Supporting Information for

Remote Sensing-Based Quantification of the Summer Maize Yield Gap Induced by Suboptimum Sowing Dates over North China Plain

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Introduction

This supplementary contains two texts, one table, and four figures.

Text S1. An overview of the PRYM-Maize model

Text S1.1. Leaf-level photosynthesis model

The simple intercellular transport model [1,2] is adopted to simulate the leaf-scale photosynthesis of maize. It has been incorporated into multiple terrestrial land process models to simulate the photosynthesis of C_4 plants and is useful [3–5]. The basic equations are presented as

$$A_n = \min\left(A_v, A_e, A_s\right) - R_d, \quad \text{(S1)}$$

$$A_v = V_{\text{m}}, \quad \text{(S2)}$$

$$A_e = \varepsilon \cdot Q, \quad \text{(S3)}$$

$$A_s = 0.7 \times 10^6 \cdot \frac{C_i}{P_{\text{atm}}}, \quad \text{(S4)}$$

where A_n is the net photosynthesis rate (μmol m^{-2} s^{-1}); A_v, A_e, and A_s represent Rubisco, potential electron transport, and export limited photosynthesis rates, respectively (μmol m^{-2} s^{-1}); R_d denotes the dark respiration (μmol m^{-2} s^{-1}), and $R_d = 0.015V_m$; V_m denotes the maximum carboxylation rate (μmol m^{-2} s^{-1}); Q denotes the incident photosynthetically active radiation on the leaf surface (μmol m^{-2} s^{-1}); ε denotes the intrinsic quantum efficiency; c_i denotes the intercellular partial pressure of CO_2 (Pa); and P_{atm} denotes the atmosphere pressure (Pa).

V_m is calculated as a function of temperature (T) and nitrogen (N) supply [6–8], and ε is simply assumed to be limited by $f_N(N)$ because the electron transport rate correlates well with V_m [9,10], such that

$$V_{\mathrm{m}} = V_{\mathrm{m25}} 2.4^{(T-25)/10} f_T(T) \cdot f_N(N), \tag{S5}$$

$$\frac{1}{f_T(T)} = 1 + \exp\left(\frac{-220,000 + 710(T+273)}{R_{\mathrm{gas}}(T+273)} \right), \tag{S6}$$

$$\varepsilon = \varepsilon_{\mathrm{m}} \cdot f_N(N), \tag{S7}$$

where V_{m25} denotes the maximum carboxylation rate at the temperature of 25 °C, and it is set to 60 μmol m^{-2} s^{-1} for maize [9,11]; R_{gas} denotes the mole constant of gas, 8.3143 J mol^{-1} K^{-1}; $f_N(N)$ denotes the restrictive function of nitrogen supply, which varies between 0 and 1; and ε_m denotes the maximum value for ε, 0.067 mol mol^{-1} [1]. Because spatial information for field nitrogen supply is unavailable, we used satellite-retrieved NDVI to calculate $f_N(N)$, as described by Zhang, Zhang, Bai [12]:

$$f_N(N) = \begin{cases} f_{\min} & ,\mathrm{NDVI} \le \mathrm{NDVI}_{\min} \\ \left(\frac{\mathrm{NDVI} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}} \right)^2 & ,\mathrm{NDVI}_{\min} < \mathrm{NDVI} < \mathrm{NDVI}_{\max} \\ 1 & ,\mathrm{NDVI} \ge \mathrm{NDVI}_{\max} \end{cases}, \tag{S8}$$

where NDVI denotes the normalized difference vegetation index, NDVI_{min} represents the value of NDVI in which photosynthesis is fully stressed by nitrogen (0.4); NDVI_{max} is the peak value of NDVI time series during the growing season and is calculated as the 95th percentile of time-series NDVI values during the growing season; and f_{min} is the value of $f_N(N)$ under full nitrogen stress, and we set it to 0.3 in this study.

