Article

# Environmental Impact Assessment of Rice–Wheat Rotation Considering Annual Nitrogen Application Rate

Yulin Yang[1,2,3], Xiaohu Liu[1,2,3], Yinglong Chen[1,2,3], Qiang Xu[1,2,3], Qigen Dai[1,2,3*], Huanhe Wei[1,2,3], Ke Xu[1,2,3], Hongcheng Zhang[1,2,3]

[1] Jiangsu Key Laboratory of Crop Genetics and Physiology/Jiangsu Key Laboratory of Crop Cultivation and Physiology, Agricultural College of Yangzhou University, Yangzhou 225009, China; dx120200100@stu.yzu.edu.cn (Y.Y.); mx120220749@stu.yzu.edu.cn (X.L.); chenyinglong@yzu.edu.cn (Y.C.); qiangxu@yzu.edu.cn (Q.X.); 006931@yzu.edu.cn (H.W.); xuke@yzu.edu.cn (K.X.); hczhang@yzu.edu.cn (H.Z.)

[2] Jiangsu Co-Innovation Center for Modern Production Technology of Grain Crops, Yangzhou University, Yangzhou 225009, China

[3] Research Institute of Rice Industrial Engineering Technology of Yangzhou University, Yangzhou 225009, China

* Correspondence: qgdai@yzu.edu.cn

**Table S1.** Life cycle inventory of rice-wheat rotation from 2020 to 2021.

| Treatments | Rice2020 | | | | | | | | | Wheat2020-2021 | | | | | | | | | Annual yield |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Seed | Urea | $Ca(H_2PO_4)_2$ | KCl | Pesticide [a] | Diesel | Electricity | Irrigation | Yield | Seed | Urea | $Ca(H_2PO_4)_2$ | KCl | Pesticide [a] | Diesel | Electricity | Irrigation | Yield | |
| | ———————— kg ha$^{-1}$ ——————— | | | | | L ha$^{-1}$ | kWh ha$^{-1}$ | m$^3$ ha$^{-1}$ | kg ha$^{-1}$ | ———————— kg ha$^{-1}$ ——————— | | | | | L ha$^{-1}$ | kWh ha$^{-1}$ | m$^3$ ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ |
| R0W0 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 4972 | 150 | 0 | 750 | 240 | 5.5 | 80 | | | 1803 | 6776 |
| R0W180 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6056 | 150 | 409 | 750 | 240 | 5.5 | 80 | | | 4140 | 10196 |
| R0W240 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6305 | 150 | 545 | 750 | 240 | 5.5 | 80 | | | 5406 | 11711 |
| R0W300 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6358 | 150 | 682 | 750 | 240 | 5.5 | 80 | | | 5184 | 11541 |
| R0W360 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6341 | 150 | 818 | 750 | 240 | 5.5 | 80 | | | 4738 | 11079 |
| R180W0 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7719 | 150 | 0 | 750 | 240 | 5.5 | 80 | | | 1909 | 9628 |
| R180W180 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7919 | 150 | 409 | 750 | 240 | 5.5 | 80 | | | 4465 | 12384 |
| R180W240 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7938 | 150 | 545 | 750 | 240 | 5.5 | 80 | | | 5521 | 13458 |
| R180W300 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8011 | 150 | 682 | 750 | 240 | 5.5 | 80 | | | 5269 | 13280 |
| R180W360 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8032 | 150 | 818 | 750 | 240 | 5.5 | 80 | | | 4627 | 12659 |
| R240W0 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9089 | 150 | 0 | 750 | 240 | 5.5 | 80 | | | 2016 | 11105 |
| R240W180 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9274 | 150 | 409 | 750 | 240 | 5.5 | 80 | | | 4668 | 13942 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R240W240 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9308 | 150 | 545 | 750 | 240 | 5.5 | 80 | 5676 | 14984 |
| R240W300 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9386 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5129 | 14515 |
| R240W360 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9392 | 150 | 818 | 750 | 240 | 5.5 | 80 | 4784 | 14176 |
| R300W0 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9859 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2425 | 12284 |
| R300W180 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9924 | 150 | 409 | 750 | 240 | 5.5 | 80 | 4831 | 14755 |
| R300W240 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9936 | 150 | 545 | 750 | 240 | 5.5 | 80 | 5804 | 15741 |
| R300W300 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9953 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5210 | 15163 |
| R300W360 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9952 | 150 | 818 | 750 | 240 | 5.5 | 80 | 4695 | 14647 |
| R360W0 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8670 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2522 | 11193 |
| R360W180 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8633 | 150 | 409 | 750 | 240 | 5.5 | 80 | 4960 | 13594 |
| R360W240 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8636 | 150 | 545 | 750 | 240 | 5.5 | 80 | 5663 | 14299 |
| R360W300 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8605 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5078 | 13683 |
| R360W360 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8574 | 150 | 818 | 750 | 240 | 5.5 | 80 | 4788 | 13362 |
| R420W0 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7832 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2693 | 10525 |
| R420W180 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7807 | 150 | 409 | 750 | 240 | 5.5 | 80 | 5007 | 12815 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R420W240 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7781 | 150 | 545 | 750 | 240 | 5.5 | 80 | | | 5511 | 13292 |
| R420W300 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7744 | 150 | 682 | 750 | 240 | 5.5 | 80 | | | 5030 | 12774 |
| R420W360 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 7716 | 150 | 818 | 750 | 240 | 5.5 | 80 | | | 4739 | 12454 |

