Simulation of Atmospheric Ozone Impact on Rice Yield and Analysis of the Yield Loss Variations

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ABSTRACT

A simple growth model to simulate effects of ozone on growth and yield of paddy rice was developed, and was used to assess the ozone impact on rice production in the Kanto region of Japan for the period 1981-1985. Estimated yield loss by ozone ranged from 0% to 7% by locations, and the production loss amounted up to 4.6 % of the total rice production. The simulated yield loss correlated with the seasonal mean ozone concentration with a significant scattering, which indicated the perturbation of the ozone dose-yield loss relationship (D-R relationship). To locate the causes of the perturbation, the yield loss was partitioned into the yield loss caused by the ozone exposure before heading (vegetative growth) and that after heading (reproductive growth). Correlations between the yield losses and the mean ozone concentrations for both vegetative and reproductive growth were further examined by scatter plots. Interpretation of the results of these analyses was facilitated by theoretical considerations on the possible causes of the perturbation of the D-R relationship. Results of the analyses indicated that the simulated yield loss caused by ozone is mainly due to the ozone exposure after heading. The analyses also identified the big difference between the ozone impact during the vegetative growth and that during the reproductive growth as the primary cause of the perturbation of the D-R relationship. Weather and transplanting timing were also recognized as additional perturbing factors. Effects of other factors intrinsic in the ozone impact on growth processes were also suggested.

INTRODUCTION

Ozone is one of the major air pollutants across the world. Its impacts on crop production have been comprehensively assessed in the U.S. (e.g. Heck et al., 1983; Heck et al., 1991). Effects of ozone on the yield of various crops, e.g. soybean and cotton, were described by the Weibull distribution function (Heck et al., 1984). The relationships between the mean ozone concentration across a season and the relative yield loss (dose-response relationship) were used to assess economic impacts of the ozone air pollution in the U.S. (Adams et al., 1989). The dose-response relationships were also used to assess ozone impacts on crop production in Japan (Kobayashi, 1988).

While the dose-response relationships have been used quite ubiquitously, it is well known that other environmental and genetic variations, e.g. soil moisture and cultivars (Heagle et al., 1988), could alter the relationship. The interactive effect of soil moisture stress has been addressed with a soybean growth model (Kobayashi et al., 1990). The model analysis suggested that the reduced ozone impact under soil moisture stress is due to the limitation of available soil water rather than the stomatal closure (Kobayashi et al., 1993).

Although rice is the primary crop across the Pacific-Rim countries, only two studies (Olszyk et al., 1988; Adams et al., 1989) have included rice among other species in the assessment of crop loss due to ozone. Both studies were based on the dose-response relationship derived from the results of an experiment in California (Kats et al., 1985).

To address the impact of ozone on rice production, a program was performed from 1986 through 1991 in Japan. Field experiments using ozone exposure chambers were conducted, and a rice growth model was developed from the results of the experiments. The model was used to assess the ozone impact on regional rice production in Japan. The perturbations of the ozone dose-yield loss relationship were also studied with the model.

Objectives of this paper are to:

(i) outline the results of the ozone impact assessment, and to

(ii) address the perturbations of the ozone dose-yield loss response relationship.

Further details of the model structure and results of the assessment have been presented elsewhere (Kobayashi, 1992).

THE OZONE IMPACT ASSESSMENT

Domain and method

The ozone impact on rice production was assessed for the 'Kanto district', which includes Tokyo and the surrounding six Prefectures (Fig. 1). This region is one of the most polluted areas in terms of air quality in Japan, and is also a major agricultural region. Considerable crop losses caused by ozone have been estimated for soybean and peanut (Kobayashi, 1988).

The Kanto district was divided into grid cells with 7.5 min. longitude by 5 min. latitude each, c.a. 10 x 10 km. Cells on the prefectural boundaries were divided into the respective prefectures by the boundary. The simulation was performed by the grid cells and the boundary cells for the five seasons from 1981 through 1985. To assess the impact of anthropogenic ozone, the simulation was performed with the base and the actual concentrations of ozone. The yield loss was determined from the ratio of the simulated yield with the actual ozone concentration to that with the base-level ozone.

The base-level ozone concentration was set rather arbitrarily at 20 ppb, which is about 1.5 percentile of the daily ozone concentrations for the five seasons.

The model

The model structure is shown in Fig. 2. The model simulates growth of rice plants on the time step of one day. Daily dry matter accumulation is determined by the amount of solar radiation absorbed by the plant canopy and the light-use efficiency (LUE). Light absorption is determined by the leaf area index, which is calculated from the increments of leaf number and leaf size per leaf number. The model also calculates heading date from the daily mean air temperature and the latitude, using a model of the developmental growth of rice (Kawakata & Okada, 1989). At the harvesting time, the total dry matter is multiplied by the harvest index to determine the rice yield.

Among the growth processes simulated by the model, light utilization is the only process subjected to the ozone impact. The effect of ozone on LUE is described by a quadratic function in vegetative growth and a linear function in the reproductive growth (Fig. 3). The ozone impact is much greater in the reproductive growth than in the vegetative growth. The model was written in the SAS programing language (SAS Institute Inc., 1988a), and the simulation results were analyzed and displayed with

SAS/STAT (SAS Institute Inc., 1988c) and SAS/GRAPH (SAS Institute Inc., 1988b) softwares.

Results of the assessment

The simulated yield loss for each cell with the 20 ppb base ozone concentration ranged from 0 % to 7% on the average of the five seasons. This yield loss translated into the total production loss ranging from 16,000 ton in 1981 to 78,500 ton in 1985, which corresponded to 1.1 % (1981) to 4.6 % (1985) of the total rice production in this region (Kobayashi, 1992).

Problems of the simulated dose-response relationship

The simulated yield loss correlated with the seasonal mean ozone concentration with significant scattering (Fig. 4). In the figure, the simulated yield loss for each cell in each of the five seasons is represented by a dot, which numbers to 1875 in total. The scattering of the dots indicates perturbations of the dose-response relationship. What causes this perturbation? Because the simulation is deterministic, i.e. no random variables are included, the perturbation should be ascribed to some factors other than random variation.

