**Supplementary data**

**Title:** **Identification of photosynthetic parameters for superior yield of two super hybrid rice varieties: A cross-scale study from leaf to canopy**

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**FIGURE S1** Daily mean temperature, precipitation and photosynthetic active radiation (PAR) during rice growing season at Rugao County, Jiangsu Province, China in 2020.

**FIGURE S2** Schematic of the Diurnal canopy photosynthesis simulator (DCaPS, recomposed from Wu et al. (2018).

**FIGURE S3** Effects of N rates on yield at maturity of different rice varieties.

**TABLE S1. Description of parameters and their values or equations in the Diurnal Canopy Photosynthesis Simulator (DCaPS)**

|  |  |  |  |
| --- | --- | --- | --- |
| **Symbol** | **Description** | **Units** | **Value or Equation** |
| **Environment parameters** |
| So | Total daily extra-terrestrial solar radiation†(1) | MJ m-2 ground day-1 |  |
| Sg | Total daily incident solar radiation†(2) | MJ m-2 ground day-1 |  |
| RATIO | Atmospheric transmission ratio†(2) | dimensionless | 0.75 |
| sch | Solar constant in energy unit per hour†(2) | J m-2 ground hr-1 | 4896000 |
| sc | Solar constant in energy unit per second†(2) | J m-2 ground s-1 | 1360 |
| Lat | Latitude in radians | radians | Table S3 |
| Rl | Radius vector†(1) | radians | 1/ |
| *Dl* | Solar declination†(1) | radians |  |
| Wl° | Sunset hour-angle†(1) | ° |  |
| *Ll* | Day length†(1) | hr |  |
| Day | Day of year | dimensionless | Table S3 |
| VPDa | Air vapour pressure deficit†(3) | kPa |  |
| SVPa | Air saturated vapour pressure†(3) | kPa |  |
| SVPd | Air dew-point vapour pressure†(3) | kPa |  |
| Ca | Air CO2 partial pressure | bar | 405.3 |
| Oa | Air O2 partial pressure | bar | 210000 |
| Io | Total incident solar radiation†(4) | MJ m-2 ground s-1 |  |
| Idir | Incident direct radiation†(2) | MJ m-2 ground s-1 |  |
| Idif | Incident diffuse radiation†(2), (5) | MJ m-2 ground s-1 |  |
| PARo | Total incident photosynthetic active radiation | mol PAR m-2 ground-1 |  |
| PARdir | Direct incident photosynthetic active radiation†(6) | mol PAR m-2 ground-1 |  |
| PARdif | Diffuse incident photosynthetic active radiation†(6) | mol PAR m-2 ground-1 |  |
| PARabs,can | Absorbed PAR of canopy†(7), (8) | mol PAR m-2 ground-1 |  |
| PARabs,sun | PAR absorbed by the sunlit leaves†(7), (8) | mol PAR m-2 ground-1 |  |
| PARabs,sh | PAR absorbed by the shaded leaves | mol PAR m-2 ground-1 |  |
| tfrac | t as a fraction of *Ll* passed at t from tsunrise | dimensionless |  |
| tsunrise | Time of sunrise | hr |  |
| tsunset | Time of sunset | hr |  |
| *sun* | Angle of solar elevation | radians |  |
| Ta | Air temperature†(9) | ℃ |  |
| Tmax | Maximum Ta of DAY | ℃ | Table S3 |
| Tmin | Minimum Ta of DAY | ℃ | Table S3 |
| m | Amount of time since time of minimum temperature†(9) | hr |  |
| n | Amount of time since tsunset†(9) | hr |  |
| xlag | Lag coefficient for the maximum temperature from tsunrise†(9) | dimensionless | 1.8 |
| ylag | Lag coefficient for the night-time temperature from tsunrise†(9) | dimensionless | 2.2 |
| zlag | Lag coefficient for the minimum temperature from tsunrise†(9) | dimensionless | 1 |
| **Canopy architecture parameters** |
| LAIcan | Canopy leaf area index | m2 leaf m-2 ground | Table S3 |
| LAIsun | LAI of sunlit leaf fraction†(8) | m2 leaf m-2 ground |  |
| LAIsh | LAI of shade leaf fraction†(8) | m2 leaf m-2 ground |  |
| L | Cumulative LAI from the top of the canopy | m2 leaf m-2 ground-1 | Table 3 |
| Kb | Direct and scattered direct PAR extinction coefficient†(7), (8) | dimensionless |  |
| Kd | Diffuse and scattered diffuse PAR extinction coefficient†(7), (8) | dimensionless |  |
| kb | Direct radiation extinction coefficient†(7), (8), (10) | dimensionless |  |
| kd | Diffuse PAR extinction coefficient†(8) | dimensionless | 0.78 |
|  | Leaf level scattering coefficient for PAR† (8) | dimensionless | 0.15 |
| *cb* | Canopy level reflection coefficient for direct PAR† (8) | dimensionless |  |
