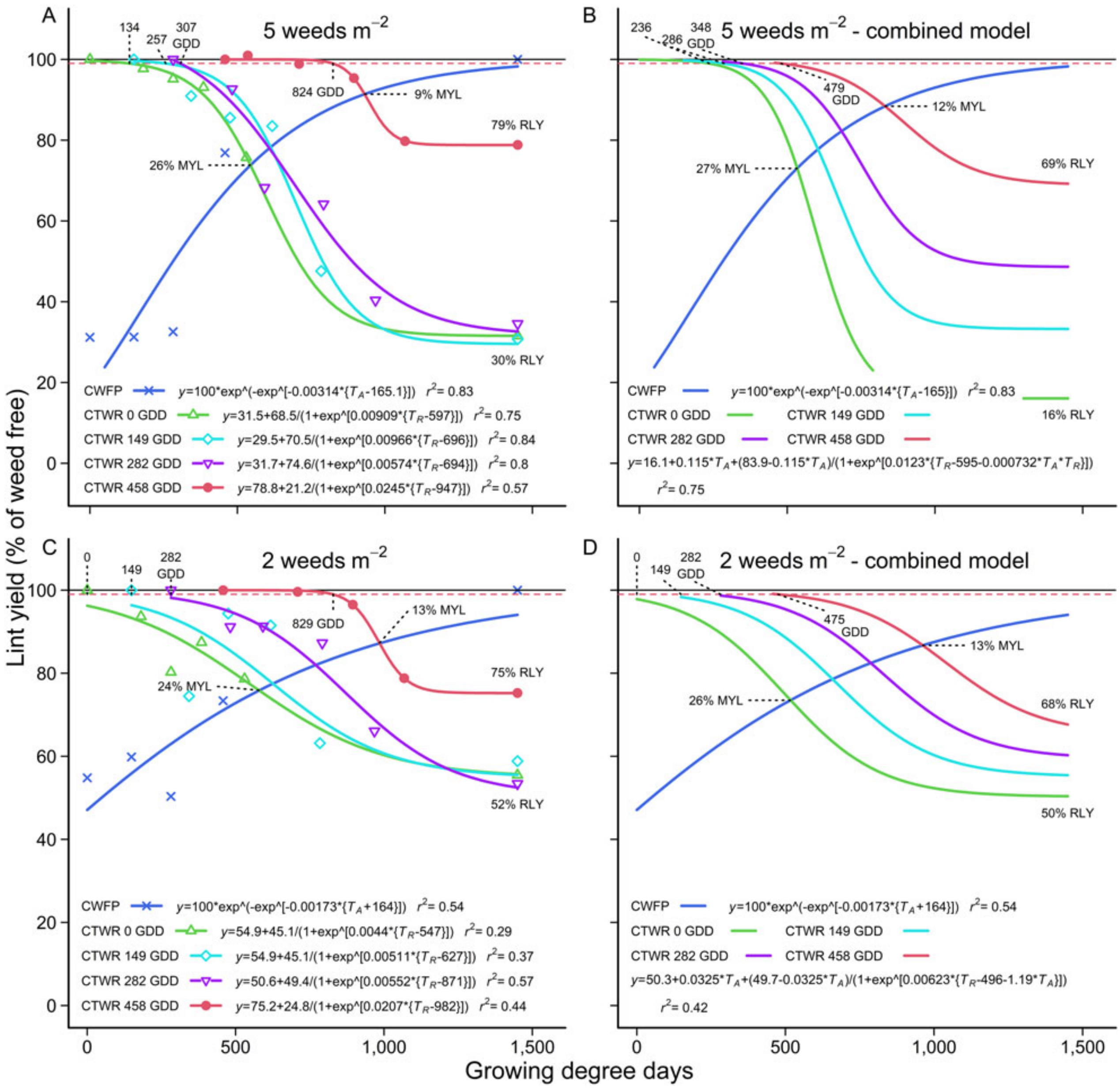

Figure 5. Critical period for weed control (CPWC) for 5, and 2 mungbean plants m^{-2} competing with cotton in the 2007-2008 season. Mungbean was added at: 0, 149, 282, and 458 growing-degree days (GDD) after cotton. Actual data and example curves from models combining the data are shown for each weed density. Data points are treatment means. Horizontal black and dashed red lines indicate the weed-free yield and 1% yield-loss threshold, respectively. The intersections of the critical time for weed removal (CTWR) and critical weed-free period (CWFP) lines with the yield-reduction threshold defines the CPWC for each time of weed introduction. Numbers above the weed-free yield indicate the start of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, and T_R is time of weed removal.

rainfall, the crops were irrigated on four occasions in 2007-2008 and five occasions in 2006-2007. We contend that this combination of lower maximum temperatures and increased early-season rainfall in the 2007-2008 season was a major contributor to the greater growth rate of mungbean in this season (Figure 6, and 7) and the stronger competitive effect of mungbean in 2007-2008 when compared with the results of the previous season (Figure 4, and 5 compared with Figure 1, and 2, respectively).