The seasonal mean ozone concentration was divided into the mean ozone concentrations before and after heading. The scatter plots of the simulated yield loss on the mean ozone concentrations (Fig. 5) showed much better correlation for the reproductive growth than for the vegetative growth. This appears to have resulted from the model assumption: the effect of ozone on LUE is much greater in reproductive growth than in vegetative growth (Fig. 3).

However, it is still unclear how the impact of ozone on the growth process translated into the correlation between the yield loss and the mean ozone concentration. As statistics textbooks (e.g. Rawlings, 1988) caution us, a distinction must be made between correlation or association and causality. A higher correlation does not necessarily mean a greater responsibility. Or, if the ozone exposure after heading is in fact dominating the yield loss, how dominant is it? As assumed in the model, the ozone exposure before heading does affect the growth, if in a lesser extent than after heading. How can we quantify the contributions of the ozone exposures in the respective growth periods to the yield loss? Furthermore, what causes the perturbations of the dose-response relationships for the vegetative growth (Fig. 5A) and for the reproductive growth (Fig. 5B)?

The above questions are addressed in the next part.

ANALYZING THE SIMULATED DOSE-RESPONSE RELATIONSHIP

The ozone effect on LUE

In the model, the effect of ozone on the light-use efficiency (LUE) is described as,

$$\varepsilon = \varepsilon_v (1 - c_v Oc^2) \qquad \text{before heading, and}$$

$$\varepsilon = \varepsilon_r (1 - c_r Oc) \qquad \text{after heading,}$$

where ε is LUE under ozone exposure, ε_v and ε_r are LUE for the vegetative and reproductive growth, respectively, under no ozone impact, Oc is the daily mean 7-h (9:00-16:00) ozone concentration, and c_v and c_r are the model coefficients. The above relationships can be generally denoted as,

$$\varepsilon = \varepsilon_0 [1 - f(Oc)].$$

Then, the simulated rice yield (Y) can be described as,

$$Y = HI \sum_{i=1}^{N_h} Sabs_i \, \varepsilon_0 [1 - f(Oc_i)], \tag{1}$$

where HI is the harvest index, $Sabs$ is the absorbed solar radiation on a daily basis, and N_h is the number of days from transplanting to harvest.

Partitioning the relative yield loss

The relative yield loss (y) is defined as,

$$y = 1 - Y/Yb,$$

where Yb is the simulated yield at the base ozone concentration. The relative yield loss (y) is partitioned into the yield loss due to the ozone exposure before heading (yv) and the yield loss after heading (yr) as noted below.

Let Yv be the simulated yield of rice subjected to the ozone exposure for the vegetative growth and, after heading, moved to the base ozone concentration , viz.,

$$Yv = HI \sum_{i=1}^{N_r} Sabs_i \, \varepsilon_0 [1 - f(Oc_i)] + HI \sum_{i=N_r+1}^{N_h} Sabs_i \, \varepsilon_0 [1 - f(Ob)],$$

where N_f is the number of days from transplanting to heading, and O_b is the base ozone concentration. Similarly, let Y_r be the simulated yield of rice grown in the base ozone concentration and then exposed to ozone as,

$$Y_r = HI \sum_{i=1}^{N_f} S_{abs_i} \varepsilon_0 [1 - f(O_b)] + HI \sum_{i=N_f+1}^{N_h} S_{abs_i} \varepsilon_0 [1 - f(O_{c_i})].$$

The relative yield losses for the respective growth periods are defined as,

$$y_v = 1 - Y_v/Y_b \text{, and}$$
$$y_r = 1 - Y_r/Y_b.$$

Substitutions of Y_v and Y_r in these equations by their definitions noted above yields

$$y = y_v + y_r .$$

The relative yield loss is thus partitioned into the yield loss due to the ozone exposure in the vegetative growth and the yield loss in the reproductive growth.

By performing the partitioning for all the 1875 cells, the following sets of the simulated yield losses are obtained.

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_{1875} \end{pmatrix} = \begin{pmatrix} yv_1 \\ yv_2 \\ \vdots \\ yv_{1875} \end{pmatrix} + \begin{pmatrix} yr_1 \\ yr_2 \\ \vdots \\ yr_{1875} \end{pmatrix},$$

or in a vector format,

$$\mathbf{y} = \mathbf{y_v} + \mathbf{y_r}. \qquad (2)$$

Thus, the 1875 sets of the simulated yield losses are expressed as the three vectors in a linear space of 1875 dimension. Although the whole vector space cannot be viewed at once, the three vectors span a two-dimensional space, i.e. a plane. The vectors can easily be visualized as arrows on the plane.

Mean ozone vectors and the yield loss plane

The mean ozone concentrations across the whole season, before heading, and after heading can also be expressed as vectors in the same 1875-dimensional space. Those vectors do not, however, reside in the same subspace as the yield loss vectors, and hence cannot be plotted in the plane. To resolve this situation, the mean ozone vectors can be projected to the yield loss plane. The projected vectors can then be visualized. Note that the projected vectors represent only a part of the original vectors.

Scatter plots

The above approach can be regarded as a way to visualize the data in a multidimensional space by reducing the dimension of the space. Another way to view the multidimensional data is to plot a scattergram as shown below.

Let **A** be a matrix composed of the four vectors, viz.,

$$\mathbf{A} = (\mathbf{y}, \mathbf{O}, \mathbf{O}_v, \mathbf{O}_r),$$

where $\mathbf{y}$ is the yield loss vector, and $\mathbf{O}$, $\mathbf{O}_v$ and $\mathbf{O}_r$ are the vectors of the mean ozone concentrations for a whole season, for vegetative growth, and for reproductive growth, respectively.

By transposing the matrix **A**, the four vectors in the 1875-dimensional space can be viewed as the 1875 vectors in a four-dimensional space. By representing each of the 1875 vectors as a dot, they can be expressed as a scatter plot in the four-dimensional space. The scatter plots in the planes y - O, y -O_v and y-O_r are the projections of the four-dimensional scatter plot to the two-dimensional subspaces. The whole aspects of the four-dimensional space can thus be visualized. This approach is appropriate when correlations between the variables are of primary concern, which is the case here.

