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PARAMETER SENSITIVITY AND UNCERTAINTY OF RADIATION INTERCEPTION MODELS FOR INTERCROPPING SYSTEM

Abstract: Estimating the interception of radiation is the first and crucial step for the prediction of production for intercropping systems. Determining the relative importance of radiation interception models to the specific outputs could assist in developing suitable model structures, which fit to the theory of light interception and promote model improvements. Assuming an intercropping system with a taller and a shorter crop, a variance-based global sensitivity analysis (*EFAST*) was applied to three radiation interception models (*M1*, *M2* and *M3*). The sensitivity indices including main (S_i) and total effects (ST_i) of the fraction of intercepted radiation by the taller (f_{taller}), the shorter ($f_{shorter}$) and both intercrops together (f_{all}) were quantified with different perturbations of the geometric arrangement of the crops (10-60 %). We found both f_{taller} and $f_{shorter}$ in *M1* are most sensitive to the leaf area index of the taller crop (LAI_{taller}). In *M2*, based on the main effects, the leaf area index of the shorter crop ($LAI_{shorter}$) replaces LAI_{taller} and becomes the most sensitive parameter for $f_{shorter}$ when the perturbations of widths of taller and shorter crops (W_{taller} and $W_{shorter}$) become 40 % and larger. Furthermore, in *M3*, f_{taller} is most sensitive to LAI_{taller} while $f_{shorter}$ is most sensitive to $LAI_{shorter}$ before the perturbations of geometry parameters becoming larger than 50 %. Meanwhile, LAI_{taller} , $LAI_{shorter}$ and K_{taller} are the three most sensitive parameters for f_{all} in all three models. From the results we conclude that *M3* is the most plausible radiation interception model among the three models.

Keywords: intercropping, global sensitivity analysis, Extended Fourier Amplitude Sensitivity Test, radiation interception, uncertainty analysis

Introduction

Intercropping is an agricultural practice of cultivating two or more crop species simultaneously in the same field [1]. Compared to sole cropping, one of the main advantages of intercropping is an increase of the interception of solar radiation [2, 3]. Zhang et al. [4] compared four wheat and cotton intercropping systems with sole cropping systems and found the accumulated light interception per unit cultivated area in intercropping systems were higher than sole-cropping systems. Coll et al. [5] also indicated that maize-soybean and sunflower-soybean intercrops resulted in an improved radiation productivity compared with soybean sole crops. Meanwhile, many studies have shown

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relationships between dry matter production and cumulative intercepted photosynthetically active radiation (*PAR*) [6-9]. Haverkort and Bicaumpala [10] defined the slope of the relationship between total dry matter in periodic harvests and corresponding cumulative intercepted radiation up to the time of harvest as radiation use efficiency (*RUE*) and many crop models simulate crop production based on the *RUE*. Therefore, it is important to determine intercepted *PAR* in both sole and intercropping systems. Generally, intercepted *PAR* in sole cropping system could be easily obtained by experiments. However, measurement of radiation interception in intercropping systems is difficult due to the spatially heterogeneous canopy [11]. For reducing the labour cost, it is necessary to develop modelling approaches to simulate *PAR* interception for intercropping systems. Another motivation for modelling intercepted *PAR* of intercrops is the optimization of intercropping arrangement, which also has significant effects for the interception of *PAR*, but it is very time-consuming and costly to be totally determined by experiments [2, 11]. Meanwhile, good models for intercepted *PAR* of intercrops also benefit regional or large scale assessment of the impact of monoculture versus intercropping. In the past few decades, several mathematical models for radiation capture in the intercropping system were developed. For example, Sinoquet and Bonhomme [12] proposed a radiation-transfer model based on a turbid-medium analogy; Tsubo and Walther [13] developed an explanatory model to quantify instantaneous radiation transmission in the maize-soybean intercropping system. However, due to a large number of input variables and complicated mathematics is required, these models were not widely used although they might give satisfactory descriptions of light distribution in intercropping systems. To increase the practicability, Tsubo and Walther [13] also proposed a statistical model (hereafter noted as *M1* model) based on the assumption that the canopy structure of an additive intercropping system could be divided into several distinct layers by height and they also did some experiments and proved that the statistical model is equal to the geometrical model for radiation simulation. However, researches also pointed out that *M1* model may result in large errors for strip intercropping systems [14, 15] and proposed an improved row-crop radiation-transmission model (hereafter noted as *M2* model) based on the approach first developed by Gijzen and Goudriaan [16] considering both architectural and geometrical relationships. Many other researchers also developed radiation inception model for intercropping system based on the same approach and the model developed by Gou et al. [11] is one typical representative (hereafter noted as *M3* model). However, due to the huge cost of intercropping experiments, data used for validating these models are usually limited. For example, in the study of Wang et al. [15], actual measurements of *PAR* were only conducted on a few days, and no model evaluation was shown. Furthermore, models might have some structure shortcomings and could give some errors when extreme inputs were given, but this issue is hard to be detected by limited experiments. Sensitivity analysis is an approach for evaluating the response of model outputs to variation in model input parameters, for quantifying the importance of input parameters, and for exploring model structure [17, 18]. Sensitivity analysis can be classified into local and global categories according to the strategy used to explore the parameter space [19-21]. Local methods change one parameter at a time around a basis point while keeping the other parameters at nominal values. Although the local method has a low computational cost, it has a crucial shortcoming that it could not detect interactions between parameters which are very common in crop models. But global sensitivity analysis overcomes this drawback and can explore the entire multi-dimensional parameter space simultaneously and quantified both the single and