Full-season competition with 50 mungbean plants m^{-2} caused an 84% reduction in relative lint yield in the 2007-2008 season (Figure 4A), 25% more yield loss than was recorded from the same treatment in the previous season (Figure 1A). A similarly greater yield loss was observed from comparable treatments with all weed densities and times of weed addition and removal in the 2007-2008 season when compared with the 2006-2007 season. The CPWC with 50 mungbean plants m^{-2} commenced 124 GDD after crop planting and continued late into the season (1,287 GDD), with the point of minimum yield loss from a single weed-control input at 30% yield loss, similar to the loss observed in the previous season. The level of competition from the mungbean was similar for the later weed additions at 149 GDD and 282 GDD, but mungbean was less competitive when added at 458 GDD, with a maximum 48% reduction in relative yield, and a minimum yield loss from a single

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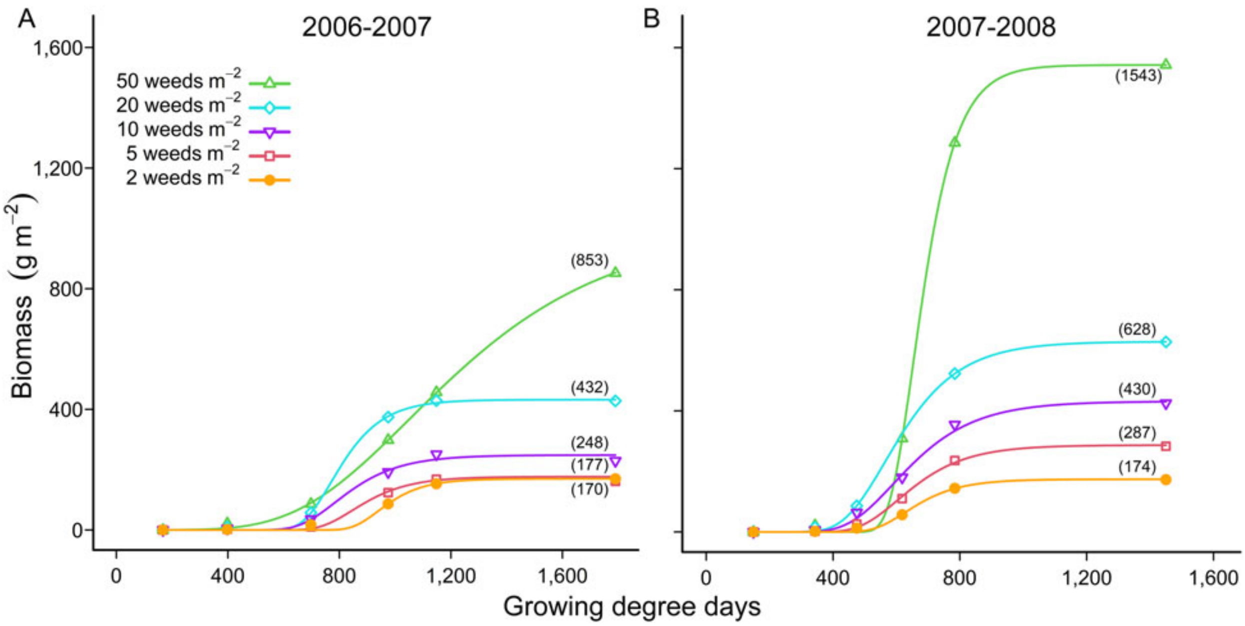

