Determining the critical period for broadleaf weed control in high-yielding cotton using mungbean as a mimic weed

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Abstract

Research using the critical period for weed control (CPWC) has shown that high-yielding cotton crops are very sensitive to competition from grasses and large broadleaf weeds, but the CPWC has not been defined for smaller broadleaf weeds in Australian cotton. Field studies were conducted over five seasons from 2003 to 2015 to determine the CPWC for smaller broadleaf weeds, using mungbean as a mimic weed. Mungbean was planted at densities of 1, 3, 6, 15, 30, and 60 plants m^{-2} with or after cotton emergence and added and removed at approximately 0, 150, 300, 450, 600, 750, and 900 degree days of crop growth (GDD). Mungbean competed strongly with cotton, with season-long interference; 60 mungbean plants m^{-2} resulted in an 84% reduction in cotton yield. A dynamic CPWC function was developed for densities of 1 to 60 mungbean plants m^{-2} using extended Gompertz and exponential curves including weed density as a covariate. Using a 1% yield-loss threshold, the CPWC defined by these curves extended for the full growing season of the crop at all weed densities. The minimum yield loss from a single weed control input was 35% at the highest weed density of 60 mungbean plants m^{-2}. The relationship for the critical time of weed removal was further improved by substituting weed biomass for weed density in the relationship.

Introduction

Greater than 99% of cotton planted in Australia during the past decade has used the glyphosate-tolerance trait (Tony May, Monsanto Australia, personal communication, February 2017), with glyphosate being the most commonly used herbicide applied to these crops (Thornby et al. 2013). This widespread use of glyphosate in cotton has led to high levels of weed control and has contributed to ever-increasing crop yields, such that Australia continues to have the highest average yields of cotton in the world (Dowling 2016).

However, the heavy reliance on glyphosate for weed control in cotton has resulted in increasing issues with glyphosate-resistant weeds and a species shift toward glyphosate-tolerant weeds (Werth et al. 2013), with many of these being small- to medium-sized broadleaf weeds. Werth et al. (2013) surveyed 19 Australian fields planted with cotton and found 40 weed species remaining after weed-control inputs, three species of which were large broadleaf weeds, 10 species were grass weeds, and the other 27 species were small- to medium-sized broadleaf weeds. These weeds either emerged after the last in-crop weed-control input or were not controlled by the input. The glyphosate-resistance status of the weeds from these fields was not tested, but five of these species were among those known to have developed resistance to glyphosate (Heap 2020), including the two species most commonly found in these fields, hairy fleabane [*Erigeron bonariensis* (L.) Cronquist] and annual sowthistle (*Sonchus oleraceus* L.). Charles (2015) surveyed 73 cotton fields in the southern Australian cotton-growing area between 2013 and 2015 and recorded the presence of 49 weed species remaining after weed-control measures had been undertaken, with an average weed density of 1.2 weeds m^{-2}. Of these weeds, 43 species were small- to medium-sized broadleaf weeds. Five of the species observed in these fields were among those known to have developed resistance to glyphosate in Australia. Most of these species were present at relatively low densities of fewer than 1 weed m^{-2}, but higher densities were observed, with an average of eight common purslane (*Portulaca oleracea* L.) m^{-2} recorded in one field during 2015. Another field had an average weed density of greater than 12 weeds m^{-2} in 2015, with Venice mallow (*Hibiscus trionum* L.) and jungle rice [*Echinochloa colona* (L.) Link], each present at greater than 5 plants m^{-2}.

The aim of every cotton grower should be to control weeds before they cause economic damage to the crop (i.e., damage exceeding the cost of controlling the weeds) and before the weeds set seed, enabling the cotton grower to greatly reduce the number of seeds in the weed seedbank over time (Thornby et al. 2013). The onset of seed set can be determined by examining the weeds, but there is limited information available to growers to enable them to estimate the cost of damage caused by broadleaf weeds in high-yielding cotton crops, with the competitive ability of the weeds varying with species and depending on weed size and density (Charles et al. 2019a).

The competitive effects of some medium-sized broadleaf weeds have been determined for cotton, including Benghal dayflower (*Commelina benghalensis* L. jio) (Webster et al. 2009), black nightshade (*Solanum nigrum* L.) (Keeley and Thullen 1989), coffee senna [*Senna occidentalis* (L.) Link] (Higgins et al. 1985), ladysthumb (*Persicaria maculosa* L.) (Askew and Wilcut 2002a), prickly sida (*Sida spinosa* L.) (Buchanan et al. 1977; Chandler 1977), redroot pigweed (*Amaranthus retroflexus* L.) (Buchanan and Burns 1971b; Buchanan et al. 1980), sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby] (Buchanan and Burns 1971a; Buchanan et al. 1980), smellmelon [*Cucumis melo* L. var. *dudaim* (L.) Naud.] (Tingle et al. 2003), tropic croton (*Croton glandulosus* L.) (Askew and Wilcut 2001), spurred anoda [*Anoda cristata* (L.) Schltdl.], velvetleaf (*Abutilon theophrasti* Medik.), and Venice mallow (Chandler 1977). However, of these, only Venice mallow was recorded in the surveys of Australian cotton fields conducted by Werth et al. (2013). Venice mallow, black nightshade, and prickly sida were reported in the surveys of Charles (2015), but little to no information is available on the competitive ability of the remaining 40 broadleaf weed species recorded in these surveys.

Of the species for which the competitive effect has been determined, the yield reductions from season-long competition range from 33% to 55% for ladysthumb (Askew and Wilcut 2002a); 60% for tropic croton, with 3.5 plants m^{-1} (Askew and Wilcut 2001); and 38% to 80% for 7 sicklepod plants m^{-1} (Buchanan and Burns 1971a). Redroot pigweed reduced cotton yield by between 22% and 90% with 7 plants m^{-1} (Buchanan and Burns 1971b), prickly sida reduced yield by between 45% and 90% (Buchanan et al. 1977), and coffee senna reduced yield by between 17% and 55% with 2 to 4 plants m^{-1} (Higgins et al. 1985). Season-long competition of Venice mallow caused no significant reduction in lint yield, whereas prickly sida reduced the yield by approximately 66% and spurred anoda and velvetleaf reduced yield by nearly 100% at densities of 5 weeds m^{-1} (Chandler 1997). The high level of variation observed in a number of these experiments was attributed to factors including seasonal variation and differences between sites in soil type and disease incidence (Buchanan and Burns 1971a, 1971b; Buchanan et al. 1977; Higgins et al. 1985).