Note, however, that any intrinsic relations between the vectors become implicit when the vectors are aggregated into the matrix **A**. A quantitative relation between the vectors may be estimated with regressions, but it is solely based on the correlations instead of the intrinsic relations. Therefore, the regression might be inappropriate when there exists such intrinsic relations between the vectors, e.g. $\mathbf{y}$, $\mathbf{y}_v$, $\mathbf{y}_r$ in eqn. 2.

Relations between the scatter plot and the vector expression in the multidimensional space have been outlined in the context of multivariate statistics (Kendall, 1975).

Sources of the perturbation of the dose-response relationship

The perturbation of the dose-response relationship could originate from various factors as shown below.

Taking the first order derivative of the function f in eqn. 1, the simulated yield can be written as,

$$Y = HI \sum_{i=1}^{N_h} S_{abs_i}\, \varepsilon_0 \,[1 - f(O_b) - f'(O_b)\,(O_{c_i} - O_b) - e_i],$$

where e_i is sum of the higher order terms. The relative yield loss y is,

$$y = HI \sum_{i=1}^{N_h} S_{abs_i}\, \varepsilon_0 \,[f'(O_b)\,(O_{c_i} - O_b) + e_i] / Y_b. \tag{3}$$

Eqn. 3 indicates that the relative yield loss (y) can be expressed as a linear function of the weighted mean of the daily ozone concentration (O_c). Since the dose-response relationship is based on non-weighted mean ozone concentration, a disparity between the weighted mean and the non-weighted mean may cause the perturbation of the dose-response relationship. The weight ($S_{abs_i}\, \varepsilon_0\, f'(O_b) / Y_b$) and the approximation error (e_i) could be the sources of the disparity.

Before the canopy closure, S_{abs} increases with the increment of the leaf area. Incident solar radiation directly alters S_{abs}. Temperature also affects S_{abs} via its effects on the leaf area increase in the vegetative stage. The model parameter ε_0 may be the most influential factor in the weighting. As shown in Fig. 3, ε_0 , and hence the weighting, differs greatly between the vegetative and the reproductive growth periods. Although ε_0 is not directly affected by the environmental variables, a change in the timing of the heading would alter the switching from the model parameter value for vegetative growth to that for reproductive growth. Net effect of this is the altered weighting by ε_0. Timing of the transplanting should be the primary determinant of the heading date, but temperature and day length may also have some impacts via their effects on development rate. The first derivative $f'(O_b)$ may also participate in the weighting for the same reason as ε_0.

The effect of the approximation error (e_i in eqn. 3) depends on the form of the function f. For reproductive growth, in which f is linear, e_i can be omitted. Whereas, it may cause the disparity between the weighted and non-weighted mean ozone concentrations in vegetative growth, in which f is a quadratic function.

Separating the effects of weather variables and transplanting date

As noted above, various factors may be involved in the perturbation of the dose-response relationship. Among them, the effects of cell-to-cell variation in the weather variables and the transplanting date were examined here. For this purpose, medians of the rice planting date and the weather variables across the cells were calculated, and these same median values were used to simulate the yield loss in all the cells. Dose-response relationship between the mean ozone concentrations and the relative yield loss calculated with the above simulation was examined in the same way as for the original simulation.

RESULTS AND DISCUSSION ON THE SIMULATED DOSE-RESPONSE RELATIONSHIP

Contributions of the ozone exposures before and after heading

The relationships between the yield loss vectors: $\mathbf{y}$, $\mathbf{y}_v$ and $\mathbf{y}_r$, are shown in Fig. 6. Note that the vector sum $\mathbf{y}_v + \mathbf{y}_r$ gives the yield loss vector $\mathbf{y}$. Associations between the vectors are represented by the angles between them, and the magnitudes of the yield losses are represented by the vector norms. The yield loss due to the ozone exposure after heading ($\mathbf{y}_r$) is close to the total yield loss ($\mathbf{y}$), as the small angle between the two vectors shows. The size of the vector $\mathbf{y}_r$ is also close to that of the vector $\mathbf{y}$, hence, the total yield loss is certainly dominated by the yield loss due to the ozone exposure after heading. The yield loss due to the ozone impact before heading, as represented by the vector $\mathbf{y}_v$, is small, and deviates from the vector $\mathbf{y}$ greater than the vector $\mathbf{y}_r$.

Relationships between the mean ozone concentrations and the yield losses

Also shown in Fig. 6 are the projections of the mean ozone concentrations. Their scale is not the same as for the yield loss vectors, and, therefore, only the orientations have the meaning when the vectors are compared between the yield losses and the mean ozone concentrations. Fig. 6 shows that the yield loss vector ($\mathbf{y}$) considerably deviates from the projected seasonal mean ozone concentration ($\mathbf{P}$) as the angle between them shows. This deviation between the vectors $\mathbf{y}$ and $\mathbf{P}$ represents the perturbation of the dose-response relationship.

Deviation is also notable between the projections $\mathbf{P}_v$ and $\mathbf{P}_r$, as well as between the yield losses $\mathbf{y}_v$ and $\mathbf{y}_r$. Whereas, there are close associations between the vectors within each growth period, as indicated by the small angles between $\mathbf{y}_r$ and $\mathbf{P}_r$, and between $\mathbf{y}_v$ and $\mathbf{P}_v$. The above situation with the projections was quite similar with the original vectors for the mean ozone concentrations $\mathbf{O}_r$ and $\mathbf{O}_v$ (figure not shown here).

Thus, Fig. 6 indicates that the perturbation of the dose-response relationship as indicated by the disparity between the vectors $\mathbf{y}$ and $\mathbf{P}$ is obviously due to the difference between the positioning of the yield loss vectors and that of the mean ozone vectors. In the former, $\mathbf{y}_r$ is by far greater than $\mathbf{y}_v$, and hence their sum $\mathbf{y}$ is close to $\mathbf{y}_r$. To the contrary, the projected vector for the seasonal mean ozone concentration ($\mathbf{P}$) is 'drawn' by the vector $\mathbf{P}_v$. Net result of this is the deviation between the vectors $\mathbf{P}$ and $\mathbf{y}$. In other words, the perturbation of the dose-response relationship is primarily due to the difference between the weighting for the yield loss and that for the mean ozone concentration.