[a] Pesticides were calculated as the total of insecticide, herbicide, and fungicide (active ingredient).

**Table S2**. Life cycle inventory of rice-wheat rotation from 2021 to 2022.

| Treatments | Rice2021 | | | | | | | | | Wheat2021-2022 | | | | | | | | | Annual yield |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Seed | Urea | $Ca(H_2PO_4)_2$ | KCl | Pesticide [a] | Diesel | Electricity | Irrigation | Yield | Seed | Urea | $Ca(H_2PO_4)_2$ | KCl | Pesticide [a] | Diesel | Electricity | Irrigation | Yield | |
| | kg ha$^{-1}$ | | | | | L ha$^{-1}$ | kWh ha$^{-1}$ | m$^3$ ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | | | | | L ha$^{-1}$ | kWh ha$^{-1}$ | m$^3$ ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ |
| R0W0 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 5184 | 150 | 0 | 750 | 240 | 5.5 | 80 | | | 1629 | 6813 |
| R0W180 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6331 | 150 | 409 | 750 | 240 | 5.5 | 80 | | | 4819 | 11150 |
| R0W240 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6400 | 150 | 545 | 750 | 240 | 5.5 | 80 | | | 6473 | 12873 |
| R0W300 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6420 | 150 | 682 | 750 | 240 | 5.5 | 80 | | | 5742 | 12162 |
| R0W360 | 60 | 0 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 6426 | 150 | 818 | 750 | 240 | 5.5 | 80 | | | 5428 | 11854 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R180W0 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8049 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2144 | 10193 |
| R180W180 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8153 | 150 | 409 | 750 | 240 | 5.5 | 80 | 4952 | 13105 |
| R180W240 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8329 | 150 | 545 | 750 | 240 | 5.5 | 80 | 6450 | 14778 |
| R180W300 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8330 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5990 | 14319 |
| R180W360 | 60 | 409 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 8328 | 150 | 818 | 750 | 240 | 5.5 | 80 | 5317 | 13645 |
| R240W0 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9711 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2333 | 12044 |
| R240W180 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9760 | 150 | 409 | 750 | 240 | 5.5 | 80 | 5078 | 14837 |
| R240W240 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9809 | 150 | 545 | 750 | 240 | 5.5 | 80 | 6557 | 16365 |
| R240W300 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9810 | 150 | 682 | 750 | 240 | 5.5 | 80 | 6034 | 15844 |
| R240W360 | 60 | 545 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9813 | 150 | 818 | 750 | 240 | 5.5 | 80 | 5306 | 15119 |
| R300W0 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 10897 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2808 | 13704 |
| R300W180 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 10952 | 150 | 409 | 750 | 240 | 5.5 | 80 | 5364 | 16317 |
| R300W240 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 10962 | 150 | 545 | 750 | 240 | 5.5 | 80 | 6579 | 17541 |
| R300W300 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 10978 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5822 | 16800 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R300W360 | 60 | 682 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 10715 | 150 | 818 | 750 | 240 | 5.5 | 80 | 5198 | 15914 |
| R360W0 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9953 | 150 | 0 | 750 | 240 | 5.5 | 80 | 2741 | 12694 |
| R360W180 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9921 | 150 | 409 | 750 | 240 | 5.5 | 80 | 5592 | 15513 |
| R360W240 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9901 | 150 | 545 | 750 | 240 | 5.5 | 80 | 6510 | 16411 |
| R360W300 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9914 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5674 | 15587 |
| R360W360 | 60 | 818 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9881 | 150 | 818 | 750 | 240 | 5.5 | 80 | 5112 | 14992 |
| R420W0 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9325 | 150 | 0 | 750 | 240 | 5.5 | 80 | 3000 | 12325 |
| R420W180 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9311 | 150 | 409 | 750 | 240 | 5.5 | 80 | 5551 | 14863 |
| R420W240 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9303 | 150 | 545 | 750 | 240 | 5.5 | 80 | 6500 | 15803 |
| R420W300 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9293 | 150 | 682 | 750 | 240 | 5.5 | 80 | 5602 | 14895 |
| R420W360 | 60 | 955 | 395 | 263 | 12.4 | 120 | 300 | 6500 | 9282 | 150 | 818 | 750 | 240 | 5.5 | 80 | 5052 | 14334 |