Determining the competitive effect of these weeds enables the critical period for weed control (CPWC) to be determined for each species. It also helps to define the period of the season during which the crop is most sensitive to weed competition, such that the damage caused by weed competition exceeds the cost of controlling the weeds (Charles et al. 2019b, 2019c; Fast et al. 2009; Korres and Norsworthy 2015; Webster et al. 2009). However, to our knowledge, the CPWC is yet to be determined for many of the broadleaf weeds found in Australian cotton fields. As an alternative to undertaking experiments using naturally occurring weeds, a range of mimic weeds have been used in competition experiments. Mimic weeds have the advantages of giving better control over weed density, more uniform weed emergence, and better experimental repeatability (Charles et al. 2019a). Mimic broadleaf weeds used in competition experiments have included common sunflower (*Helianthus annuus* L.) (Charles et al. 2019a; Charles and Taylor 2007), mungbean (Charles et al. 2019a), rapeseed (*Brassica napus* L.) (Vollmann et al. 2010), and white mustard (*Sinapis alba* L.) (Didon and Boström 2003; Lotz et al. 1996). A mimic weed is generally chosen that has similar morphologic characteristics to the actual weed for which it is being substituted and is often of the same genus.

Charles et al. (2019a) compared the competitive effects of Venice mallow, a real weed, and mungbean, a mimic weed, in irrigated cotton and found that although the real and mimic weeds were dissimilar in many morphologic characteristics (i.e., node and leaf number, leaf area and size, and dry weight at midseason), they had similar competitive effects on the lint yield of cotton when competing at densities of 3 to 30 weeds m^{-1}. Charles et al. (2019a) concluded that in fully irrigated cotton, the competitive effects of a range of weeds might be satisfactorily extrapolated from the results of mimic weeds, provided the real and mimic weeds are of similar dry weight and height at midseason or the relationship accounts for differences in plant dry weight and height. They proposed a generalized relationship estimating the yield loss of high-yielding, irrigated cotton from weed competition over a range of weed species, heights, and dry weights.

Charles et al. (2019b) determined the CPWC for a large broadleaf mimic weed, common sunflower, in high-yielding cotton and found that the CPWC extended from crop emergence through to mid-season or longer, depending on weed density. The point of minimum yield loss from a single weed-control input declined from 31% for one common sunflower plant m^{-2} to 76% for 50 weeds m^{-2}. The CPWC for 50 common sunflower plants m^{-2} extended season long, from crop emergence to harvest, much longer than had been observed in previous studies on lower-yielding crops (Bukun 2004; Cardoso et al. 2011; Korres and Norsworthy 2015). Similarly, Charles et al. (2019c) reported the CPWC for a mimic grass weed, Japanese millet [*Echinochloa esculenta* (A. Braun) H. Scholz], for which the CPWC extended from crop emergence to midseason for 10 weeds m^{-2} or more in high-yielding cotton. However, the point of minimum yield loss from Japanese millet was only 14% for 10 weeds m^{-2}, declining to 30% for 200 weeds m^{-2}. Hence, although the CPWC was similar for the two weeds at their lowest densities, the potential for yield loss was greater for a single common sunflower plant m^{-2} than for any of the observed densities of Japanese millet of up to 200 plants m^{-2}.

The objective, therefore, for this study was to determine the CPWC for a medium-sized broadleaf weed in high-yielding, irrigated cotton over a series of seasons, using mungbean as a mimic weed, and to evaluate the impact of the weed density on the CPWC.

Materials and Methods

Field studies using commercial cotton cultivars were conducted at the Australian Cotton Research Institute, Narrabri (30.12°S, 149.36°E; elevation 201 m) on a heavy alluvial clay (fine, thermic, smectitic, Typic Haplustert) soil over five seasons. Cotton was planted at 15 seeds m row^{-1} on September 30, 2003, using the commercial cultivar 'Sicot 289 RRI'; on October 4, 2004, using 'Sicot 289 BR'; on October 6, 2006, and October 8, 2007, using 'Sicot 80 BRF'; and on October 21, 2015, using 'Sicot 71 BRF.' The crops were grown in line with commercial practices on raised hills, 1-m apart. Fields were fertilized with 180 kg N ha^{-1}, applied before

planting and were irrigated as required using flood irrigation triggered by computer modelling of the crop's water requirements. The mungbean cultivar 'Berken' 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 with trifluralin (TriflurX®, 480 g L^{-1}; Nufarm Australia, Melbourne, Victoria, Australia) incorporated before planting at 1.1 kg ai ha^{-1}. Weed-free plots were maintained using glyphosate (Roundup Ready® herbicide, 690 g kg^{-1}; Monsanto Australia, Melbourne, Victoria, Australia) at 1 kg ai ha^{-1} (2004 to 2005 season and later), and hand hoeing was performed as needed.

Experimental Design

The experiments were conducted using split plots within a randomized, complete block design with four replications within each season. Times of weed planting were main plots and times of weed removal and weed densities were subplots, each 4 rows wide (4 m) by 10 m long. Mungbean was planted with the crop or at predetermined periods after cotton emergence, sown to achieve 0, 1, 3, 6, 15, 30, and 60 plants m^{-2}. Times of weed planting and removal were measured in growing degree days (GDD) since planting, using 15.5 C as the base temperature (Bukun 2004), defined as:

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

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

Weed planting and removal times were targeted to occur at 150, 300, 450, 600, 750, and 900 GDD, but actual times were influenced by factors such as rainfall and irrigation scheduling, with not all weed densities and times of weed planting and removal occurring in all seasons. Weed emergence was delayed by inadequate soil moisture on some occasions, with not all target weed densities achieved in all seasons.

