Modelling the effects of sub-lethal doses of herbicide and nitrogen fertilizer on crop–weed competition

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Summary

The effects of sub-lethal dose of herbicide and nitrogen fertilizer on crop–weed competition were investigated. Biomass increases of winter wheat and a model weed, *Brassica napus*, at no-herbicide treatment with increasing nitrogen were successfully described by the inverse quadratic model and the linear model respectively. Increases in weed competitivity (β_0) of the rectangular hyperbola and parameter B in the dose–response curve for weed biomass, with increasing nitrogen were also successfully described by the exponential model. New models were developed by incorporating inverse quadratic and exponential models into the combined rectangular hyperbola with the standard dose–response curve for winter wheat biomass yield and the combined standard dose—response model with the rectangular hyperbola for weed biomass, to describe the complex effects of herbicide and nitrogen on crop–weed competition. The models developed were used to predict crop yield and weed biomass and to estimate the herbicide doses required to restrict crop yield loss caused by weeds and weed biomass production 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.

Keywords: crop–weed competition, modelling, herbicide dose, nitrogen fertilizer, dose–response, inverse quadratic model, winter wheat.

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Introduction

Nitrogen is a key element for plant growth and development. Plants take up nitrogen mainly as nitrate (NO_3^-) under normal conditions and ammonia (NH_3) under certain conditions, such as when growing in acid or waterlogged soils where nitrification by microorganism is inhibited (Rice & Pancholy, 1972). Availability of nitrogen for crop plants is an important limiting factor in agricultural production. In the absence of weeds and disease, increased application of nitrogen fertilizer generally increases crop yield. With heavy dependence on inorganic nitrogen fertilizer, farmers now use less organic fertilizer. Excessive use of inorganic nitrogen has been blamed for the nitrate pollution of water. Agriculture is the main source of nitrate pollution in EU countries, normally accounting for over 60% of total nitrate loss to water (Tunney, 1992). The reform of the Common Agricultural Policy (CAP) recommends reduction of agrochemical inputs (e.g. Lowe & Whitby, 1997). Regulations for protecting water from nitrate pollution from agriculture have encouraged farmers to use less inorganic nitrogen fertilizer.

Many efforts have also been made to reduce the use of herbicide by investigating the interactions between reduced doses of herbicide and crop–weed competition in cereal crops, such as spring barley (e.g. Christensen, 1994), winter wheat (Brain *et al.*, 1999; Kim *et al.*, 2002)

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and spring wheat (e.g. Salonen, 1992). Christensen (1994) showed a significant interaction between the competitive ability of varieties and herbicide performance and suggested a potential reduction of herbicide use with more competitive crop varieties. To explain interactions between herbicide dose and crop–weed competition, Brain *et al.* (1999) and Kim *et al.* (2002) developed models by combining the rectangular hyperbola (Cousens, 1985) and the standard dose–response model (Streibig, 1980), based on weed biomass and weed competitivity respectively. These approaches suggest that decisions for herbicide dose should consider the nature of crop–weed competition. However, if such reduced herbicide doses are applied in combination with the reduction of nitrogen fertilizer in crop fields, the interactions between nitrogen fertilizer and herbicide dose in crop–weed competition may lead to unexpected consequences. As Richards (1993) highlighted, the combination of reduced rates of herbicide and nitrogen may lead to failure in weed control, with a potential risk of economic loss resulting from the failure in weed control and subsequent lower crop yields. To avoid such failure and consequent economic loss, it is essential to understand the interactions between herbicide dose–response and nitrogen when crop and weed compete and to quantify these interactions in terms of crop yield or weed seed production.

To achieve successful weed management and economically acceptable crop yield with environmental advantages, more intelligent decision making for weed control is required. This needs to consider the interaction between sub-lethal doses of herbicide and nitrogen on crop–weed competition. The implementation of the combined models developed by Kim *et al.* (2002, 2006a) was most likely to satisfy this requirement. Therefore, this study was conducted to examine the relationships between crop–weed competition and nitrogen and between herbicide dose–response and nitrogen, so that they can be incorporated into new combined models (Kim *et al.*, 2002) and to predict crop yield and weed biomass production. The objective of this article is the development of an empirical model of crop yield and weed biomass that incorporates the dose-responses of herbicides and nitrogen application. In order to parameterize the model, the effects of a range of nitrogen and herbicide doses were tested on a model weed at different densities in winter wheat.

Materials and methods

Plunge bed experiment

To investigate the effects of nitrogen and herbicide on crop–weed competition, an experiment was carried out in a plunge bed, containing silty clay soil 50 cm in depth, at Long Ashton Research Station, UK. The experiment consisted of a single replicate of a split–split plot design. Five nitrogen levels (including no nitrogen) were the main plot treatments. Each main plot was 5 m × 8.5 m with a 1.0 m buffer zone between them. These main plots were split for five herbicide doses (including no-herbicide), each split plot being 5 m × 1.7 m. The split plots were further split for four weed densities (including zero), each split–split plot being 1.2 m × 1.7 m.

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. Background weeds, which had established naturally, were removed by hand in February 1999. To avoid soil compaction and the disturbance of experimental plots, weeding was conducted on a metal plank suspended above the bed and running on two trolleys at either side of the bed.

Prior to planting, five replicate samples of the soil were analysed on 20 October 1998 to measure chemical properties of the soil. The soil had a pH of 6.5, organic matter of 4.1% and total available nitrogen of 75 kg ha^{-1}. The level of exchangeable phosphorous was 52 mg kg^{-1}, potassium 136 mg kg^{-1} and magnesium 155 mg kg^{-1}. Four levels of nitrogen, 45, 90, 180 and 360 kg ha^{-1}, in the form of ammonium nitrate (NH_4NO_3) were applied evenly onto the soil surface by hand; 50% was applied on 17 March 1999 and 50% on 10 May 1999. Soil was sampled from the weed-free plot after nitrogen application to measure soil nitrogen content (nitrate only), as described by Keeney and Nelson (1982). Soil nitrate content on 26 March 1999 was 1.8, 4.4, 8.6, 14.7 and 36.6 ppm in the plots of 0, 45, 90, 180, 360 kg N ha^{-1} respectively.