[a] Pesticides were calculated as the total of insecticide, herbicide, and fungicide (active ingredient).

**Table S3**. On-field environmental pollutants from rice cultivation (2021).

| Treatment | $CH_4$ | $N_2O$ | $NO_x$ | $NH_3$ | N leaching | N runoff | P runoff | P leaching | Cd | Pb | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ |
| R0W0 | 176.20 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.7054 | 0.0947 | 0.0028 | 0.0021 | 0.0037 | 0.0266 |
| R0W180 | 238.12 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.7054 | 0.0947 | 0.0028 | 0.0021 | 0.0037 | 0.0266 |
| R0W240 | 267.31 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.7054 | 0.0947 | 0.0028 | 0.0021 | 0.0037 | 0.0266 |
| R0W300 | 262.35 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.7054 | 0.0947 | 0.0028 | 0.0021 | 0.0037 | 0.0266 |
| R0W360 | 252.21 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.7054 | 0.0947 | 0.0028 | 0.0021 | 0.0037 | 0.0266 |
| R180W0 | 179.30 | 1.35 | 0.01 | 32.76 | 3.24 | 4.86 | 0.7054 | 0.0947 | 0.0029 | 0.0040 | 0.0039 | 0.0269 |
| R180W180 | 245.84 | 1.39 | 0.01 | 32.76 | 3.24 | 4.86 | 0.7054 | 0.0947 | 0.0029 | 0.0040 | 0.0039 | 0.0269 |
| R180W240 | 269.85 | 1.40 | 0.01 | 32.76 | 3.24 | 4.86 | 0.7054 | 0.0947 | 0.0029 | 0.0040 | 0.0039 | 0.0269 |
| R180W300 | 264.25 | 1.40 | 0.01 | 32.76 | 3.24 | 4.86 | 0.7054 | 0.0947 | 0.0029 | 0.0040 | 0.0039 | 0.0269 |
| R180W360 | 249.63 | 1.39 | 0.01 | 32.76 | 3.24 | 4.86 | 0.7054 | 0.0947 | 0.0029 | 0.0040 | 0.0039 | 0.0269 |
| R240W0 | 182.42 | 1.79 | 0.01 | 43.68 | 4.32 | 6.48 | 0.7054 | 0.0947 | 0.0029 | 0.0046 | 0.0040 | 0.0270 |
| R240W180 | 250.57 | 1.83 | 0.01 | 43.68 | 4.32 | 6.48 | 0.7054 | 0.0947 | 0.0029 | 0.0046 | 0.0040 | 0.0270 |
| R240W240 | 273.25 | 1.84 | 0.01 | 43.68 | 4.32 | 6.48 | 0.7054 | 0.0947 | 0.0029 | 0.0046 | 0.0040 | 0.0270 |