Correlations between the yield losses and the mean ozone concentrations are depicted by the scatter plots (Fig. 7). The correlation before heading (Fig. 7A) is much lower than after heading (Fig. 7B). Note, however, that the scale for Fig. 7A is only less than one fourth of that for Fig. 7B. The scattering *per se* does not differ much between the two growth periods. Also note that the scattering in Fig. 7B is somewhat smaller than that in Fig. 5B. This is reflected to the smaller angle between the vectors $\mathbf{y}_r$ and $\mathbf{P}_r$ than between $\mathbf{y}$ and $\mathbf{P}_r$ (Fig. 6).

Results of the simulation with the median inputs

The results of the simulations with median weather and transplanting date are shown in Fig. 8. Although the yield losses are generally smaller than the corresponding yield losses in the original simulation (Fig. 6), relations between them are quite similar to the original simulation. Notably, the yield loss vector $\mathbf{y}_r$ is closer to the projected mean ozone vector $\mathbf{P}_r$ than in the original simulation. This is clearly reflected in Fig. 9, where the yield losses with the median inputs were plotted on the mean ozone concentrations. The relationship between the yield loss and mean ozone concentration for the reproductive growth is closer in Fig. 9B than in Fig. 7B. This indicates that the weather and the timing of transplanting may serve as the perturbing factors to the ozone-yield loss relationship after heading.

Interestingly, the dose-response relationship for the vegetative growth still shows a considerable variation (Fig. 9A). This variation may be ascribed to either the approximation error (e_i) or the temporal variation in the weighing $(S_{abs_i} \varepsilon_0 f'(O_b) / Y_b)$ in eqn. 3. Further analyses in a similar approach would identify the causes of the perturbations.

CONCLUSIONS

In summary, the simulated yield loss caused by ozone in the Kanto district is mainly due to the ozone exposure after heading. The relationship between seasonal mean ozone concentration and the relative yield loss perturbs primarily because of the big difference between the yield loss before heading and that after heading. Weather and transplanting timing may serve as additional perturbing factors to the ozone-yield loss relationship. The perturbation of the dose-response relationship could also be caused by the other factors intrinsic in the ozone impact on growth processes.

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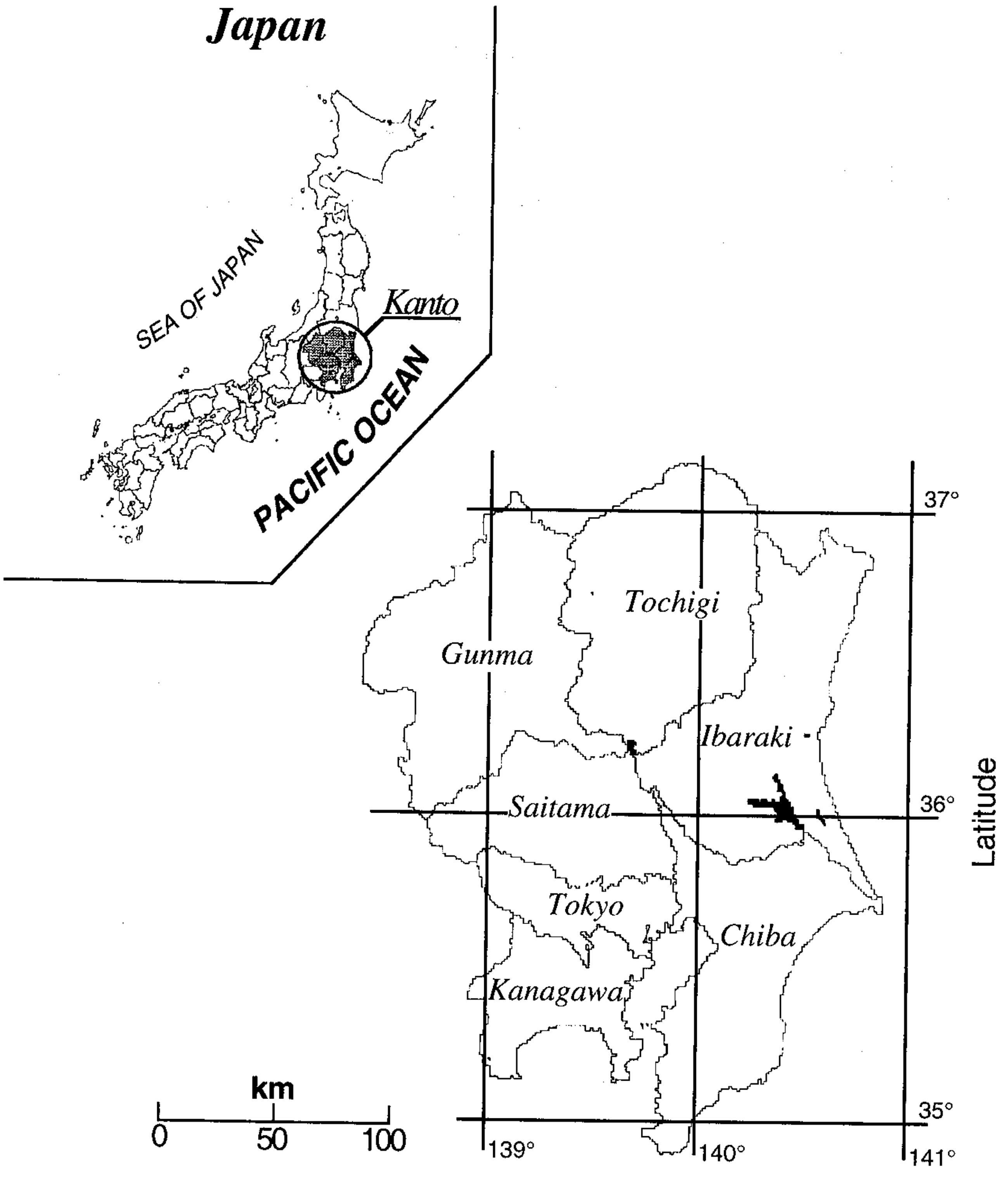

Fig. 1. The Kanto district of Japan.

