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COVER PAGE

TITLE: Developing a Threshold Model for Controlling Weeds in Glyphosate Resistant Cotton

DISCIPLINE: Weed Management

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ABBREVIATIONS: CPWC, critical period for weed control; LAI_C, leaf area index of the crop; LAI_W, leaf area index of the weed, LW, relative leaf area of weed; q, the relative damage coefficient; $RGRL_C$, the relative growth rate of the crop leaf area; $RGRL_W$, the relative growth rate of the weed leaf area.

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Graham W. Charles, and Ian N. Taylor

ABSTRACT

The commercial adoption of genetically modified, Roundup Ready Flex® cotton (*Gossypium hirsutum* L.) brings to the Australian cotton industry the opportunity to develop new weed management systems that are less reliant on residual herbicides. The development of weed control thresholds will be an important step in optimising such a system based largely on a non-residual post-emergence herbicide, glyphosate. This work explores the development of a weed control threshold and the critical period for weed control (CPWC) for irrigated Roundup Ready Flex cotton. Data from field experiments were used to define the CPWC and fitted to weed competition models. Sunflower (*Helianthus annuus* L.) and Japanese millet (*Echinochloa esculenta* (A. Braun) H. Scholz) were used as mimic weeds in these experiments to reduce variability in the results. The CPWC defined by the data was dependant on the control threshold adopted, weed species and weed density, ranging from 9 to 61 days post-crop emergence for sunflower and 5 to 54 days post-crop emergence for Japanese millet. A simple empirical crop yield loss model was fitted to the data, but was sensitive to season and to achieve a good fit required reparameterization for each data set. This problem was partly addressed by relating model parameters to day degrees and weed density. A statistical model was also applied to the data and gave a similar overall fit, relating yield loss to plant height, leaf area index and day degrees. To further develop the CPWC concept for Australian cotton will require the adoption of a new crop yield loss modelling approach to more accurately predict the impact of weed competition. We conclude that a future model might be improved by including alternative measurements of plant growth such as leaf area index and plant height.

INTRODUCTION

Over the last two decades, the Australian cotton industry developed an aggressive attitude towards controlling weeds in conventional irrigated cotton crops using a range of management tools in an integrated manner to achieve a high level of weed control (Charles and Taylor, 2004). The industry relied heavily on residual herbicides for in-crop weed control, but in some situations, these herbicides adversely affected cotton establishment and growth, and contaminated the riverine environment (Taylor et al., 2004).

The commercial release of genetically modified, glyphosate tolerant, Roundup Ready® cotton in 2000 saw a rapid transition to this material, with approximately 77% of the planted cotton area using Roundup Ready varieties in the 2005/6 season (Charles and Taylor, 2006). The use of these varieties allowed cotton growers to reduce their reliance on pre-emergence residual herbicides, with a reduction in the use of full pre-emergence residual herbicide programs (such as broadcast trifluralin and diuron pre-planting in combination with pendimethalin and fluometuron at planting) and an increase in the use of banded residual herbicides (commonly a 40% band of pendimethalin and fluometuron at planting, with no pre-planting residual herbicide). There was a corresponding large increase in the use of glyphosate in-crop, and small reductions in the use of inter-row cultivation and hand-hoeing (Werth et al., 2006).

The commercial release of Roundup Ready Flex® cotton varieties in Australia in the 2006/7 season brought the potential for cotton growers to further modify their in-crop weed control programs, potentially replacing all pre-emergence residual herbicide applications with targeted post-emergence herbicides. These applications could be strategically targeted to manage weeds post-emergence, controlling identified populations of weeds before they negatively impacted on the crop, or were able to reproduce. Such a system would have the advantages of reducing the time and labor requirements at planting, eliminating the potential damage to cotton seedlings from pre-emergence residual herbicides, and could greatly reduce the risk of off-site movement of residual herbicides.

However, for a post-emergence herbicide application to be efficiently targeted on weeds, it is desirable to have an established weed population threshold for spraying, in combination with a detailed knowledge of the spectrum of weeds controlled by a herbicide and the required rates.

In a Roundup Ready Flex system, it is important that glyphosate is not simply applied every few weeks throughout the crop’s life. While such a strategy, based on multiple glyphosate applications alone is simple and would optimize crop yield in the short-term, it would quickly lead to species shift and the development of weed problems with species which are tolerant of, or resistant to glyphosate (Charles and Taylor, 2006). To optimize a sustainable Roundup Ready Flex system, glyphosate needs to used strategically in combination with other weed management tools so that weed management is achieved without imposing excessive selection pressure for glyphosate tolerance or resistance. The development of a weed control threshold is an important step in optimizing a weed management system.

The critical period for weed control. A weed control threshold is a component of the broader concept of the critical period for weed control (CPWC) established by Nieto et al. (1968). In a more recent review of this concept and its development, Knezevic et al. (2002) identified that the CPWC had particular application for use with herbicide tolerant crops, such as Roundup Ready Flex cotton, where the primary method of weed control is using a broad-spectrum, non-residual, post-emergence herbicide; in this case glyphosate. The CPWC concept has the advantage over a density dependant weed control threshold in that it identifies the critical middle period in the season where weeds compete strongly with the crop and can cause yield reductions. The CPWC concept identifies a period earlier in the season before weed control is required, when weeds are too small to effectively compete with the crop and their control is not justified on economic grounds. It also identifies a third period later in the season when the crop is large enough that newly emerging weeds are not able to effectively compete with the crop and again cause no significant yield penalty. From the point of yield, weeds emerging during the first and third periods have no impact on yield, and so no weed control threshold is required during these periods. However, weeds may need to be controlled outside of the middle CPWC for a variety of other reasons, including crop contamination, harvesting difficulties, their contribution to the weed seed bank, or the risk that they may harbor crop pests or diseases. Weed populations which exceed the weed control threshold during the middle CPWC period must be controlled to minimize yield losses.