Metsulfuron-methyl (Ally®, DuPont UK Ltd, Stevenage, UK) 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). Application was made using an Oxford Precision Sprayer (E.D.M. Engineering, UK) with a 3 m boom adjusted to spray only 1.7 m wide by locking nozzles and with two windscreens at each side to avoid herbicide drift to other plots. The sprayer was fitted with LP015F110 flat fan spray nozzles (Spraying System, USA) and operated at a pressure of approximately 210 kPa and a volume rate of 190–200 L ha^{-1}.

Assessment was conducted on 17 June 1999, 10 weeks after herbicide application. Winter wheat and *B. napus* were harvested from an area of 0.25 m^2 and dried at 95°C for 24 h for biomass determination.

Model development

Crop biomass yield

To explain the relationship between the effects of weed competition and sub-lethal doses of herbicide on crop yield (Y), Brain *et al.* (1999) developed a new model by combining the hyperbolic model (Cousens, 1985) and the standard dose–response model (Streibig, 1980). Kim *et al.* (2002) modified the model on the basis of weed density (x) rather than weed biomass in Brain *et al.*'s (1999) model.

$$Y = \frac{Y_0}{1 + \frac{\beta_0 x}{1 + \left(\frac{Dose}{CD_{50}}\right)^B}} \tag{1}$$

where Y_0 is the weed-free crop biomass yield, β_0 is weed competitivity (a weed density of $1/\beta_0$ will reduce the crop yield by 50%) at no-herbicide treatment, CD_{50} is the competitive dose required to reduce weed competitivity by 50% (previously described as e^{LD50} by Kim *et al.* (2002), and B is the response rate or steepness of the curve.

The approach of combining two sub-models into one model enabled the prediction of crop yield as affected by crop–weed competition and herbicide treatment simultaneously (Brain *et al.*, 1999; Kim *et al.*, 2002). 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. Kim *et al.* (2006b)) 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. Prior to applying the combined model in this study, it was necessary to investigate the changes of each parameter with increasing nitrogen level (i). Equation 1 was thus rewritten to Eqn 2 with different parameters at different nitrogen level (i):

$$Y_i = \frac{Y_{0i}}{1 + \frac{\beta_{0i} x}{1 + \left(\frac{Dose}{CD_{50i}}\right)^{B_i}}} \tag{2}$$

The inverse quadratic curve (Nelder, 1966) (which allows for the adverse effects of high nitrogen levels on yield) was employed to investigate the relationship between the weed-free wheat biomass (Y_0) and nitrogen (i). The inverse quadratic model replaced the weed-free wheat biomass (Y_0) in Eqn 2 as follows:

$$Y_i = \frac{\frac{a+bN}{1+cN+dN^2}}{1 + \frac{\beta_{0i} x}{1 + \left(\frac{Dose}{CD_{50i}}\right)^{B_i}}} \tag{3}$$

where a, b, c and d are unknown parameters.

In Eqn 3, parameters β_{0i}, B_i and CD_{50i} were further modified. Kim *et al.* (2006b)) revealed that parameters B and CD_{50} for the dose–response of *B. napus* to metsulfuron-methyl were constant. The consequent crop yield loss because of weed interference can be explained by the weed biomass (Brain *et al.*, 1999). Therefore, it was initially proposed that the parameters B and CD_{50} were constant regardless of nitrogen levels.

It was hypothesized that the weed competitivity (β_0) may change with increasing nitrogen level, corresponding to increased weed biomass but also to crop competitivity, which may also change and affect the extent of the weed competitivity. Parameter β at no-herbicide treatment may be determined as a function of the relative competitivity of crop to weed or *vice versa*. It was assumed that parameter β_0 may change with increasing nitrogen either as an exponential curve or a straight line, or may remain constant.

Weed biomass

The combined model developed by Kim *et al.* (2002) described the biomass of *B. napus* as affected by herbicide dose and weed density (x). Therefore, this model was selected as a starting model.

$$W = \frac{Cx}{\left(1 + \left(\frac{Dose}{ED_{50}}\right)^B\right)(1 + Ax)} \tag{4}$$

where W represents the weed biomass, C represents the biomass of an individual weed plant without inter-specific competition and herbicide treatment, ED_{50} is the effective dose required to reduce weed biomass by 50% (previously described as e^{LD50} by Kim *et al.* (2002), B is the response rate or steepness of the curve, and A is a measure of intra-specific competition of the weed.

If different levels of nitrogen fertilizer are applied, parameters for Eqn 4 need to be estimated at each nitrogen level (i). Equation 4 thus can be rewritten as follows:

$$W_i = \frac{C_i x}{\left(1 + \left(\frac{Dose}{ED_{50i}}\right)^{B_i}\right)(1 + A_i x)} \tag{5}$$

A linear model was used, following Kim *et al.* (2006b)), to describe the relationship between the biomass of a single plant grown at a range of nitrogen levels without herbicide treatment and inter-specific competition. The linear model replaced the individual weed biomass (C_i) at no-herbicide treatment in Eqn 5 as follows:

$$W_i = \frac{(a + bN)x}{\left(1 + \left(\frac{Dose}{ED_{50i}}\right)^{B_i}\right)(1 + A_i x)} \tag{6}$$

where a, b, c and d are unknown parameters.

In Eqn 6, parameters A, B and ED_{50} were further modified. Models (logistic curve, exponential curve, straight line and the constant) were tested to select the best descriptive model for each parameter change with increasing nitrogen level.