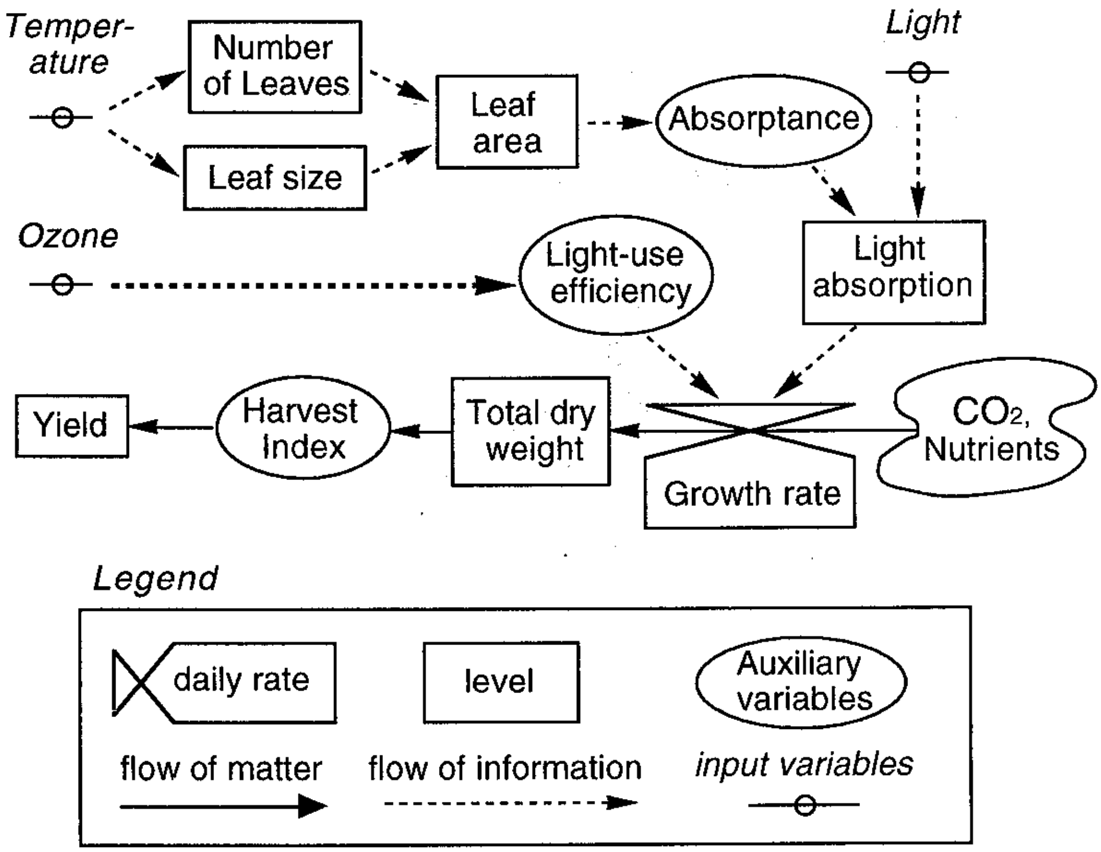

Fig. 2. Block diagram of the rice growth model.

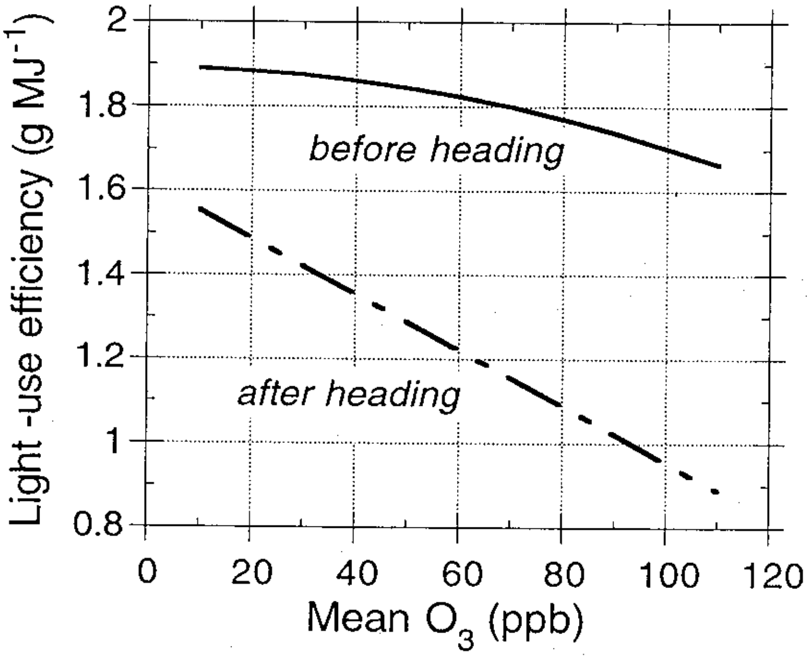

Fig. 3. Modeled relationships between daily 7-h (9:00-16:00) mean ozone concentration and the light-use efficiency.

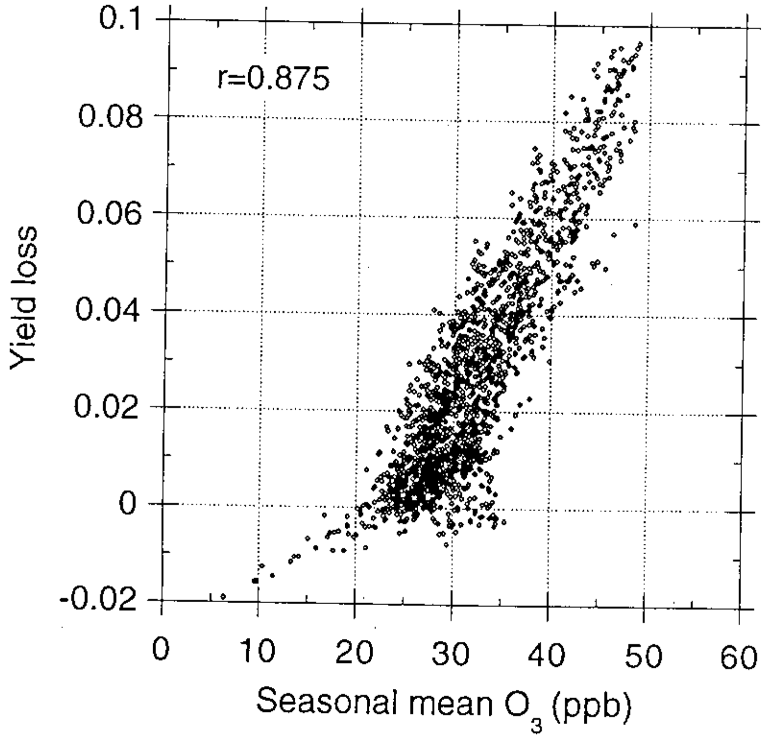

Fig. 4. Relationship between seasonal mean ozone concentration and simulated yield loss.

