Modeling the Effects of Nitrogen Fertilizer and Multiple Weed Interference on Soybean Yield

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Abstract: Understanding the effects of nitrogen (N) fertilizer on soybean-weed competition is essential for establishing a practical tool for N application and weed management. A two-year field experiment was conducted in a soybean field located in Bogatyrka (43.82° N, 131.6° E), Primorsky krai, Russia, to investigate the effects of N fertilizer and multiple-weed interference on soybean (Glycine max) yield and to model these effects. Soybean yield loss caused by the interference of multiple weeds including common ragweed (Ambrosia artemisiifolia), barnyard grass (Echinochloa crus-galli), and American slough grass (Beckmannia syzigachne) at different levels of N fertilizer was accurately described by a combined model incorporating inverse quadratic and exponential models into the rectangular hyperbolic model for two parameters $Y_0$ and $\beta$, respectively. The combined model used in our study indicated that the application of N up to 36 kg N ha$^{-1}$ can increase weed-free soybean yield by 2.2 Mg ha$^{-1}$ but soybean yield under multiple-weed interference can sharply decrease with increasing total density equivalent, particularly at 36 kg N ha$^{-1}$. These results, including the combined model, thus can support decision making for weed management under different N uses in soybean cultivation.

Keywords: crop-weed competition; combined model; multiple weed interference; nitrogen fertilization; soybean; Primorsky krai

1. Introduction

Nitrogen (N) fertilizer plays an important role in soybean production although soybean requires much less N fertilizer than other crops. Soybean is less dependent on N fertilizer because symbiotic rhizobia provide soybean with ammonium $(\text{NH}_4^+)$ by biologically fixing $\text{N}_2$ gas in the air. Nonetheless, soybean cultivation requires a significant amount of N fertilizer, particularly at its early growth stage when rhizobia have not established a symbiotic relationship with soybean. On average, 55% of soybean N demand is reported as being met by biological $\text{N}_2$ fixation [1]. Therefore, a full basal dressing of approximately 16 to 30 kg N ha$^{-1}$ is artificially applied for soybean cultivation to supply insufficient N by biological $\text{N}_2$ fixation in order to promote early vegetative growth and thus to attain maximum soybean yield in practice [2–4].

In the region of Primorsky krai, Russia, soybean is intensively cultivated during four months from late May until late September due to the short frost-free period, resulting in a short growing season. Due to this, N application is essential to promote early soybean
growth and thus to secure soybean yield in the region. However, soybean growth and yield have been severely interfered with regional weed species, although N application increases soybean yield. In the region, soybean yield is as low as 64.5% of the average yield (1.69 Mg ha\(^{-1}\)) in neighboring regions, including Heilongjiang province of China [5–7]. *Ambrosia artemisiifolia* (common ragweed), *Echinochloa crus-galli* (barnyard grass), and *Bekkmania syzigachne* (American slough grass) are dominant in the soybean fields of Primorsky krai [8]. Their competition effects on soybean yield under N fertilization have not been fully investigated. *Ambrosia artemisiifolia* and *E. crus-galli* are known as nitrophilous weed species which increase their biomass along with increasing N level [9,10]. When weeds are not adequately managed, N application can increase weed growth; rather, crop yield can be offset by weeds outcompeting for N. Many studies have reported that crop yield can be reduced more by nitrophilous weed species at high N fertilization [11–16]. For soybean, a study investigating the effects of N fertilizer and duration of weed interference on yield reported that a competitive advantage for soybean was detected under N fertilization [17]. More information for soybean yield versus weed interference under N fertilization is needed to evaluate the effects of N fertilizer and weed interference on soybean yield. As multiple weed species are present in real fields, it is necessary to consider weed interference via a mixture of multiple weed species.

A rectangular hyperbolic model has provided a tool to evaluate how crop yield is influenced by weed interference under field conditions [8,18–21]. Kim et al. [14] developed a modified version of the rectangular hyperbolic model to describe crop yield loss caused by single-weed interference at a given N level. However, the model cannot account for the effect of multiple-weed interference on crop yield. Crop yield loss often occurs as a result of multiple-weed interference under commercial-scale production [8]. A model for the effects of N fertilizer and multiple-weed interference on soybean yield would be useful to support decision making for weed management in combination with a N fertilizer use scenario.

Therefore, this study was conducted to investigate the effects of N fertilization and multiple-weed interference on soybean yield and to model these effects based on the rectangular hyperbolic model [19].