A_s could not be solved by Eq.(S4) alone because the value of c_i is not easily obtained on a regional scale, and Eqs.(S1) and (S4) are combined with A_n calculation based on fluid physics [6,7,13] to avoid C_i.

$$A_n = (C_a - C_i) \cdot g, \tag{S9}$$

$$g = \frac{P_{\mathrm{atm}} \cdot g_{\mathrm{st}}}{R_{\mathrm{gas}} \cdot (T+273)}, \tag{S10}$$

where C_a denotes the partial pressure of CO_2 in the atmosphere, and it is set to 39 Pa; g denotes the stomatal conductance measured in μmol m^{-2} s^{-1} Pa^{-1}; g_{st} denotes the stomatal conductance measured in m s^{-1}. Combining Eqs. (S1), (S4), and (S9), we obtain a form of A_s in terms of g rather than C_i:

$$A_s = \frac{g \cdot c_a + R_d}{g \cdot P_{\mathrm{atm}} / (1.8 \times 10^4 V_m) + 1}, \tag{S11}$$

Daily canopy scale photosynthesis rate (daily gross primary productivity, GPP_{daily}) is scaled from instantaneous leaf-level photosynthesis rate (Eq. (S1)) using a two-leaf canopy radiative transfer model [6,7,14].

$$\mathrm{GPP}_{\mathrm{daily}} = A_{\mathrm{c,day}} \times (Hr_{day} \times 3600) \times M_C \times 10^{-6}, \tag{S12}$$

$$A_{\text{c,day}} = \text{LAI}_{\text{shd}} \cdot A_{n,\text{shd}} + \text{LAI}_{\text{sun}} \cdot A_{n,\text{sun}} , \quad \text{(S13)}$$

where $\text{GPP}_{\text{daily}}$ denotes the daily gross primary productivity on a canopy scale (gC m^{-2} d^{-1}); $A_{\text{c,day}}$ denotes the net photosynthesis rate on a canopy scale during the daytime (μmol m^{-2} s^{-1}); Hr_{day} denotes the length of daytime in hours (from sunrise to sunset); M_{C} denotes the mole mass of carbon (12 g mol^{-1}); subscripts "shd" and "sun" represent the shaded leaves and sunlight leaves, respectively; LAI denotes the total leaf area index, LAI_{shd} and LAI_{sun} denote the LAI of shaded and sunlight leaves, respectively; and $A_{\text{n,shd}}$ and $A_{\text{n,sun}}$ denote the A_{n} value of shaded leaves and sunlight leaves, respectively. To calculate maize yield, we simulate the growth of maize grain on a daily step as a function of development stage (DVS) and daily net primary productivity ($\text{NPP}_{\text{daily}}$), as presented in Supplementary Text S1.3. At daily steps, g_{st} is calculated according to Bai, Zhang, Zhang [15]:

$$g_{\text{st},i} = g_{\text{sm,2000}} \cdot f_1(\text{VPD}) \cdot f_2(Q_i) \cdot f_3(T) \cdot f_4(swc) , \quad \text{(S14)}$$

where f_1(VPD), $f_2(Q_i)$, $f_3(T)$, and $f_4(swc)$ are restrictive functions of VPD, photosynthetically active radiation (PAR: Q), T, and soil water content (swc), respectively; $g_{\text{sm,2000}}$ denotes the maximum stomatal conductance at Q = 2000 μmol m^{-2} s^{-1}, and it was calculated as a function of NDVI [15]. The subscript "i" indices sunlight leaves (sun) and shaded leaves (shd), respectively.

Text S1.2. Daily photosynthesis rate on a canopy scale

A two-leaf canopy structure model based on the radiative transfer theory [6,7,14] was used to scale leaf scale photosynthesis rate to the canopy scale, which showed good reliability in simulating canopy scale photosynthesis rate [4,6].