The CPWC approach has been applied to a wide range of crops including canola (*Brassica napus* L.), chickpeas (*Cicer arietinum* L.), corn (*Zea mays* L.), cotton, peppers (*Capsicum annuum* L.), red beet (*Beta vulgaris* L.) and soybean (*Glycine max* (L.) Merr.) (Amador-Ramirez, 2000; Halford et al., 2001; Martin et al., 2001; Eyherabide and Cendoya, 2002; Tingle et al., 2003; Bukin 2004; Mohammadi et al., 2004; Norsworthy and Oliveira, 2004; Kavaliauskaite and Bobinas, 2006, Williams, 2006).

The objectives of these studies were to use a grass and a large erect weed to: 1) define the CPWC for Australian cotton; 2) evaluate the influence of weed type and density on the CPWC; 3) describe the relationship between cotton yield and the density of these weeds; and 4) evaluate the crop and weed components that contribute to predictive crop yield loss models.

MATERIALS AND METHODS

Experiments to define the CPWC and develop a yield loss model in Australian cotton were undertaken over three seasons, from 2003-04 to 2005-06, at the Australian Cotton Research Institute, Narrabri, NSW, Australia, using sunflower and Japanese millet as model weeds. Sunflower (variety Hyoleic 43), was used to mimic the effect of an erect broadleaf weed species in cotton, ensuring uniform weed emergence, density and growth habit. Sunflower was chosen for its similarity in growth habit to thornapple (*Datura ferox* L.), a common weed of cotton production (Charles and Taylor, 2004). Plots were otherwise maintained weed-free, with trifluralin (TriflurX, 480 g L^{-1}, Nufarm Australia) at 1.1 kg a.i. ha^{-1}, incorporated pre-planting, and hand-hoed as needed. A second experiment using Japanese millet (var. shirohie), as the mimic weed was established beside the sunflower experiment. Japanese millet was chosen for its similarity in growth habit to awnless barnyard grass (*Echinochloa colona* (L.) Link), a common weed of cotton production (Charles and Taylor, 2004). Plots were otherwise maintained weed-free with hand-hoeing as needed.

The site was a heavy alluvial clay soil (fine, thermic, smechitic, Typic Haplustert) and was flood irrigated as required during the growing season. Irrigation scheduling was based on computer modelling of the crop’s requirements. The field was irrigated five times during the growing season (six times in 2005-06) and 468, 454 and 501 mm of rain were recorded in 2003-04, 2004-05 and 2005-06, respectively. All field operations were consistent with standard commercial practices.

The field was pre-irrigated prior to planting. Cotton, variety Sicala 289B, was planted at 15 seeds m^{-1} of row on October 19, 2003, October 13, 2004, and October 1, 2005. Sunflower and Japanese millet, were planted parallel to the cotton row, 100 mm off-set to the western-side. The weeds were planted at the same time as the cotton, or added at intervals post-crop emergence (weed additions).

The experiments used a split-plot design within a randomized complete block with 4 replicates. The main plot treatments were five weed densities, with a weed-free control. Sunflower densities were 1, 2, 4, 9 and 16 weeds m^{-1} of row. Millet densities were 9, 17, 40, 75 and 140 weeds m^{-1} of row. Weeds were removed by hand-hoeing. Main plots were 12 rows (12 m) by 20 m, and sub-plots 4 rows by 10 m. Sub-plots of six times of weed addition or weed removal were randomly imposed within each weed density main plot.

Plant height, node number (cotton only), leaf number, leaf area and oven dried biomass were recorded on 10 crop and weed plants at each time of weed removal. These measurements were taken on all weed densities at each removal time. At the end of the season, the cotton was harvested using a modified commercial picker with a single picking head, and sub-samples were ginned using a single-saw gin to determine lint yield. Average lint yield in the weed-free plots was 1583, 1878 and 2286 kg lint/ha in 2003-04, 2004-05 and 2005-06, respectively.

Data from the three seasons were fitted to the empirical crop loss model of Kropff and Spitters (1991) using the model: Yield loss=$q*L_w/(1+(q-1)*L_w)$. The parameter q was the relative damage coefficient and L_w the relative leaf area (leaf area of the weed compared to the total leaf area of crop and weed), calculated as $L_w=LAI_w/(LAI_c+LAI_w)$, where LAI_w and LAI_c were the leaf area index of the weed and crop, respectively. Data from the 2003-04 season were used to define the initial values for the parameter q. Day degrees were determined from daily maximum and minimum temperatures using a base of 12^oC (Constable, 1976). Data were tested for significance by analysis of variance and regression analysis using GenStat (GenStat. Ver 9.1. 2006. Lawes Agricultural Trust, Rothamsted Experimental Station, VSN International, Hemel Hempstead, UK). Only results which were significant at the 5% level are discussed. Relationships were fitted using DeltaGraph (DeltaGraph Ver 4.0. 1998. DeltaPoint Inc., Monterey, CA, USA).

RESULTS AND DISCUSSION

The CPWC defined by these experiments was relative to the yield loss threshold adopted and dependant on the density of weeds present. A 5% yield loss threshold defined the CPWC for the large mimic weed, sunflower at 1 weed m^{-1} of row as 164 to 348 day degrees, or from 17 to 35 days post-crop emergence. At 9 weeds m^{-1} of row, the CPWC extended from 74 to 660 day degrees, or 9 to 61 days post-crop emergence (Figure 1).