2. Materials and Methods

2.1. Field Experiments

Field experiments were conducted in 2013 and 2014 to evaluate the effects of N fertilizer and multiple-weed interference on soybean yield in Bogatyryka, Primorsky krai, Russia (43.82° N, 131.6° E). The respective mean daily temperature and total rainfall during the growing season (May to October) were 16.7 °C and 557.1 mm in 2013 and 15.3 °C and 408.5 mm in 2014, respectively [8,22]. The soil in this region had a silty-loam texture with a cation exchange capacity of 22.6 cmol kg\(^{-1}\), organic matter content of 29.6 g kg\(^{-1}\), total N concentration of 1.58 g kg\(^{-1}\), available phosphorus (P) concentration of 18.2 mg kg\(^{-1}\), and a pH of 6.6 [8,22]. N fertilizer was applied in the form of urea (CO(NH\(_2\))\(_2\)) at 0, 12, 24, and 36 kg N ha\(^{-1}\) on 27 May 2013 and 22 May 2014. The other basal fertilizers were applied yearly at a rate of 31–31 (kg ha\(^{-1}\) = PO\(_4\)-K\(_2\)O before N application.

Soybean (*Glycine max* cv. Heinong 48) was planted at a seeding rate of 80 kg ha\(^{-1}\) with a row width of 70 cm at different N fertilizer plots. Weed seedlings that emerged naturally within rows were manually thinned to a target plant density for individual weed species *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne* and different plant density combinations of these weeds up to the V6 stage of soybean in pre-marked plots. Other weed species were manually removed. The maximum plant densities and the number of pre-marked plots for competition between soybean and single weed species were as follows: *A. artemisiifolia*, 49, 24, 20, and 17 plants m\(^{-2}\) in 17, 11, 9, and 10 plots at 0, 12, 24, and 36 kg N ha\(^{-1}\) in 2013, respectively, and 49, 43, 43, and 45 plants m\(^{-2}\) in 17, 17, 17, and 14 plots in 2014; *E. crus-galli*, 91, 91, 16, and 23 plants m\(^{-2}\) in 9, 9, 11, and 13 plots in 2013, respectively, and 100, 139, 139, and 139 plants m\(^{-2}\) in 11, 13, 13, and 16 plots in 2014; *B. syzigachne*, 26, 71, 23, and 31 plants...
12, 24, and 36 kg N ha\(^{-1}\) in 11, 11, 9, and 10 plots in 2013, respectively, and 110, 56, 70, and 100 plots m\(^{-2}\) in 18, 13, 15, and 16 plots in 2014 (Table S1). The maximum total plant densities and the number of pre-marked plots for competition between soybean and various combinations of three weed species were as follows: 91, 279, 304, and 31 plants m\(^{-1}\) in 39, 35, 33, and 37 plots at 0, 12, 24, and 36 kg N ha\(^{-1}\) in 2013, respectively, and 110, 139, 139, and 139 plants m\(^{-2}\) in 68, 67, 69, and 71 plots in 2014 (Table S1). In the main plot of each N fertilization, pre-marked plots were laid out in a completely randomized design with a single replicate. The size of each main plot was 100 m by 56 m, while the size of each pre-marked plot was 4.2 m by 2 m including a buffer area. The sampling area for harvest was 2.1 m by 1 m in each pre-marked plot, and three soybean rows were harvested by hand at maturity in October of each year. The soybean seed yield was adjusted to 14% moisture content after its seed weight and moisture content were measured at harvest.

2.2. Model Development

A rectangular hyperbolic model was used to describe the competition effects of three weed species in a single stand (single-weed interference) or in a mixture (multiple-weed interference) on soybean yield (Equation (1)) [8,19,20].

\[
Y = \frac{Y_0}{1 + \beta_1 \left( X_1 + \frac{\beta_2}{\beta_1} X_2 + \frac{\beta_3}{\beta_1} X_3 \right)} \quad (1)
\]