$$\text{GPP}_{\text{daily}} = A_{\text{c,day}} \times \left(Hr_{day} \times 3600\right) \times M_C \times 10^{-6} , \quad \text{(S15)}$$

$$A_{\text{c,day}} = \text{LAI}_{\text{shd}} \cdot A_{n,\text{shd}} + \text{LAI}_{\text{sun}} \cdot A_{n,\text{sun}} , \quad \text{(S16)}$$

$$\text{LAI}_{\text{sun}} = 2\cos\theta\left(1-\exp\left(-0.5\times\Omega\times\text{LAI}/\cos\theta\right)\right), \quad \text{(S17)}$$

$$\text{LAI}_{\text{shd}} = \text{LAI} - \text{LAI}_{\text{sun}} , \quad \text{(S18)}$$

$$\theta = \frac{\pi}{8} + \frac{3}{4}\theta_{\text{n}} , \quad \text{(S19)}$$

$$\begin{aligned}\cos\theta_{\text{n}} = {} & \sin\left(-23.45\times\frac{\pi}{180}\cos\left(\frac{360\left(\text{DoY}+10\right)}{365}\right)\right)\sin\varphi \\ & +\cos\left(-23.45\times\frac{\pi}{180}\cos\left(\frac{360\left(\text{DoY}+10\right)}{365}\right)\right)\cos\varphi\end{aligned} , \quad \text{(S20)}$$

where $\text{GPP}_{\text{daily}}$ denotes the daily gross primary productivity on a canopy scale (gC m^{-2} d^{-1}), $A_{\text{c,day}}$ denotes the net photosynthesis rate on a canopy scale during the daytime (μmol m^{-2} s^{-1}); Hr_{day} denotes the length of daytime in hours (from sunrise to sunset); M_{C} denotes the mole mass of carbon (12 g mol^{-1}); subscript 'shd' and 'sun' represents the shaded leaves and sunlight leaves respectively; LAI denote the total leaf area index, LAI_{shd} and LAI_{sun} denotes the leaf area index of shaded and sunlight leaves respectively; and $A_{\text{n,shd}}$ and $A_{\text{n,sun}}$ denote the A_{n} value of shaded leaves and sunlight leaves respectively; θ and θ_{n} denotes the mean solar zenith angle during the daytime and solar zenith angle at noon (rad); DoY denotes the

Julian day; and φ denotes the local latitude (rad). Hr_{day} is calculated according to Duffie and Beckman [21]:

$$Hr_{\mathrm{day}} = \frac{15}{2}\arccos\left(-\tan\varphi \cdot \tan\delta\right) \ , \tag{S21}$$

$$\delta = 23.5\sin\left(\frac{\mathrm{DoY}+284}{365}2\pi\right)\times\frac{\pi}{180}, \tag{S22}$$

where δ denotes the solar declination (rad).

Photosynthetically active radiation (PAR) on sunlight leaves (Q_{shd}) and shaded leaves (Q_{shd}) are two critical variables in canopy photosynthesis rate simulations. The calculations of $A_{\mathrm{n,shd}}$ and $A_{\mathrm{n,shd}}$ require the values Q and stomatal conductance (g_{st}) on shaded leaves (Q_{shd} and $g_{\mathrm{st,shd}}$) and sunlight leaves (Q_{sun} and $g_{\mathrm{st,sun}}$), and Q_{shd} and Q_{sun} are also needed for the calculations of $g_{\mathrm{st,shd}}$ and $g_{\mathrm{st,sun}}$. We referred to Norman [14],Chen, Liu, Cihlar [6] and Liu, Chen, Cihlar [7] for obtaining Q_{shd} and Q_{sun} in the daytime:

$$C = 0.07\times\Omega\times Q_{\mathrm{dir}}\times\left(1.1-0.1\mathrm{LAI}\right)\times\exp\left(-\cos\theta\right), \tag{S23}$$

$$Q_{\mathrm{dif\_under}} = Q_{\mathrm{dif}}\times\exp\left(-0.5\times\Omega\times\mathrm{LAI}/\cos\overline{\theta}\right), \tag{S24}$$

$$\cos\overline{\theta} = 0.537+0.025\mathrm{LAI}, \tag{S25}$$

$$Q_{\mathrm{shd}} = \left(Q_{\mathrm{dif}}-Q_{\mathrm{dif\_under}}\right)/\mathrm{LAI}+C, \tag{S26}$$

$$Q_{\mathrm{sun}} = Q_{\mathrm{dir}}\frac{\cos\alpha}{\cos\theta}+Q_{\mathrm{shd}} \ , \tag{S27}$$