interactive effects of parameters for specific output [22]. In this study, we applied the extended Fourier Amplitude Sensitivity Test (*EFAST*) global sensitivity analysis to study the sensitivity of three outputs - (1) fraction of intercepted *PAR* by taller crop (f_{taller}), (2) fraction of intercepted *PAR* by shorter crop ($f_{shorter}$), and (3) fraction of *PAR* intercepted by two intercrops (f_{all}) - to different crop parameters in three widely used radiation interception models. The effects of parameter variation ranges and the uncertainty in the three outputs were also evaluated. The results were verified by interpretation against the structure of the three radiation interception models and the advantages and limitations of these models were also discussed.

Materials and methods

Radiation interception models

Three radiation interception models were evaluated in our study. The first model (*M1*) was proposed by Tsubo and Walther [13].

Fig. 1. Schematic illustration of the three radiation interception models applied in a stripwise intercropping system: a) model 1, b) model 2 and c) model 3

In *M1*, two canopy layers are defined in an intercropping system and their boundaries are determined by the canopy heights of the two intercrops. The upper layer comprises only the taller crop while the lower layer consists of both crops. The fractions of radiation intercepted by the intercrops are determined by crop heights (H) and LAI (Fig. 1a) by directly applying the Beer's law:

$$I_j = I_{j0} \left[1 - \exp(-k_{j1} LAI_{j1} - k_{j2} LAI_{j2}) \right] \quad (1)$$

where I_j is the daily amount of light intercepted within layer j ; I_{j0} is amount of solar radiation entering the top of layer j and k_{j1} , k_{j2} and LAI_{j1} , LAI_{j2} are the radiation extinction coefficients and leaf area indices contained within layer j for two crops respectively.

Fig. 2. Schematic diagram of the determination of fractions of *PAR* intercepted by intercrops in model 2 [15]. $F_{i1black}$ is the fraction of *PAR* above $i1$ layer attenuated by crop 1's canopy before reaching layer ii . $F_{ii1black}$ is the fraction of *PAR* above $ii1$ layer attenuated by crop 1's canopy before reaching the soil surface. $F_{i2black}$ is the fraction of *PAR* above $i2$ layer attenuated by crop 2's canopy before reaching the layer ii . $F_{ii2black}$ is the fraction of *PAR* above $ii2$ layer attenuated by crop 2's canopy before reaching the soil surface. F_1 to F_{10} indicate 10 different parts of incident *PAR*. F_6 , F_7 , and F_8 are belong to crop 2 and others are belong to crop 1