Insert Figure 1 here

The experimental value for the CPWC was also sensitive to weed species. The CPWC defined by the millet experiment was dependent on the yield loss threshold adopted and the density of weeds present. A 5% yield loss threshold defined the CPWC at 9 millet m^{-1} of row as 40 to 353 day degrees, or from 5 to 36 days post-crop emergence. At 140 millet m^{-1} of row, the CPWC was defined as 76 to 579 day degrees, or from 9 to 54 days post-crop emergence (Figure 2).

Insert Figure 2 here

The CPWCs defined in these experiments were shorter than those defined using a natural weed population in cotton in Turkey (Bukun, 2004), which extended from 100 to 1174 day degrees from crop planting. The differences in estimated CPWC relate to the competitiveness of the weeds, and the steepness of the yield loss relationships, with more rapid response from weed removals and weed additions in the Australian data. It may also relate to differences in seasonal conditions and the competitiveness of the crops, as the Turkish cotton was taller, but lower yielding.

The sensitivity of the CPWC approach to a range of factors limits the value of this approach based on weed density. Experimental field results to define the CPWC are determined by the yield loss threshold adopted and tend to be season, site, crop and weed specific, making it difficult to establish an effective model defining the CPWC. Variables such as crop density and growth habit, weed density and spectrum, tillage system, time of emergence (both crop and weed), temperature, soil moisture and soil fertility over the growing season all add to variability between sites and seasons (Halford et al., 2001; Knezevic et.al, 2002; Norsworthy and Oliveira, 2004). At one site, Halford et al. (2001), for example, failed to define any CPWC for soybeans in consecutive seasons, but in the same seasons observed large effects of weeds on soybean yields on another site.

Theoretically, it should be possible to reduce the impact of some of these factors, such as row spacing, the time of crop and weed emergence (Halford et al., 2001), soil fertility (Knezevic et al., 2002), and seasonal conditions (temperature and soil moisture) by measuring these variables during an experiment and using crop growth and weed competition models to describe their effect on crop competition. However, to be valuable in the commercial world, it is essential that the information required by a model is easily measured and the result is robust.

Crop yield loss models. Simple models relating crop yield loss to weed density have been developed by many researchers. Cousens (1985) compared a number of these simple models and concluded that the rectangular hyperbola model gave the best fit to a range of data sets and was a biologically sensible model. Cousens et al. (1987) developed the concept further, including time of emergence as an important factor in the model.

However, in practice, many of the simpler crop competition models suffer from the same problems as the CPWC relationships. Models can be readily fitted to experimental data, but the results tend to be site and season specific, due to factors such as successive weed germinations over time, making it impossible to clearly define the time of weed emergence. Parameters in the models can vary between sites and seasons and must be recalculated for each data set. Consequently, although the models can accurately describe a data set, they are not able to accurately predict the impact of weeds on a crop without reparameterization.

Kropff and Spitters (1991) identified the difficulty with this approach and developed a more robust empirical model based on relative leaf area (L_w). This model uses leaf area to effectively integrate a range of crop and weed data including weed density, time of weed emergence and the relative growth rates of crop and weed.

Data from the 2003-04 sunflower density study were used to define the parameters of the crop yield model of Kropff and Spitters (1991) based on relative leaf area. The model gave a good correlation between the observed and predicted crop yield loss (r=0.94) for this data set (Figure 3). However, to achieve this fit, it was necessary to estimate the value of the parameter q for each time of observation, as q varied, generally increasing over time. Consequently, this model was descriptive but not predictive. To enable the model to be used predictively, Kropff and Spitters (1991) developed a relationship for q at time t (q_t), as a function of q at time 0 (q_0) and the relative growth rate of leaf area of the crop and weed. However, to use the relationship requires that both q_0 and the relative growth rates are determined for each site and season. Consequently, this relationship offers little advantage as it still requires that q (q_0) is measured for each site and season, and that the relative growth rate of each weed species is known. Relative growth rate will also vary between sites and seasons and is sensitive to weed density and both inter- and intra-specific competition.

Insert Figure 3 here

To use the relationship in a more predictive way, we related the observed values of q from the 2003-04 sunflower study to day degrees since emergence in a similar approach to that used by Wilson et al. (1995). The form of the relationship was: $q=-a+a*\exp(b*x)$, where a and b were parameters of the equation and x was day degrees (Figure 4a). However, the observed values of q not only varied with time (day degrees), but were also related to weed density, with the a parameter in the equation increasing with increasing weed density. The a parameter was subsequently related to weed density in a simple relationship (Figure 4b), allowing the value of q to be described by these functions.

Insert Figure 4 here

The relationships were combined and observed and predicted yield loss compared for the sunflower study, using the value of q estimated by the relationships and the relative leaf area measured in the experiments. The model gave a good fit to the 2003-04 data (Figure 5a) (r =0.94), but a poorer fit for 2004-05 (Figure 5b) (r=0.88) and the 2005-06 data (Figure 5c) (r=0.71). The relationships were also fitted to the Japanese millet data and gave a reasonable fit to the 2004-05 data (Figure 5d) (r=0.86), but a poor fit to the 2005-06 data (Figure 5e) (r=0.46). The fit of the combined data set was (r=0.83), with a high degree of variation occurring towards the middle of the relationship (between 20% and 80% observed yield loss). To improve these fits required reparameterizing the model for each season, site and weed species. The fit might be improved by incorporating the relationship ($q_t=q_0*\exp(\mathrm{RGRL}_c-\mathrm{RGRL}_w)t$ (Kropff and Spitters,1991), but this approach still requires that the model parameters are determined for each site, season and weed.