where \(Y_0\) is weed-free soybean yield (Mg ha\(^{-1}\)) and \(\beta\) is a measure of weed competitiveness (\(\beta_1, \beta_2, \beta_3\)), and \(\beta_1\) are the competitiveness of each species in order to convert its original density into a relative density, i.e., the so-called density equivalent [18]. In this study, \(A.\ artemisiifolia\) is the reference weed species. Thus, \(X_1+\cdot(\beta_2/\beta_1)X_2+\cdot(\beta_3/\beta_1)X_3\) is the total density equivalent, which is the sum of the relative densities of \(A.\ artemisiifolia, E.\ crus-galli,\) and \(B.\ syzigachne\), calculated based on the density equivalent [18]. If N fertilizer is applied to a soybean field at different levels, two parameters \(Y_0\) and \(\beta\) for the rectangular hyperbolic model may change with applied N (\(n\)). Therefore, at each N level, Equation (1) can be rewritten as follows:

\[
Y = \frac{Y_{0n}}{1 + \beta_{1n} \left( X_1 + \frac{\beta_{2n}}{\beta_{1n}} X_2 + \frac{\beta_{3n}}{\beta_{1n}} X_3 \right)} \quad (2)
\]

where \(Y_{0n}\) and \(\beta_{in}\) are the parameters for the \(i\)-th level of applied N. However, Equation (2) requires many parameters to predict soybean yield loss caused by weed interference for a wide range of N levels. Weed-free soybean yield (\(Y_{0n}\)) may change with increasing N level as a function of the inverse quadratic curve since excess N may be toxic [14,23]. Weed competitiveness (\(\beta_{in}\)) may change as a function of the exponential curve [14]. To describe the relationship between the parameters and applied N, inverse quadratic and exponential models were used as follows:

\[
Y_{0i} = \frac{a + bN}{1 + cN + dN^2} \quad (3)
\]

\[
\beta_{ni} = \left(\frac{m}{l}\right)^N \quad (4)
\]

where \(a, b, c,\) and \(d\) are unknown parameters for weed-free soybean yield, \(l\) and \(m\) are unknown parameters for weed competitiveness, and N is the level of applied nitrogen. Therefore, the inverse quadratic and exponential models for two parameters \(Y_{0i}\) and \(\beta_{ni}\), respectively, were incorporated into Equation (2) to give a combined model (Equation (5)) as follows:

\[
Y = \frac{\frac{a + bN}{1 + cN + dN^2} X_1 + \frac{l_mN^N}{l_m^N} X_2 + \frac{l_mN^N}{l_m^N} X_3}{1 + l_m^N X_1 + \frac{l_mN^N}{l_m^N} X_2 + \frac{l_mN^N}{l_m^N} X_3} \quad (5)
\]
where $X_1 + (l_2m_2^N/l_1m_1^N)X_2 + (l_3m_3^N/l_1m_1^N)X_3$ is the total density equivalent (plants m$^{-2}$).

2.3. Statistical Analyses

All measurements were initially subjected to analysis of variance (ANOVA). Non-linear regression analyses were then conducted to fit the rectangular hyperbolic model (Equation (2)) to the yield data, corresponding to the plant density combination of three weed species at different N levels. Inverse quadratic and exponential models were regressed on the parameters $Y_0$ and $\beta_i$ affected by applied N, respectively. The performance of the models was evaluated by the pseudo-$R^2$. Parameter estimates were compared between years using dummy variables [24]. Significant difference (5% level) between values was determined based on whether or not the confidence intervals of the dummy variables contain zero. Lack-of-fit of the rectangular hyperbolic model (Equation (2); Full model) was tested to check that the inverse quadratic and exponential models (Equations (3) and (4)) were appropriate for each parameter change with increasing N. The combined model (Equation (5); Reduced model) was compared with the Full model by calculating the $F$-value as follows:

$$F = \frac{RSS_r - RSS_f}{d_f - df_r}$$

where $RSS$ and $df$ are the residual sum of square and the degree of freedom, respectively, and $r$ and $f$ are the Reduced and Full models. If the $F$-value was lower than the tabulated $F$-value (5% level) with ($df_r - df_f$, $df_f$) degrees of freedom, the Reduced model could be accepted. All the statistical analyses were conducted using Genstat [25].