At the time of weed removal, weed density was recorded on 1 m of row in each plot, and height and aboveground biomass were recorded on 10 cotton and weed plants. The values used for statistical analysis were averages of these 10 plants. Plants were weighed after drying at 70 C for at least 72 h in a forced-air oven. Cotton was mechanically harvested, and seed-cotton yield was recorded from the central two rows of each plot. A single-saw gin was used to determine ginning percentage and lint yield from subsamples from one row.

Statistical Analysis

Relative lint yield (i.e., lint yield relative to the weed-free control in each season) was analyzed by ANOVA using R statistical software, version 3.4.2 (R Foundation for Statistical Computing, Vienna, Austria) with a significance level of $P < 0.05$, with replicate, year, time of weed interference, and removal and weed density as factors. Analysis indicated no significant year effect; thus, the data sets from the five seasons could be combined. Relative lint yield was significantly related to time of weed removal and interference and weed density.

The effect of weed interference on relative lint yield at each weed density was modelled using Gompertz, logistic, and exponential functions as described by Charles et al. (2019b, 2019c), with the exponential function substituted for the logistic function where the shape of the curve did not allow the logistic function to be fit; or

where the application of the exponential function improved the fit of the data, as indicated by the Akaike information criterion (AIC). These functions were extended to include weed density as a covariate, as described by Charles et al. (2019b, 2019c).

Weed and crop height and biomass from treatments where weeds established at the start of the season were analyzed using ANOVA, with replicate, year, time of weed removal, and weed density as factors. Analysis indicated the data could be best related to weed density and the time of weed removal, with no significant year effect, allowing the data sets from the five seasons to be combined. Data were modelled using Gompertz and exponential functions, with the AIC used to determine the model of best fit. Extended Gompertz and exponential functions including weed density as a covariate were fit to the weed and crop height and biomass data, and the model of best fit was determined using the AIC.

Combinations of the duration of weed competition, density, biomass, and height were tested to improve the quality of fit of the weed interference and weed removal relationships using the extended Gompertz and exponential models by including these as additional covariates in the relationships. The model of best fit was determined using the AIC.

Results and Discussion

Plant Height and Biomass

Weed and crop height were reduced by increasing weed density (Figure 1). Mungbean plant height at midseason (800 GDD) was reduced by 15% by increasing mungbean density from 1 to 60 plants m^{-2} (52 and 45 cm tall, respectively), but no difference remained at the end of the season (1,600 GDD) (Figure 1A), as was observed with tropic croton (Askew and Wilcut 2001), jimsonweed (*Datura stramonium L.*) (Scott et al. 2000), and ladysthumb (Askew and Wilcut 2002a).

Crop height was reduced by increasing mungbean density, with weed-free cotton 23-cm taller at midseason than cotton competing with 60 mungbean plants m^{-2}, 59- and 36-cm tall, respectively (Figure 1B). The difference in height increased to 36 cm at cotton harvest, with weed-free cotton 104 cm tall compared with 68 cm for cotton competing with 60 weeds m^{-2}. Similarly, other studies have shown cotton height decreased in response to increasing levels of weed competition (Barnett and Steckel 2013; Charles et al. 2019b, 2019c; Robinson 1976; Scott et al. 2000). The mungbean plants were shorter than the crop throughout the season at the lowest density of 1 mungbean plant m^{-2}, and almost half the height of the cotton at harvest, with mungbean plants 52-cm tall at midseason and 58 cm at harvest, compared with cotton plants that were 63-cm tall at midseason, increasing to 95-cm tall at harvest. The mungbean plants were taller than the crop at midseason (45 and 36 cm, respectively) at the highest weed density of 60 mungbeans m^{-2}, but by harvest, the cotton was taller than the mungbean plants, having reached 68 cm compared with mungbean at 56 cm (Figure 1A and 1B).

Mungbean is an intermediate-sized broadleaf mimic weed, with 76 to 650 g m^{-2} above-ground, dry biomass at crop harvest, with densities of 1 and 60 plants m^{-2}, respectively, larger than Venice mallow (Chandler 1977; Charles et al. 2019a), but similar in weight to Benghal dayflower (Webster et al. 2009), tropic croton (Askew and Wilcut 2001) and velvetleaf and prickly sida (Chandler 1977). At the end of the season, the biomass of mungbean plants in our experiment, when competing with cotton, was only about half the
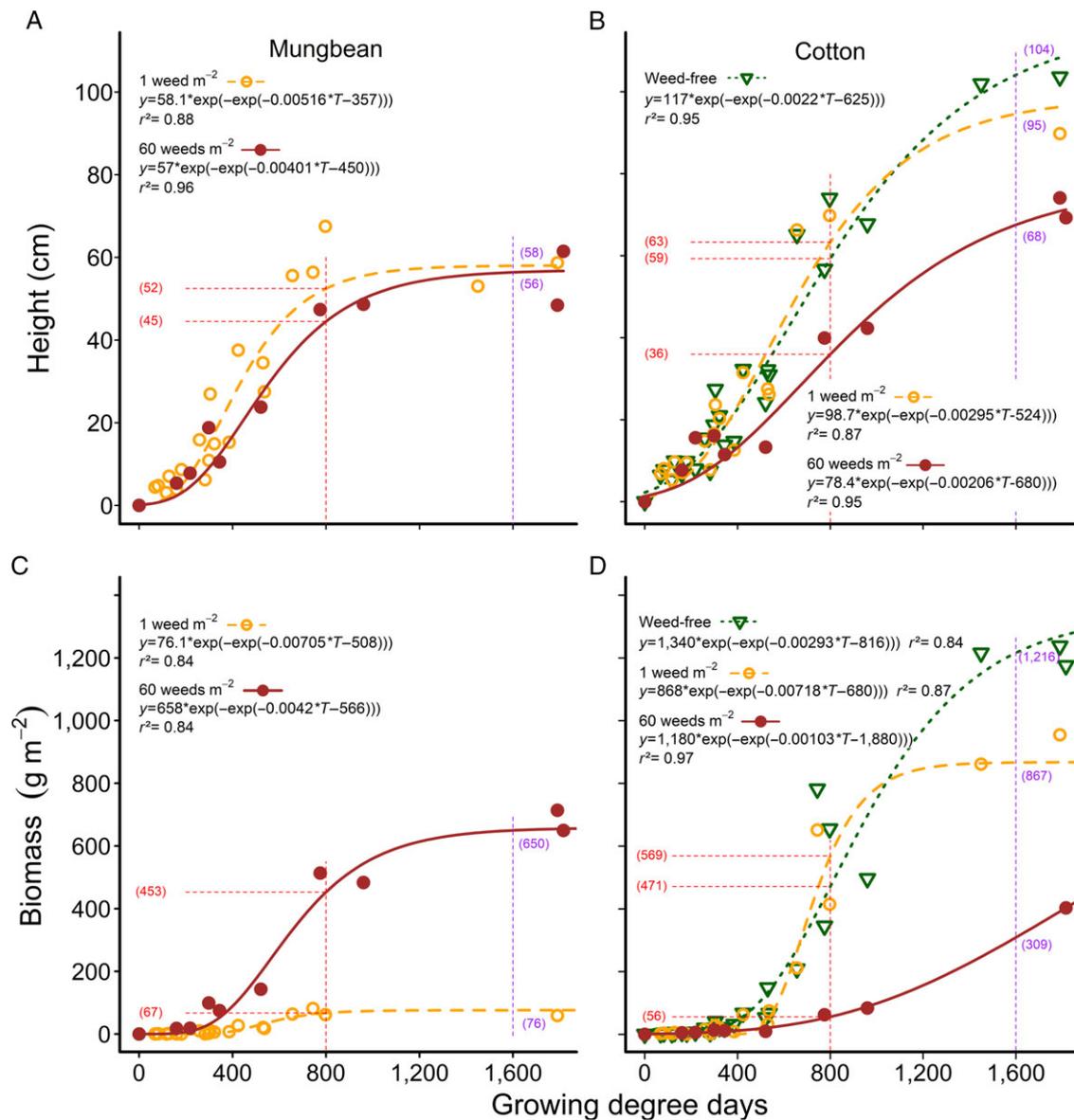
Figure 1. Graphs of (A) mungbean and (B) cotton height, and (C) mungbean and (D) cotton dry, aboveground biomass over the growing season for weed densities of 0 (weed-free), 1, and 60 plants m^{-2}. Data points are treatment means. Values at midseason (800 growing degree days [GDD]) are indicated by the dashed red lines and bracketed values, and at cotton harvest (1,600 GDD) by dashed purple lines and bracketed values. Parameters of the models are as follows: y is weed or crop height or biomass; T is the cumulative degree days since planting.