Insert Figure 5 here

One of the reasons for the difficulties with this model is that the model is primarily driven by the value of q, and not by the relative leaf area of crop and weeds. Consequently, the model is very sensitive to the value of q, which needs to be re-estimated in each new situation. It is conceivable that in a situation where the crop and weed were of similar size and architecture and equally competitive, the relative leaf area of weed (L_w), may remain relatively constant throughout the life of the crop, giving no information to the model.

This approach using a simple crop and weed model appears to have little value for prescribing weed management decisions in cotton crops, where a complex of weed species is present, with a range of germination times and the model parameters are unknown. Much more sophisticated crop models are now available, but a review by Dean et al. (2003) comparing four sophisticated crop models found that increasing levels of model complexity did not necessarily lead to improvements in model accuracy compared to relatively simple competition models. Given the difficulties these models had in simulating a simple competition scenario with a single weed, it seems unlikely that they are suited to field situations where a complex of weed species is present.

A STATISTICAL MODEL

As an alternative approach, we applied a statistical model to the data from the sunflower and millet studies using regression modelling to determine the crop and weed parameters which were easily measurable and most closely correlated with crop yield loss. Biomass and leaf area index were transformed (natural log and square-root transformations) to normalize their variance. Predicted values that were not meaningful (negative yields losses and yield losses over 100%), were restricted to 0 and 100% yield loss, respectively.

Of the crop parameters measured, crop yield loss was most closely correlated with weed biomass, weed height, weed leaf area index, crop biomass and day degrees at weed removal (*r*=0.84 for the combined data sets). However, biomass was not easily measured in the field. A relationship correlating crop yield loss with weed height, weed leaf area index, crop height and day degrees was adopted as it gave a good fit to the data and was much more easily estimated in the field (*r*=0.81 for the combined data sets) (Figure 6f). The statistically derived model gave a good fit to the sunflower data (*r*=0.93, 0.88 and 0.71 for the 2003-04, 2004-05 and 2005-06 data sets, respectively (Figures 6a, 6b and 6c)), and the 2004-05 Japanese millet data (*r*=0.86, Figure 6d), but a much poorer fit for the 2005-06 Japanese millet data (*r*=0.44, Figure 6e). Relative leaf area, the measure used in the earlier empirical model was poorly correlated with crop yield loss in these data. The statistical model was also relatively insensitive to weed species and season.

Insert Figure 6 here

CONCLUSION

While this model does not fulfil the criteria of Cousens (1985) of being biologically meaningful, it gives a statistically similar fit to the data compared to the empirical model and a visually better fit to the data towards the middle of the relationships between 20% and 80% observed yield loss (compare Figures 5f and 6f). The observed poor fit of relative leaf area and the relatively good fit with plant height and leaf area index suggest that these components should be part of a future empirical model for weed competition in cotton. Future models based of leaf area index and plant height are likely to be more robust and give an improved fit compared to models based solely on weed density or relative leaf area.

Future work in this project will explore the development of crop yield loss models based on leaf area index and plant height, and examine the opportunity for using sensors such as the Greenseeker® sensor (NTech Industries Inc., Ukiah, CA.), to capture data quickly and efficiently. A robust relationship based on the use of electronic sensors to assess weed competition would be invaluable for developing a crop yield loss model and weed management threshold approach which is readily accessible to cotton growers.

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CAPTIONS FOR FIGURES

Figure 1. The critical period for weed control (CPWC) for a large model weed, sunflower, at 1 or 9 weeds m^{-1} of row in irrigated cotton. The logistic equation fitted to the weed removals data was $y=a/(1+b*\exp(c*x)$, where y is the relative yield, and x is crop day degrees. The parameter estimates and r coefficient for 1 sunflower m^{-1} of row were a=1.153, b=0.1179, and c=0.003636, r=0.99, and for 9 sunflowers m^{-1} of row were: a=1.011, b=0.0388, and c=0.006740, r=0.99. The Gompertz equation fitted to the weed addition data was $y=a*\exp(-b*\exp(-c*x)$, where y is the relative yield, and x is crop day degrees. The parameter estimates and r coefficient for 1 sunflower m^{-1} of row were a=0.9913, b=2.797, and c=0.01202, r=0.99, and for 9 sunflowers m^{-1} of row were: a=0.9807, b=7.996, and c=0.008375, r=0.99.

Figure 2. The critical period for weed control for a model grass weed, Japanese millet, at nine or 140 weeds m^{-1} of row in irrigated cotton. The logistic equation fitted to the weed removals data was $y=a/(1+b*\exp(c*x)$, where y is the relative yield, and x is crop day degrees. The parameter estimates and r coefficient for 9 Japanese millet m^{-1} of row were a=0.4864, b=0.5219, and c=-0.001683, r=0.97, and for 140 m^{-1} of row were: a=1.859, b=0.7631, and c=0.002975, r=0.98. The Gompertz equation fitted to the weed addition data was $y=a*\exp(-b*\exp(-c*x)$, where y is the relative yield, and x is crop day degrees. The parameter estimates and r coefficient for 9 Japanese millet m^{-1} of row were a=0.9695, b=0.5429, and c=0.009319, r=0.98, and for 140 m^{-1} of row were: a=0.9706, b=0.2098, and c=0.007911, r=0.99.