Figure 6. Increases in weed biomass over the 2006-2007 and 2007-2008 seasons for mungbean densities of 50, 20, 10, 5, and 2 plants m^{-2}. Weed biomass at the end of the season is indicated by bracketed values at the ends of the curves.

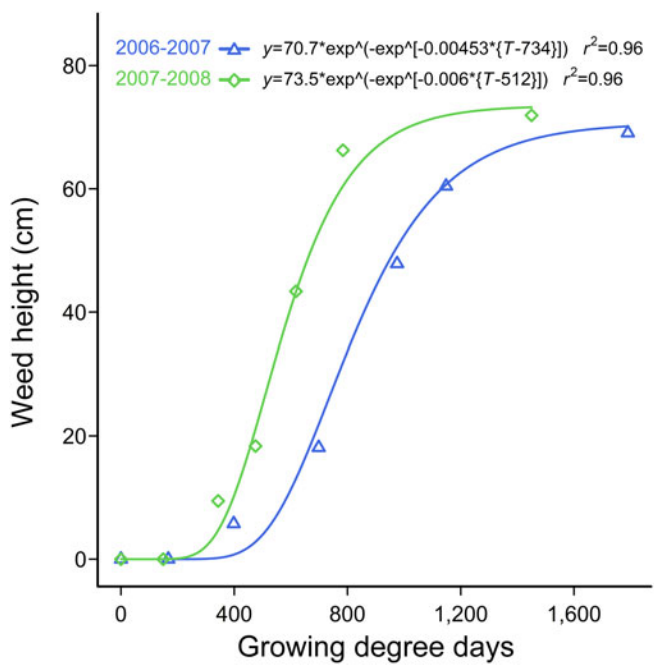

Figure 7. Increases in weed height over the 2006-2007 and 2007-2008 seasons combined over mungbean densities. The equations for the curves are presented within the figures, where *y* is the relative lint yield, and *T* is time of weed removal.

weed-control input of 13% (Figure 4A). Full-season yield loss predicted by the combined CTWR curves with 50 mungbean plants m^{-2} reduced from a maximum of 82% to 58% yield loss with weeds added 0 GDD and 458 GDD after crop planting, respectively (Figure 4B), although the combined model predicted less yield loss for weeds introduced at 149 GDD and 282 GDD after crop planting than was observed (Figure 4A).

Full-season competition with 20 mungbean plants m^{-2} caused an 82% reduction in relative lint yield (Figure 4C), with the CPWC commencing 85 GDD after crop planting, and continued until 882 GDD, with the point of minimum yield loss of 25% from a single weed-control input. The level of competition from mungbean was again similar for the later weed additions at 149 GDD and 282 GDD, but mungbean was less competitive when added at 458 GDD, with a maximum 28% reduction in relative yield, and a minimum yield loss from a single weed-control input of 8% (Figure 4C). Full-season yield loss predicted by the combined CTWR curves with 20 mungbean plants m^{-2} reduced from 95% to 38% with weeds added 0 and 458 GDD after crop planting, respectively (Figure 4D).

The level of weed competition generally declined with lower weed densities and with later weed additions (Figure 4E, and 5). The reductions in cotton yield from 10, 5, and 2 mungbean plants m^{-2} followed the trends of the higher densities, with maximum reductions in relative lint yield of 69%, 70% and 48%, respectively (Figure 4E, 5A, and 5C). The CPWC commenced at emergence or up to 203 GDD post weed addition (Figure 4E) and continued until 1,377 GDD or later.