Statistical analysis

As this experiment consisted of a single replicate, an estimate of the variability of the results was obtained from non-linear regression analysis. A variance-stabilizing transformation with the natural $\log_e$ was used for weed biomass. Non-linear regression was used to fit various components of the models, using the transform-both-sides techniques (Rudemo *et al.*, 1989) for weed biomass. Each model in the sequence was compared with its predecessor by calculating the F-value as follows:

$$F = \left(\frac{RSS_{i+1} - RSS_i}{df_{i+1} - df_i}\right) \bigg/ \left(\frac{RSS_f}{df_f}\right) \qquad (7)$$

where RSS and df represent the residual sum of square and the degree of freedom, respectively, $i + 1$ represents the reduced model from its predecessor (i) and f represents the full model (the most complex model; Eqn 2 for crop yield and Eqn 5 for weed biomass). If the F-value was lower than the tabulated F-value (5% level) with (df_{i+1}–df_i,df_f) degrees of freedom, the reduced model could be accepted. All statistical analyses were carried out using Genstat (Genstat Committee, 1993)

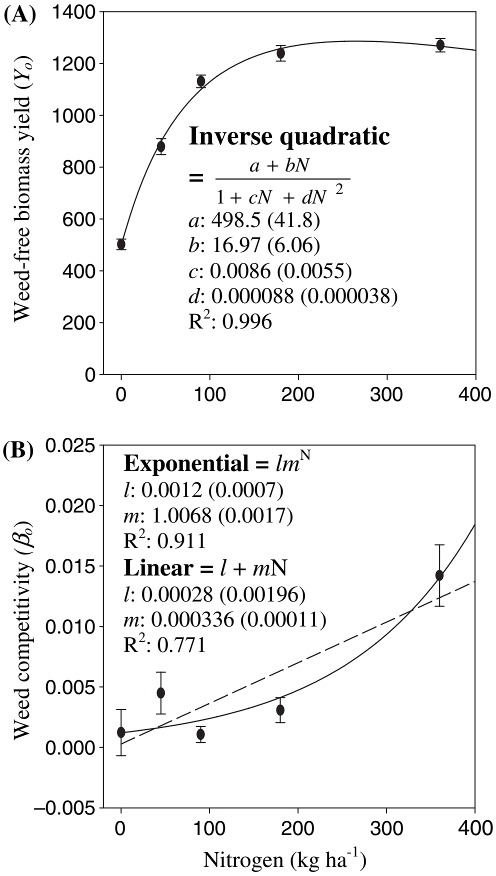


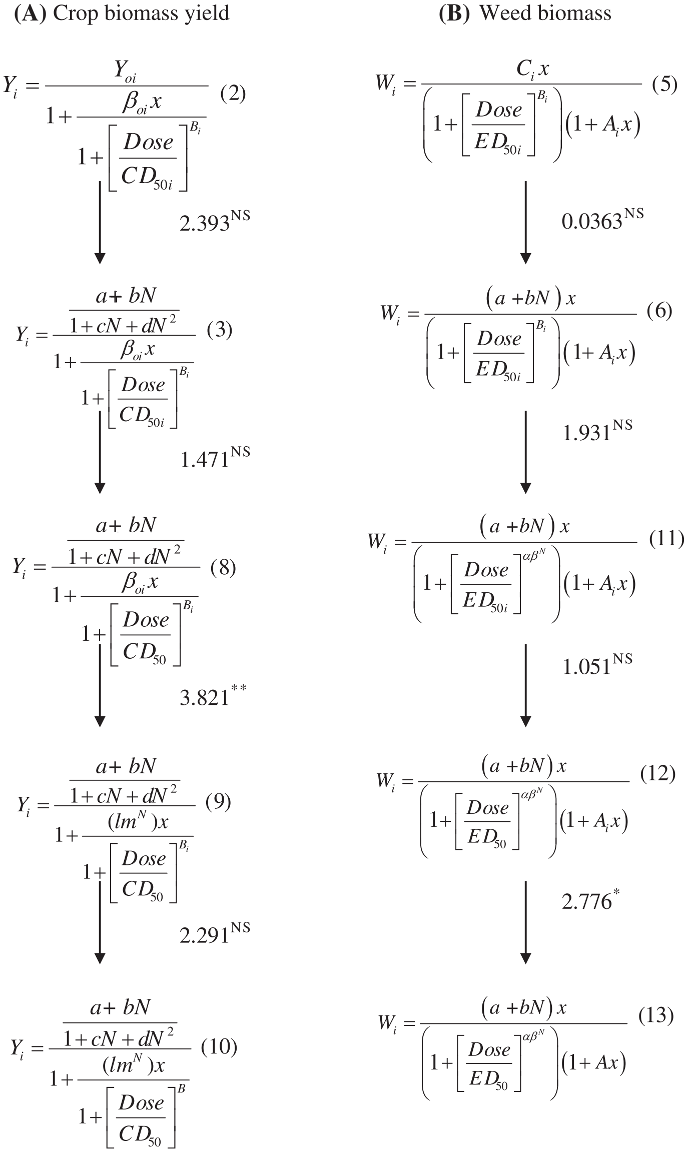
Fig. 1 Changes of the weed-free biomass yield (Y_0, g m^{-2}) of winter wheat (A) and the weed competitivity (β_0) of *Brassica napus* at no-herbicide treatment (B) with increasing nitrogen. The vertical bars are the SE of the each parameter estimates at each nitrogen level, obtained by fitting Eqn 2. The continuous lines are fitted lines by using the inverse quadratic model (—-) for the weed-free biomass yield (Y_0) and linear (- - - -) and exponential (—-) models for the weed competitivity (β_0).