The second model (*M2*) was constructed by Wang et al. [15] for strip intercropping systems (Fig. 1b). In *M2*, the development of intercrops was separated into three phases. More exactly, phase 1 is the period after the emergence of crop 1 and before the emergence of crop 2 (crop 1 only); phase 2 is the period after the emergence of crop 2 and before the harvest of crop 1 (co-growth period); phase 3 is after the harvest of crop 1 and before the harvest of crop 2 (crop 2 only). For calculating the intercepted radiation of intercrops, the incident *PAR* on intercropped canopy is divided into 10 different parts (Fig. 2) and

the values of each part were calculated separately by combining the strip-planted model with a horizontally homogeneous mixed canopy model based on the studies of Brutsaert et al. [23], Keating and Carberry [2], Pronk et al. [24] and Zhang et al. [4]. Besides, H and LAI , the inputs of $M2$ also include the width of intercrops (Fig. 1b). The basic theories for the third model ($M3$) are similar with $M2$. However, two additional phases containing the exchange of height of crop 1 and crop 2 and the height of crop 1 becomes equal to crop 2 are considered. In addition, $M3$ also considers the space between different crop strips (S_{taller} and $S_{shorter}$, Fig. 1c). For derivations and details of $M1$, $M2$, and $M3$, please refer to Tsubo and Walher [13], Wang et al. [15], and Gou et al. [11].

Sensitivity analysis method

The extended Fourier Amplitude Sensitivity Test (*EFAST*) is used as a global sensitivity analysis method in our study. *EFAST* is a variance-based method which uses a variance ratio to estimate the importance of parameters based on the variance decomposition. When applying it to $M1$, $M2$, and $M3$, the variance of the output Y can be decomposed into the effects of the input parameters ($P_1, P_2, \dots, P_k$):

$$V(Y) = \sum_{i=1}^k V_i + \sum_{i=1}^k \sum_{j>i}^k V_{ij} + \dots + V_{1,2,\dots,k} \quad (2)$$

where V_i denotes the variance allocated to the i^{th} parameter P_i . V_{ij} denotes the variance allocated to the interactions between P_i and P_j . $V(Y)$ is the total variance of Y caused by the uncertainties of all parameters. The sensitivity of output Y to P_i is quantified by the ratio of the variance caused by P_i to the $V(Y)$ %, which is the first-order effects (S_i , Eq. (3)):

$$S_i = \frac{V_i}{V(Y)} = \frac{V[E(Y|P_i)]}{V(Y)} \quad (3)$$

where $E(Y|P_i)$ is the conditional expectation of Y with a specific P_i value. Furthermore, the total-order sensitivity index of a single parameter (index i) and the interaction of more parameters that involve index i and at least one index $j \neq i$ from 1 to k :

$$ST_i = \sum S_i + \sum_{j \neq i} S_{ij} + \sum S_{1,\dots,k} \quad (4)$$

Generally, ST_i only contained the first two terms in Eq. (4). The first-order (main sensitivity) index (S_i) reflects the sensitivity of parameter i by itself while total-order (total sensitivity) index (ST_i) indicates the contributions of parameter i and the interactions between parameter i and other parameters for the outputs. For more details about *EFAST*, please refer to Sobol [25], Zhao et al. [22], Varella et al. [17], and Wang et al. [26].

Sensitivity analysis numerical experiment

The parameters for the three models could be divided into two types named crop growth parameters and intercropping geometry parameters, respectively. The range of crop growth parameters were determined from a very small value to a very large value based on both common sense and previous researches. More exactly, the lower and upper limit for crop height (H_{taller} and $H_{shorter}$) were set as 0.01 m to 2 m based on the height of typical cereal crops such as wheat [4, 8] and maize [13-15]. Similarly, the lower and upper limit for leaf area index (LAI_{taller} and $LAI_{shorter}$) were set as 0.01 to 10 respectively. The range of

extinction coefficient (K_{taller} and $K_{shorter}$) was determined as 0.32 to 1 from Gonzalez-Amaro et al. [27]. Different from the crop growth parameters, the default values for intercropping geometry parameters were based on Gou, et al. [11]. In addition, a more detailed numerical experiment is performed on the intercropping geometry parameters (W and S for model 2 and model 3 respectively). The geometry parameters variation ranges are separately set to those cases, which are $\pm 10\%$, $\pm 20\%$, $\pm 30\%$, $\pm 40\%$, $\pm 50\%$, and $\pm 60\%$ perturbations of the default values (Table 1). In fact, these cases proportionally magnify the lower and upper boundaries of the range of the geometry parameters, and with the boundary condition amplified, the parameter space is also enlarged. The outputs of the three radiation interception models are fraction of PAR intercepted by the taller crop (f_{taller}), fraction of PAR intercepted by shorter crop ($f_{shorter}$), and fraction of PAR intercepted by both intercrops (f_{all}).