3. Results

3.1. Effect of Nitrogen on Soybean-Weed Competition under Single Weed Interference

Soybean yield at different levels of N fertilizer was regressed on single species weed density using the rectangular hyperbolic model (Table 1). The $Y_0$ and $\beta$ parameter values at different levels of N fertilizer showed little or no difference between years within weed species (Table S2), so the two-year data for each weed species were pooled and the model was regressed on the pooled data (Table 1). Weed-free soybean yield ($Y_0$) and weed competitiveness ($\beta$) values at no N application were 1.61 Mg ha$^{-1}$ and 0.093, 1.55 Mg ha$^{-1}$ and 0.086, and 1.56 Mg ha$^{-1}$ and 0.046 for A. artemisiifolia, E. crus-galli, and B. syzigachne, respectively. The weed-free soybean yield value increased with increasing N level; approximately 1.77 Mg, 2.05 Mg, and 2.26 Mg ha$^{-1}$ at 12, 24, and 36 kg N ha$^{-1}$, respectively, equivalent to 12.7%, 30.6%, and 43.9% yield increases compared with the yield at no N application, 1.57 Mg ha$^{-1}$ (Table 1). Thus, the weed-free soybean yield showed the inverse quadratic increase with N fertilizer (Figure S1). The weed competitiveness value also increased with increasing N level. For A. artemisiifolia, weed competitiveness value was 0.127, 0.203, and 0.529 at 12, 24, and 36 kg N ha$^{-1}$, respectively, equivalent to approximately 1.4-fold, 2.2-fold, and 5.7-fold increases compared with the value at no N application; for E. crus-galli, 0.142, 0.384, and 0.369 at 12, 24, and 36 kg N ha$^{-1}$, respectively, equivalent to approximately 1.7-fold, 4.5-fold, and 4.3-fold increases; for B. syzigachne, 0.063, 0.090, and 0.100 at 12, 24, and 36 kg N ha$^{-1}$, respectively, equivalent to approximately 1.4-fold, 2.0-fold, and 2.2-fold increases (Table 1; Figure S2). Thus, the weed competitiveness of single species showed an exponential increase with N fertilizer (Table 2; Figure S2).
Table 1. Parameter estimates for the rectangular hyperbolic model for the regression of soybean yield as a result of single-weed interference caused by *Ambrosia artemisiifolia* (A), *Echinochloa crus-galli* (B), and *Beckmannia syzigachne* (C) at different nitrogen levels in 2013 and 2014 and for the pooled two-year data. The numbers in parentheses are standard errors.

| Nitrogen (kg N ha⁻¹) | Weed Species | Parameter Estimates | Pseudo R² |  |  |  |
|----------------------|--------------|---------------------|-----------|-----|-----|-----|
|                      |              |  |                      |  |     |     |
|                      |              | Y₀ | β                    |  |     |     |
|                      |              |  | 2013 | 2014 | Pooled | 2013 | 2014 | Pooled | 2013 | 2014 | Pooled |
| 0                    | A            | 1.62 | (0.095) | 1.44 | (0.086) | 1.61 | (0.096) | 0.052 | (0.0104) | 0.085 | (0.0132) | 0.093 | (0.0159) | 0.86 | 0.91 | 0.81 |
|                      | B            | 1.52 | (0.169) | 1.39 | (0.058) | 1.55 | (0.085) | 0.066 | (0.0259) | 0.086 | (0.0114) | 0.086 | (0.0177) | 0.84 | 0.97 | 0.89 |
|                      | C            | 1.64 | (0.101) | 1.40 | (0.079) | 1.56 | (0.131) | 0.047 | (0.0089) | 0.063 | (0.0122) | 0.046 | (0.0130) | 0.80 | 0.92 | 0.65 |
| 12                   | A            | 1.73 | (0.122) | 1.81 | (0.138) | 1.77 | (0.090) | 0.130 | (0.0324) | 0.118 | (0.0249) | 0.127 | (0.0206) | 0.86 | 0.84 | 0.84 |
|                      | B            | 1.74 | (0.085) | 1.82 | (0.163) | 1.78 | (0.093) | 0.135 | (0.0353) | 0.148 | (0.0582) | 0.142 | (0.0354) | 0.96 | 0.86 | 0.90 |
|                      | C            | 1.72 | (0.107) | 1.82 | (0.157) | 1.75 | (0.102) | 0.040 | (0.0079) | 0.089 | (0.0251) | 0.065 | (0.0125) | 0.89 | 0.81 | 0.80 |
| 24                   | A            | 2.10 | (0.104) | 1.96 | (0.048) | 2.04 | (0.070) | 0.232 | (0.0396) | 0.220 | (0.0175) | 0.203 | (0.0236) | 0.95 | 0.98 | 0.94 |
|                      | B            | 2.07 | (0.170) | 1.96 | (0.041) | 2.02 | (0.080) | 0.413 | (0.1170) | 0.307 | (0.0477) | 0.384 | (0.0664) | 0.86 | 0.99 | 0.94 |
|                      | C            | 2.18 | (0.141) | 1.96 | (0.073) | 2.08 | (0.077) | 0.082 | (0.0205) | 0.093 | (0.0106) | 0.090 | (0.0112) | 0.88 | 0.95 | 0.92 |
| 36                   | A            | 2.39 | (0.240) | 2.16 | (0.097) | 2.26 | (0.058) | 0.545 | (0.0839) | 0.594 | (0.1040) | 0.529 | (0.0603) | 0.98 | 0.98 | 0.98 |
|                      | B            | 2.40 | (0.184) | 2.16 | (0.105) | 2.25 | (0.096) | 0.436 | (0.1010) | 0.291 | (0.0568) | 0.369 | (0.0557) | 0.91 | 0.94 | 0.92 |
|                      | C            | 2.41 | (0.157) | 2.17 | (0.074) | 2.27 | (0.075) | 0.113 | (0.0218) | 0.109 | (0.0095) | 0.100 | (0.0100) | 0.93 | 0.96 | 0.94 |