Results

Modelling crop biomass yield as affected by weed interference, herbicide dose and nitrogen fertilizer

Winter wheat biomass data on 17 June 1999 were subjected to non-linear regression analysis by fitting Eqn 2 to obtain the parameter estimates for the combined model at each nitrogen level. In order to examine the behaviour of each parameter with increasing nitrogen, parameter estimates were then plotted against nitrogen (Fig. 1). Weed-free biomass yield (Y_0) increased with increasing nitrogen, with the increase in Y_0 at every increase of nitrogen consecutively diminished until finally there was no increase as nitrogen increased from 180 to 360 kg N ha^{-1} (Fig. 1A). The inverse quadratic model provided a good description of the relationship between Y_0 and nitrogen ($R^2 = 0.996$). Weed competitivity (β_0) at no-herbicide treatment showed little change up to 180 kg N ha^{-1}, but thereafter increased (Fig. 1B). The trend of increase in β_0 was modelled by the exponential and linear models. The regression analyses suggested that the exponential model is better than the linear model, as it fitted with a smaller residual mean square value (3.53×10^{-6}), as compared with that of the linear model (9.04×10^{-6}). Conversely, both the CD_{50} and parameter B values had very large standard errors and showed no clear trends with increasing nitrogen (data not shown), so that they were likely to be constant rather than having a specific trend with increasing nitrogen. It was therefore assumed that the inverse quadratic and exponential models could be used to describe the relationships between weed-free yield (Y_0) and nitrogen, and between weed competitivity (β_0) at no-herbicide treatment and nitrogen, respectively, whereas the CD_{50} and parameter B were assumed to be constant.

Based on the above assumptions, equations were fitted sequentially and F-values were summarized in Fig. 2A. When Eqns 2 (Full model) and 3 were fitted, there was no evidence that Eqn 3 fitted less well than



$$Y_i = \frac{Y_{oi}}{1+\dfrac{\beta_{oi}x}{1+\left[\dfrac{Dose}{CD_{50i}}\right]^{B_i}}} \quad (2)$$

$$\Big\downarrow \; 2.393^{NS}$$

$$Y_i = \frac{\dfrac{a+bN}{1+cN+dN^2}}{1+\dfrac{\beta_{oi}x}{1+\left[\dfrac{Dose}{CD_{50i}}\right]^{B_i}}} \quad (3)$$

$$\Big\downarrow \; 1.471^{NS}$$

$$Y_i = \frac{\dfrac{a+bN}{1+cN+dN^2}}{1+\dfrac{\beta_{oi}x}{1+\left[\dfrac{Dose}{CD_{50}}\right]^{B_i}}} \quad (8)$$

$$\Big\downarrow \; 3.821^{**}$$

$$Y_i = \frac{\dfrac{a+bN}{1+cN+dN^2}}{1+\dfrac{(lm^N)x}{1+\left[\dfrac{Dose}{CD_{50}}\right]^{B_i}}} \quad (9)$$

$$\Big\downarrow \; 2.291^{NS}$$

$$Y_i = \frac{\dfrac{a+bN}{1+cN+dN^2}}{1+\dfrac{(lm^N)x}{1+\left[\dfrac{Dose}{CD_{50}}\right]^{B}}} \quad (10)$$

$$W_i = \frac{C_i x}{\left(1+\left[\dfrac{Dose}{ED_{50i}}\right]^{B_i}\right)(1+A_i x)} \quad (5)$$

$$\Big\downarrow \; 0.0363^{NS}$$

$$W_i = \frac{(a+bN)x}{\left(1+\left[\dfrac{Dose}{ED_{50i}}\right]^{B_i}\right)(1+A_i x)} \quad (6)$$

$$\Big\downarrow \; 1.931^{NS}$$

$$W_i = \frac{(a+bN)x}{\left(1+\left[\dfrac{Dose}{ED_{50i}}\right]^{\alpha\beta^N}\right)(1+A_i x)} \quad (11)$$

$$\Big\downarrow \; 1.051^{NS}$$

$$W_i = \frac{(a+bN)x}{\left(1+\left[\dfrac{Dose}{ED_{50}}\right]^{\alpha\beta^N}\right)(1+A_i x)} \quad (12)$$

$$\Big\downarrow \; 2.776^{*}$$

$$W_i = \frac{(a+bN)x}{\left(1+\left[\dfrac{Dose}{ED_{50}}\right]^{\alpha\beta^N}\right)(1+Ax)} \quad (13)$$

Fig. 2 Model trees for the biomass yield of winter wheat (A) and weed biomass (B) as affected by weed density, herbicide dose and nitrogen level. The values presented are the *F*-values.

Eqn 2, indicating that the weed-free biomass yields (Y_0) at different nitrogen levels were well described by the inverse quadratic model incorporated into Eqn 2 by replacing Y_{0i}. The reduction from Eqn 3 to Eqn 8 revealed no evidence that Eqn 8 fitted less well than Eqn 3, indicating that CD_{50} was constant regardless of nitrogen level. The reduction from Eqn 8 to Eqn 9 showed significantly worse fitness of Eqn 9 than Eqn 8. Nevertheless, the direct comparison of Eqn 9 with Eqn 2 showed no evidence of a significant difference between them, reflecting that the increase in the weed competitivity with increasing nitrogen can be explained by the exponential model, in agreement with the previous suggestion (Fig. 1B). Finally, there was no evidence that Eqn 10 fitted less well than Eqn 9, confirming that the parameter B was not significantly affected by nitrogen. Therefore, the final model Eqn 10 is a good description of the crop biomass yield as affected by weed interference, herbicide dose and nitrogen fertilizer. This result therefore indicates that the hyperbolic model combined with the dose–response model (Eqn 2) can be modified to give Eqn 10 by incorporating the inverse quadratic and exponential models for the parameters W_0 and β, respectively, with constant CD_{50} and parameter B.