biomass of spurred anoda (Chandler 1977), pale smartweed [*Persicaria lapathifolium* (L.) Delarbre] (Askew and Wilcut 2002b), ladysthumb (Askew and Wilcut 2002a), and mixed-weed populations, including the large weeds common cocklebur (*Xanthium strumarium* L.) (Bukun 2004; Tursun et al. 2016) and jimsonweed (Tursun et al. 2015), and our mungbean was much smaller than large thornapple (*Datura ferox* L.) (Charles et al. 2019a). Mungbean biomass m^{-2} increased with increasing mungbean plant density, but the rate of increase in biomass was less than the rate of increase in density. Total weed biomass increased seven-fold at midseason, from 67 to 453 g m^{-2}, as weed density increased 60-fold from 1 to 60 mungbean plants m^{-2} (Figure 1C).

By the end of the season, a three-fold increase in weed density from 1 to 3 mungbean plants m^{-2} had resulted in a 2.6-fold

increase in weed biomass, from 76 to 194 g m^{-2} (data not shown). However, the relationship was not linear, with a 60-fold increase in weed density from 1 to 60 mungbean plants m^{-2} resulting in only a nine-fold increase in weed biomass, from 76 to 650 g m^{-2} (Figure 1C). This decline in the rate of response to increasing weed density indicated that high levels of intraspecific competition were occurring at the higher mungbean plant densities, as occurred with high densities of velvetleaf (Ma et al. 2016) and common sunflower (Charles et al. 2019c). Cortés et al. (2010) observed a similar trend with velvetleaf, where doubling the density from 1 to 2 weeds m^{-2} increased weed biomass 1.7-fold, but increasing the density 25-fold to 25 weeds m^{-2} only increased weed biomass 5.5-fold. There was no density-related decline in weed numbers over time in our treatments, indicating the weed density was not sufficiently high to cause self-thinning (Deng et al. 2012).
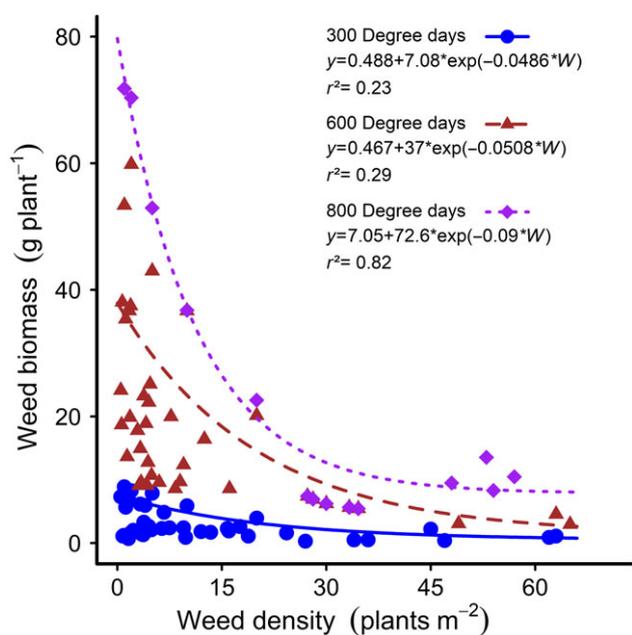
Figure 2. Reduction in mungbean aboveground biomass with increasing weed density at 300, 600, and 800 growing degree days. Parameters of the models are as follows: y is weed biomass; W is the weed density. Data points are treatment means.

The decrease in mungbean biomass plant^{-1} with increasing weed density became more pronounced over time, with the steepness of the response curves of weed density and biomass increasing with time (Figure 2). The same response was observed with velvetleaf (Cortés et al. 2010; Ma et al. 2016) and common sunflower (Charles et al. 2019c), but the curves were much steeper for these larger, more competitive weeds.