Table 2. Parameter estimates for the exponential model for the regression of weed competitiveness of *Ambrosia artemisiifolia* (β₁), *Echinochloa crus-galli* (β₂), and *Beckmannia syzigachne* (β₃) as a function of applied nitrogen in 2013 and 2014 and for the pooled two-year data presented in Table 1. The numbers in parentheses are standard errors.

| Year | Parameter β | Ambrosia artemisiifolia (β₁) | Echinochloa crus-galli (β₂) | Beckmannia syzigachne (β₃) |
|------|-------------|-------------------------------|-------------------------------|-----------------------------|
|      | l₁ m₁ R²  | l₁ m₁ R² | l₁ m₁ R² | l₁ m₁ R² |
| 2013 | 0.052 (0.0071) | 1.067 (0.0044) | 0.99 | 0.114 (0.0606) | 1.041 (0.0178) | 0.72 | 0.037 (0.0082) | 1.032 (0.0077) | 0.87 |
| 2014 | 0.046 (0.0144) | 1.073 (0.0099) | 0.98 | 0.119 (0.0438) | 1.028 (0.0130) | 0.65 | 0.072 (0.0082) | 1.009 (0.0043) | 0.49 |
| Pooled | 0.053 (0.0185) | 1.065 (0.0111) | 0.97 | 0.124 (0.0598) | 1.034 (0.0165) | 0.76 | 0.050 (0.0053) | 1.021 (0.0039) | 0.94 |

3.2. Effect of Nitrogen on Soybean-Weed Competition under Multiple Weed Interference

The competitiveness of individual weed species at different N levels was converted into a density equivalent by dividing with the competitiveness of *A. artemisiifolia* as the reference species (Table 1; Table S3). In the pooled data, the density equivalents of *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne* at no N application were 1.00, 0.92, and 0.49, respectively. These values for *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne* in N applied plots were 1.00, 1.12, and 0.50 at 12 kg N ha⁻¹ and 1.00, 1.89, and 0.44 at 24 kg N ha⁻¹ and 1.00, 0.70, and 0.19 at 36 kg N ha⁻¹, respectively (Table S3). Various plant density combinations of the three weed species were converted into a total density equivalent by multiplying the actual density of each weed with its density equivalent. Soybean yield
at different levels of N fertilizer was regressed on the total density equivalent of multiple weed species using the rectangular hyperbolic model (Figure 1). A pairwise comparison of parameter estimates showed that the $Y_0$ and $\beta$ parameter values at different levels of N fertilizer showed little or no difference between years (Table S2), so the two-year data were pooled and the model was regressed on the pooled data (Figure 1). Weed-free soybean yield and multiple-weed competitiveness values at no N application were 1.63 Mg ha$^{-1}$ and 0.079, respectively (Table 3). These values increased as follows: weed-free soybean yield, 1.75 Mg, 2.07 Mg, and 2.25 Mg ha$^{-1}$ at 12, 24, and 36 kg N ha$^{-1}$, respectively, equivalent to approximately 7.4%, 27.0%, and 38.0% yield increases compared with the yield at no N application; multiple-weed competitiveness, 0.121, 0.295, and 0.463 at 12, 24, and 36 kg N ha$^{-1}$, respectively, equivalent to approximately 1.5-fold, 3.7-fold, and 5.9-fold increases (Table 3).