Table 1

Lower and upper boundaries of crop parameters (W is the width of crop strips; S is the space between crop strips). Percentages indicate the degree of perturbations of the default values of W and S

Variables	Default	10 %		20 %		30 %		40 %		50 %		60 %	
		lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper
W_{taller} [m]	0.75	0.68	0.83	0.6	0.9	0.53	0.98	0.45	1.05	0.38	1.13	0.3	1.2
$W_{shorter}$ [m]	0.63	0.56	0.69	0.5	0.75	0.44	0.81	0.38	0.88	0.31	0.94	0.25	1
S_{taller} [m]	0.44	0.39	0.48	0.35	0.53	0.31	0.57	0.26	0.61	0.22	0.66	0.18	0.7
$S_{shorter}$ [m]	0.44	0.39	0.48	0.35	0.53	0.31	0.57	0.26	0.61	0.22	0.66	0.18	0.7

Uncertainty analysis

We set the sample size $N = 1000$ for the sensitivity analysis to attain a stable convergence. So a total number of 10^4 ($1000 \times 2 \times 6 + 1000$) simulations were run, with 1 perturbation for model 1 and 6 perturbations for model 2 and model 3 respectively. The parameter generation and indices calculation of *EFAST* were applied by SimLab software with reference to Shi et al. [28], Wang et al. [26] and Sellier et al. [29]. We also collected the results for three output variables of fraction of PAR intercepted by taller crop (f_{taller}), fraction of PAR intercepted by shorter crop ($f_{shorter}$), and fraction of PAR intercepted by two intercrops (f_{all}) of three models. Box plot was used to illustrate the uncertainty in outputs derived from the variation in the crop growth and intercropping geometrical parameters.

Results and discussion

Sensitivity of outputs to crop and parameters

In $M1$, the effects of the six parameters on three fractions of intercepted PAR and the sum of these are similar except of some small difference. f_{taller} is most sensitive to LAI_{taller} when considering both S_i and ST_i (Fig. 3). Furthermore, based on S_i , K_{taller} is the second sensitive paramter for f_{taller} in $M1$ (Fig. 3a). The reasons of the order of LAI_{taller} and K_{taller} are both LAI_{taller} and K_{taller} are the exponential terms of the formulas in $M1$ [13]. Meanwhile, the S_i value of $f_{shorter}$ indicates that $f_{shorter}$ is also most sensitive to LAI_{taller} (Fig. 4a). This finding is caused by the theory of $M1$, which divides intercrops' canopy into two layers and the shade of the taller crop could significantly affect the PAR interception of the shorter crop. However, this is not in accordance with our common sense and some previous studies [30-32]. $LAI_{shorter}$ is the most sensitive parameter for $f_{shorter}$ because it is also in the

exponential term of the formulas in $M1$ [13]. For f_{all} , LAI_{taller} and $LAI_{shorter}$ are again the first two most sensitive parameters, which indicates that the taller crop plays more important role in PAR interception between intercrops and is also in accordance with f_{taller} and $f_{shorter}$ (Fig. 5). However, the sensitivity order of parameters determined by S_i and ST_i for f_{taller} and $f_{shorter}$ are not the same except for the most sensitive parameter (Figs. 3b and 4b). It is caused by the interactive effects of different parameters in the formulas in $M1$.

Fig. 3. Main and total sensitivity indices of the fraction of light interception of the taller crop ($FPAR_{taller}$) as affected by six input variables in model 1 (K is extinction coefficient; H is crop height; LAI is leaf area index)

Fig. 4. Main and total sensitivity indices of the fraction of light interception of the shorter crop ($F_{PAR_{shorter}}$) as affected by six input variables in model 1 (K is extinction coefficient; H is crop height; LAI is leaf area index)

In $M2$, similar to $M1$, LAI_{taller} is also the most sensitive parameters for f_{taller} in both S_i and ST_i because it is part of the exponential term of the formulas in $M2$ [15] (Fig. 6). An interesting finding is that $LAI_{shorter}$ replaces LAI_{taller} and becomes the most sensitive parameter for $f_{shorter}$ when the perturbations of W_{taller} and $W_{shorter}$ become 40 % or larger based on S_i (Fig. 7a).