The point of minimum yield loss from a single weed-control input declined from 28% yield loss with 10 mungbean plants m^{-2} emerging with the crop, to 9% yield loss with 5 mungbean plants m^{-2} added 458 GDD after crop planting (Figure 4E, and Figure 5A, respectively). Mungbean was less competitive when added later in the season, with a maximum 25% reduction in relative yield with 2 mungbean plants m^{-2} added 458 GDD after crop planting (Figure 5C). Yield loss predicted by the combined CTWR curves declined from a maximum of 84% yield loss with 5 and 10 mungbean plants m^{-2} emerging with the crop (Figure 5B, and 4F), to 20% yield loss with 10 mungbean plants m^{-2} added 458 GDD after crop planting (Figure 4F).

The quality of the cotton fiber was largely unaffected by weed competition, with no differences in fiber length, strength, micronaire, short fiber content or fiber uniformity related to weed density or the timing of weed addition or removal (data not presented). Ginning percentage was higher on the control

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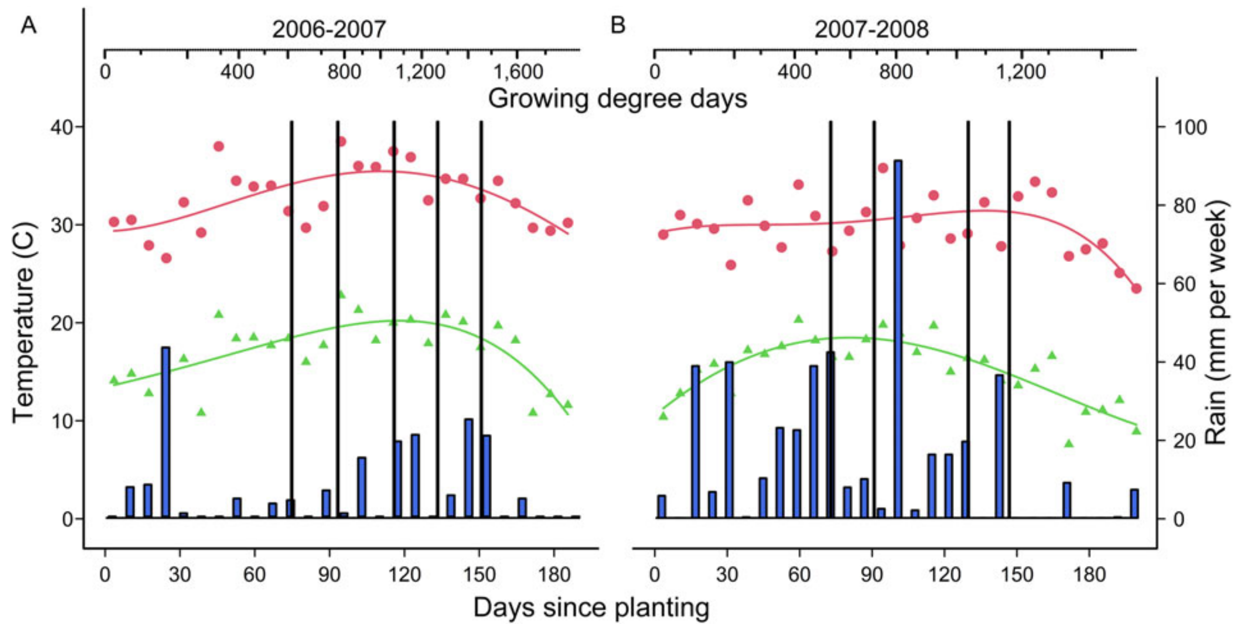

Figure 8. Weekly average maximum (red dots and line) and minimum (green dots and line) temperatures and rainfall (blue bars) for the 2006-2007 and 2007-2008 seasons. Irrigation events are indicated by vertical black bars.

plots than on the weedy plots, 40.8% compared with 38.9%, respectively.