| R240W300 | 261.12 | 1.84 | 0.01 | 43.68 | 4.32 | 6.48 | 0.7054 | 0.0947 | 0.0029 | 0.0046 | 0.0040 | 0.0270 |
| R240W360 | 253.27 | 1.83 | 0.01 | 43.68 | 4.32 | 6.48 | 0.7054 | 0.0947 | 0.0029 | 0.0046 | 0.0040 | 0.0270 |
| R300W0 | 193.99 | 2.23 | 0.01 | 54.60 | 5.40 | 8.10 | 0.7054 | 0.0947 | 0.0030 | 0.0052 | 0.0041 | 0.0270 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R300W180 | 254.33 | 2.27 | 0.01 | 54.60 | 5.40 | 8.10 | 0.7054 | 0.0947 | 0.0030 | 0.0052 | 0.0041 | 0.0270 |
| R300W240 | 276.05 | 2.28 | 0.01 | 54.60 | 5.40 | 8.10 | 0.7054 | 0.0947 | 0.0030 | 0.0052 | 0.0041 | 0.0270 |
| R300W300 | 262.93 | 2.28 | 0.01 | 54.60 | 5.40 | 8.10 | 0.7054 | 0.0947 | 0.0030 | 0.0052 | 0.0041 | 0.0270 |
| R300W360 | 251.21 | 2.27 | 0.01 | 54.60 | 5.40 | 8.10 | 0.7054 | 0.0947 | 0.0030 | 0.0052 | 0.0041 | 0.0270 |
| R360W0 | 196.68 | 2.67 | 0.02 | 65.52 | 6.48 | 9.72 | 0.7054 | 0.0947 | 0.0030 | 0.0058 | 0.0041 | 0.0271 |
| R360W180 | 257.29 | 2.71 | 0.02 | 65.52 | 6.48 | 9.72 | 0.7054 | 0.0947 | 0.0030 | 0.0058 | 0.0041 | 0.0271 |
| R360W240 | 272.98 | 2.72 | 0.02 | 65.52 | 6.48 | 9.72 | 0.7054 | 0.0947 | 0.0030 | 0.0058 | 0.0041 | 0.0271 |
| R360W300 | 259.96 | 2.71 | 0.02 | 65.52 | 6.48 | 9.72 | 0.7054 | 0.0947 | 0.0030 | 0.0058 | 0.0041 | 0.0271 |
| R360W360 | 253.36 | 2.71 | 0.02 | 65.52 | 6.48 | 9.72 | 0.7054 | 0.0947 | 0.0030 | 0.0058 | 0.0041 | 0.0271 |
| R420W0 | 201.34 | 3.11 | 0.02 | 76.44 | 7.56 | 11.34 | 0.7054 | 0.0947 | 0.0030 | 0.0065 | 0.0042 | 0.0272 |
| R420W180 | 258.36 | 3.15 | 0.02 | 76.44 | 7.56 | 11.34 | 0.7054 | 0.0947 | 0.0030 | 0.0065 | 0.0042 | 0.0272 |
| R420W240 | 269.63 | 3.16 | 0.02 | 76.44 | 7.56 | 11.34 | 0.7054 | 0.0947 | 0.0030 | 0.0065 | 0.0042 | 0.0272 |
| R420W300 | 258.89 | 3.15 | 0.02 | 76.44 | 7.56 | 11.34 | 0.7054 | 0.0947 | 0.0030 | 0.0065 | 0.0042 | 0.0272 |
| R420W360 | 252.21 | 3.15 | 0.02 | 76.44 | 7.56 | 11.34 | 0.7054 | 0.0947 | 0.0030 | 0.0065 | 0.0042 | 0.0272 |