Modelling weed biomass as affected by weed interference, herbicide dose and nitrogen fertilizer

Biomass data of *B. napus* on 17 June 1999 were subjected to non-linear regression analysis by fitting Eqn 5 to obtain all parameter estimates at each nitrogen level. To examine the behaviour of each parameter with increasing nitrogen, parameter estimates were plotted against nitrogen. Individual plant biomass (C) of *B. napus* at no-herbicide treatment increased sharply with increasing nitrogen, so the inverse quadratic and linear models were employed to describe the change of parameter C with increasing nitrogen. The inverse quadratic curve showed slightly better fitness considering a lower residual mean square (Table 1). However, the plant biomass was steadily increased with no sign of decrease or stagnation of the plant biomass even at 360 kg N ha^{-1}, so the linear model seemed to be better in this range of nitrogen levels. Parameter B tended to increase with increasing nitrogen except for the value at 0 kg N ha^{-1}, and a reasonable hypothesis is that parameter B increases with nitrogen. Two models (linear and exponential models) were tested for describing the change of parameter B with increasing nitrogen. The regression analysis revealed that the exponential model appeared to be slightly better than the linear model considering a lower residual mean square (RMS) (Table 1). The plots of parameters ED_{50} and A against nitrogen showed that the ED_{50} appeared to decrease with increasing nitrogen and the parameter A to increase, but these changes were accompanied by large standard errors (data not shown). Considering these large standard errors, it was speculated that parameters ED_{50} and A might be constant.

On the basis of the above assumptions, equations were fitted and F-values were calculated as summarized in Fig. 2B. When Eqn 5 (Full model) and 6 were fitted, there was no evidence that Eqn 6 fitted less well than Eqn 5, indicating that C_i was well constrained with the linear model. The reduction from Eqn 6 to Eqn 11 showed no evidence that Eqn 11 fitted less well than Eqn 6, indicating that the parameter B increased exponentially with increasing nitrogen. There were no evidences that Eqn 12 fitted less well than Eqn 11 and Eqn 13 fitted less well than enq 12, indicating that both the ED_{50} and parameter A were constant regardless of nitrogen level. Therefore, Eqn 13 was a good description of weed biomass as affected by weed density, herbicide dose and nitrogen fertilizer. This result therefore indicates that the hyperbolic model combined with the dose–response model (Eqn 5) can be modified to give Eqn 13 by incorporating the linear and exponential models for the parameters C and B, respectively, with constant ED_{50} and parameter A.

Prediction

Crop biomass yield.

Using the final model Eqn 10 and estimated parameter (Table 2), winter wheat biomass yields were predicted at a complex range of herbicide doses, weed densities and nitrogen levels in Fig. 3. The model predicted increased winter wheat biomass yield with increasing nitrogen

Table 1 Summary of initial parameter estimates for the relationships between full model parameters for Eqn 5 and nitrogen

	Parameter estimates					
	Individual weed biomass at no-herbicide treatment (C)					
Models	a	b	c	d	RMS	R^2
Inverse quadratic	0.876 (0.313)	0.025 (0.0087)	−0.00344 (0.00122)	6.1×10^{-6} (2.2×10^{-6})	0.112	0.999
Linear	0.376 (0.309)	0.0485 (0.0017)			0.224	0.996
	Parameter B					
	α	β				
Exponential	1.257 (0.323)	1.0022 (0.0010)			0.327	0.561
Linear	1.275 (0.407)	0.0036 (0.0022)			0.390	0.477

The numbers in parentheses are the SEs.

Table 2 Summary of estimated parameters for the biomass yield of winter wheat

Parameter estimates							
Y_0				β_0			
a	b	c	d	l	m	CD_{50}	B
494.3 (21.0)	13.23 (2.35)	0.0053 (0.0021)	9.9×10^{-6} (1.8×10^{-6})	0.00056 (0.00029)	1.0093 (0.0016)	0.519 (0.090)	2.918 (0.918)

The numbers in parentheses are the SEs.

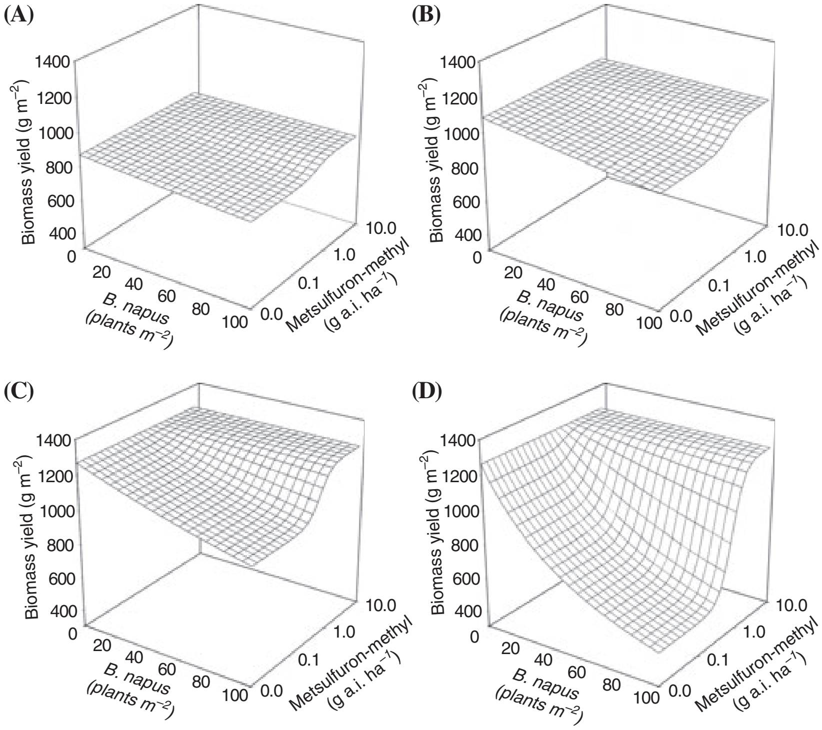


Fig. 3 Predicted biomass yield of winter wheat as affected by crop–weed competition and sub-lethal doses of metsulfuron-methyl at different nitrogen levels, 45 (A), 90 (B), 180 (C) and 360 (D) kg N ha^{-1}.

level at no-herbicide treatment without weed interference, but sharp decrease of winter wheat biomass yield with increasing weed density and nitrogen level at sub-lethal doses of herbicide, particularly at 360 kg N ha^{-1}. Weed-free biomass yields were predicted to be 867, 1085, 1269 and 1260 g m^{-2} at 45, 90, 180 and 360 kg N ha^{-1} respectively. When interfered with weeds at 100 plants m^{-2}, the crop yields were dropped down to 800, 962, 982 and 497 g m^{-2} at 45, 90, 180 and 360 kg N ha^{-1}, respectively, at no-herbicide treatment, but recovered to 858, 1067, 1223 and 1053 g m^{-2} at the sub-lethal dose 1.0 g a.i. ha^{-1} of metsulfuron-methyl.