where C denotes the multiple scattered radiation (μmol m^{-2} s^{-1}); Ω denotes the clumping index of vegetation, 0.9 is used for crops; Q_{dir} and Q_{dif} denote the direct and diffuse solar radiation in the daytime (μmol m^{-2} s^{-1}); θ denotes the daytime mean solar zenith angle; $Q_{\mathrm{dif\_under}}$ denotes the daytime radiation under the canopy (μmol m^{-2} s^{-1}); $\overline{\theta}$ denotes the solar zenith angle for radiation transmission; α denotes the inclination angle of leaves ($\pi/3$). The following method referring to Chen, Liu, Cihlar [6],Liu, Chen, Cihlar [7],Black, Chen, Lee [22] was adopted to calculate Q_{dif} and Q_{dir}:

$$R = \frac{Rg}{R_0}, \tag{S28}$$

$$\frac{Rg_{\mathrm{dif}}}{Rg} = \begin{cases} 0.13 & , R\geq 0.8 \\ 0.943+0.734R-4.9R^2+1.796R^3+2.058R^4 & , R<0.8 \end{cases}, \tag{S29}$$

$$Q_{\mathrm{dif}} = Q\cdot\frac{Rg_{\mathrm{dif}}}{Rg} \ , \tag{S30}$$

$$Q = k_{\mathrm{q}}\cdot Rg\cdot\frac{Hr_{day}}{24}, \tag{S31}$$

$$Q_{\mathrm{dir}} = Q-Q_{\mathrm{dif}}, \tag{S32}$$

where R_0 is the daily extraterrestrial solar radiation (W m^{-2}); R denotes the atmosphere transmissivity; Rg denotes the daily global solar radiation (W m^{-2}); Rg_{dif}/Rg denotes the proportion of diffuse solar radiation to the global solar radiation; k_{q} is a factor to scale solar radiation to PPFD (2.0 μmol J^{-1}); Q_{dif}/Q denotes the fraction of diffusion radiation calculated according to Black, Chen, Lee [22]. R_0 is calculated referring to Duffie and Beckman [21]:

$$R_0 = \frac{1}{\pi} S_0 \cdot \left(\cos\varphi \cdot \cos\delta \cdot \sin\omega_{\text{set}} + \omega_{\text{set}} \cdot \sin\varphi \cdot \sin\delta \right), \tag{S33}$$

$$\omega_{\text{set}} = \arccos\left(-\tan\varphi \tan\delta \right), \tag{S34}$$

where S_0 denotes the solar constant (1367 W m^{-2}); ω_{set} denotes the hour angle of sunset (rad).

Text S1.3 Respiration and dry matter partitioning on a daily step

Dry matter partitioning in each day is based on the acquisition of net primary productivity (NPP), satellite-retrieved leave area index (LAI), and accumulated biomass.

$$M_{\text{leaf}}^{(t_0)} = \text{LAI}^{(t_0)} / \text{SLA}, \tag{S35}$$

$$M_x^{(t_0)} = \sum_{t=\text{EM}}^{t_0} \left(\text{NPP}_{\text{daily}}^{(t)} \times F_x^{(t)} \right), \qquad x \in \{\text{root,stem,grain}\}, \tag{S36}$$

where superscript (t_0) denotes current date and (t) indices a specific date; $M_x^{(t_0)}$ is the accumulated dry matter of organ 'x' in the current day (gC m^{-2} d^{-1}); SLA denotes the leaf specific area (m^2 gC^{-1}), refer to Osborne, Gornall, Hooker [17] for its calculation; $\text{NPP}_{\text{daily}}$ denote the daily total NPP (gC m^{-2} d^{-1}).

