Combinatorial Modeling Approaches enable Optimum Uses of Herbicide and N fertilizer for Sustainable Weed Management and Crop Production

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Abstract

A combined model was developed by incorporating the logistic model for herbicide dose-response into the rectangular hyperbola. This combined model enabled to describe the effects of herbicide dose on grain yields of winter wheat and rice for different weed densities under single interference of *Brassica napus*, a model weed, and *Echinochloa crus-galli*, respectively. Incorporation of the multivariate rectangular hyperbola into the combined model also enabled to describe the effects of multiple infestations of *Galium aparine* and *Matricaria perforata* and the herbicide mixture on winter wheat yield and used to estimate the herbicide dose required to restrict crop yield loss caused by weeds to an acceptable level. To describe the complex effects of herbicide and nitrogen on crop-weed competition, a new model was developed by incorporating the inverse quadratic and exponential models into the combined rectangular hyperbola with the standard dose-response curve for winter wheat yield and further modified to estimate the herbicide dose and nitrogen level to achieve a target crop yield.

Media summary

New combined models can support optimum uses of herbicide and nitrogen fertilizer in a real field condition where multiple weed species compete with crop. The models can be used for decision-support software, enabling precise and sustainable weed management in modern crop production.

Keywords

Combinatorial modelling, crop-weed competition, herbicide, nitrogen fertilizer, multiple weeds

Introduction

The prediction of biological phenomena is a key element of decision-making in agricultural practices and allows optimised use of inputs; the right amounts at the right place and time. Various modelling approaches have been made to mathematically describe biological phenomena for specific conditions. However, such a condition is more than one, modelling them becomes complicated. In a real situation, more than one factor is involved, indicating that biological models must be able to include several factors for good description and prediction. The combinatorial approach is a method that combines individual elements to produce a new structure or system which can cover varied conditions. Therefore, combinatorial modelling may be the best approach although this approach has not been widely used for biological model development.
In crop-weed competition, the rectangular hyperbola (Cousens, 1985) has been widely used to describe crop-weed competition in crop yield as influenced by a weed at a range of weed densities. Kim *et al*. (2002, 2006a, 2006b, and 2006c) have developed several models to describe and predict crop-weed competition under complex situations such as herbicide, nitrogen fertilizer and multiple weed interference, by combinatorial methods, i.e. incorporating other existing models into the rectangular hyperbola. In this paper, we report summary of such efforts and recent works applied into rice-weed competition in Korea.

Materials and methods

Model development

In crop-weed competition, the rectangular hyperbola (equation 1) is commonly used to describe the relationship between crop yield (*Y*) and initial weed density (*x*) (Cousens, 1985) for crop grown at a single density.

$$Y = Y_o/(1+\beta x) \tag{1}$$

Here Y_o is the weed-free crop yield and β is the competitivity of the weed (a weed density of $1/\beta$ will reduce the crop yield by 50 %). When herbicide is applied at a range of doses up to its full recommended dose, equation 1 can be modified by incorporating constant Y_o for the weed-free crop yield and Streibig's (1980) standard dose response model for β to give equation (2).

$$Y = \frac{Y_o}{1+\dfrac{\beta_o x}{1+\left(\dfrac{Dose}{CD_{50}}\right)^B}} \tag{2}$$

Here β_o is weed competitivity at no herbicide treatment, CD_{50} is the competitive dose required to reduce weed competitivity by 50%, and *b* is the response rate or steepness of the curve.

When multiple weed species compete with crop and there is no significant interaction between weed species, the rectangular hyperbola for a single weed infestation (equation (1)) can be rewritten to give following multivariate rectangular hyperbola for describing the relationship between crop yield (Y) and initial weed densities of multiple numbers (*n*) of weed species. The general equation for this relationship is

$$Y = \frac{Y_o}{1+\beta_1 x_1+\beta_2 x_2+\beta_3 x_3+.....+\beta_n x_n} \tag{3}$$

where, subscripted numbers are weed species.
If the relationship between the weed competitivity of each weed species and herbicide dose is explained by the standard dose-response curve as the above equation (2), equation (3) can be rewritten as follows

$$Y = \frac{Y_o}{1+\dfrac{\beta_{o1} x_1}{1+\left(\dfrac{Dose}{CD_{50^1}}\right)^{B_1}}+\dfrac{\beta_{o2} x_2}{1+\left(\dfrac{Dose}{CD_{50^2}}\right)^{B_2}}+......+\dfrac{\beta_{on} x_n}{1+\left(\dfrac{Dose}{CD_{50^n}}\right)^{B_n}}} \tag{4}$$