**Table S4**. On-field environmental pollutants from wheat cultivation (2021–2022)

| Treatment | $N_2O$ | $NO_x$ | $NH_3$ | N leaching | N runoff | P runoff | P leaching | Cd | Pb | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg N ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ | kg ha$^{-1}$ |
| R0W0 | 0.40 | 0.00 | 0.00 | 0.00 | 0.00 | 1.7190 | 0.2970 | 0.0028 | 0.0023 | 0.0063 | 0.0480 |
| R0W180 | 2.61 | 0.71 | 9.90 | 6.30 | 13.14 | 1.7190 | 0.2970 | 0.0029 | 0.0041 | 0.0065 | 0.0483 |
| R0W240 | 3.32 | 0.94 | 13.20 | 8.40 | 17.52 | 1.7190 | 0.2970 | 0.0029 | 0.0048 | 0.0065 | 0.0484 |
| R0W300 | 4.03 | 1.18 | 16.50 | 10.50 | 21.90 | 1.7190 | 0.2970 | 0.0029 | 0.0054 | 0.0066 | 0.0485 |
| R0W360 | 4.73 | 1.41 | 19.80 | 12.60 | 26.28 | 1.7190 | 0.2970 | 0.0029 | 0.0060 | 0.0067 | 0.0486 |
| R180W0 | 0.62 | 0.00 | 0.00 | 0.00 | 0.00 | 1.7190 | 0.2970 | 0.0028 | 0.0023 | 0.0063 | 0.0480 |
| R180W180 | 2.75 | 0.71 | 9.90 | 6.30 | 13.14 | 1.7190 | 0.2970 | 0.0029 | 0.0041 | 0.0065 | 0.0483 |
| R180W240 | 3.47 | 0.94 | 13.20 | 8.40 | 17.52 | 1.7190 | 0.2970 | 0.0029 | 0.0048 | 0.0065 | 0.0484 |
| R180W300 | 4.17 | 1.18 | 16.50 | 10.50 | 21.90 | 1.7190 | 0.2970 | 0.0029 | 0.0054 | 0.0066 | 0.0485 |
| R180W360 | 4.88 | 1.41 | 19.80 | 12.60 | 26.28 | 1.7190 | 0.2970 | 0.0029 | 0.0060 | 0.0067 | 0.0486 |
| R240W0 | 0.74 | 0.00 | 0.00 | 0.00 | 0.00 | 1.7190 | 0.2970 | 0.0028 | 0.0023 | 0.0063 | 0.0480 |
| R240W180 | 2.87 | 0.71 | 9.90 | 6.30 | 13.14 | 1.7190 | 0.2970 | 0.0029 | 0.0041 | 0.0065 | 0.0483 |
| R240W240 | 3.58 | 0.94 | 13.20 | 8.40 | 17.52 | 1.7190 | 0.2970 | 0.0029 | 0.0048 | 0.0065 | 0.0484 |
| R240W300 | 4.29 | 1.18 | 16.50 | 10.50 | 21.90 | 1.7190 | 0.2970 | 0.0029 | 0.0054 | 0.0066 | 0.0485 |
| R240W360 | 4.99 | 1.41 | 19.80 | 12.60 | 26.28 | 1.7190 | 0.2970 | 0.0029 | 0.0060 | 0.0067 | 0.0486 |
| R300W0 | 0.84 | 0.00 | 0.00 | 0.00 | 0.00 | 1.7190 | 0.2970 | 0.0028 | 0.0023 | 0.0063 | 0.0480 |
| R300W180 | 2.96 | 0.71 | 9.90 | 6.30 | 13.14 | 1.7190 | 0.2970 | 0.0029 | 0.0041 | 0.0065 | 0.0483 |
| R300W240 | 3.67 | 0.94 | 13.20 | 8.40 | 17.52 | 1.7190 | 0.2970 | 0.0029 | 0.0048 | 0.0065 | 0.0484 |
| R300W300 | 4.38 | 1.18 | 16.50 | 10.50 | 21.90 | 1.7190 | 0.2970 | 0.0029 | 0.0054 | 0.0066 | 0.0485 |
| R300W360 | 5.06 | 1.41 | 19.80 | 12.60 | 26.28 | 1.7190 | 0.2970 | 0.0029 | 0.0060 | 0.0067 | 0.0486 |
| R360W0 | 0.76 | 0.00 | 0.00 | 0.00 | 0.00 | 1.7190 | 0.2970 | 0.0028 | 0.0023 | 0.0063 | 0.0480 |
| R360W180 | 2.88 | 0.71 | 9.90 | 6.30 | 13.14 | 1.7190 | 0.2970 | 0.0029 | 0.0041 | 0.0065 | 0.0483 |
| R360W240 | 3.59 | 0.94 | 13.20 | 8.40 | 17.52 | 1.7190 | 0.2970 | 0.0029 | 0.0048 | 0.0065 | 0.0484 |
| R360W300 | 4.29 | 1.18 | 16.50 | 10.50 | 21.90 | 1.7190 | 0.2970 | 0.0029 | 0.0054 | 0.0066 | 0.0485 |
| R360W360 | 5.00 | 1.41 | 19.80 | 12.60 | 26.28 | 1.7190 | 0.2970 | 0.0029 | 0.0060 | 0.0067 | 0.0486 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R420W0 | 0.72 | 0.00 | 0.00 | 0.00 | 0.00 | 1.7190 | 0.2970 | 0.0028 | 0.0023 | 0.0063 | 0.0480 |
| R420W180 | 2.83 | 0.71 | 9.90 | 6.30 | 13.14 | 1.7190 | 0.2970 | 0.0029 | 0.0041 | 0.0065 | 0.0483 |
| R420W240 | 3.54 | 0.94 | 13.20 | 8.40 | 17.52 | 1.7190 | 0.2970 | 0.0029 | 0.0048 | 0.0065 | 0.0484 |
| R420W300 | 4.25 | 1.18 | 16.50 | 10.50 | 21.90 | 1.7190 | 0.2970 | 0.0029 | 0.0054 | 0.0066 | 0.0485 |
| R420W360 | 4.95 | 1.41 | 19.80 | 12.60 | 26.28 | 1.7190 | 0.2970 | 0.0029 | 0.0060 | 0.0067 | 0.0486 |