Weed biomass.

By using Eqn 13 and parameter estimates (Table 3), the biomass of *B. napus* was predicted for a range of herbicide doses and nitrogen levels (Fig. 4). The prediction showed sharp increase of *B. napus* biomass at 270–360 kg ha^{-1} of nitrogen, as also seen in the previous initial plotting (Fig. 3A), at 0–0.1 g a.i. ha^{-1} of metsulfuron-methyl. At 270¯360 kg N ha^{-1}, winter wheat biomass did not also decrease (Fig. 1A). Meanwhile, at 0.1–1.0 g a.i. ha^{-1} of metsulfuron-methyl, *B. napus* biomass decreased very sharply; the rate of the decrease was greater as the amount of nitrogen increased. At plant density of 100 *B. napus* plants m^{-2}, the model predicted 233, 240 and 961 g m^{-2} of *B. napus* biomass at no-herbicide treatment, and 60, 46 and 81 g m^{-2} at 1.0 g a.i. ha^{-1} of metsulfuron-methyl, at 90, 180 and 360 kg N ha^{-1} respectively.

Table 3 Summary of estimated parameters for the biomass of *Brassica napus* as affected by plant density, metsulfuron-methyl and nitrogen

Parameter estimates					
C			*B*		
a	*b*	*A*	*α*	*β*	ED$_{50}$
1.588 (0.484)	0.02687 (0.00893)	0.00698 (0.00550)	1.106 (0.116)	1.00265 (0.00038)	0.4877 (0.0946)

The numbers in parentheses are the SEs.

Application of the models

The main purpose of the modelling approach to crop–weed competition studies is to implement more effective weed management by incorporating the results into the weed control decision-making process. Modelling crop–weed competition excluding herbicide dose treatments has provided only simple answers on weed control threshold levels. In comparison, the combined models developed here were able to calculate the herbicide dose required to restrict crop yield loss to less than a chosen level $p_{(N)}$% (Brain *et al.*, 1999; Kim *et al.*, 2002).

The final model in this study (Eqn 10) was rearranged to calculate the percent biomass yield loss as compared with no-herbicide treatment, at a given nitrogen level ($p_{(N)}$) as follows:

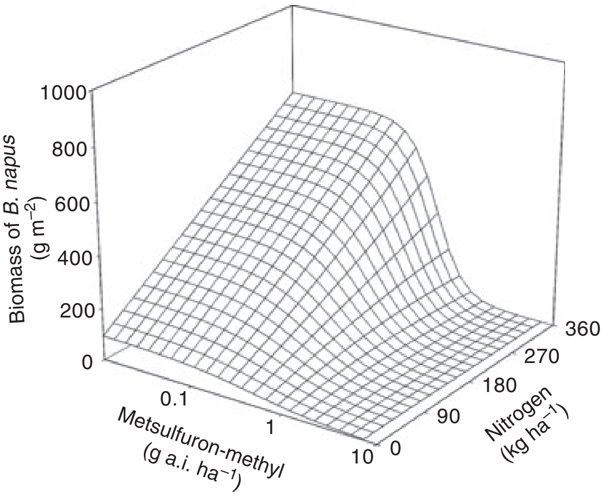


Fig. 4 Predicted biomass of *Brassica napus* as affected by metsulfuron-methyl and nitrogen at the plant density of 100 plants m^{-2}.

$$p_{(N)} = \left(1 - \frac{Y}{\frac{a+bN}{1+cN+dN^2}}\right) \times 100 = \left(1 - \frac{1}{1 + \frac{lm^N x}{1+(\mathrm{Dose}\times \mathrm{CD}_{50}^{-1})^B}}\right) \times 100 \qquad (14)$$

To give a herbicide dose (D_p) required to restrict crop biomass yield loss to less than $p_{(N)}$% at a given nitrogen level, Eqn 14 was then rearranged as follows:

$$D_p = \mathrm{CD}_{50}\left(\frac{lm^N(100 - p_{(N)})x}{p_{(N)}} - 1\right)^{1/B} \qquad (15)$$

If the acceptable biomass yield loss ($p_{(N)}$) is decided on the basis of economic returns, herbicide dose can be simply calculated to input all parameter estimates (Table 2), weed density present in the field, nitrogen levels applied and $p_{(N)}$ values. Figure 5 shows the estimated herbicide dose required to restrict crop yield loss to $p_{(N)}$% at different nitrogen levels. If the acceptable yield loss is 1% at 100 *B. napus* plants m^{-2}, the herbicide dose requirement will be 1.2 g and 1.7 g a.i. ha^{-1} of metsulfuron-methyl at 90, 180 kg N ha^{-1} respectively. In addition, as the absolute biomass yield increased with increasing nitrogen, the herbicide dose needs to be decided along with the nitrogen level for a particular target yield.