Figure 3. Comparison of observed and predicted yield loss from the 2003-04 sunflower study. Yield loss was predicted using the emperical model of Kropff and Spitters (1991) based on relative leaf area. The equation of the model was: Yield Loss=$q*L_w/(1+(q-1)*L_w)$, where q was the relative damage coefficient, estimated from the data, and L_w the relative leaf area of weeds, calculated as $L_w=LAI_w/(LAI_c+LAI_w)$. LAI_w was the leaf area index of weeds and LAI_c, the leaf area index of the crop at the time of observation. The r coefficient for the comparison was 0.94.

Figure 4. Relationship between observed values for parameter q and day degrees since emergence (base 12^0C) for the 2003-04 sunflower study. The fitted curves a) were in the form: $q=-a+a*\exp(b*x)$, where a =0.0009886, 0.001122, 0.001419, 0.001726 and 0.002430 for 1, 2, 4, 8 and16 weeds m^{-1} of row respectively, and b=0.007. The a value of the equations was related to

weed density b) by a logistic curve in the form:*a*=*b*/(1+*c**exp(*d**x*)), where *b*=0.002921, *c*=2.259, *d*=-0.1560, and *x* is weed density (weeds m^{-1} of row).

Figure 5. Relationship between observed values and predicted estimates of yield loss using an emperical model with sunflower as a mimic weed in cotton for the a) 2003-04, b) 2004-05 and c) 2005-06 seasons. The relationships for Japanese millet is also shown for d) 2004-05, and e) 2005-06, and f) the combined data set. The *r* coefficients for the comparisons were 0.94, 0.88, 0.71, 0.86, 0.46 and 0.83, respectively.

Figure 6. Relationship between observed values and predicted estimates of yield loss using a statistically derived model with sunflower as a mimic weed in cotton for a) 2003-04, b) 2004-05 and c) 2005-06 seasons. The relationships for the mimic weed Japanese millet are also shown for d) 2004-05, and e) 2005-06, and f) the combined data set. The model fitted was: Yield loss=0.0297+0.000282*day degrees+0.00119*weed height+0.00161*sqrt(weed leaf area index)+0.00234*crop height. The *r* coefficients for the comparisons were 0.93, 0.88, 0.71, 0.86, 0.44 and 0.81, respectively.

FIGURES

Figure 1.

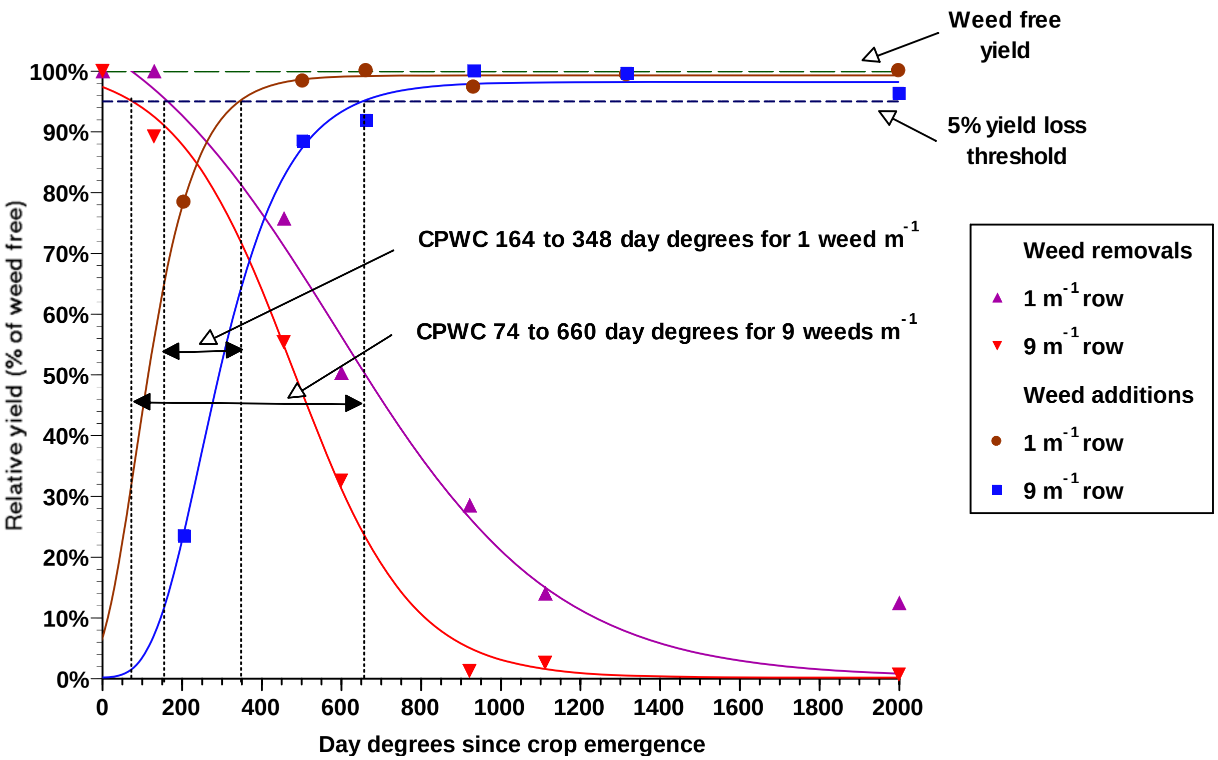


Figure 2.