The net dry matter produced by photosynthesis, $\text{NPP}_{\text{daily}}$, is calculated as a difference between $\text{GPP}_{\text{daily}}$ and daily total respiration rate:

$$\text{NPP}_{\text{daily}}^{(d)} = \text{GPP}_{\text{daily}}^{(d)} - R_a^{(d)}, \tag{S37}$$

$$R_a^{(d)} = R_g^{(d)} + R_{m,\text{stem}}^{(d)} + R_{m,\text{root}}^{(d)} + R_{m,\text{leaf}}^{(d)} + R_{m,\text{grain}}^{(d)}, \tag{S38}$$

$$R_g^{(d)} = r_g \cdot \text{GPP}_{\text{daily}}^{(d)}, \tag{S39}$$

$$R_{m,x}^{(d)} = r_{m,x} \cdot M_x^{(d)} \cdot Q_{10,x}^{(T-25)/10}, \tag{S40}$$

where R_{a}, R_{g}, and R_{m} denote the daily total, growth, and maintenance respiration rates (gC m^{-2} d^{-1}); r_{g} and r_{m} denote the growth respiration (0.25) and maintenance coefficients (Table S1); $x \in$ {stem, root, leaf, grain}; Q_{10} denotes the temperature sensitivity parameter of respiration reflecting the increments of respiration rate with an increase of temperature by 10 °C.

We used the dry matter allocation method adopted by Osborne, Gornall, Hooker [17] to calculate the fraction of daily dry matter partitioned to organ 'x' (Fr_x). This method calculates Fr_x as a function of the development stage (DVS). The method to calculate the Fr_x of leaf, stem, and root is presented as follows,

$$Fr_x^{(t_0)} = \frac{\exp\left(a_x + b_x \cdot \text{DVS}^{(t_0)} \right)}{\left(\sum_{x \in \{\text{leaf,stem,root}\}} \exp\left(a_x + b_x \cdot \text{DVS}^{(t_0)} \right) \right) + 1}, \tag{S41}$$

and Fr_x is the residual of the Fr_x value of the three organs above：

$$Fr_{\text{gain}}^{(t_0)} = 1 - \left(Fr_{\text{leaf}}^{(t_0)} + Fr_{\text{stem}}^{(t_0)} + Fr_{\text{root}}^{(t_0)} \right), \quad \text{(S42)}$$

where a_x and b_x were empirical coefficients (Table S1), which controls the shape of the curve of Fr_x; DVS denotes the development stage of the crop (0 – 2), and DVS = 1 indicates the flowering when the accumulation of grains starts. DVS = 2 indicates the maturity stage.

Text S2. Persistent factors assessment

Factors affecting Yg could be categorized into the persistent and non-persistent factors. Persistent factors include field managements, soil properties, and terrains. In this study, Yg_0 was induced by suboptimum SDT. However, SDT is also affected by persistent and non-persistent factors. A satellite-based method proposed by Farmaha, Lobell, Boone [25] is useful for disaggregating the two components. This method uses time-series Yg rasters to calculate the persistent factors percentage (PFP) in Yg within a small region and could be summarized as the following four steps.

(a) Use one of the time-series Yg rasters as a 'Ranking raster', and group pixel-level Yg in ranking raster in small Yg (SYg) or large Yg (LYg) (orange regions in Figure S2), which respectively correspond to bottom or top decile of Yg distribution; mean values of SYg or LYg in ranking raster are denoted as SYg_R or LYg_R.

(b) Track the values of pixels, grouped into SYg or LYg in step (a), across other years' rasters (called 'Non-raking raster'); mean values of SYg or LYg pixels (yellow regions in Figure S2) in non-ranking rasters are denoted as SYg_{NR} or LYg_{NR}.

(c) Calculate PFP based on the selected ranking year as follows:

$$\text{PFP}_{\text{SYg}} = \frac{\sum\left(\text{SYg}_{\text{NR}} - \overline{\text{Yg}}_{\text{ann}}\right) / (\text{NY} - 1)}{\text{SYg}_{\text{R}} - \overline{\text{Yg}}_{\text{ann}}}, \quad \text{(S43)}$$

$$\text{PFP}_{\text{LYg}} = \frac{\sum\left(\text{LYg}_{\text{NR}} - \overline{\text{Yg}}_{\text{ann}}\right) / (\text{NY} - 1)}{\text{LYg}_{\text{R}} - \overline{\text{Yg}}_{\text{ann}}}, \quad \text{(S44)}$$

where PFP_{SYg} and PFP_{LYg} denote the PFP values computed based on SYg and LYg groups, respectively; NY denotes the number of years under investigation; Yg_{ann} denotes mean annual regional Yg for all years.