Discussion

Nitrogen effects on crop–weed competition

Although derived from a single experiment, the results showed the expected increase in biomass of *B. napus* with increasing nitrogen, even under competition with winter wheat. Biomass of winter wheat grown in monoculture increased with increasing nitrogen only up to 180 kg N ha^{-1}, but did not increase any further at 360 kg N ha^{-1}, indicating that *B. napus* utilizes increased nitrogen more effectively than winter wheat. As a crop, *B. napus* requires a large amount of nitrogen for optimum yield (Holmes & Ainsley, 1979; Archer & Vaidyanathan, 1982), generally 200–250 kg N ha^{-1} and sometimes larger on chalk soils (Ogilvy, 1985). Iqbal and Wright (1997) reported that at a high nitrogen doses, *Sinapis arvensis*, a similar species to *B. napus* in growth characteristics, showed significant increases in biomass and nitrogen uptake when grown in mixture with winter wheat compared with growth in monoculture. At a low nitrogen dose, biomass and nitrogen uptake were significantly lower. It is generally accepted that winter wheat needs 100–200 kg N ha^{-1} for optimum grain yield, although this varies with soil physicochemical

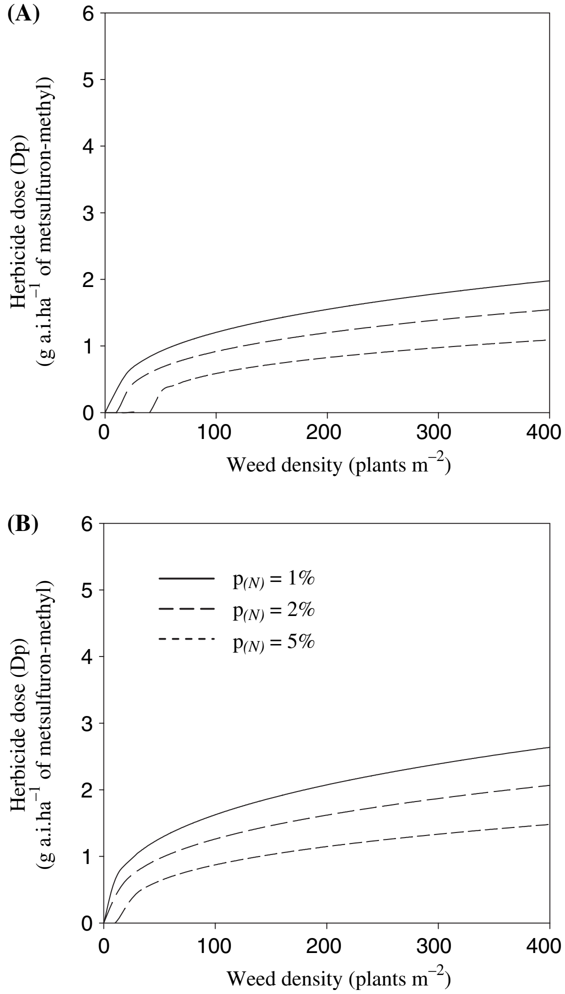


Fig. 5 Estimated doses (D_p) of metsulfuron-methyl to restrict biomass yield loss of winter wheat to less than $p_{(N)}$%, 1%, 2% and 5%, for a range of plant densities of *Brassica napus* and at 90 (A) and 180 (B) kg N ha^{-1} nitrogen levels.

properties, previous crops and target yields. No increase of winter wheat biomass at 360 kg N ha^{-1} may be attributed to a decrease in fertile tiller numbers (data not shown), because of increased shading (Willey & Holliday, 1971) and reduced red and far-red light ratio (Smith, 1982). Our study showed similar interactions to that of Ågren (1985), as winter wheat growth increased proportionally with increasing nitrogen until a certain growth stage, after which the increase slowed, possibly because of increasing intra-specific competition for light and other nutrients. In comparison, the main part of the *B. napus* canopy was above the winter wheat canopy at later growth stages, so that *B. napus* occupied a better position for competing with winter wheat for light.

The exponential increase of β_0 indicated that increased nitrogen from 180 to 360 kg N ha^{-1} gave a much greater advantage to *B. napus* than to wheat, resulting in a significant wheat biomass yield loss, more than 50% at 100 *B. napus* plants m^{-2} at 360 kg N ha^{-1}. Similar results were also observed in other weeds. For instance, *Galium aparine* is considered a nitrophilous weed and increases its competitive ability with increasing nitrogen level (Pulcher-Haussling & Hurle, 1986; Rooney *et al.*, 1990; Wright & Wilson, 1992), and *Avena fatua* (Carlson & Hill, 1985; Wright & Wilson, 1992) and *Bromus sterilis* (Lintell-Smith *et al.*, 1991) have also been found to increase their competitive abilities over the crop with increasing nitrogen level, resulting in greater crop yield losses at higher nitrogen levels. These findings may be related to the relative responses of crop and weed to nitrogen. As a result of increased nitrogen supply and the relative response rate to the increased nitrogen, the balance in crop and weed competition may be altered. In this study, the balance appeared to be constant irrespective of nitrogen level up to 180 kg N ha^{-1}, but increased nitrogen to 360 kg N ha^{-1} changed the balance in favour of *B. napus*. This imbalance at 360 kg N ha^{-1} causing severe crop yield loss may be attributed to (i) increased intra-specific competition of winter wheat for light and/or (ii) greater advantage of *B. napus* in plant height and growth characteristics over winter wheat at later growth stages. Therefore, it is suggested that these comparative characteristics and situations may be the reason for differences in the nitrogen response of winter wheat and *B. napus*.