Using Combined Functions in the 2007-2008 Season

Data sets from all weed densities in the 2007-2008 season were combined and fit to extended Gompertz and logistic equations with weed density, height, biomass, and combinations of these as additional covariates in the equations (Figure 9). The CTWR model including weed density reached the lower asymptote at 84% yield loss from season-long competition (Figure 9A), 27% greater loss than the 57% yield loss estimated for season-long competition with the same weed density in the 2006-2007 season (Figure 3A). Similarly, the CTWR model including weed height estimated a maximum 84% yield loss from season-long competition from 1 m tall weeds (Figure 9B), compared with 53% yield loss in the previous season with 94-cm tall weeds (Figure 3B).

The inclusion of weed biomass in the model gave the best fit of the three covariates, demonstrating the yield loss from weed infestations ranging from 1 g to 1.3 kg m^{-2}, introduced up to 458 GDD after crop planting, with an estimated 95% yield loss from full-season competition from the maximum observed biomass of 1.3 kg m^{-2} (Figure 9C). The minimum yield loss from weed competition from a single weed-control input where 1.3 kg m^{-2} of weeds were present was 94% (Figure 9C). The combination of weed density and height gave a better fit than any of the covariates alone (Figure 9D), estimating yield loss for weeds from 2-cm tall and 2 plants m^{-2}, to 1-m tall and 50 plants m^{-2}. However, the CTWR relationship provides a poor fit when a high density of tall weeds was present at the start of the season, estimating 52% yield loss when weeds were removed at 0 GDD. This result contrasts with the 0% yield losses at 0 GDD predicted when using weed density, height, or biomass alone as a covariate (Figure 9A, 9B, and 9C). The poor initial fit indicates that although the relationship including weed density and height (Figure 9D) is statistically superior to the simpler relationships, it is not describing the data well at the start of the season.

Combining the Data Over Seasons

Analysis of the data by ANOVA showed significant year by treatment interactions, requiring that the data for each year is presented separately. However, comparison of the cotton yields from the control plots showed little variation between the years (2,392 and 2,371 kg lint ha^{-1}, 2006-2007 and 2007-2008, respectively). In addition, examination of the mungbean's height and biomass data from each year indicated that the differences between the two seasons could be related to differences in the pattern of the weed's growth in each season (Figure 6, and 7). On the basis of these observations, we contend that our data can be combined over seasons and relationships developed for this combined data set, provided the relationships include weed biomass or weed height as factors in the relationships, thus incorporating this seasonal difference in weed growth.

Data from the two seasons were combined and fit to extended Gompertz and logistic equations with weed height and biomass, and combinations of these and weed density as additional covariates in the equations (Figure 10). The CTWR model including weed height reached the lower asymptote at 63% yield loss from season-long competition, with a minimum of 38% yield loss from a single treatment (Figure 10A). The CTWR model including weed biomass gave the better fit of the two covariates and estimated a maximum 62% yield loss from season-long competition from weeds with a biomass of 1.3 kg m^{-2} and a minimum of 49% yield loss from a single treatment (Figure 10B). However, this model gives little separation in the CWFP relationship related to weed biomass, such that the time of weed addition had far more influence on the curves than did weed biomass per se. This result is not consistent with the outputs of the previous weed biomass CWFP models (Figure 3C,