(d) Repeat step (a) for each year, and use the steps followed to calculate PFP_{SYg} and PFP_{LYg} based on each selected ranking raster; then PFP_{SYg} and PFP_{LYg} based on each raking raster are averaged to obtain the final values.

Table S1. Values of coefficients for calculating maize respiration and dry matter allocation.

Coefficients	Values (Dimensional)	Coefficients	Values (Unit: g CH_2O per gram dry matter)
a_{leaf}	13.0	$r_{\text{m,grain}}$	0.005
a_{stem}	12.5	$r_{\text{m,leaf}}$	0.011
a_{root}	12.5	$r_{\text{m,stem}}$	0.006
b_{leaf}	-11.2	$r_{\text{m,root}}$	0.006
b_{stem}	-10.0		
b_{root}	-12.4		

Figure S1: The diagram for calculating small yield gap（SYg）and large yield gap（LYg）in ranking and non-ranking rasters.

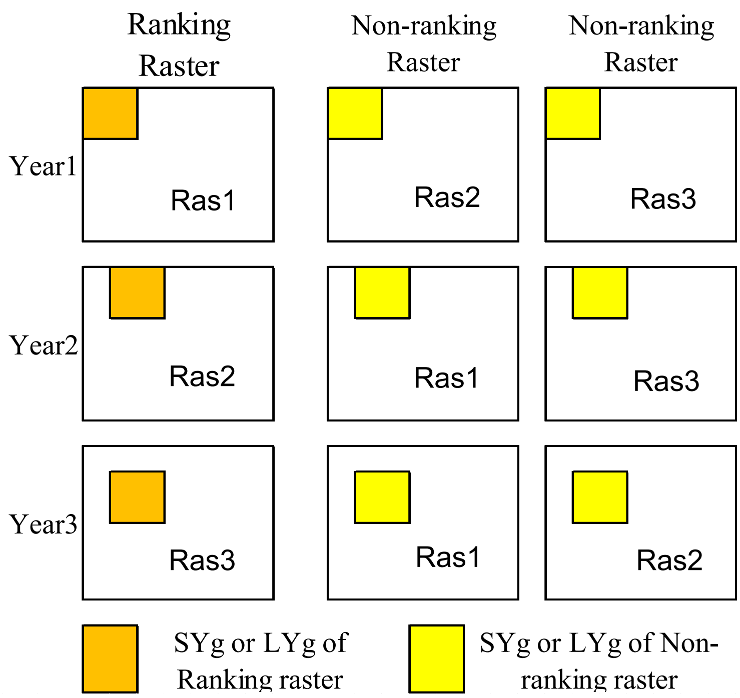


Figure S2. One km pixels that were continuously cropped with summer maize in the period 2010 to 2015 over the NCP.

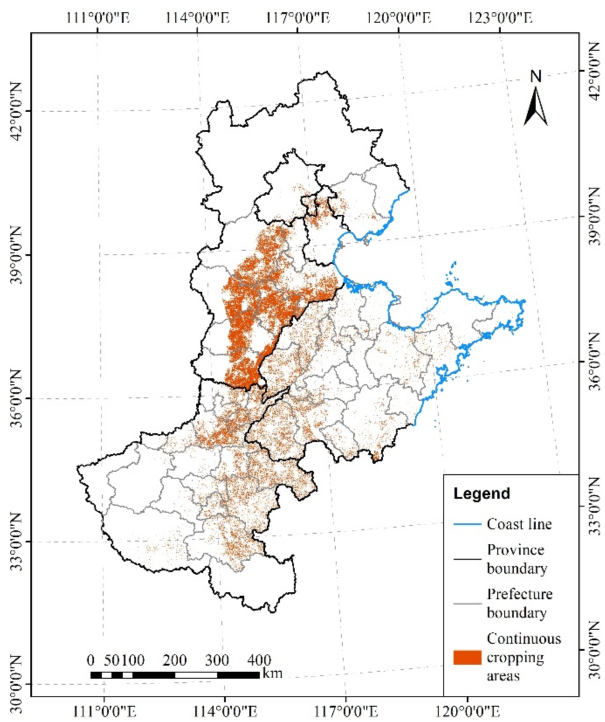


Figure S3. Persistent factor percentage (PFP) based on 1 km Yg_0 (a) and 5 km Yg_0 (b), and a comparison between 1 km PFP and 5 km PFP over space (c). The value intervals in the legends of panel (a) and (b) are right-closed and left-open. PFP_{SYg} denotes the PFP value