When different levels of nitrogen are applied to the field, the crop-weed competition and the herbicide dose-response of weeds may be changed, possibly resulting in different crop yield. The inverse quadratic curve (Nelder, 1966), which allows for the adverse effects of high nitrogen levels on yield, can be employed to describe the relationship between the weed-free crop yield (Y_o) and nitrogen levels (*N*). Kim *et al*. (2006a) empirically described relationships between the herbicide dose-response and nitrogen level for weed biomass by individually examining parameters of the dose-response model with increasing nitrogen level. Individual investigation of the other parameters β_o, *B* and CD_{50} with nitrogen level revealed that β_o increases exponentially with increasing nitrogen level, while *B* and CD_{50} are constant. As the consequent crop yield loss due to weed interference can be explained by the weed biomass (Brain *et al.* 1999), equation (2) can be modified by incorporating inverse quadratic curve, exponential curve, and constant values for Y_o, β_o, *B* and CD_{50}, respectively, to give equation (5).

$$Y = \frac{\dfrac{a+bN}{1+cN+dN^2}}{1+\dfrac{(lm^N)x}{1+\left(\dfrac{Dose}{CD_{50}}\right)^B}} \tag{5}$$

where *a*, *b*, *c*, *d*, *l* and *m* are unknown parameters.

Field experiments

For the development and confirmation of equation (2), two field experiments were conducted at Long Ashton Research Station (LARS), Bristol, UK in 1996/97 and National Institute of Agricultural Science and

Technology (NIAST), Suwon, Korea in 2007. At LARS, two winter wheat cultivars (*Triticum aestivum* L. cvs. Avalon and Spark) with contrasting competitive abilities were drilled at a density of *ca* 300 plants/m^2 on 10 October 1996, immediately after four different densities of *Brassica napus* L. as a model weed were sown by hand. The target densities of *B. napus* were 0, 25, 50 and 100 plants/m^2. Metsulfuron-methyl (Ally®, DuPont), which has a recommended dose of 6.0 g a.i./ha, was applied at 0.375, 0.75, 1.5, 3.0 and 6.0 g a.i./ha with 250 litres/ha of water using a CO_2-pressurised sprayer on 15 April 1997. Grain yield per 1 m^2 plot was measured on 28 July 1997. The experiment consisted of four replicates in a split-split plot design. At NIAST, rice (*Oryza sativa* L. cv. Ilmi-byeo) seedlings aged 30 days old were transplanted on 25 May 2007 and *Echinochloa crus-galli* grown at 1 leaf stage was transplanted at densities of 0, 1, 8, 24, 48, 96 plants/m^2. Flucetosulfuron (Fluxo®, LG Life Science Ltd.), which has a recommended dose of 21 g a.i./ha, was applied directly to the flooded soil at 1.3125, 2.625, 5.25, 10.5, 21 g a.i./ha by hand. Grain yield per 1 m^2 was measured on 15 October 2007. The experiment consisted of three replicates in a split-split plot design.

For the confirmation of equation (3), a field experiment was conducted at NIAST. After covering the puddled paddy field with paper mulch to prohibit volunteer weed establishment, rice (*Oryza sativa* L. cv. Ilmi-byeo) seedlings aged 30 days old were transplanted on 25 May 2007. Five common paddy weed seedings, *E. crus-galli*, *Eleocharis kuroguwai*, *Scirpus juncoides*, *Ludwigia prostrata*, and *Aeschynomen indica*, were transplanted in 100 weed density combinations. Grain yield per 1 m^2 was measured on 15 October 2007. The experiment consisted of single replicate in a completely randomized design. For the development of equation (4), a field experiment was conducted at LARS in 1997/98. Winter wheat cultivar, Avalon, was drilled at a density of approximately 300 plants m^{-2} on 4 October 1997. Prior to drilling the winter wheat, two weed species, *Galium aparine* L. and *Matricaria perforata* Merát, were sown singly and in mixture by hand on 3 October, and thinned to the target weed density combinations in February 1998. The total weed density combination was 25 consisting of 5 densities (0, 5, 10, 20 and 40 plants m^{-2}) of *G. aparine* × 5 densities (0, 30, 60, 120 and 240 plants m^{-2}) of *M. perforata* at each herbicide dose. Metsulfuron-methyl and fluroxypyr (Starane II®, DowElanco, UK), which has a recommended dose of 200 g a.i.ha^{-1}, were tank-mixed and applied at × 1/16, × 1/8, × 1/4, × 1/2, × 1/1 of the full recommended dose of the herbicide mixture, 6 g a.i.ha^{-1} and 200 g a.i.ha^{-1} of metsulfuron-methyl and fluroxypyr, respectively, on 18 March 1998. Grain yield was measured on 28 July 1998. The experiment consisted of a single replicate of a split plot design with 6 doses of herbicide (metsulfuron + fluroxypyr) (including no-herbicide treatment) as the main plot. The main plots were split with 25 weed density combinations as subplots.