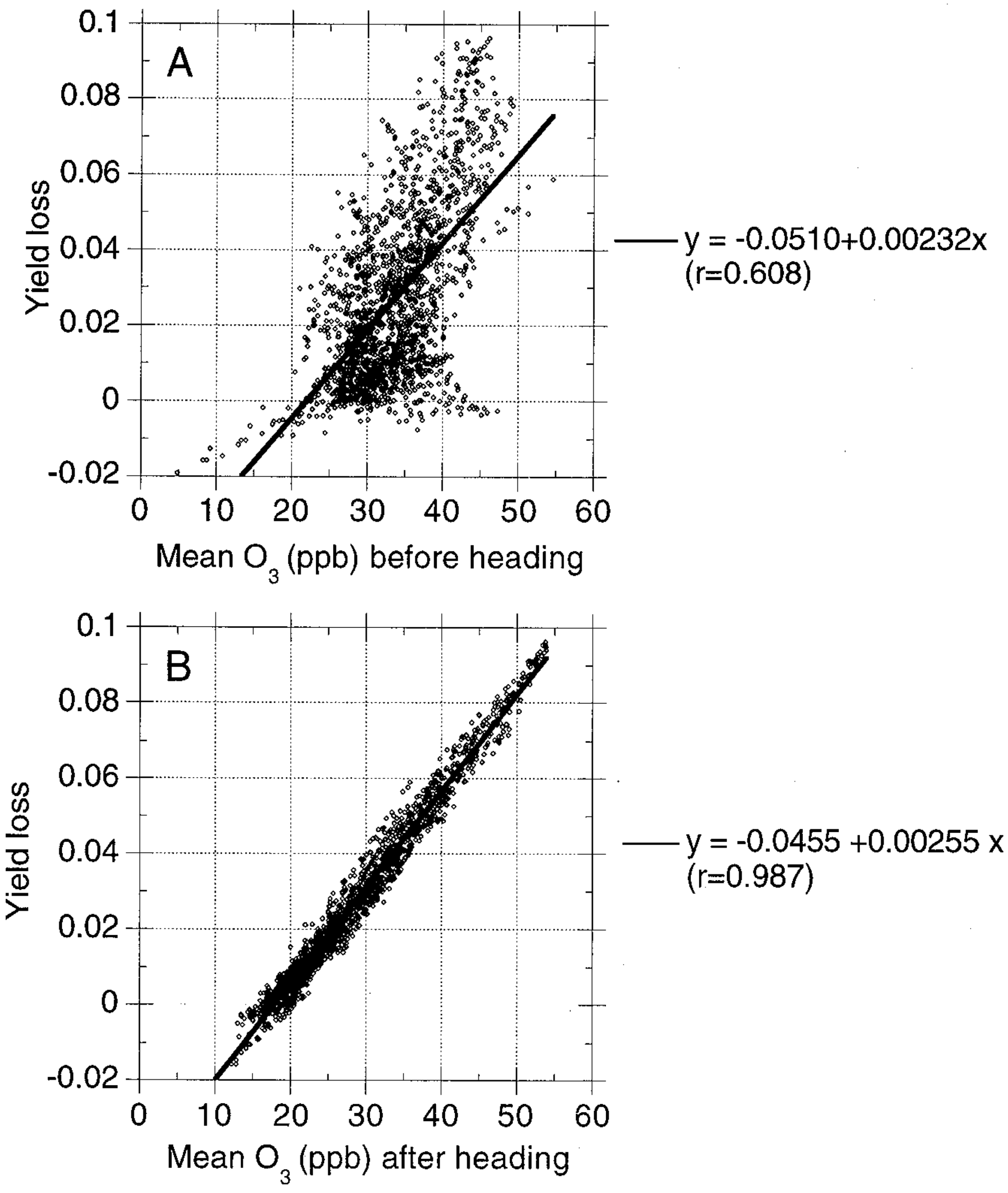

Fig. 5. Relationships between the simulated yield loss and mean ozone concentrations before (A) and after (B) heading.