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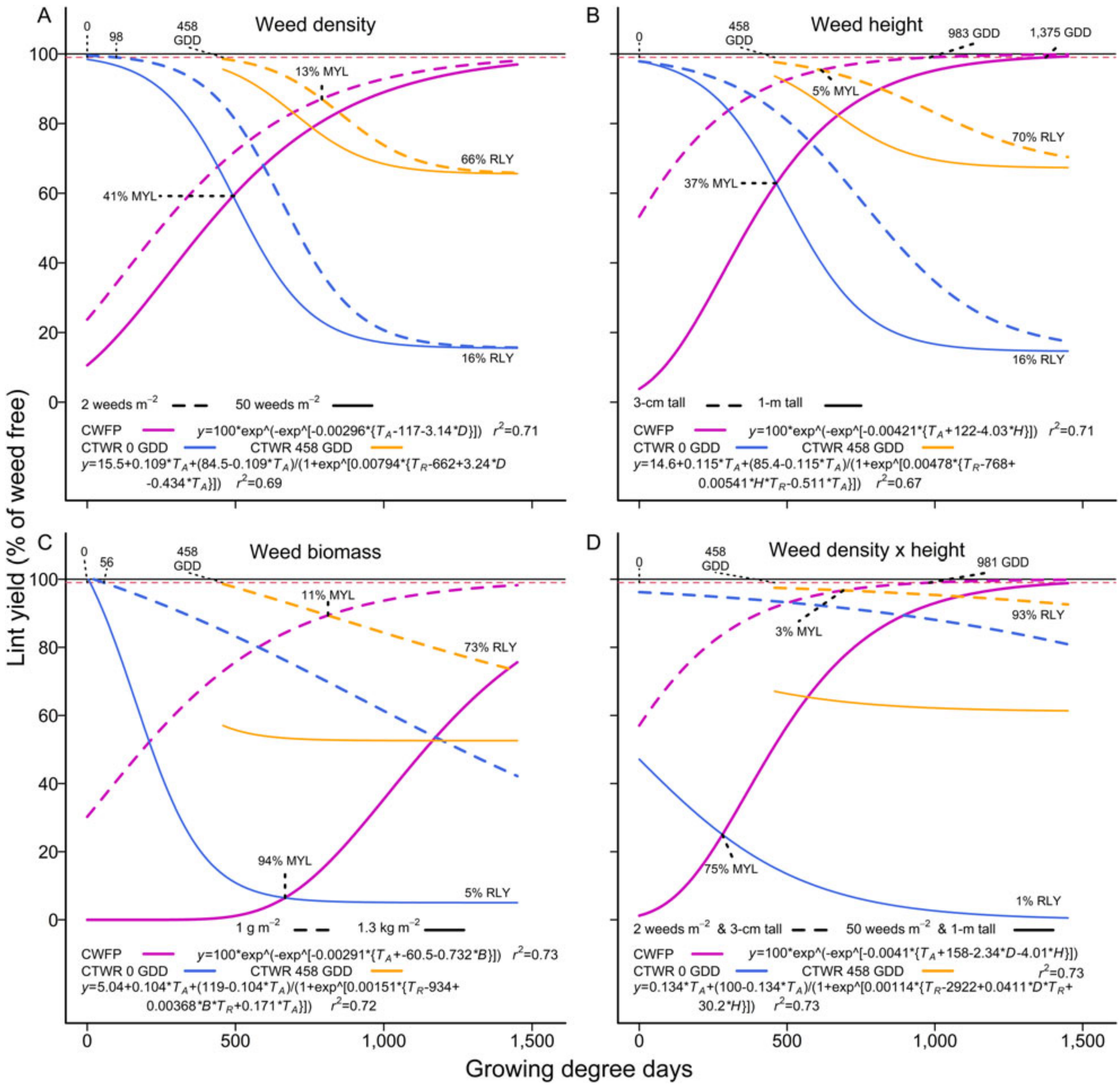

Figure 9. Critical period for weed control (CPWC) for mungbean competing with cotton over a range of times of weed addition and removal and weed densities in the 2007-2008 season. Models include weed density (A), weed height (B), weed biomass (C), and both weed density and height (D) as covariates. The derived curves for mungbean added 0, and 458 growing-degree days (GDD) after crop planting are presented as examples for the critical timing for weed removal (CTWR) and critical weed-free period (CWFP) relationships. Horizontal black and dashed red lines indicate the weed-free yield (WFY) and 1% yield-loss threshold (YLT), respectively. The intersections of the CTWR and CWFP lines with the YLT defines the CPWC for each time of weed introduction. Numbers above the WFY indicate the start of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, T_R is time of weed removal, and *D*, *H*, and *B* are weed density, height and biomass, respectively.

and 9C) indicating that although this relationship is statistically valid, it does not give appropriate weighting to the effect of weed biomass.