Fig. 5. Main and total sensitivity indices of the fraction of light interception of the two crops ($FPAR_{all}$) as affected by six input variables in model 1 (K is extinction coefficient; H is crop height; LAI is leaf area index)

According to the theory of $M2$, the PAR above shorter crop can be attenuated by shorter crop's canopy before reaching the soil surface, and the attenuated fraction is calculated from $H_{shorter}$ and $W_{shorter}$, which is one component of $f_{shorter}$ ($FI7$ in Fig. 2). Meanwhile, LAI_{taller} has no effect on the calculation of $FI7$ [15]. In addition, the S_i and ST_i of $LAI_{shorter}$ and LAI_{taller} are very close to each other in $f_{shorter}$, which is different but more reasonable than in $M1$ (Fig. 7). S_i and ST_i for the fraction f_{all} in $M2$ indicate that the taller crop is more important and LAI_{taller} is the most sensitive parameter for PAR interception in $M2$ (Fig. 8).

Fig. 6. Main and total sensitivity indices of the fraction of light interception of the taller ($FPAR_{taller}$) as affected by six input variables in model 2 (K is extinction coefficient; H is crop height; LAI is leaf area index; W is the width of crop strips; S is the space between crop strips)

In $M3$, LAI_{taller} is the most sensitive parameter for f_{taller} and K_{taller} and W_{taller} are additional sensitive parameters for f_{taller} (Fig. 9). Furthermore, when the perturbation of W_{taller} becomes 60 %, the sensitivity of W_{taller} is larger than K_{taller} for f_{taller} based on S_i (Fig. 9a). Meanwhile, H_{taller} and $H_{shorter}$ also have high ST_i for f_{taller} which is caused by the interactive effects of parameters in $M3$ (Fig. 9b).

Fig. 7. Main and total sensitivity indices of the fraction of light interception of the shorter ($FPAR_{shorter}$) as affected by six input variables in model 2 (K is extinction coefficient; H is crop height; LAI is leaf area index; W is the width of crop strips; S is the space between crop strips)

Furthermore, for the effects on $f_{shorter}$, $W_{shorter}$ replaces $LAI_{shorter}$ and becomes the most sensitive parameter based on S_i when the perturbation of $W_{shorter}$ becomes 60 % (Fig. 10a). This finding is because the contribution of $W_{shorter}$ increases with its perturbation in the calculation of compressed LAI of shorter crops [11]. Meanwhile, the sensitivity of W_{taller} , $W_{shorter}$, S_{taller} , and $S_{shorter}$ also increases with perturbation for f_{taller} , $f_{shorter}$, and f_{all} when considering both S_i and ST_i (Figs. 9 and 10).

Fig. 8. Main and total sensitivity indices of the fraction of light interception of the two crops ($F_{PAR_{all}}$) as affected by six input variables in model 2 (K is extinction coefficient; H is crop height; LAI is leaf area index; W is the width of crop strips; S is the space between crop strips)

As in $M3$, S_i and ST_i of $LAI_{shorter}$ for fall is much larger than LAI_{taller} , $M3$ seems to be more reasonable for calculating PAR interception of intercropping systems than $M1$ and $M2$ (Figs. 9 and 10). Similar with $M2$, the taller crop in $M3$ is more important and LAI is the most sensitive parameter for PAR interception in intercropping systems (Fig. 11).

Fig. 9. Main and total sensitivity indices of the fraction of light interception of the taller ($FPAR_{taller}$) as affected by six input variables in model 3 (K is extinction coefficient; H is crop height; LAI is leaf area index; W is the width of crop strips; S is the space between crop strips)

This finding is also in accordance with $M2$ (Figs. 6 and 7) and indicates that the effects of widths and spaces on PAR interception can be reasonably reflected in both $M2$ and $M3$. In addition, both S_{taller} and $S_{shorter}$ have smaller S_i and ST_i than W_{taller} and $W_{shorter}$ for f_{taller} and $f_{shorter}$ respectively (Figs. 9 and 10). But this phenomenon might be caused by the lower and upper boundaries of space both being smaller than width (Table 1).