**Figure 1.** Soybean yield as a function of the total density equivalent at different nitrogen levels in 2013 (···) and 2014 (—) and for the pooled two-year (—) data. The lines are fitted values calculated using the rectangular hyperbolic model and parameter estimates (Table 3).

**Table 3.** Parameter estimates for the rectangular hyperbolic model for the regression of soybean yield as a result of multiple weed interference expressed as the total density equivalent at different nitrogen levels in 2013 and 2014 and for the pooled two-year data. The numbers in parentheses are the standard errors.

| Nitrogen (kg N ha$^{-1}$) | Parameters | $Y_0$ | $\beta$ | Pseudo $R^2$ |
|---------------------------|------------|-------|---------|--------------|
|                           |            | 2013  | 2014    | Pooled       | 2013  | 2014    | Pooled       |
| 0                         |            |       |         |              |       |         |              |
|                           | $Y_0$      |       |         |              |       |         |              |
|                           |            | 1.65  | 1.38    | 1.63         | 0.066 | 0.076   | 0.079        |
|                           | (0.105)    | (0.093)| (0.071) | (0.0129)     | (0.0097)| (0.0084)|              |
| 12                        | $\beta$    |       |         |              |       |         |              |
|                           |            | 1.71  | 1.79    | 1.75         | 0.094 | 0.141   | 0.121        |
|                           | (0.092)    | (0.106)| (0.073) | (0.0129)     | (0.0182)| (0.0117)|              |
| 24                        | $Y_0$      |       |         |              |       |         |              |
|                           |            | 2.11  | 1.99    | 2.07         | 0.254 | 0.313   | 0.295        |
|                           | (0.110)    | (0.080)| (0.066) | (0.0348)     | (0.0256)| (0.0213)|              |
| 36                        | $\beta$    |       |         |              |       |         |              |
|                           |            | 2.40  | 2.14    | 2.25         | 0.472 | 0.454   | 0.463        |
|                           | (0.153)    | (0.093)| (0.082) | (0.0630)     | (0.0391)| (0.0341)|              |

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3.3. Responses of Weed-Free Soybean Yield and Multiple-Weed Competitiveness to Nitrogen

Inverse quadratic and exponential models were regressed on the weed-free soybean yield and multiple-weed competitiveness affected by applied N in the pooled data, respectively (Figure 2). These models showed good performance with high pseudo-$R^2$. Weed-free soybean yield slightly increased with increasing N level from 0 to 36 kg N ha$^{-1}$, and multiple-weed competitiveness exponentially increased with an increase of N up to 36 kg N ha$^{-1}$. Thus, inverse quadratic and exponential models can be sufficient to describe N effects on weed-free soybean yield and multiple-weed competitiveness, respectively.

![Figure 2](image_url)

Figure 2. Weed-free soybean yield (a) and multiple-weed competitiveness (b) as a function of applied nitrogen in the pooled two-year data.

3.4. Combined Model for Soybean Yield Affected by Multiple-Weed Competitiveness and Applied Nitrogen

The rectangular hyperbolic model was incorporated with inverse quadratic and exponential models to describe the relationships between weed-free soybean yield and applied N, and between multiple-weed competitiveness and applied N, respectively. In order to check that inverse quadratic and exponential models were appropriate, the combined model was compared with the rectangular hyperbolic model by lack-of-fit test. Statistical analyses revealed that there was no significant difference between the rectangular hyperbolic model (Full model) and the combined model (Reduced model) to describe soybean yield affected by both multiple-weed competitiveness and applied N (Table S4). Thus, the rectangular hyperbolic model can be modified to the combined model by replacing the parameters $Y_0$ and $\beta$ with the inverse quadratic and exponential models, respectively.

Using the combined model (Equation (5)) and estimated parameters (Table 4), soybean yield was predicted in Figure 3. A steep decline of soybean yield was predicted with increasing total density equivalent, particularly at 36 kg N ha$^{-1}$ although weed-free soybean yield increased with increasing N up to 36 kg N ha$^{-1}$. Weed-free soybean yield value was predicted to be 1.65 Mg, 1.84 Mg, 2.03 Mg, and 2.23 Mg ha$^{-1}$ at 0, 12, 24, and 36 kg N ha$^{-1}$, respectively. However, when interfered with multiple-weed species at 12 plants m$^{-2}$, soybean yield was reduced to 52%, 33%, 20%, and 11% of weed-free plot at 0, 12, 24, and 36 kg N ha$^{-1}$, respectively. Thus, in a N applied condition, proper weed management should be made to achieve maximum soybean yield in the Far-Eastern regions of Russia.
Thus, the rectangular hyperbolic model can be modified to the combined model by re-
placing the parameters

\[ Y = \frac{a}{1 + b X + c X^2} \]

with

\[ Y = \frac{\beta_0}{1 + \beta_1 X + \beta_2 X^2} \]

The parameters in the rectangular hyperbolic model are denoted as \( a \), \( b \), and \( c \), while those in the combined model are \( \beta_0 \), \( \beta_1 \), and \( \beta_2 \). The parameters are estimated using statistical methods.