Crop biomass was reduced by increasing mungbean plant density, but again, the response was not directly proportional to the increase in mungbean density. Cotton biomass was not reduced by the presence of 1 mungbean plant m^{-2} at midseason, but was reduced by 88% by 60 mungbean plants m^{-2} (Figure 1D). Cotton biomass was reduced by 29% at cotton harvest when competing with 1 mungbean plant m^{-2}, but the reduction in crop biomass had declined from the midseason reduction of 88% to 74% when competing with 60 weeds m^{-2}.

Cotton Lint Yield and Weed Density

Cotton yields averaged 5,260 kg seed cotton ha^{-1} and 2,100 kg lint ha^{-1} for the weed-free plots over the five seasons of this study. Mungbean plants competed strongly with cotton at the highest weed densities, with season-long interference resulting in an 84% reduction in cotton lint yield with 60 mungbean plants m^{-2} (Figure 3F) and a 73% yield reduction in lint yield with 30 mungbean plants m^{-2} (Figure 3E). This level of yield loss was much greater than the 20% yield loss reported by Charles et al. (2019a) for cotton competing with 30 mungbean plants m^{-2}, where the plants were grown in bins with limited rooting depth, yielding 1,410 kg lint ha^{-1} (weed-free controls). Mungbean plants competed less strongly at lower densities, with season-long interference resulting in a 41% reduction in lint yield with 3 mungbean plants m^{-2} (Figure 3B), similar to the results for a range of other broadleaf weeds (Askew and Wilcut 2002a; Buchanan and Burns 1971a, 1971b; Buchanan et al. 1977; Higgins et al. 1985). Even at the lowest density of 1 plant m^{-2}, mungbean in the current study

reduced cotton-lint yield by 25% from season-long crop competition (Figure 3A).

Webster et al. (2009) used the point of minimum yield loss from a single control input (the intersection point of the weed removal and weed interference curves) as a way of measuring the relative competitiveness of crop and weed. However, in our data, there was no consistent trend in the point of minimum yield loss with increasing weed density, even though the maximum yield losses consistently increased with increasing weed density (Figure 3A–3F). This finding contrasts with the observations of Charles et al. (2019b, 2019c), who reported consistent reductions in the point of minimum yield loss with increasing weed density for the mimic weeds common sunflower and Japanese millet in high-yielding cotton, with average yields of 2,040 and 2,070 kg lint ha^{-1}, respectively (weed-free controls).

An alternative approach for understanding the relationship between weed competition and crop yield is to determine the critical period for weed control, using an arbitrary lint yield-loss threshold of, for example, 5% (Ghosheh et al. 1996), such that the CPWC is defined by the upper intersection of the critical time for weed removal (CTWR) and critical weed-free period (CWFP) curves with the threshold at each weed density (Figures 3A–3F). The critical periods so derived extended from 83 to 1,230 GDD with 1 mungbean plant m^{-2} to 139 to 1,040 GDD with 60 mungbean plants m^{-2} (Figure 3A and F). Thus, as was observed with the point of minimum yield loss, there was, again, no consistent trend in the critical period with increasing mungbean density, with the end of the CPWC greater for one mungbean plant than for 60 plants m^{-2}. This observation again contrasts with previous work showing strong relationships between increasing weed density and increasing yield loss (Askew and Wilcut 2001, 2002a, 2002b; Cortés et al. 2010; Higgins et al. 1985; Ma et al. 2016; MacRae et al. 2013; Scott et al. 2000) over cotton yields ranging from 4,550 to 1,040 kg seed cotton ha^{-1} (Cortés et al. 2010; Higgins et al. 1985).

A lack of consistent response in the CPWC relationships with increasing weed density was also observed by Charles et al. (2019b, 2019c), with common sunflower and Japanese millet used as mimic weeds in high-yielding cotton. They concluded that the lack of response in the lower limit of the CPWC could be attributed, at least in part, to the sensitivity of the derived CPWC to the shape of the fitted CWTR curves, with the shape of the curves as they approach the yield loss-threshold changing with increasing weed density. This change in curve shape, in turn, led to anomalous results when the curves intersected the threshold at or soon after crop emergence (Charles et al. 2019b, 2019c). The issue with the shape of the curves changing with changes in weed density was exaggerated in our data where exponential curves were used to describe the relationships for the lower weed densities, because it was not possible to fit logistic curves to the data for 1, 3, 6, and 15 weeds m^{-2}. However, logistic curves were fit to the 30 and 60 weeds m^{-2} relationships, because these curves best described these data. This change in curve type appeared to contribute to the lack of consistent results for both the point of minimum yield loss and the start of the CPWC in our data.