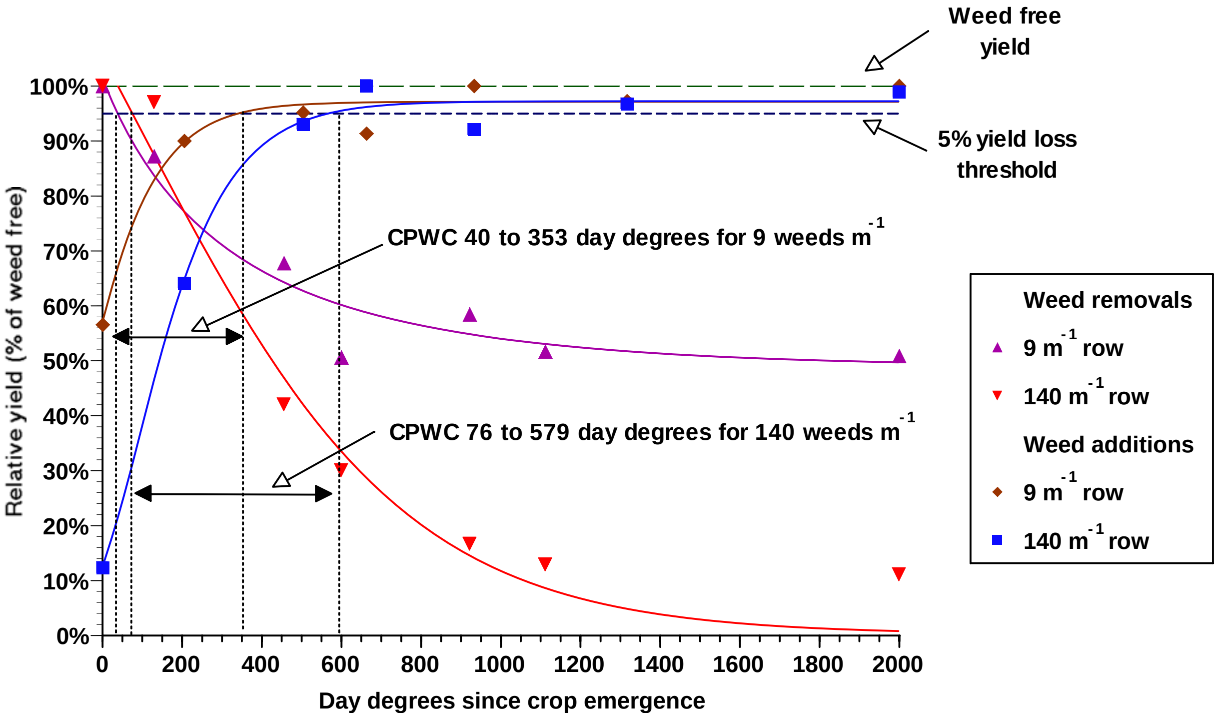

Weed free yield
5% yield loss threshold
CPWC 40 to 353 day degrees for 9 weeds m^{-1}
CPWC 76 to 579 day degrees for 140 weeds m^{-1}
Weed removals
▲ 9 m^{-1} row
▼ 140 m^{-1} row
Weed additions
◆ 9 m^{-1} row
■ 140 m^{-1} row
Relative yield (% of weed free)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Day degrees since crop emergence

Figure 3.

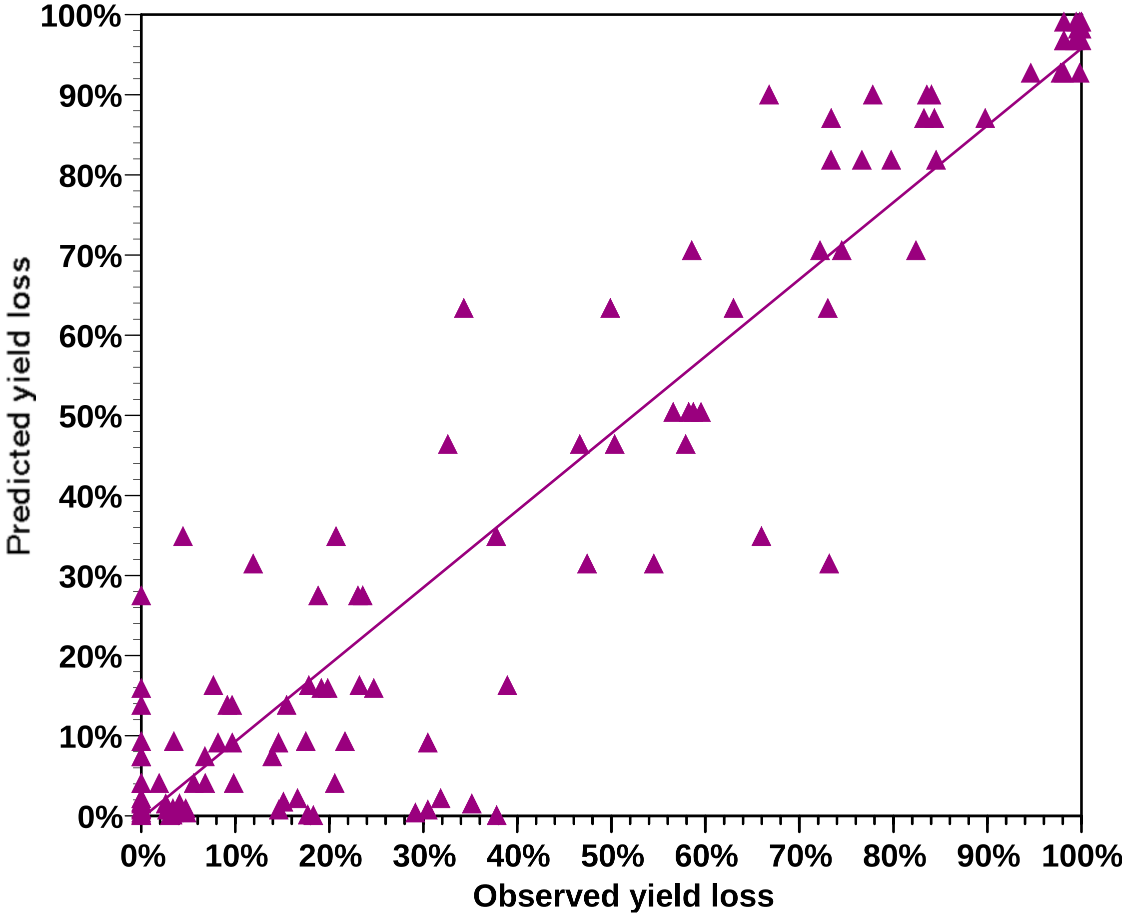

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Predicted yield loss
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Observed yield loss