Fig. 10. Main and total sensitivity indices of the fraction of light interception of the shorter ($FPAR_{shorter}$) as affected by six input variables in model 3 (K is extinction coefficient; H is crop height; LAI is leaf area index; W is the width of crop strips; S is the space between crop strips)

Fig. 11. Main and total sensitivity indices of the fraction of light interception of the two crops ($FPAR_{all}$) as affected by six input variables in model 3 (K is extinction coefficient; H is crop height; LAI is leaf area index; W is the width of crop strips; S is the space between crop strips)

Uncertainty of the outputs resulting from cultivar parameters

The fractions of intercepted PAR are about 0-1, 0-0.9, and 0-0.8 for the taller crop in $M1$, $M2$, and $M3$ respectively (Fig. 12). For the shorter crop, the ranges are 0-0.9, 0-0.8, and 0-0.5 in $M1$, $M2$, and $M3$ respectively. These findings indicate that $M3$ has the smallest uncertainty for the fractions of intercepted PAR . Furthermore, the uncertainty of the fractions of intercepted PAR increased slightly but are generally stable with the increase of perturbation in both $M2$ and $M3$ (Fig. 12).

Fig. 12. The empirical frequency distributions for the fractions of intercepted PAR for taller, shorter and the two intercrops in three different models. The line in the box is the median, the edges of the box are lower hinge (the 25 %) and the upper hinge (the 75 %), the up and low boundary line out of the box indicate the maximum and minimum value and the cross symbols near the up and low boundaries are the 99 % and 1 % hinges respectively. Sub-plots a), b), and c) indicate model 1, model 2, and model 3 respectively

Based on the median value in Figure 12, the fraction of intercepted PAR for taller and two intercrops decreases from $M1$ to $M3$. For example, the median fraction of intercepted PAR for the taller crop in $M1$ is about 0.82, while it is only about 0.64 and 0.38 in $M2$ and $M3$ respectively. Meanwhile, the fraction of intercepted PAR for shorter crop in $M1$, $M2$, and $M3$ is about 0.18, 0.28, and 0.22 respectively. Therefore, in $M1$ the two crops intercept almost 100 % of PAR while in $M2$ and $M3$ they intercept about 90 and 60 % of PAR . The difference of intercepted PAR among $M1$, $M2$, and $M3$ is because $M2$ considers the

width of crop strips and $M3$ considers both width of crop strips and space between intercrops. The experimental data presented by Gou et al. [11] and Wang et al. [15] pointed out that $M1$ could overestimate the intercepted PAR in intercropping systems, thus confirming our results.

Advantages and limitations of the radiation interception models

Among all three models analyzed in our study, $M1$ needs the lowest number of parameters. But it can only consider a horizontally homogeneous leaf area and cannot simulate strip intercropping systems. Meanwhile, LAI_{taller} is the most sensitive parameter for $f_{shorter}$ in $M1$, which is not plausible and indicates that there might be some shortcomings in the structure of the equations governing $M1$. $M2$ can take account for the width of strip intercropping systems but it still cannot consider the spaces between different crop strips. This shortcoming of $M2$ is improved by $M3$, which can consider both width and space between intercrops. Meanwhile, the medians of intercepted PAR in $M1$ and $M2$ are both higher than 90 %, which is obviously an overestimation compared with previous studies [33-35]. In addition, $M2$ also has some structural shortcomings that might give us significantly unreasonable estimation of intercepted PAR . This is shown in the following example of an intercropping system with the crop and arrangement parameters listed in Table 2.

