Three-dimensional numerical simulations of windbreak effects on pollen dispersal and cross-pollination

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Abstract. Based on the atmospheric turbulence diffusion model, a three-dimensional numerical model was applied for predicting the cross-pollination rate distribution in leeward area of windbreaks by considering actual weather observation data, daily fluctuation parameter of pollen release rate, pollen life during flowering period, etc. Several cases of cross-pollination effect of windbreak distributions in the field were simulated. It is demonstrated that windbreak nets and windbreaks plant or forest are effective in suppressing pollen dispersal and cross-pollination. By simulating pollen diffusion under actual weather conditions using this model, it is possible to evaluate the effect of cross-pollination by the windbreak facilities and give advises of how to set windbreaks for suppressing crossing.

1. Introduction
When genetically modified crops are cultivated in general field, there is a concern that diffusion of transgenes into ecosystems due to crossing with surrounding non-recombinant crops [1]. As a method of suppressing crossing, technologies for weakening the wind by windbreak nets and windbreaks plant or forest, suppressing soaring and spreading of pollen are conceivable. Comprehensive studies on the dynamical effects of windbreaks on natural wind profiles have been reported (e.g., [2] – [7]), especially in the recent literature [8], wake-moment coefficient and lateral wake deflection of three-dimensional windbreaks are explored for better predictions of the windbreak drag coefficient. Generally, windbreaks suppress wind speed on their leeward side within the distance of 10–20 times of their height. The denser the windbreak, the narrower is the area of wind suppression. In the case of very dense windbreaks, such as a board, the air flow on the leeward side circulates toward the upstream direction. Therefore, a moderate-density windbreak is more effective than a very dense windbreak to suppress wind speed on the leeward side. Although the pollen dispersion by wind (e.g., [9], [10]) and the effects of wind reduction by windbreaks have been well studied (e.g., [2] – [8]), their effects in suppressing pollen dispersal and cross-pollination rates have not yet been reported. It is difficult to conduct on-site observations for evaluating the suppression effect for all cases when using these technologies on the farmer field scale.

In this subject, we develop a numerical model to evaluate the effect of cross-pollination by wind protection facilities and covering materials such as windbreak nets and windbreaks plant or forest and develop a method to simulate the effect on cross-pollination [11]. This method can be used to develop efficient hybridization control methods, such as when actually cultivating genetically modified crops.
Several cases of simulations of cross-pollination effect of windbreak distributions were done in this paper.

2. Methods
In the present study, we conducted numerical experiments on pollen dispersal and cross-pollination by applying the 3-D regional and diffusion transport models A2Cflow and A2Ct&d. A2Cflow predicts atmospheric state using an Eulerian approach, and A2Ct&d predicts particle transport using a Lagrangian approach. The pair of models used in this study was developed by Yamada Science and Art Inc. to simulate the turbulent transport of airborne materials based on the work of [12] and [13]. The details of our model modification are described in [11]. In the present study, several cases of cross-pollination effect of windbreak distributions in the field were simulated by using the model. We first predicted the wind field using the A2Cflow model and then calculated pollen dispersal by the A2Ct&d model. Pollen dispersals from both the donor and recipient maize were calculated, and then the cross-pollination rates were calculated from the two distributions.

The three-hourly horizontal wind speed (u, v), temperature (T), and relative humidity (RH) from the grid point value (GPV) data produced by the Japan Meteorological Agency were used to force the model variables toward large scale variables. The hourly horizontal wind speed observed by the AWS in each domain was also nudged into the model to adjust the wind at 2.5 m height. Time intervals of integration were automatically determined in the model and were 0.1-0.5s. A2Ct&d required pollen emission rates in the pollen dispersion calculation. Regarding the pollen emission, from the observation data, the daily fluctuation parameter of pollen emission and the pollen lifetime during flowering period were also taken into consideration. In the case of corn, a function of temperature change was used [14], and changes between days and daily emission pattern during the period as shown in Figure 1 were put in. In the case of rice, pollen emission amount E (h) was given as a function of time h so as to match the observation value of daily average. The falling speed of pollen is 0.3 m/s.

$$E = 300e^{10.5((h+0.5)/12-1)^2}$$

(1)

After the calculation of the pollen dispersal, the cross-pollination rate (C) within the recipient plot was calculated from the donor (N_D) and the recipient pollen concentrations (N_R) at the height of the ears (0.75 m) as:

$$C = \frac{\sum(D_i \cdot R_{i-2})}{\sum N_{R_{i-2}} \sum (N_{D_i} + N_{R_i})}$$

(2)

where i indicates calculated day. In the calculation, a weighting average with respect to the amount of recipient pollen was applied to take into account of the variation of recipient pollen number. Generally, maize is a protandrous species, i.e., pollen shed begins several days before silking, from 0 to 5 days depending on the combination of drought stress and plant density. In this study the protandry score was 2 days. In the numerator and the denominator of equation (1), the weighting average coefficient N_R has the subscript i-2, which means the weighting average was applied with respect to the pollen number of the recipient two days prior to the calculated day.

3. Results
3.1. Field experiments: verification of the model
The experimental field contained three domains, each of which included a pair of donor and recipient plots with windbreaks in between, as illustrated in Figure 2. The windbreaks comprised a 6-m-tall windbreak net in domain A, bare land in domain B, and a sorghum windbreak in domain C.
Figure 1. Release pattern (diurnal and inter-days) of corn pollen (point observation and alphabet indicates the day, line simulation).