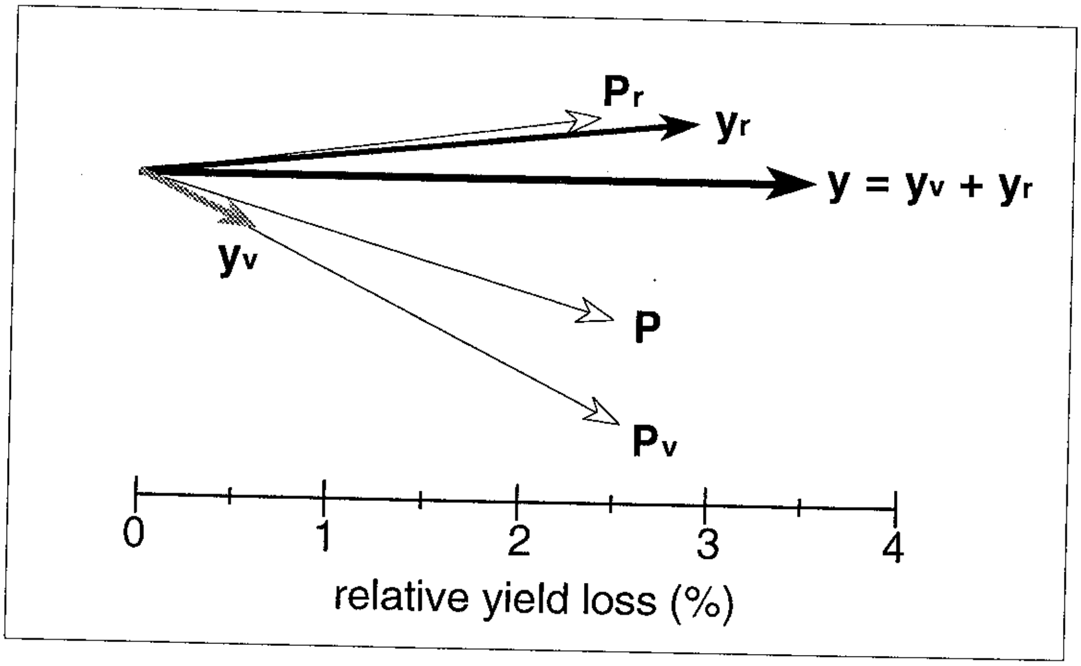

Fig. 6. Vector expression of the relative yield losses (**y**, **y**$_v$, **y**$_r$) and the mean ozone concentrations (**P**, **P**$_v$, **P**$_r$).

The scale shows relative yield loss (%).

y: yield loss due to the ozone exposure for an entire season,

y$_v$: yield loss due to the ozone exposurebefore heading,

y$_r$: yield loss due to the ozone exposure after heading,

P: projection of the vector for the seasonal mean ozone concentration,

P$_v$: projection of the vector for the mean ozone concentration before heading,

P$_r$: projection of the vector for the mean ozone concentration after heading.

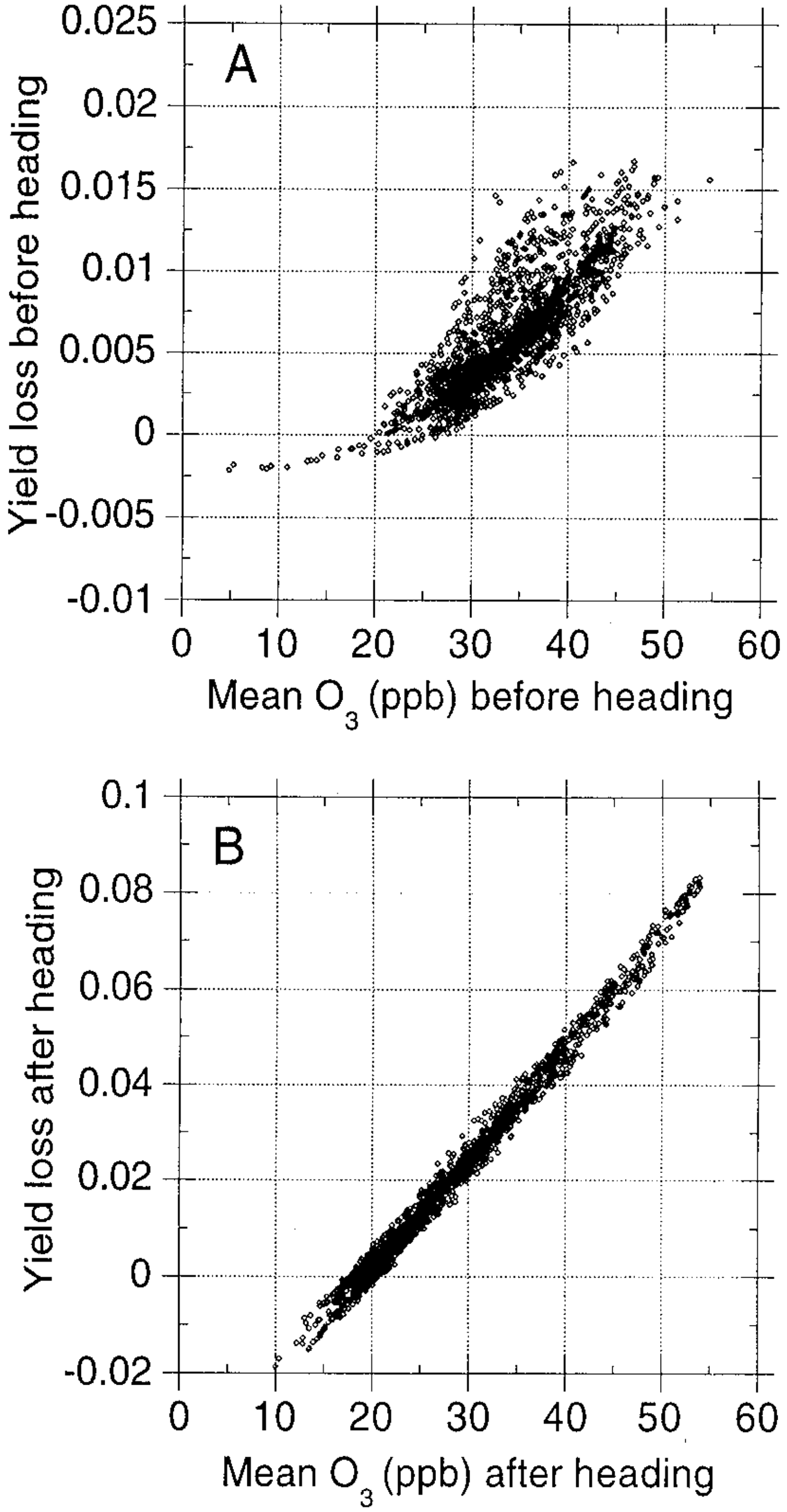

Fig. 7. Relationships between mean ozone concentration and yield loss for the ozone exposures before (A) and after (B) heading.