Table 4. Parameter estimates for the combined model for the regression of soybean yield as a result of multiple-weed interference expressed as the total density equivalent and applied nitrogen in the pooled two-year data. The numbers in parentheses are standard errors.

| Parameters | \( Y_{bi} \) | \( \beta_i \) | Pseudo R\(^2\) |
|------------|-------------|-------------|-------------|
| \( a \)    | 1.65        | 1.65        | 0.86        |
| \( b \)    | 0.016       | 0.016       |             |
| \( c \)    | 2.96 \times 10^{-18} | 0.05 \times 10^{-20} |             |
| \( d \)    | 1.05        | 1.05        |             |
| \( l \)    | 0.081       | 0.081       |             |
| \( m \)    | 1.05        | 1.05        |             |

Figure 3. Soybean yield as a function of the total density equivalent and applied nitrogen in the pooled two-year data. The mesh is fitted values calculated using the combined model and parameter estimates (Table 4).

4. Discussion

N fertilizer was applied to promote early soybean growth and thus to secure soybean yield due to the short frost-free period in the region of Primorsky krai, Russia. N application at 36 kg N ha\(^{-1}\) was effective for high soybean production in the region. In our study, soybean yield increased to 2.2 Mg ha\(^{-1}\) as N application increased to 36 kg N ha\(^{-1}\) over years at the Bogatyryka field. In similar weather conditions (Northern Great Plains in USA), low N application of 16 kg N ha\(^{-1}\) at planting enhanced early vegetative soybean growth and resultant seed yield compared to untreated plot [2]. Similarly, for high soybean production, N application in a range from 22.5 to 30 kg N ha\(^{-1}\) was effective in Northeast China, closely linked to the Far-Eastern regions [3,4]. Other regional studies also reported a high increase of soybean yield with increasing N level up to 36 kg N ha\(^{-1}\) [26–28]. However, soybean yield can be reduced more by enhanced weed competitiveness under N-fertilized conditions where weed biomass increases but resultant growth of soybean decreases. Particularly, N application up to 36 kg N ha\(^{-1}\) increased multiple-weed competitiveness to soybean, resulting in a significant yield loss more than 89% at 12 plants m\(^{-2}\) of the total density equivalent (Figure 3). Previous studies also indicated that N fertilizer increases weed competitiveness against crops including rice [11], wheat [14,29] and oilseed rape [30]. The N effect on weed competitiveness with crops might be dependent on interference relationships, since N application changes both crop growth and weed biomass. Our study indicates that A. artemisiifolia and E. crus-galli more increased their competitiveness over soybean by five-fold and three-fold increases compared with the value of B. syzigachne, respectively, as N application increased up to 36 kg N ha\(^{-1}\) (Table 1; Figure S2). Thus, when A. artemisiifolia and E. crus-galli are not adequately managed, N application can increase
their competitiveness; rather, soybean yield can be offset by nitrophilous weed species at high N fertilization.

The combined rectangular hyperbolic model used in our study to describe N effects on weed-free soybean yield and multiple-weed competitiveness is useful in supporting decision making for weed management in combination with a N fertilizer use scenario. The combined model suggests weed threshold values for soybean yield, in consideration of weed interference under N-fertilized conditions. If target soybean yield is decided at a given N level, economic thresholds (ETs) of multiple-weed species can be predicted by comparing the cost of controlling weed species with the benefit gained by herbicide application (e.g., Song et al. [8], Cousens [31], Zanin et al. [32]). In this region, the sequential application of herbicides, S-metolachlor followed by bentazon + imazamox, is recommended for respective pre- and post-emergence weed control (e.g., Song et al. [22]). Soybean price and herbicide cost are US $650 Mg$^{-1}$ and US $87.2$ ha$^{-1}$, respectively, and N costs are US $16.2$, US $32.3$, and US $48.5$ ha$^{-1}$ for 12, 24, and 36 kg N ha$^{-1}$, respectively (e.g., Song et al. [22]). Using these values, the proportion of yield loss caused by unit total density equivalent obtained in our study, and assuming a 90% herbicide efficacy, the calculated ETs are 1.46, 0.90, 0.57, and 0.38 plants m$^{-2}$ at 0, 12, 24, and 36 kg N ha$^{-1}$, respectively (Table 5). Therefore, thorough weed management should be made to achieve maximum soybean yield in the region in combination with N application. In a combination of 36 N kg ha$^{-1}$, the sequential application of herbicides at ET greater than 0.38 plants m$^{-2}$ may secure the maximum soybean yield of 2.2 Mg ha$^{-1}$.