The combination of weed density and height (Figure 10C) gave a statistically better fit than either covariate alone, estimating yield loss for weeds from 2-cm tall and 2 plants m^{-2}, to 1 m tall and 50 plants m^{-2}. However, as occurred with the 2007-2008 relationship (Figure 9D), the CTWR relationship provides a poor fit when a high density of large weeds was present at the start of the season, estimating 64% yield loss when weeds were removed at 0 GDD. This result contrasts with the small yield losses at 0 GDD predicted when using weed height, or biomass alone as a covariate. Also, the CTWR relationship estimated only 1% to 8% yield loss from weeds 2-cm tall with 2 plants m^{-2} introduced at 0 to 458 GDD, much less than the yield losses predicted when using weed height, or biomass alone as a covariate. The poor fit indicates that although the relationship including weed density and height (Figure 10C) is statistically superior to the simpler relationships, it is not describing the data well for low weed numbers and weed height, nor at the start of the season.

The inclusion of both weed biomass and height as covariates in the CPWC model (Figure 10D) gave a statistically superior fit

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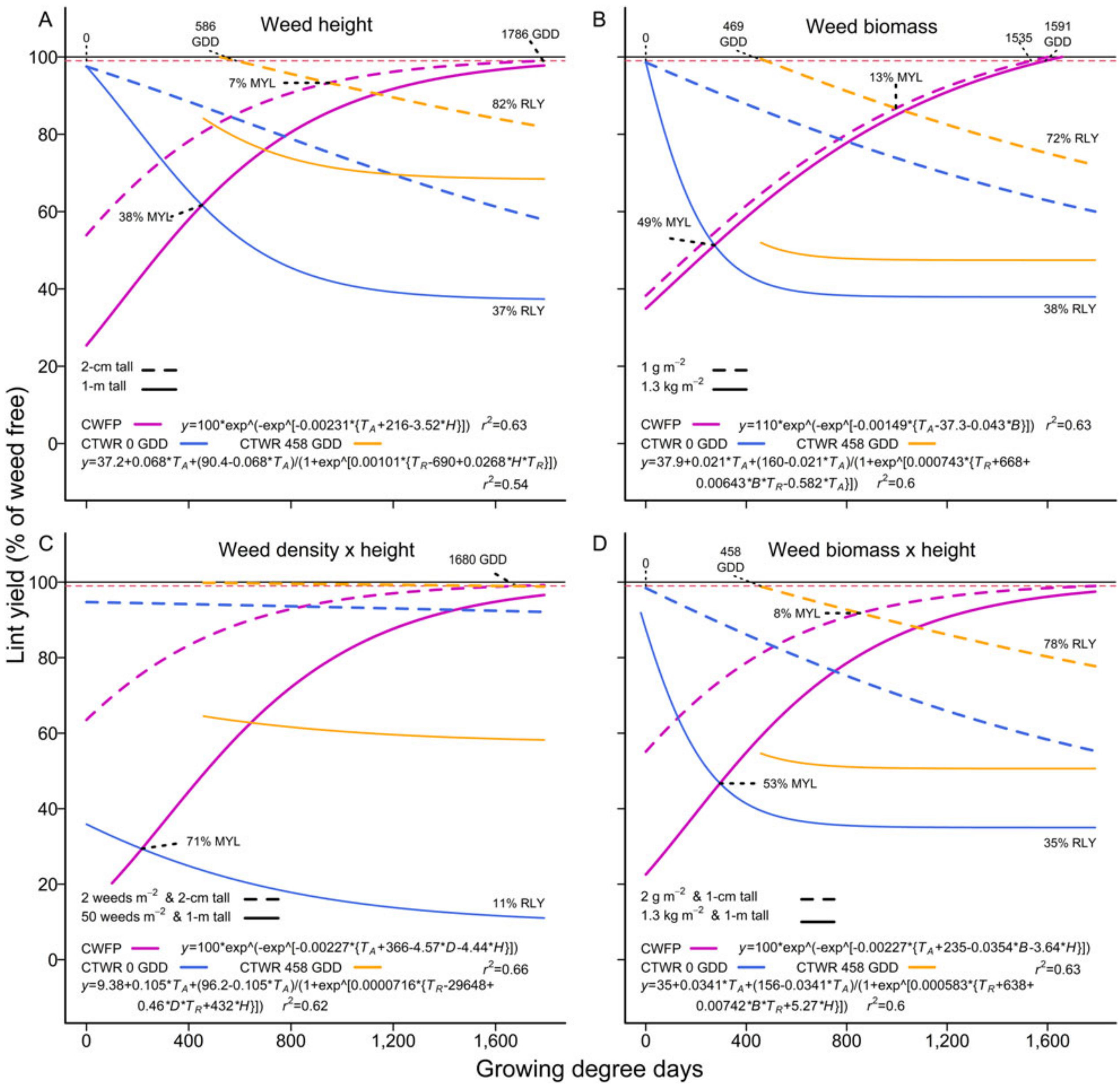