calculated in terms of Yg of croplands grouped in small Yg, as defined in Farmaha, Lobell, Boone [25] or illustrated in Supplementary Text S2. In this study, PFP was calculated for each pixel using surrounding pixels within a buffer of 50 km. However, not all pixels within the buffer were used, only pixels that met the criteria (see Section 2.3.4—Step 4) for computing Yp from Yp_0 were kept.

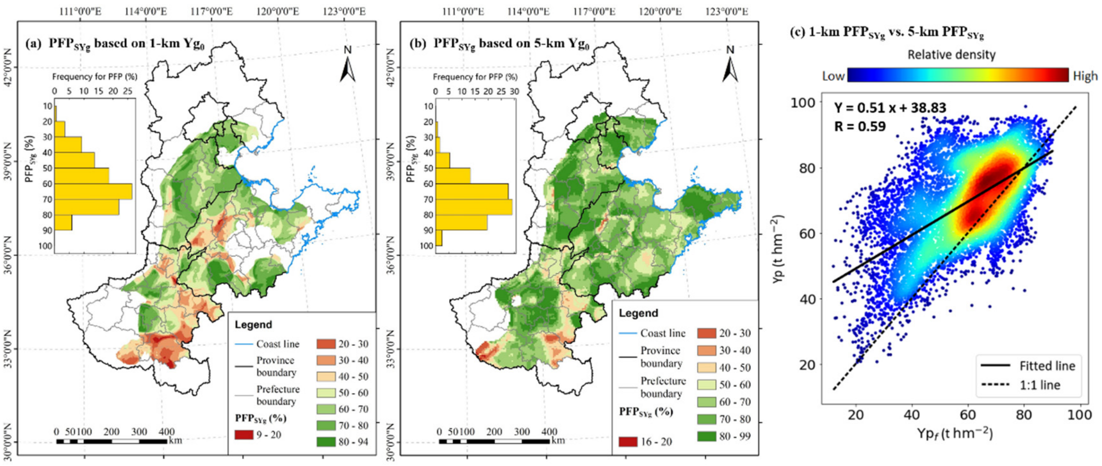
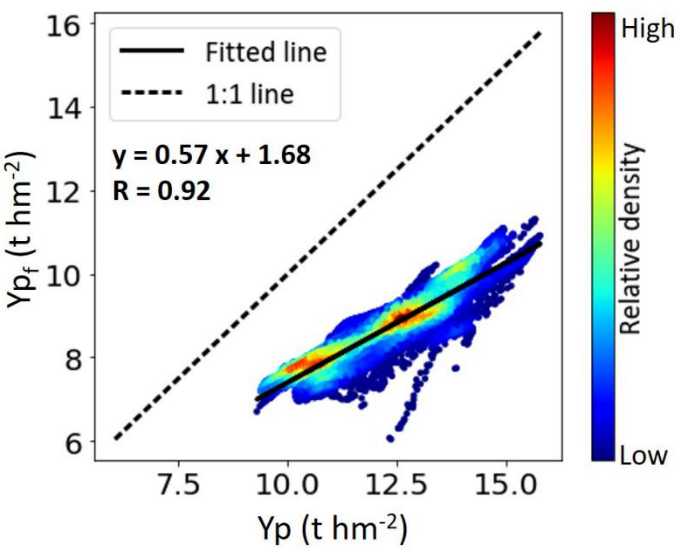


Figure S4. Modeled yield potential (Yp) vs. modeled farmers' yield penitential (Yp_f).



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