Nitrogen effects on herbicide dose–response of weed and weed competitivity

Nitrogen and herbicide dose–response of the weed. It was reported that the herbicide dose–response of *B. napus* in monoculture was not affected by nitrogen application (Kim *et al.*, 2006b), indicating that the ED_{50} and parameter *B* (rate of dose–response) were constant irrespective of nitrogen level. However, in mixture with winter wheat, our results showed that the herbicide dose–response of *B. napus* was influenced by nitrogen application. It is thus speculated that the altered dose–response of *B. napus* in mixture is due to the presence of winter wheat. In this study, the dose required to reduce *B. napus* biomass to less than 50% of the control was 0.442 g a.i. ha^{-1}, whereas it was 3.321 g a.i. ha^{-1} in monoculture (Kim *et al.*, 2006b). Therefore, the presence of winter wheat may provide (i) favourable conditions for herbicide action and (ii) unfavourable conditions for the regrowth of *B. napus* sprayed with herbicide, resulting in altered herbicide dose–response with decreased ED_{50} values with increasing nitrogen level. This implies that sub-lethal herbicide doses reduce the growth rate of *B. napus* and increase the asymmetric competition in favour to winter wheat. A significant decrease in light penetration with increasing nitrogen was observed at the time of herbicide treatment, when *B. napus* was much smaller than winter wheat (data not shown). *Brassica napus* treated with a sub-lethal dose may become less and less competitive because of increased shading resulted from better canopy development of winter wheat with increasing nitrogen. This finding is in agreement with Christensen (1994) and Kim *et al.*'s (2002) reports that more competitive crop cultivars allowed better herbicidal performances at sub-lethal doses. Further studies may be required to investigate the mechanisms for this.

Nitrogen and herbicide dose–response of weed competitivity and crop yield. Although the herbicide dose–response of weeds was affected by nitrogen, the herbicide dose–response of weed competitivity was not affected, so that the CD_{50} and parameter *B* were constant, regardless of nitrogen level. The level of crop–weed competition is also influenced by weed species, sowing date and yearly variation in weather, which may significantly affect the relationship between weed competitivity and herbicide dose. Kim *et al.* (2006b)) reported that herbicide dose–responses of *G. aparine*, Matricaria perforata and Papaver rhoeas were significantly affected by nitrogen fertilizer in their monocultures. If these weed species compete with winter wheat, herbicide dose–responses of their competitivities can be significantly affected by nitrogen level. Nevertheless, the herbicide application increased crop yield more at higher nitrogen levels, particularly 360 kg N ha^{-1}, at which weed competitivity was much greater than at lower nitrogen levels. Therefore, in a system using high nitrogen fertilization, herbicide application needs to be carefully integrated.

The CD_{50} for the weed competitivity (β) was 0.519 ± 0.090, similar to 0.4877 ± 0.0946 of the ED_{50} for weed biomass. The similarity of these values suggests that the dose–response curve of a weed in mixture with crop can be directly incorporated into the model for predicting crop yield, as demonstrated by Brain *et al.* (1999) and Kim *et al.* (2002).

Implications and recommendations

Increased weed competitivity with increasing nitrogen results in greater crop yield loss at higher nitrogen levels. Although the herbicide dose–response of weed competitivity was not affected by nitrogen, a greater increase in crop yield because of herbicide application was gained at higher nitrogen levels, at which weed competitivity was much greater than at lower nitrogen levels. The models developed in this study appear to provide a reasonable prediction of crop yield and weed biomass and have also been used to estimate the herbicide dose required to restrict crop yield loss or weed biomass production to less than a chosen level. This study provides a framework to integrate both fertilizer management and weed management.

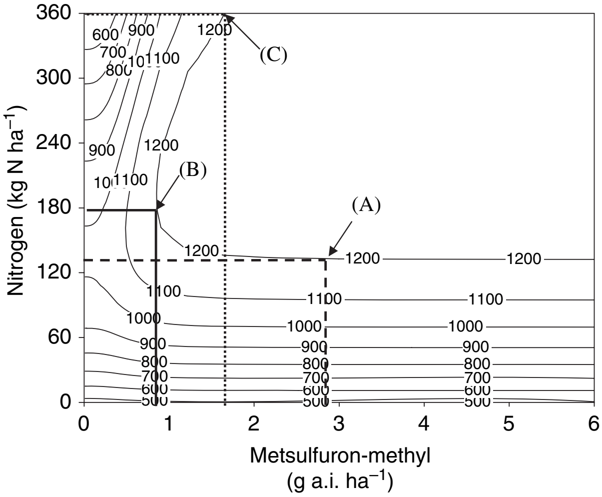


Fig. 6 Target yields of winter wheat that can be achieved by the combination of herbicide and nitrogen with a 100 *Brassica napus* plants m^{-2} infestation. Each isocline represents the target yield. The points A, B, and C indicate 140 N kg + 2.9 g a.i., 180 N kg + 0.9 g a.i., and 360 N kg ha^{-1} + 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}.

As nitrogen affects both the crop and weed, while herbicide generally affects only the weed when less than the recommended dose was used, decision making for weed control should take both nitrogen fertilizer application rate and herbicide dose into account. Figure 6 shows an example of this integrated management, based on Eqn 10 and parameter estimates (Table 2) provided in this study. If a weed infestation of 100 plants m^{-2} is expected or observed, it may be possible to establish various decisions with different combinations of nitrogen application rate and herbicide dose. If the target biomass yield is 1200 g m^{-2}, a nitrogen rate of at least 140 kg ha^{-1} and a herbicide dose of 2.9 g a.i. ha^{-1} is predicted (point (A) in Fig. 6). At a nitrogen application of 180 kg N ha^{-1}, a lower dose of herbicide, about 0.9 g a.i. ha^{-1}, can achieve the target yield (point (B) in Fig. 6). At nitrogen applications of more than 180 kg N ha^{-1}, herbicide dose requirement increases with increasing nitrogen level, so the herbicide dose of about 1.7 g a.i. ha^{-1} may be required when 360 kg N ha^{-1} is applied (point (C) in Fig. 6). Similar approaches can be made based on weed biomass or weed seed production in consideration of long-term weed population dynamics using Eqn 13 and parameter estimates in Table 3. Therefore, considering costs of herbicide and nitrogen fertilizer and environmental risks, the cheapest and safest combination of herbicide dose and nitrogen rate can be selected. Jørnsgard *et al.* (1996) suggested that nitrogen application could be exploited in crop–weed management, for example, in a programme designed to reduce herbicide use by integrating its use with level of nitrogen fertilizer. Although the models developed here need to be validated over a wide range of field conditions, it can be concluded that the models and results provide a way forward to achieving a more economically sound and environmentally friendly approach to weed control.

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