Table 2
Assumed geometry of the intercropping system and crop parameters for $M2$ and $M3$

Variables	Unit	Values
K_{taller}	-	0.61
$K_{shorter}$	-	0.6
H_{taller}	[m]	1.2
$H_{shorter}$	[m]	1.18
LAI_{taller}	-	2.2
$LAI_{shorter}$	-	2
W_{taller}	[m]	0.2
$W_{shorter}$	[m]	0.8
S_{taller}	[m]	0
$S_{shorter}$	[m]	0

In this assumed intercropping system, the height H , LAI , and K of the taller crop are all larger than of the shorter crop while the W_{taller} and $W_{shorter}$ are 0.2 m and 0.8 m respectively. Based on our common sense, the f_{taller} should be larger than 20 % of f_{all} while the estimated f_{taller} by $M2$ accounts for only 17.98 % of f_{all} . Meanwhile, if we use the same parameters as inputs for $M3$, f_{taller} accounts for 20.93 % of f_{all} . Therefore, we deem that $M3$ is the optimal radiation interception model for intercropping systems among the three models. However, there are still some shortcomings of $M3$. Firstly, although $M3$ considers the space between strips of intercrops, it cannot consider the space between crops in the same strip and therefore it cannot consider plant density, which is also a factor affecting PAR interception [36]. Secondly, it is still ambiguous for determining the strip width in $M3$. More exactly, it is reasonable to calculate strip width based on the canopy width of intercrops [37]. However, it is still difficult to simulate canopy width. Thirdly, $M3$ also does not consider the boundary effects of PAR interception in an intercropping system which might have

some complex effects [38]. Furthermore, the importance of parameters also change with the perturbations of geometry parameters (Figs. 9-11), which indicated that there are some unknown interactions between crop growth and geometry parameters on the light interception in *M3*. In addition, all the three radiation interception models can not consider more than two intercrops and the light quality [3].

Conclusion

Sensitivity of three outputs (f_{taller} , $f_{shorter}$ and f_{all}) of three radiation interception models (*M1*, *M2*, and *M3*) to different geometry and crop parameters for intercropping systems were analyzed using a variance-based global sensitivity analysis method (*EFAST*). LAI_{taller} is the most sensitive parameter for both f_{taller} and $f_{shorter}$ in *M1*. Similarly, LAI_{taller} is still the most sensitive parameter for both f_{taller} and $f_{shorter}$ in *M2* until the perturbations of W_{taller} and $W_{shorter}$ become 40 % and larger than 40 %, then $LAI_{shorter}$ replaces LAI_{taller} and becomes the most sensitive parameter for $f_{shorter}$. However, in *M3*, LAI_{taller} is the most sensitive parameter for f_{taller} while $LAI_{shorter}$ is the most sensitive parameter for $f_{shorter}$ before the perturbations of geometry parameters becoming larger than 50 %. In both *M2* and *M3*, the sensitivity of W_{taller} , $W_{shorter}$, S_{taller} , and $S_{shorter}$ increases with their perturbations for f_{taller} , $f_{shorter}$, and f_{all} . Meanwhile, LAI_{taller} , $LAI_{shorter}$, and K_{taller} are three most sensitive parameters for f_{all} in all three models. In addition, the inconsistency of the order of S_i and ST_i and the effects of perturbations also indicate there have some unknown interactions between crop growth and geometry parameters for the light interception in the intercropping systems. The sensitivity analysis also indicated some structure limitations for these radiation interception model, which were further proved by the uncertainly analysis. More exactly, *M1* and *M2* could overestimate the intercepted *PAR* for intercropping system and even though *M3* is the optimal method among the three, it still needs to be improved by considering plant density, canopy width, boundary effects, and more than two intercrops in future studies.

In addition, this study showed that *EFAST* can be employed to investigate the importance of parameter to various outputs in the radiation interception model. Meanwhile, it also give us some information about the limitations of model from the view of model theory and structure. This could be useful for improving the availability of radiation interception model and then benefiting the crop production prediction for intercropping systems by combining radiation interception models with process-based crop models.

Nevertheless, there are still some limitations of this study. Firstly, although we considered up to 60 % of the intercropping geometry parameters and a relatively large range for the crop growth parameters, it was still inevitable to ignore some extreme scenarios, which might affect the results of the *EFAST* for sensitivity analysis. Secondly, the present study only indicated the sensitivity of the parameters in three radiation interception models from the view of mathematics. However, the mechanism of these parameters in the three models and their interactions still need further studies.

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