To investigate the effects of nitrogen and herbicide on crop-weed competition and to develop equation (5), an experiment was carried out in a plunge bed, containing silty clay soil 50 cm in depth, at LARS in 1998/99. Winter wheat, cv. Avalon, was sown in rows (14 cm between rows) by hand at approximately 350 plants m^{-2} on 22 October 1998. A model weed, *Brassica napus* L. (oilseed rape cv. Apex), was sown by hand followed by raking to cover the seed with soil on 26 October 1998. *Brassica napus* was then thinned to the target densities, 0, 25, 50 and 100 plants m^{-2} on 12 February 1999. Metsulfuron-methyl (Ally®) was applied at 0.5, 1.0, 2.0 and 6.0 g a.i. ha^{-1} on 7 April 1999, when the wheat was at growth stage 30 and *B. napus* at 22~23 (Zadoks *et al*., 1974). Assessment was conducted on 17 June 1999, 10 weeks after herbicide application. Winter wheat was harvested from an area of 0.25 m^2 and dried at 95 °C for 24 hours for biomass determination. The experiment consisted of a single replicate of a split-split plot design.

Results

Weed competitivity (β) decreased with increasing herbicide dose, and the response of weed competitivity to metsulfuron-methyl was well explained by the standard dose-response curve (Figure 1), confirming that the rectangular hyperbolic model and the dose response model can be combined to give equation (2).

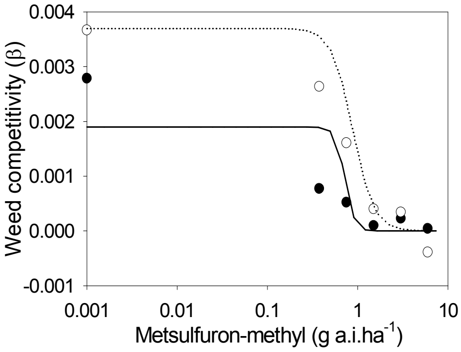

Figure 1. The relationship between weed competititivities (β) and metsulfuron-methyl for Avalon (●) and Spark (○). Weed competitivities were obtained from separate analysis of grain yield by fitting equation (1) at each dose of metsulfuron-methyl. The continuous lines are fitted lines calculated using equation the standard dose-response model.

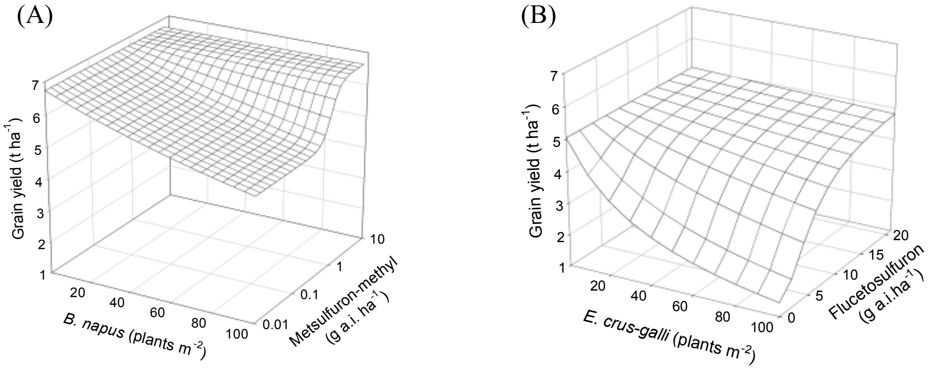

Figure 2. Predicted grain yield of winter wheat cv. Avalon (A) and rice cv. Ilmi-byeo (B) as affected by competition and sub-lethal doses of metsulfuron-methyl, using equation (2) and the parameter estimates.

Regarding crop yield as affected by weed infestation and herbicide application, equation (2) and estimated parameters (Kim *et al*., 2002) successfully simulated grain yields of winter wheat cultivar, Spark (Figure 2A). Rice grain yield as affected by *E. crus-galli* infestation and flucetosulfuron at a range of doses was also well described by equation (2) (Figure 2B).