Figure 4

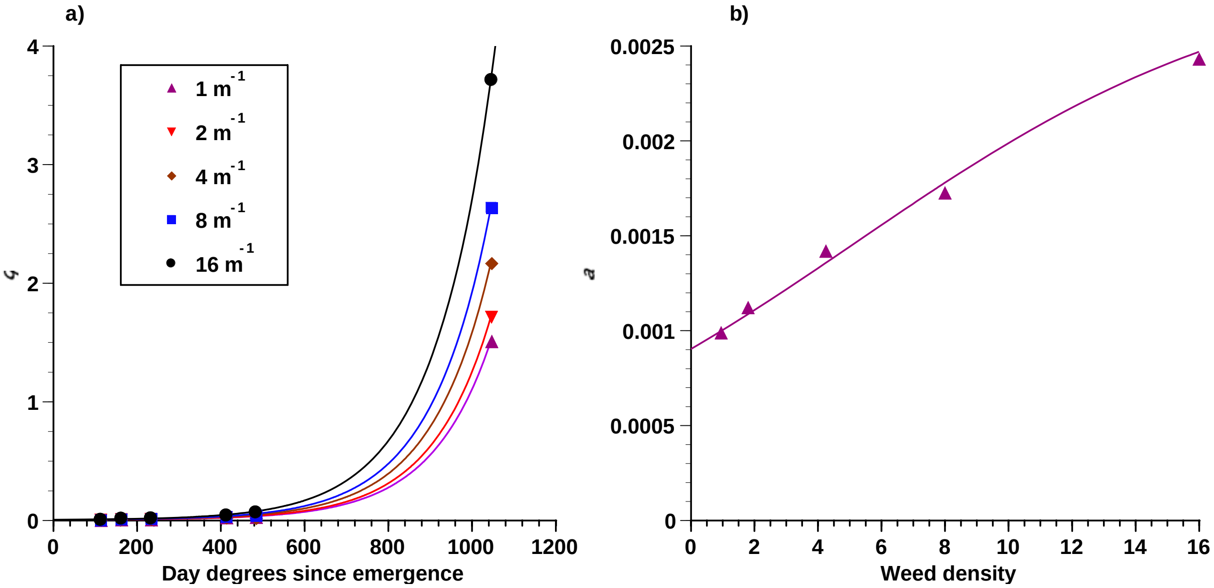

a)
4
3
2
1
0
ς
1 m⁻¹
2 m⁻¹
4 m⁻¹
8 m⁻¹
16 m⁻¹
0
200
400
600
800
1000
1200
Day degrees since emergence
b)
0.0025
0.002
0.0015
0.001
0.0005
0
a
0
2
4
6
8
10
12
14
16
Weed density