| *h* | Reflection coefficient of a canopy with horizontal leaves† (8) | dimensionless |  |
| *cd* | Canopy level reflection coefficient for diffuse PAR† (8) | dimensionless | 0.036 |
| G | Leaf shadow projection coefficient† (10) | dimensionless |  |
|  | Parameter used for calculation of G† (10) | ° |  |
|  | Canopy average leaf inclination relative to the horizontal† (8) | radians | 60° |
| Tl | Leaf temperature | ℃ | Ta |
| **Canopy nitrogen status parameters** |
| SLNave | Average canopy nitrogen concentration per unit leaf area | g N m-2 leaf | Table S3 |
| SLNratio\_top | Ratio of SLNave to SLNo | dimensionless | Table S3 |
| SLNtop | SLN at the top of the canopy | g N m-2 leaf | Table S3,  |
| SLNL | SLN at L† (8) | g N m-2 leaf |  |
| Nave | Average canopy nitrogen concentration per unit leaf area | mmol N m-2 leaf |  |
| Ntop | SLN at the top of the canopy | mmol N m-2 leaf |  |
| NL | SLN at L | mmol N m-2 leaf |  |
| Nb | SLN when leaf photosynthesis = 0† (11) | mmol N m-2 leaf | 21.43 |
| TNC | Total canopy nitrogen concentration† (8) | mmol N m-2 ground |  |
| *KN* | Canopy photosynthetic nitrogen extinction coefficient | dimensionless |  |
| **Photosynthetic parameters** |
| v | Slope of linear relationship between *Vcmax* per leaf area at 25 ℃ and N†(8), (12), (13) | mol CO2 mmol-1 N s-1 | Table S3,  |
| *J* | Slope of linear relationship between *Jmax* per leaf area at 25 ℃ and N†(8), (12), (13) | mol CO2 mmol-1 N s-1 | Table S3,  |
| R | Slope of linear relationship between Rd per leaf area at 25 ℃ and N†(8), (12), (13) | mol CO2 mmol-1 N s-1 | 0.01v |
| P | Values of v,*J* or R | mol CO2 mmol-1 N s-1 | v,*J* or R |
| Pcan25 | Values of *Vcmax*, *Jmax* or Rd for the whole canopy at 25 ℃†(8) | mol CO2 m-2 ground-1 s-1 |  |
| Psun25 | Values of *Vcmax*, *Jmax* or Rd for the sunlit leaf fraction at 25 ℃†(8) | mol CO2 m-2 ground-1 s-1 |  |
| Psh25 | Values of *Vcmax*, *Jmax* or Rd for the shade leaf fraction at 25 ℃ | mol CO2 m-2 ground-1 s-1 |  |
| *Vcamx\_g25* | Maximum Rubisco carboxylation rate per ground area at 25 ℃ | mol CO2 m-2 ground-1 s-1 | Table S2 |
| *Jmax\_g25* | Maximum rate of electron transport per ground area at 25 ℃ | mol CO2 m-2 ground-1 s-1 | Table S2 |
| Rd\_g25 | Leaf day respiration per ground area at 25 ℃ | mol CO2 m-2 ground-1 s-1 | Table S2 |
| *Kc* | Michaelis constant of Rubisco for CO2 | bar | Table S2 |
| *Ko* | Michaelis constant of Rubisco for O2 | bar | Table S2 |
| *A* | Net CO2 assimilation rate†(14) | mol CO2 m-2 ground-1 s-1 |  |
| *Ac* | Rubisco limited net CO2 assimilation rate†(14) | mol CO2 m-2 ground-1 s-1 |  |
| *Aj* | Electron transport limited net CO2 assimilation rate†(14) | mol CO2 m-2 ground-1 s-1 |  |
| *\** | CO2 compensation point in the absence of Rd†(14) | bar |  |
| *\** | Half the reciprocal of *Sc/o*†(14) | dimensionless |  |
| *Sc/o* | Relative CO2/O2 specificity of Rubisco†(14) | bar bar-1 |  |
| *Vcamx/Voamx* | Ratio of maximum Rubisco carboxylation rate to maximum Rubisco oxygenation rate | dimensionless | Table S2 |
| *J* | Potential electron transport rate†(14) | mol e- m-2 ground s-1 |  |
| ** | Empirical curvature factor†(14) | dimensionless | 0.7 |
| *f* | Spectral correction factor†(14) | dimensionless | 0.15 |
| *I2* | PAR absorbed by Photosystem II†(14) | mol PAR m-2 ground-1 s-1 |  |
| **CO2 diffusion parameters** |
| Ci | Intercellular airspace CO2 partial pressure | bar | Table 3， |
| Cc | Chloroplast CO2 partial pressure†(15) | bar |  |
| Ol | O2 partial pressure inside leaves | bar | Oa |
| Oc | O2 partial pressure at chloroplast | bar | Ol |
| a | Slope of linear relationship between Ci/Ca and VPDa†(16) | kPa-1 | -0.12 |
| b | Intercept of linear relationship between Ci/Ca and VPDa†(16) | dimensionless | 0.9 |
| Ci/Ca | Ratio of Ci to Ca | dimensionless | Table S3 |
| gm | Mesophyll conductance per leaf area | mol CO2 m-2 leaf s-1 bar-1 | Table S3 |
| gm\_g | Mesophyll conductance per ground area | mol CO2 m-2 grounds-1 bar-1 |  |
| **Final output** |
| *A*can,DAY | Daily canopy photosynthesis | mol CO2 m-2 ground day-1 |  |