For herbicide dose decision-making equation (2) was also applied to determine herbicide application dose. If a threshold of acceptable percentage yield loss is denoted by *p* %, equation (2) can be rearranged to give the dose, D_p, required to reduce the yield loss to less than *p* % (equation (6)).

$$D_p = CD_{50}\left(\frac{(100-p)\beta_o x_o}{p} - 1\right)^{\frac{1}{b}} \tag{6}$$

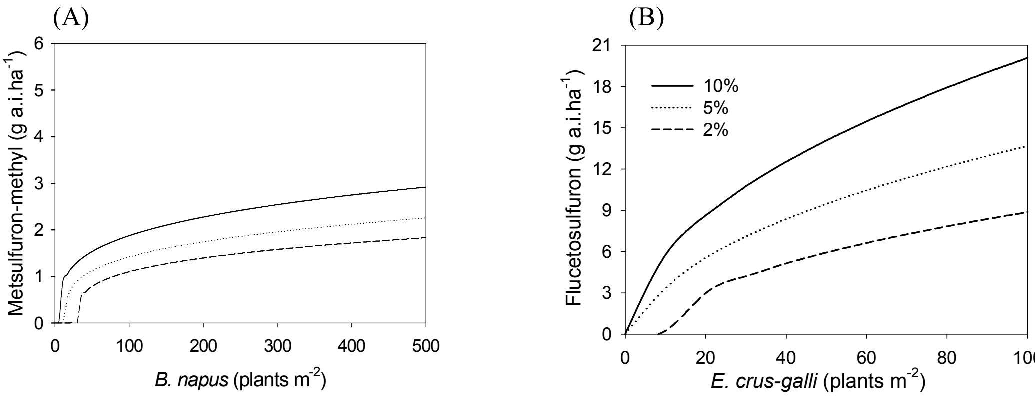

Figure 3. Estimated metsulfuron-methyl and flucetosulfuron doses (D_p) to restrict grain yield losses of winter wheat (A) and rice (B) to less than *p*% for a range of weed densities.

As an example of its use, if an acceptable yield loss is 5%, and *B. napus* density is 100 plants m^{-2}, a metsulfuron-methyl dose of 2.0 g a.i. ha^{-1} will still provide effective control (Figure 3A). The estimated metsulfuron-methyl dose of 2.0 g a.i.ha^{-1} is 1/3 of its full recommended dose. In case of rice infested with *E. crus-galli* at 100 plants m^{-2}, a flucetosulfuron dose of about 14 g a.i.ha^{-1} is required, which is 2/3 of its full recommended dose. These results indicate that the combined model (equation (2)) can support optimum herbicide use.

When multiple weed species comprising 5 weed species, *E. crus-galli*, *E. kuroguwai*, *S. juncoides*, *L. prostrata*, and *A. indica* were infested in rice field, rice grain yield was predicted based on equivalent density, relative competitivities of the weeds to *E. crus-galli* calculated in previous studies conducted in 2003-2006 (data not shown), and compared with fitted observed yield data in 2007 (Figure 4A). There was no significant difference between predicted yield from equation (3) and fitted observed yield to equation (3), indicating that multivariate rectangular hyperbola without interaction parameter is sufficient enough for describing competition between crop and multiple weed species. To exemplify equation (4), grain yield of winter wheat grown in competition with *G. aparine* and *M. perforata* in 25 density combinations was estimated when applied with metsulfuron-methyl and fluroxypyr mixture at a range of doses (Kim *et al.*, 2006b). Equation (4) well predicted decreased grain yield decreases with increasing weed density as a function of rectangular hyperbola and increased grain yield with increasing herbicide dose as a function of the standard dose-response model (Figure 4B). These results indicate that if we know weed competitivity (parameter β) and herbicide sensitivity, i.e. parameters LD_{50} and B for its dose-response to herbicide, crop yield can be easily predicted regardless of number of weed species infested.