Charles et al. (2019b, 2019c) also noted that increasing weed density did not have a large additional effect on the CPWC at higher weed densities, because the competitive effect of the weeds was not directly proportional to the density of weeds, due to increasing interspecific competition between the weeds with increasing weed density. Consequently, at higher weed densities, increasing weed density made proportionally less difference to
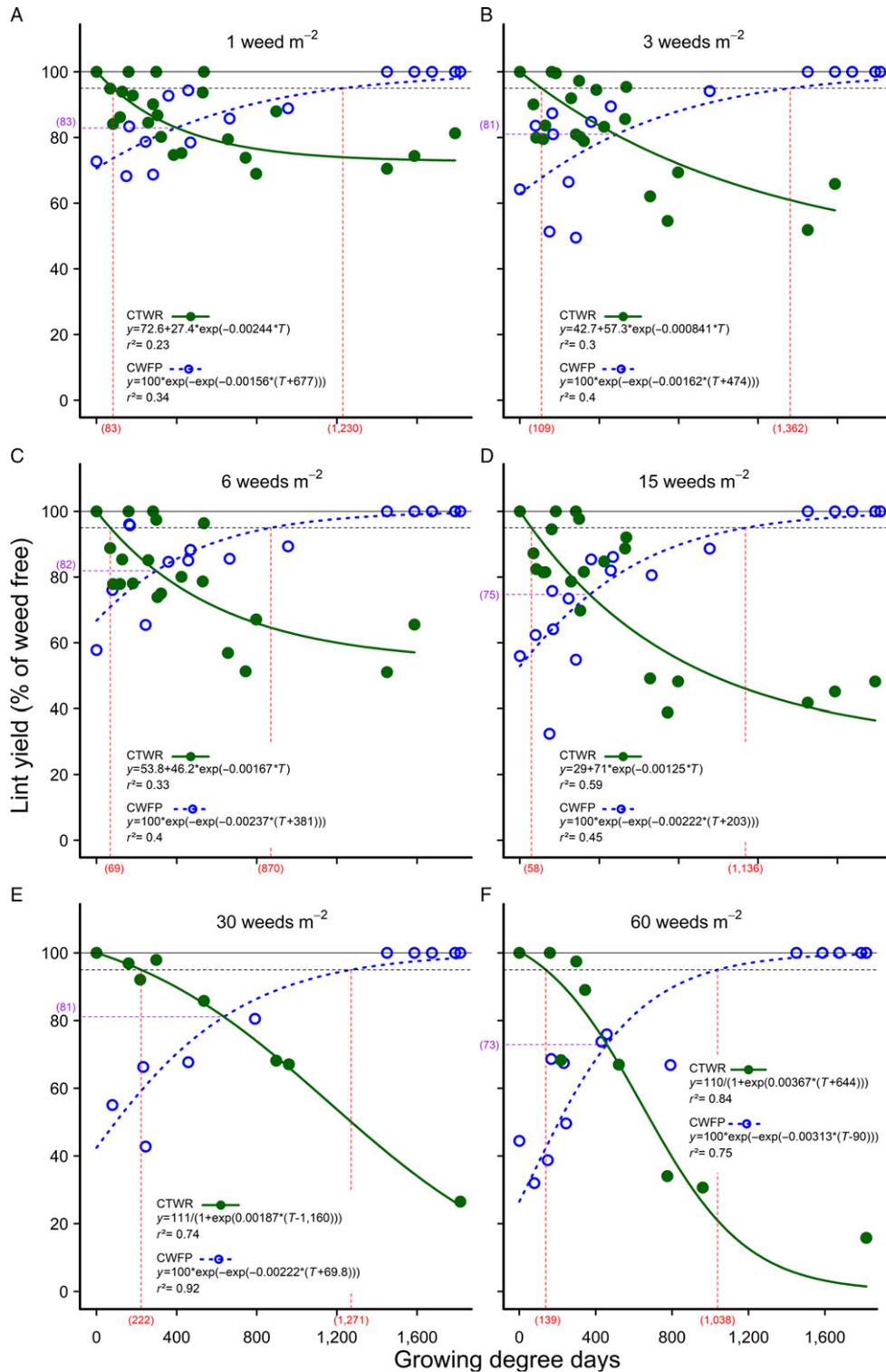
Figure 3. Relationships between the relative cotton-lint yield and mungbean interference durations (i.e., CTWR, indicated by green lines; CWFP, indicated by blue lines) for mungbean densities of (A) 1, (B) 3, (C) 6, (D) 15, (E) 30, and (F) 60 plants m^{-2}. Parameters of the functions are as follows: y is the relative lint yield; T is the cumulative degree days since planting. Data points are treatment means. Weed-free yields are indicated by horizontal solid lines and horizontal dashed lines indicate a 5% yield-reduction threshold. The intersection of the CTWR and CWFP lines with the yield-reduction threshold defines the critical period for weed control (CPWC). Dashed red lines and bracketed values show the limits of the derived CPWC curves. Dashed purple lines and bracketed values indicate the point of minimum yield loss. CTWR, critical time for weed removal; CWFP, critical weed-free period.

the level of weed competition experienced by the crop; thus, large increases in weed density caused only relatively small increases in the duration of the CPWC in their data. Ma et al. (2016), for example, reported a large reduction in cotton yield from 1 velvetleaf plant m crop row^{-1}, but little additional effect from 9 weeds m^{-1}. No consistent increase in the duration of the

Table 1. The start and end of the CPWC using a 1% yield-loss threshold.

Weed density	CPWC start[a]	CPWC end
No. m⁻²	GDD since planting	
1	15	2,227[b]
3	21	2,370[b]
6	13	1,556
15	11	1,872[b]
30	51	2,006[b]
60	42	1,559

[a]Abbreviations: CPWC, critical period for weed control; GDD, growing degree days.
[b]These estimates of the end of the CPWC extend past full crop maturity.

CPWC with increasing weed density is apparent in our data, even though increasing weed density had a large impact on the maximum observed yield losses.

Dynamic Relationships for Cotton Lint Yield

Clearly, the cotton plants in this study were sensitive to competition from mungbean plants, with the duration of the CPWC extending to or past midseason for all weed densities, using the 5% yield loss-threshold (Figure 3). However, where the target weed is susceptible to glyphosate in a glyphosate-tolerant cotton crop, as is the case with most broadleaf weeds in the glyphosate-tolerant cotton crops commonly grown in Australia, a cost-based yield-loss threshold of less than 1% could be applied to the analysis on the basis of 2020 commodity prices. The 1% threshold extended the CPWC to full season for most weed densities (at or before crop emergence through to crop harvest for four of the six densities), but the issue in our data of an inconsistent trend in the CPWC remained (Table 1).

To address this issue of lack of consistent trend in the CPWC with increasing weed density, Charles et al. (2019b, 2019c) 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 of including weed density as a covariate in the equations, the CPWC estimated by these curves for a 1% yield reduction threshold increased from 24 to 1,680 GDD for 1 mungbean plant m⁻², and 9 to 2,060 GDD (after harvest) for 60 mungbean plants m⁻² (Figure 4).