Figure 3 shows the crossing rate calculated by the model and the crossing rate obtained by the observation. The observed result shows the cross-pollination rate near the donor boundary in domain B (no windbreak) was larger than that in domains A and C. This figure also exhibits a large variation in cross-pollination distribution in a range of three orders of magnitude. This deviation is most likely the result of the uneven development, growth and fertilization of the plants. Figure 3 (right) shows the horizontal distributions of the model predicted cross-pollination rates has a smoother distribution but similar characteristics to those of field measurements. The cross-pollination rates were larger near the donor boundary and decreased away from the donor boundary, and the values of domain B were larger than those of domains A and C. Thus, the effect on cross-pollination by the windbreak facility was largely reproduced, and monde for the effect on cross-pollination of the windbreak net was verified. Details about the verification of the model are described in [11].

Figure 2. Arrangement of the experimental cornfield.
3.2. Application of the model
Various conditions were set, and numerical simulation was carried out on the use of the windbreak net in this model. The following 5 examples are given.

3.2.1. Selection of windbreak net density. The physical property data of the windbreak net obtained by the wind tunnel experiment was applied to the numerical model, and the crossing suppression effect of the windbreak net with different mesh was compared. As a result, it became clear that the windbreak net with a mesh size of 1 mm can effectively suppress crossbreeding as compared with the windbreak net with meshes 2 mm and 4 mm. When using a windbreak net with a mesh of 1 mm, the crossing rate decreased by 18-40% compared with the case without the windbreak net, and it decreased by 14 - 25% compared with the case using the windbreak net of 2 mm or 4 mm. (Figure 4)

3.2.2. Selection of windbreak net height. In addition, we compared the cross-pollination effect of windbreak nets with different mesh and height. As a result, in the case of the windbreak net of 6 m height in 1 mm mesh, the cross-pollination effect decreased by 24% on average compared with 3 m height in 1 mm mesh, and decreased by 40% compared with the windbreak net of 3 mm and 2 mm. However, considering the cost of setting the windmill of 6 m, it seems that the cost performance is better when using the 3m height and 1 mm mesh windbreak net.
Figure 4. Simulation of cross-pollination effect of corn hybridization by windproof net mesh.

Figure 5. Simulation of cross-pollination effect of windbreak net with different height and mesh.

3.2.3. Selection of windbreak net setting position. The cross-pollination rate was calculated assuming that windbreak nets were separately installed at three positions: ① the border of the pollen donor and the recipient, ② inside the pollen donor field and ③ in front of donor field as shown in Figure 6. As a result, as shown in Figure 7, setting the windbreak net between the donor and recipient has the smallest effect of cross-pollination as Figure 3, and the most effect position for cross-pollination is inside the pollen donor field.
3.2.4. Selection of windbreak net setting position and several lines of windbreak nets. Five simulations were done for simulation different methods of installation of windbreak nets: ① net1: one line of windbreak net at the border of the pollen donor and the recipient, ② net2: one line of windbreak net inside the pollen donor field, ③ net3: two lines of windbreak net inside of donor field, ④ net4: four lines of windbreak nets inside of donor field and ⑤ net5: 4 lines of windbreak nets inside the donor field as shown in Figure 8.

As shown in Figure 9, all the simulated cross-pollination rates were lower than the case of no net. The order of effectiveness (reduction of cross-pollination rate) of windbreak net setting position and lines of windbreak nets are four lines of windbreak nets inside the donor field > three lines of...
windbreak nets inside the donor field > two lines of windbreak nets inside the donor field > one line of windbreak nets inside the donor field > one line of net between the donor and recipient > no net.

Figure 8. Position of windbreak nets for simulation different methods of installation of windbreak nets.

Figure 9. Simulation of cross-pollination effect by difference of installation position and different lines of windbreak net.

3.2.5. Selection of windbreak net setting to enclose donor field for best effect. Usually, enclosed windbreak nets are used in filed: a field is enclosed by windbreak. As shown in Figure 10, the position of the windbreak nets can reduce wind speed more effectively by placing the net in the lattice shape inside the donor field like the shape of # which we called igeta than the nets arrangement surrounding the donor field as shown in Figure 10. Therefore, the effect of cross-pollination of igeta is also larger than the square enclosed method as shown in Figure 11.
Figure 10. Distribution of wind speed by the windbreak net enclosure method (a: surround the donor field in square boxes).

Figure 10. Distribution of wind speed by the windbreak net enclosure method (b: surround the donor field within the donor field as # shape called igeta).
4. Conclusions

Based on the atmospheric turbulence diffusion model, several cases of three dimensions simulations are done for predicting the cross-pollination rate distribution through pollen diffusion by wind around windbreak nets in consideration of actual weather observation data, daily fluctuation parameter of pollen release rate, pollen life during flowering period, etc. By simulating pollen diffusion under actual weather conditions using this model, it is possible to evaluate the effect of cross-pollination by the windbreak facility. Simulations results show that windbreak nets and windbreaks plant or forest are effective in suppressing pollen dispersal and cross-pollination. We suggest that for better effect on cross-pollination, it is better to using windbreak net of 3m height with 1mm mesh and set several lines of windbreak net inside the donor field or using igeta (#) enclose windbreak nets inside the donor field. Furthermore, this model corresponds to a field mixed with crops with various geomorphological changes, and it can be used for the evaluation of the crossing rate and the suppression effect adjusted for the flowering period under actual weather conditions. We only simulated windbreak nets effects on the cross-pollination rate. Further simulations about the effects of windbreak structure on cross-pollination are needed.

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Figure 11. Simulation of cross-pollination effect by difference of enclosure method of windbreak net.
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