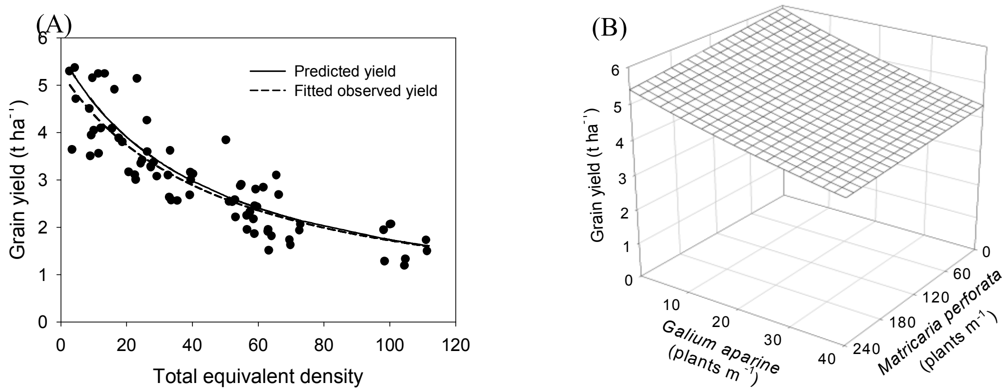

Figure 4. Predicted and observed rice grain yield as influenced by multiple weed infestation comprising 5 weed species, *E. crus-galli*, *E. kuroguwai*, *S. juncoides*, *L. prostrata*, and *A. indica*, (A) and predicted winter wheat yield as influenced by *G. aparine* and *M. perforata* at x 1/4 dose rate of metsulfuron-methyl and fluroxypyr mixture (B).

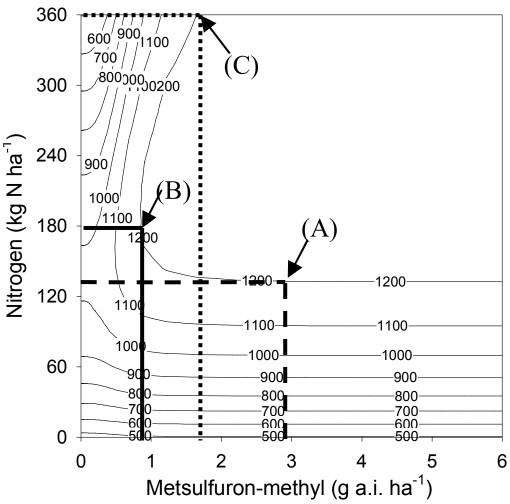

Figure 5. Target biomass yields of winter wheat that can be achieved by the combination of herbicide and nitrogen with a 100 *B. napus* plants m^{-2} infestation. Each isocline represents the target yield. The points A, B, and C indicate 140 N kg + 2.9 g, 180 N kg + 0.9 g, and 360 N kg ha^{-1} + 1.7 g a.i. ha^{-1} of nitrogen and metsulfuron-methyl combinations, respectively, required to achieve the target biomass yield of 1200 g m^{-2}.

When a range of metsulfuron-methyl doses and nitrogen fertiliser levels were applied to winter wheat grown in competition with *B. napus* at a range of densities, biomass yield of winter wheat increased with increasing nitrogen, and this increase was successfully described by the inverse quadratic model (Kim *et al.* 2006c). Increases in weed competitivity (β) of the rectangular hyperbola with increasing nitrogen was also successfully described by the exponential model, while the other parameters were constant regardless of nitrogen fertilizer. Equation (5) comprising inverse quadratic and exponential models for Y_o and β, respectively, incorporated into the combined rectangular hyperbola with the standard dose-response curve well described the complex effects of herbicide and nitrogen on crop-weed competition. Equation (5) was used to predict crop yield to estimate the herbicide doses required to restrict crop yield loss caused by weeds to an acceptable level at a range of nitrogen levels. The model for crop yield was further modified to estimate the herbicide dose and nitrogen level to achieve a target crop biomass yield. For the target crop biomass yield of 1200 g m^{-2} with an infestation of 100 *B. napus* plants m^{-2}, the model recommended various options for nitrogen and herbicide combinations; 140 and 2.9, 180 and 0.9, and 360 kg ha^{-1} and 1.7 g a.i. ha^{-1} of nitrogen and metsulfuron-methyl, respectively (Figure 5).

Conclusion

Our combinatorial approaches incorporated the effects of other factors into the rectangular hyperbola. These new models successfully simulated crop yield as affected by multiple weed interference, herbicide dose, and nitrogen fertilizer. Our models can be easily rearranged to aid decision-making in herbicide dose and nitrogen level. Based on models developed in our studies, effects of herbicide dose and nitrogen fertilizer level on grain yield of crop infested with multiple weed species in a field condition can be simulated using equation (7) we propose here. Equation (7) will be validated with further studies.

$$Y = \frac{\dfrac{a+bN}{1+cN+dN^2}}{1+\dfrac{l_1 m_1{}^N x_1}{1+\left(\dfrac{Dose}{CD_{50}{}^1}\right)^{B_1}}+\dfrac{l_2 m_2{}^N x_2}{1+\left(\dfrac{Dose}{CD_{50}{}^2}\right)^{B_2}}+\ldots\ldots+\dfrac{l_n m_n{}^N x_n}{1+\left(\dfrac{Dose}{CD_{50}{}^n}\right)^{B_n}}} \qquad (7)$$

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