Parameters with subscript e means it is determined separately for sunlit leaf fraction and shade leaf fraction; Values of parameters that listed in Table S3 are specific for rice in the present study; Reference†(1)-(16): Brock, 1981; Hammer and Wright, 1994; Goudriaan and van Laar, 1994; Charles-Edwards, 1986; Collares-Pereira and Rabl, 1979; Monteith and Unsworth, 2013; Leuning et al., 1995; de Pury and Farquhar, 1997; Parton and Logan, 1981; Ducan et al., 1967; Yin and van Laar, 2005; Evans, 1983; Harley et al., 1992; Farquhar et al., 1980; Wong et al., 1979; Zhang and Nobel, 1996.

**TABLE S2 Temperature response parameters in photosynthetic model.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Units** | **P25** | **c (dimensionless)** | **b (K)** | **Equation** | **Reference** |
| *Kc* | bar | 272.4 | 32.7 | 9741.4 |  | Bernacchi et al., 2002 |
| *Ko* | bar | 165800 | 9.6 | 2853.0 |
| *Vcmax/Vomax* | - | 4.6 | 13.2 | 3945.7 |
| *Vcmax* | mol CO2 m-2 s-1 | Variable | 26.4 | 7857.8 | Bernacchi et al., 2001 |
| Rd | mol CO2 m-2 s-1 | Variable | 18.7 | 5579.7 |
|  | **P25** | Topt (℃) | **(K)** |  |  |
| *Jmax* | mol CO2 m-2 s-1 | Variable | 28.8 | 15.5 | Farquhar et al., 1980 |
| gm | mol CO2 m-2 ground-1 s-1 bar-1 | Table 3 | 34.3 | 20.8 | Bernacchi et al., 2002 |

P25, value of modeled parameter at 25 ℃; P, value of modeled parameter at Tl; Topt and Tl, optimum and leaf temperature used in equations.