Figure 10. Critical period for weed control (CPWC) for mungbean competing with cotton over a range of times of weed addition and removal and weed densities combined over years. Models include weed height (A), weed biomass (B), both weed density and height (C), and both weed biomass and height (D) as covariates. The derived curves for mungbean added 0, and 458 growing-degree days (GDD) after crop planting are presented as examples for the critical timing for weed removal (CTWR) and critical weed-free period (CWFP) relationships. Horizontal black and dashed red lines indicate the weed-free yield (WFY) and 1% yield-loss threshold (YLT), respectively. The intersections of the CTWR and CWFP lines with the YLT defines the CPWC for each time of weed introduction. Numbers above the WFY indicate the start and end of the CPWC in GDD. Points of minimum yield loss from a single control input (MYL) are indicated within the figure. Minimum and maximum relative yield losses (RYL) are indicated by values at the ends of the CTWR curves. The equations for the curves are presented within the figures, where *y* is the relative lint yield, T_A is the time of weed addition, T_R is time of weed removal, and *D*, *H*, and *B* are weed density, height and biomass, respectively.

compared with the fit of either weed biomass or height alone (Figure 10A, and 10B). However, the fit was statistically inferior when compared with the combination of weed density and height (Figure 10C), although it better represented the competitive impact of weeds for the CTWR model for low weed densities and height, and at the start of the season. The CWFP model including weed biomass and height also gave satisfactory separation between small and large weeds and thus, for practical application, was a superior model. The CPWC commenced at crop emergence and continued full season. The CTWR model reached the lower asymptote at 65% yield loss from season-long competition from very large weeds, with a minimum of 47% yield loss from a single treatment (Figure 10D). This is consistent with the multispecies CPWC model developed by Charles et al. (2021) that also used weed height and biomass as covariates in the relationships.

Practical Implications

Application of our weed competition model using the time of weed emergence, weed biomass, and weed height will enable cotton growers to estimate the yield loss from a population of weeds to determine the need for and timing of a weed-control

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input. In addition, these models, together with an understanding of the expected growth rate of these weeds, would allow these functions to be used predictively, determining the likely impact of delaying a weed-control input. This predictive element should be of value to cotton growers to enable them to schedule treatments around other farm activities with an understanding of the expected yield losses from a delay in a weed removal treatment. Consequently, future work should focus on developing a data set of weed growth and development characteristics for the more common weeds that are problematic in cotton. This data should also provide information on the timing of weed-seed production, an important element to enable cotton growers to ensure that all weeds are controlled before they set seed, managing herbicide resistance by reducing the weed seedbank over time (Charles et al. 2019; Kores and Norsworthy 2015).

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Competing interests. Competing interests: The authors declare none.

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