Figure 5

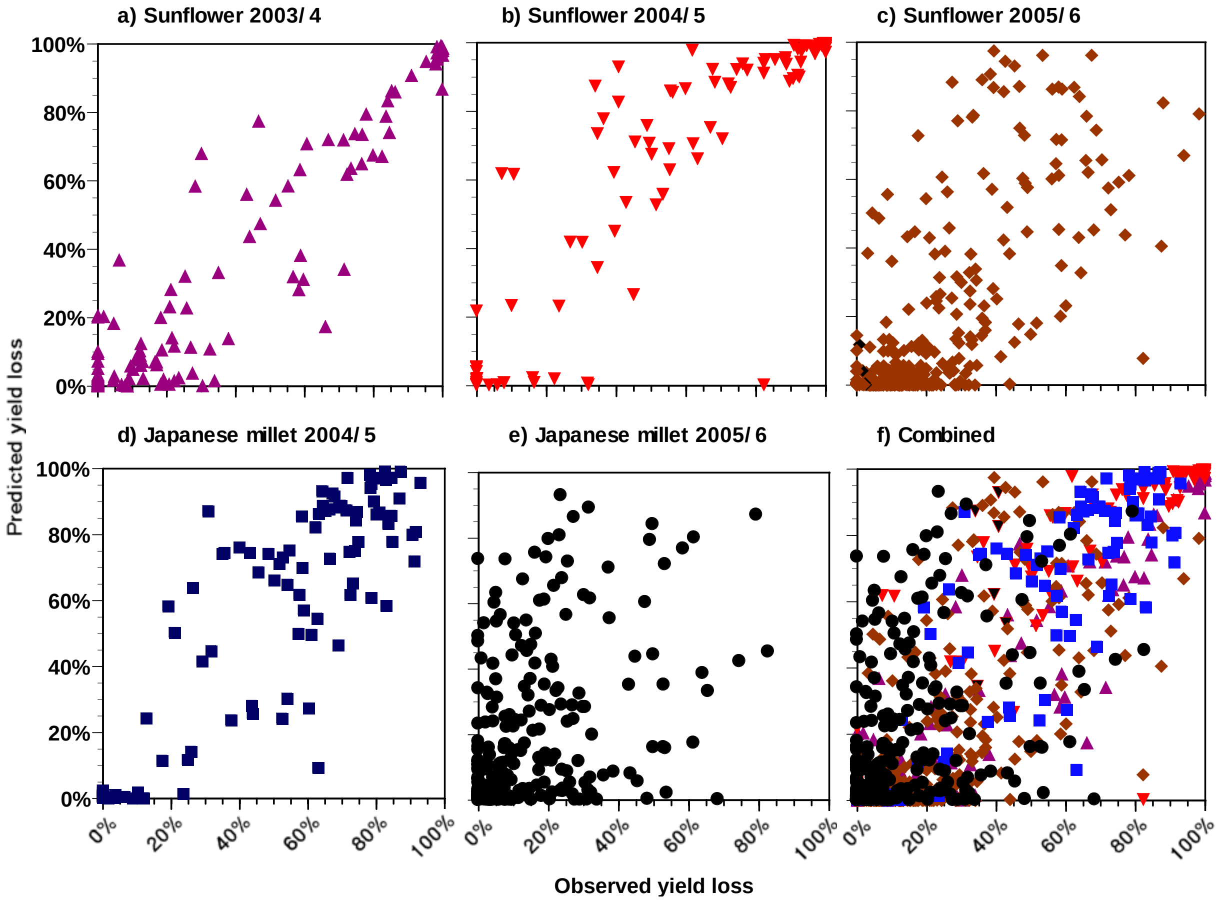
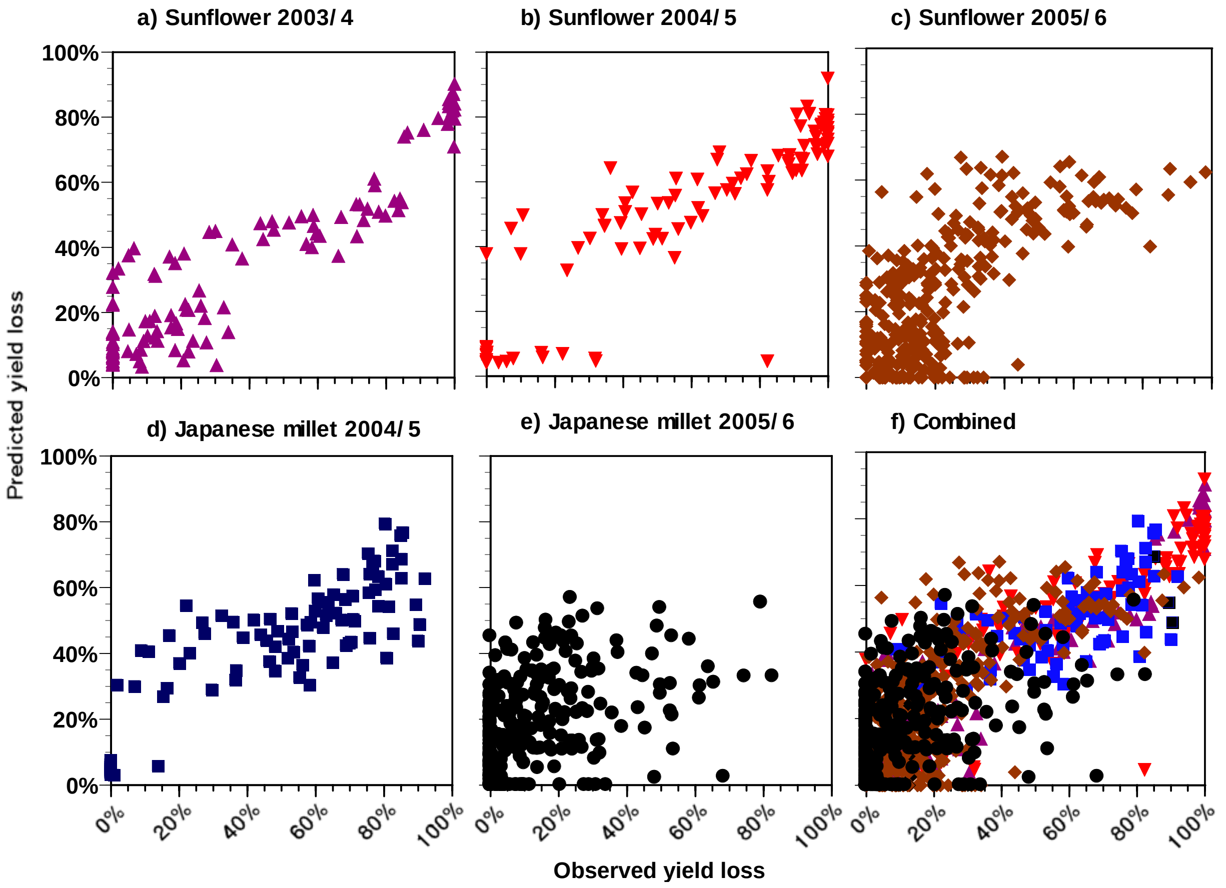

a) Sunflower 2003/ 4
b) Sunflower 2004/ 5
c) Sunflower 2005/ 6
d) Japanese millet 2004/ 5
e) Japanese millet 2005/ 6
f) Combined
Predicted yield loss
Observed yield loss
0%
20%
40%
60%
80%
100%

Figure 6


a) Sunflower 2003/ 4
b) Sunflower 2004/ 5
c) Sunflower 2005/ 6
d) Japanese millet 2004/ 5
e) Japanese millet 2005/ 6
f) Combined
Predicted yield loss
Observed yield loss
0%
20%
40%
60%
80%
100%