**TABLE S3 Parameters specific for rice in the present study used for simulating daily canopy photosynthesis.**

|  |  |  |
| --- | --- | --- |
| **Parameter** | **units** | **Value** |
| **Tillering stage** | **Flowering stage** |
| **Environment parameters** |
| Lat | radians | 32.23 |
| Day | dimensionless | 203 | 245 |
| Tmax | ℃ | 34.6 | 31.3 |
| Tmin | ℃ | 27.8 | 21.7 |
| **Canopy nitrogen status parameters** |
| LAIcan | m2 leaf m-2 ground | 3.85, 3.84, 3.26, 3.17 | 5.09, 5.06, 4.43, 4.19 |
| β | ° | 60.3, 61.3, 62.1, 63.0 | 54.0, 59.1, 59.3, 54.0 |
| **Canopy nitrogen status parameters** |
| SLNave | g N m-2 leaf | 0.52, 0.57, 0.75, 0.60 | 0.75, 0.63, 0.93, 0.93 |
| SLNratio\_top | dimensionless | 0.54, 0.78, 0.97, 0.78 | 0.78, 0.79, 0.94, 0.89 |
| SLNtop | g N m-2 leaf | 0.96, 0.73, 0.77, 0.77 | 0.96, 0.80, 0.99, 1.04 |
| **Photosynthetic parameters** |
| v | mol CO2 mmol-1 N s-1 | 2.97, 4.70, 2.72, 2.71 | 2.99, 3.45, 2.31, 1.80 |
| *J* | mol CO2 mmol-1 N s-1 | 4.54, 5.72, 4.69, 4.57 | 4.70, 5.43, 4.41, 3.29 |
| *C*i/*C*a | dimensionless | 0.700, 0.732, 0.711, 0.709 | 0.679, 0.710, 0.696, 0.693 |
| *g*m | mol CO2 m-2 leaf s-1 bar-1 |

Environment parameters are indentical for each treatment, and parameters other than environment parameters are specific for YLY3218, YLN5867, ZD11, and NJ9108.

**TABLE S4 Effects of N rates on yield components of different rice varieties.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| N rate(kg hm-2) | Cultivar | Panicles(\*104 hm-2) | Spikelets(panicle-1) | Grain filling percentage(%) | 1000-grain weight(g) |
| 2018 | 2019 | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| 0 | YLY3218 | 208.4aB | 192.3aC | 165.3aB | 212.7aB | 93.0aA | 93.5aA | 24.4bA | 25.8cAB |
| YLY5867 | 216.0aB | 175.4aB | 176.5aB | 189.6aB | 94.3aA | 95.2aA | 27.4aA | 29.0aA |
| ZD11 | 213.5aB | 183.6aD | 118.7bA | 99.2bB | 93.7aA | 97.5aA | 27.2aA | 29.4aA |
| NJ9108 | 221.7aB | 187.7aC | 154.2aA | 120.7bB | 91.4aA | 97.4aA | 24.4bA | 27.1bB |
| 90 | YLY3218 | 249.1aAB | 230.8aBC | 193.5aB | 244.0aA | 89.4aAB | 93.3bcA | 24.8bcA | 25.5bB |
| YLY5867 | 266.0aA | 233.8aAB | 182.2aAB | 249.6aA | 91.5aAB | 92.1cA | 27.9aA | 28.4aA |
| ZD11 | 236.8aB | 257.4aC | 137.5bA | 137.3bA | 93.3aA | 98.0aA | 25.9bA | 28.0aB |
| NJ9108 | 237.4aB | 221.5aBC | 168.4abA | 117.8bB | 92.5aA | 97.1abA | 24.1cAB | 28.8aA |
| 180 | YLY3218 | 281.4aA | 245.1bABC | 241.2aA | 237.3aAB | 89.3bcAB | 94.7abA | 24.8bA | 27.0cA |
| YLY5867 | 287.6aA | 258.5bA | 215.5aA | 210.5aB | 88.9cBC  | 92.7bA | 28.5aA | 28.7abA |
| ZD11 | 254.5aB | 325.1aB | 138.8bA | 149.1bA | 94.0abA | 98.0aA | 25.5bA | 27.6bBC |
| NJ9108 | 272.5aAB | 254.4bAB | 158.6bA | 126.4bB | 94.4aA | 96.1abA | 24.0bAB | 29.4aA |
| 270 | YLY3218 | 252.2bAB | 291.3bAB | 232.0aA | 254.5aA | 84.4bB | 93.6aA | 24.7bA | 26.3bAB |
| YLY5867 | 267.5bA | 255.4bA | 190.7bAB | 209.5bB | 88.3aABC | 94.3aA | 28.8aA | 29.6aA |
| ZD11 | 350.2aA | 353.8aAB | 134.7cA | 138.6cA | 92.0aA | 97.7aA | 24.2bAB | 26.6bCD |
| NJ9108 | 257.5bB | 280.0bAB | 157.8cA | 142.3cAB | 92.8aA | 94.9aA | 23.5bAB | 29.0aA |
| 360 | YLY3218 | 269.1bcA | 307.7bA | 253.3aA | 252.3aA | 81.3bB | 92.8aA | 24.5bA | 26.2bAB |
| YLY5867 | 256.6cAB | 266.7bA | 184.0bAB | 215.2bB | 85.6bC | 93.1aA | 28.8aA | 28.8aA |
| ZD11 | 392.3aA | 393.8aA | 136.9cA | 151.3cA | 92.2aA | 96.9aA | 23.2bcB | 25.8bD |
| NJ9108 | 313.7bA | 310.8bA | 170.7bA | 162.4cA | 94.1aA | 94.8aA | 22.3cB | 28.4aA |
| *ANOVA* | Variety (V) | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* |
| Nitrogen (N) | \*\* | \*\* | \*\* | \*\* | \*\* | ns | \*\* | \*\* |
| V×N | \*\* | \* | \*\* | \*\* | \*\* | ns | \*\* | \*\* |