The lower limit of the dynamic CPWC using a 1% yield-loss threshold began before crop emergence and was in line with the findings for smellmelon in a low-yielding crop (2,560 kg seed cotton ha⁻¹) (Tingle et al. 2003) and the mimic weeds common sunflower (Charles et al. 2019c) and Japanese millet (Charles et al. 2019b) in high-yielding cotton. The lower limit of the CPWC was earlier than was reported for a range of other weeds, where the CPWC commenced up to 7 wk POST (Buchanan et al. 1977; Bukun 2004; Cardoso et al. 2011; Tursun et al. 2015, 2016), for crops ranging in yield from 2,000 to 8,000 kg seed cotton ha⁻¹ (Cardoso et al. 2011; Tursun et al. 2015). This difference is likely to be related to the timing of weed emergence, with the emergence of our mimic weed, with no seed dormancy, triggered by irrigation immediately after planting in our study. This contrasts with findings of other work, where naturally occurring weed populations were used and where weed germination was triggered by rainfall events that may not have occurred until days or weeks after crop planting. Webster et al. (2009) demonstrated the importance of cotton planting date, with early-planted cotton
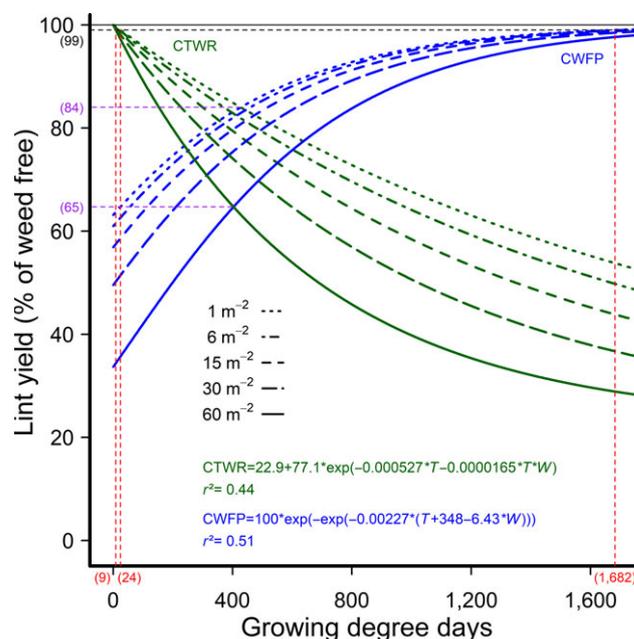

Figure 4. Dynamic relationships between the relative cotton-lint yield and mungbean interference durations (i.e., CTWR, indicated by green lines; CWFP, indicated by blue lines using extended exponential (CTWR) and logistic (CWFP) functions including weed density as a covariate. Parameters of the models are as follows: T is the cumulative degree days since planting; W the weed density. The derived relationships for mungbean densities of 1, 6, 15, 30, and 60 plants m⁻² are presented as examples. The weed-free yield is indicated by the horizontal solid line and a 1% yield-reduction threshold by the horizontal dashed line. The intersection of the CTWR and CWFP lines with the yield-reduction threshold defines the critical period for weed control (CPWC). The limits of the CPWC for 1 and 60 mungbean plants m⁻² are shown by dashed red lines and bracketed values. The end of the CPWC for 60 mungbean plants m⁻² occurs at 2,060 growing degree days, beyond the limit of the figure. Dashed purple lines and bracketed values show the points of minimum yield loss for 1 and 60 mungbean plants m⁻².

more competitive with Benghal dayflower because of delayed emergence of this weed.

The upper limit of the dynamic CPWC of 1,682 GDD for 1 mungbean plant m⁻² corresponded to 161 d or more POST and occurred after the cotton was harvested in three of the five seasons in our experiments. This extended CPWC was longer than reported by most previous researchers at between 40 and 80 d after planting (Cardoso et al. 2011; Korres and Norsworthy 2015; Tingle et al. 2003; Tursun et al. 2015, 2016; Webster et al. 2009), but in line with the results of Bukun (2004), for a naturally occurring mixed-weed population.

The approach of Charles et al. (2019b, 2019c) to develop dynamic relationships, including weed density as a covariate in the equations, could also be applied to our height and biomass data (Figure 1). In each case, a dynamic model including weed density improved the fit of the data, as indicated by the AIC. These dynamic models allowed weed and crop height and biomass to be estimated for weed densities in the observed range of 1 to 60 mungbean plants m⁻² throughout the growing season (Figure 5).