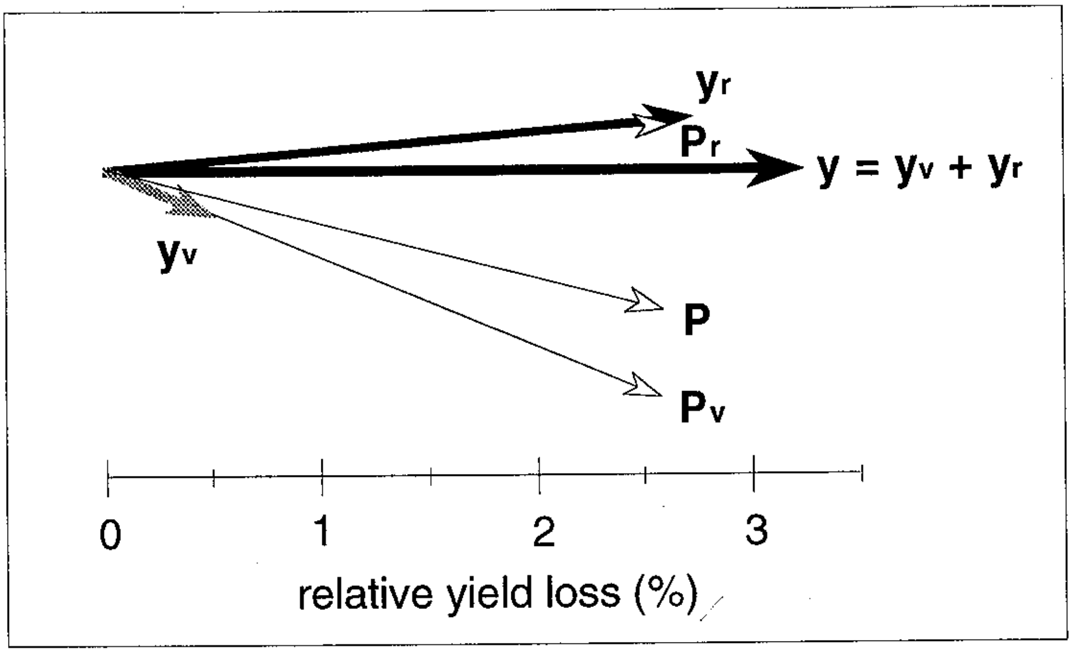

Fig. 8. Vector expression of the relative yield losses (**y**, $\mathbf{y}_v$, $\mathbf{y}_r$) and the mean ozone concentrations (**P**, $\mathbf{P}_v$, $\mathbf{P}_r$).

Simulation was performed with the median values of weather and transplanting date throughout the domain of the assessment.

Definition of the vectors are the same as for Fig. 6.

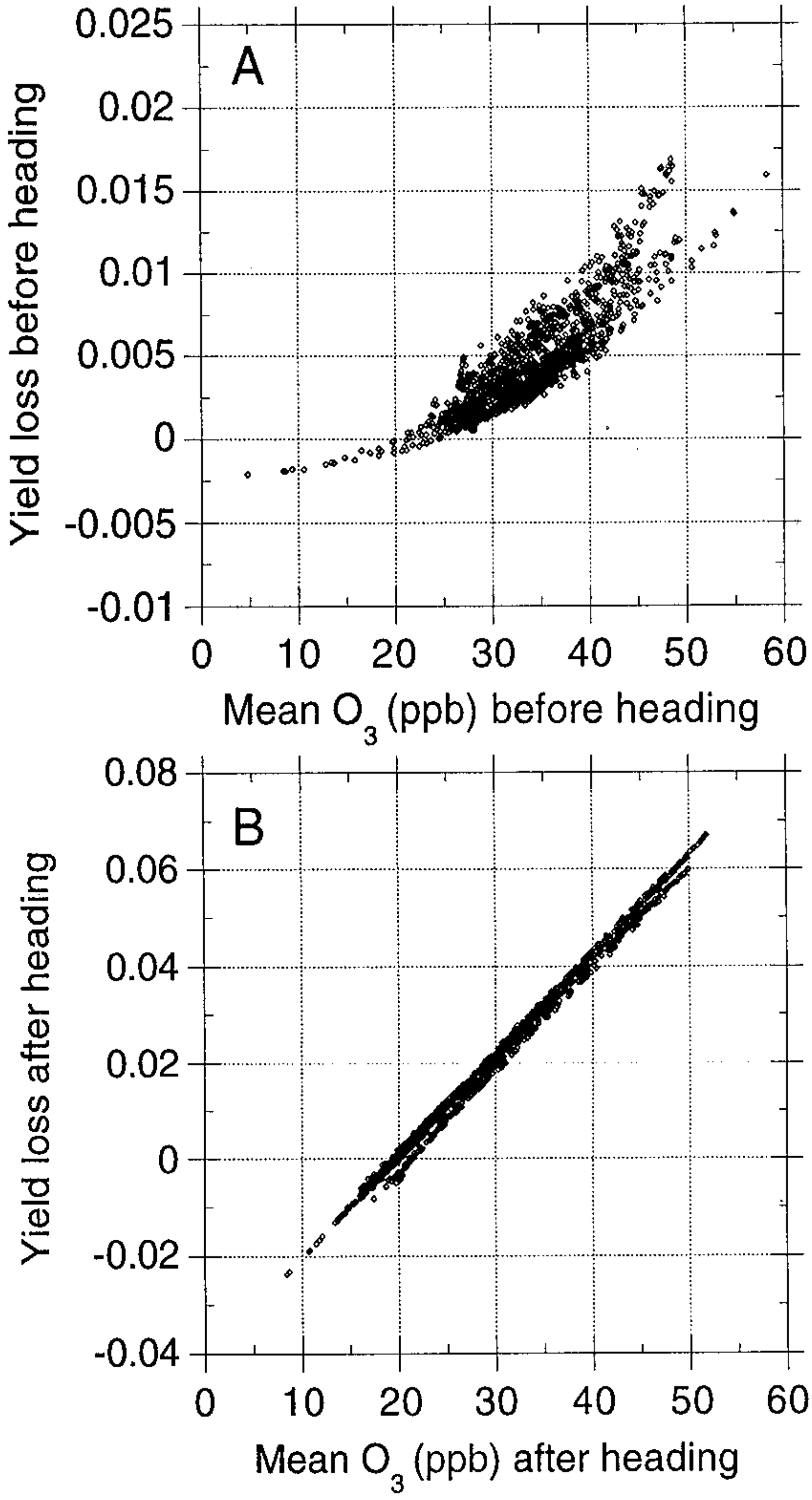

Fig. 9. Relationships between mean ozone concentration and yield loss for the ozone exposures before (A) and after (B) heading.

Simulation was performed with the same median values for weather and transplanting date across the region.