Note: Different lowercases of the same N rates means significant differences among different rice varieties at the 5% level, different uppercases of the same variety means significant differences among different N rates at the 5% level. The significance test (*P* values) of the analysis of variance two-way (*ANOVA*) between V and N and their interaction (V×N) are given (\*\* *P* <0.01; \* *P* <0.05; ns, no significant difference).

**TABLE S5 Correlation analysis between net photosynthesis rate under saturated light (*A*sat), leaf area index (LAI) and yield.**

|  |  |  |
| --- | --- | --- |
| **correlation coefficient *r*** | ***A*sat** | **LAI** |
| **Tillering stage** | **Flowering stage** | **Tillering stage** | **Flowering stage** |
| Yield | 0.907ns | 0.681ns | 0.995\*\* | 0.987\* |

\*\* P<0.01; \*P<0.05; ns, no significant difference.



**FIGURE S1** Daily mean temerature, precipitation and photosynthetic active radiation (PAR) during rice growing season at Rugao County, Jiangsu Province, China in 2020.



**FIGURE S2** Schematic of the Diurnal canopy photosynthesis simulator (DCaPS, recomposed from Wu et al. ( 2018). Model inputs are composed of environment, canopy architecture, canopy nitrogen status, CO2 diffusion, photosynthetic and temperature response parameters. Model outputs are diurnal environment variables, diurnal canopy photosynthesis. The chloroplastic CO2 partial pressure (Cc) and photosynthesis are coupled and solved simultaneously. According to the combined photosynthetic model, *Ac* and *Aj*are solved for both sunlit leaf fraction and shaded leaf fraction by the equation:

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For *Ac*, x1=*Vcamx* and x2=*Kc*/(1+*Ko*); for *Aj*, x1=*J*/4 and x2=2\*\*. When calculation of *Ac* and *Aj*,Cc is solved by equation listed in Table S1. Abbreviations: RATIO, atmospheric transmission ratio for incident solar radiation; VPDa, air vapour pressure deficit; PAR, photosynthetic active radiation; SLNave, average canopy nitrogen concentration per unit leaf area; SLNratio\_top, ratio of SLN at the top of canopy to SLNave; Tl, leaf temperature; gm, mesophyll conductance for CO2; *O*l, O2 partial pressure inside leaves. Comprehensive lists of the photosynthetic parameters are given in Tables S1, S2 and S3.



**FIGURE S3** Effects of N rates on yield at maturity of different rice varieties

Different lowercases of the same N rates means significant differences among different rice varieties at the 5% level, different uppercases of the same variety means significant differences among different N rates at the 5% level. The significance test (P values) of the analysis of variance two-way (*ANOVA*) between V and N and their interaction (V×N) are given (\*\* P <0.01; \* P <0.05; ns, no significant difference).

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