In addition to weed density and the duration of weed competition, cotton yield has been related to weed biomass, with an inverse linear relationship resulting (Cortés et al. 2010; Scott et al. 2000; Smith et al. 1990). Over a range of weed species and types, Charles et al. (2019a) found that a combination of weed biomass and weed height better described the reductions in
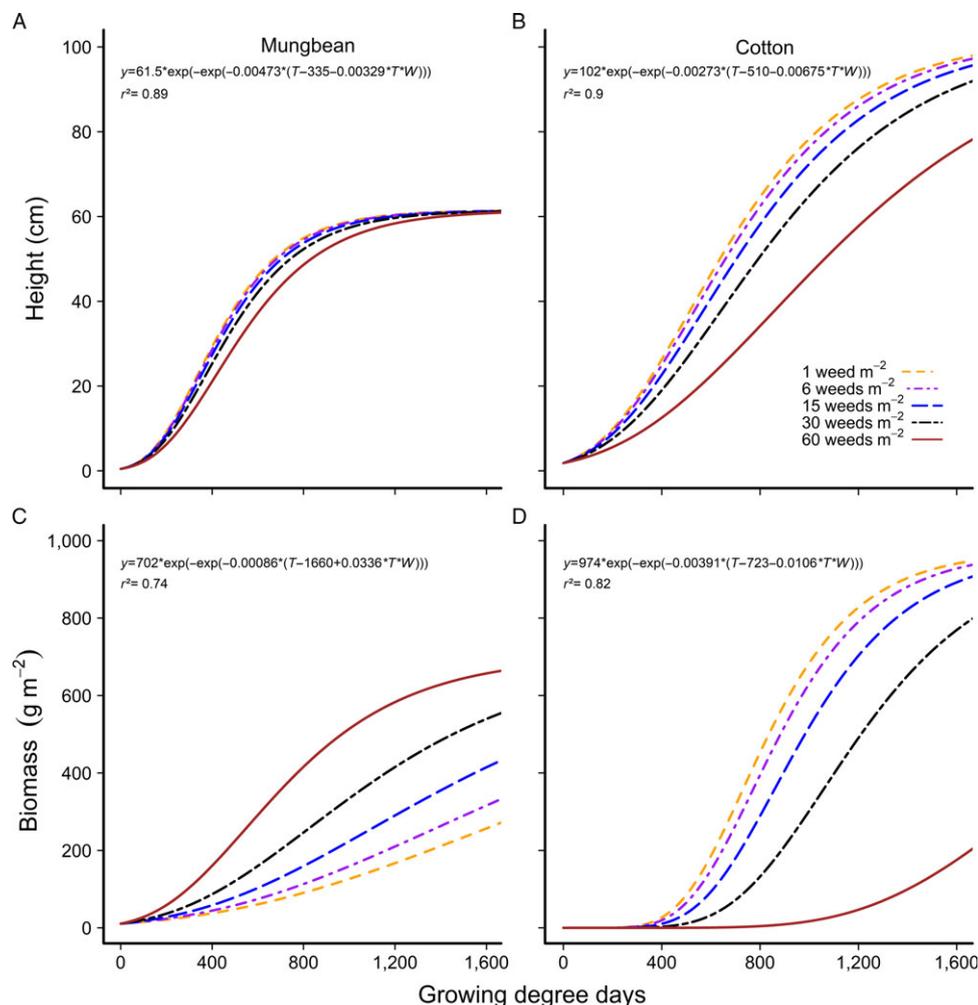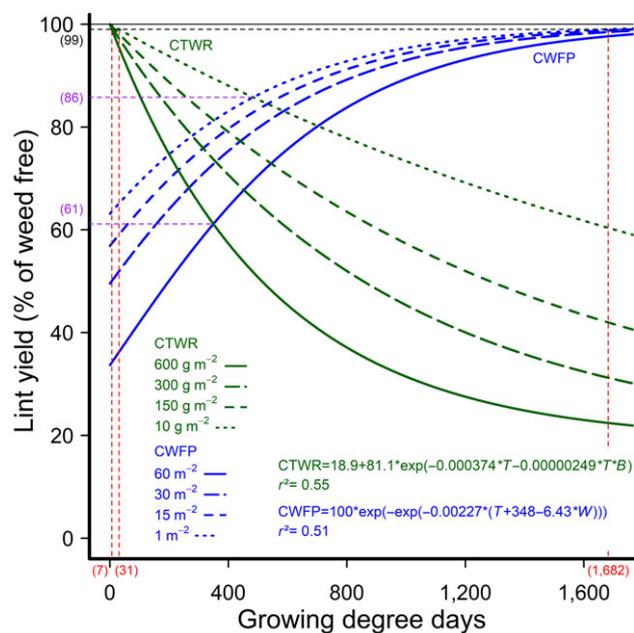
Figure 5. Dynamic relationships for (A) mungbean and (B) cotton height, and (C) mungbean and (D) cotton dry, aboveground biomass over time using extended exponential functions including weed density as a covariate. Parameters of the models are as follows: y is plant height or biomass; T is the cumulative degree days since planting; W is the weed density. The derived relationships for the mungbean densities of 1, 6, 15, 30, and 60 plants m^{-2} are shown as examples.

cotton-lint yield from weed competition than weed density. We tested combinations of the duration of weed competition, weed density, weed biomass, and weed height with our data and were unable to improve the fit of the relationship defining the CWFP. However, a combination of the duration of weed competition and weed biomass gave a significant (P < 0.05) improvement in the fit of the CTWR curve (Figure 6) compared with the earlier relationship of the duration of weed competition and weed density (Figure 4). This improved relationship made little difference to the duration of the CPWC estimated from our data, which extended for the full growing season of the crop but lowered the point of minimum yield loss from a single weed control input to 39% with the highest weed pressure (Figure 6), compared with a 35% yield loss with the earlier model (Figure 4). Using weed biomass and height as the measures of weed competitiveness, it may be possible with these dynamic functions to develop multi-species competition models, as suggested by Charles et al. (2019a, 2019c).

We conclude that a high level of weed control must be maintained throughout the cropping season in high-yielding cotton where broadleaf weeds are present at densities of 1 or more

plants m^{-2} to ensure crop losses do not exceed the cost of weed control. Weeds present at lower densities will need to be controlled before they set seed, to protect lint quality, to avoid difficulties at harvest, and to manage herbicide resistance by greatly reducing the number of seeds in the weed seedbank over time (Korres and Norsworthy 2015; Thornby et al. 2013). To achieve this reduction in the weed seedbank, cotton growers will need to adopt a more integrated approach to weed control, replacing glyphosate with alternative control tools, especially where glyphosate-tolerant and -resistant weeds are present. These tools might include applications of residual herbicides such as diuron, fluometuron, metolachlor, pendimethalin, prometryn, and trifluralin, as well as POST applications of clethodim and haloxyfop. Dicamba and glufosinate could also be used POST on cotton varieties that include the resistance genes for these chemistries, and flumioxazin and paraquat may be used as in-crop shielded applications. In addition, cotton growers should be using spot spraying, interrow cultivation, and hand hoeing to ensure weed escapes are removed before they set seed. The differing costs of these alternatives to glyphosate will alter the value of the weed-control threshold and will need to be factored into the critical-period model.

Figure 6. Dynamic relationships between the relative cotton-lint yield and mung-bean interference durations (i.e., CTWR, indicated by green lines; CWFP, indicated by blue lines), using extended exponential (CTWR) and logistic (CWFP) functions including weed density (CWFP) and weed biomass (CTWR) as covariates. Parameters of the models are as follows: y is the relative lint yield; T is the cumulative degree days since planting, B is the weed biomass; W is the weed density. The derived relationships for mungbean biomass of 10, 150, 300, and 600 g m^{-2} are presented as examples for the CTWR relationship, and mungbean densities of 1, 15, 30, and 60 plants m^{-2} are presented as examples for the CWFP relationship. The weed-free yield is indicated by the horizontal solid line and a 1% yield-reduction threshold by the horizontal dashed line. Dashed red lines and bracketed values indicate the CPWC for 1 and 60 mungbean plants m^{-2}. Dashed purple lines and bracketed values show the points of minimum yield loss for a single weed-control input at 1 mungbean plant and 10 g biomass m^{-2}, and 60 mungbean plants and 600 g dry biomass m^{-2}.

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