Table 5. Economic thresholds (ETs) of multiple-weed species including Ambrosia artemisiifolia, Echinochloa crus-galli, and Beckmannia syzigachne at different nitrogen levels in the pooled data.

| Nitrogen (kg N ha$^{-1}$) | Parameters and ETs $^{a}$ | Parameters and ETs $^{b}$ |
|------------------------|-------------------------|--------------------------|
|                        | $C_0$ ($\text{ha}^{-1}$) | $C_h$ ($\text{ha}^{-1}$) | $C_a$ ($\text{ha}^{-1}$) | $Y_o$ (Mg ha$^{-1}$) | $P$ ($\text{Mg}^{-1}$) | $L$ | $H$ | ET $^{b}$ |
| 0                      | 0                       | 87.2                     | 17.7                     | 1.65                 | 650 | 0.075 | 0.90 | 1.46  |
| 12                     | 16.2                    | 87.2                     | 17.7                     | 1.84                 | 650 | 0.125 | 0.90 | 0.90  |
| 24                     | 32.3                    | 87.2                     | 17.7                     | 2.03                 | 650 | 0.202 | 0.90 | 0.57  |
| 36                     | 48.5                    | 87.2                     | 17.7                     | 2.22                 | 650 | 0.311 | 0.90 | 0.38  |

$^{a}$ ET = $\frac{C_0 + C_h + C_a}{Y_o + P}$ ($C_0$ is urea cost (US $\text{ha}^{-1}$); $C_h$ is herbicide cost (US $\text{ha}^{-1}$); $C_a$ is application cost (US $\text{ha}^{-1}$); $Y_o$ is weed-free soybean yield (Mg ha$^{-1}$); $P$ is value per unit soybean (US $\text{Mg}^{-1}$); $L$ is a proportional loss per unit total density equivalent; $H$ is herbicide efficacy (% weed control/100). Parameters $C_0$, $C_h$, $C_a$, and $P$ were obtained from Song et al. [22]. At a given nitrogen level, parameters $Y_o$ and $L$ were calculated using the combined rectangular hyperbolic model and parameter estimates described in Table 4. $^{b}$ ET of multiple weed species at different nitrogen levels is expressed as the total density equivalent m$^{-2}$.

5. Conclusions

The combined model developed here can support decision making for weed management under different N uses in soybean cultivation across Primorsky krai and neighboring regions. It can be used to advise both herbicide and N applications for a target soybean yield. Nonetheless, the combined model and parameter estimates need to be further validated for a broad range of N rate, years, and locations.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4395/11/3/515/s1, Table S1: Weed species and densities for soybean-weed competition at different nitrogen levels in 2013 and 2014, Table S2: A pairwise comparison of parameter estimates between years using dummy variables at different nitrogen levels, Table S3: Density equivalents of Echinochloa crus-galli and Beckmannia syzigachne in comparison with Ambrosia artemisiifolia as the reference weed species at different nitrogen levels in 2013 and 2014 and for the pooled two-year data, Table S4: Summary of non-linear regression analysis and $F$-test to compare models for soybean yield as a function of the total density equivalent and applied nitrogen in the pooled two-year data, Figure S1: Weed-free soybean yield ($Y_o$) as a function of applied nitrogen in 2013 (●) and 2014 (□) and for the pooled two-year (---) data presented in Table 1. The lines are fitted values calculated using inverse...
quadratic model, Figure S2: Weed competitiveness of *Ambrosia artemisiifolia*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* as a function of applied nitrogen in 2013 (---) and 2014 (—) and for the pooled two-year (—) data presented in Table 1. The lines are fitted values calculated using exponential model.

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