# 1. Paddy-field $CH_4$ emissions

The $CH_4$ emissions from rice cultivation were calculated using Equation (S2), which is based on [22] (Tier 2).

$$Q_{CH_4}=EF_i \times t \times A \qquad (S1)$$

where $Q_{CH_4}$ is total methane emissions from rice cultivation (kg $CH_4$ ha$^{-1}$), $EF_i$ is adjusted daily emission factor for a particular harvested area (kg $CH_4$ ha$^{-1}$ day$^{-1}$), $t$ denotes cultivation period of rice (day), with the value of 138; and $A$ denotes annual harvested area of rice (ha year$^{-1}$).

Emissions from each different region can be calculated by multiplying a baseline default emissions factor with various scaling factors, as shown in Equation (S3) [22].

$$EF_i=EF_C \times SF_W \times SF_P \times SF_o \times SF_{s,r} \qquad (S2)$$

where $EF_c$ is the baseline emission factor for continuously flooded fields without organic amendments, , with the value of 1.32; $SF_w$ is a scaling factor to account for the differences in water regime during the cultivation period, with the value of 0.71; $SF_p$ is a scaling factor to account for the differences in water regime in the pre-season before the cultivation period, with the value of 0.89; $SF_O$ is a scaling factor that should vary for both type and amount of organic amendment applied and can be calculated by equation (4); and $SF_{s,r}$ is a scaling factor for soil type, rice cultivar, etc., if available.

The default conversion factor for farmyard manure was calculated by Equation (S4):

$$SF_o = (1 + \sum_i ROA_i \times CFOA_i)^{0.59} \qquad (S3)$$

where $SF_o$ is the scaling factor for both type and amount of organic amendment applied; $ROA_i$ is the application rate of organic amendment $i$, in dry weight for straw and fresh weight for others in tons ha$^{-1}$; and $CFOA_i$ is the conversion factor for organic amendment $i$ (in terms of its relative effect, with respect to straw applied shortly before cultivation). In this study, organic amendment only indicates straw incorporation.

# 2. On-field $N_2O$ emissions

The formula for estimating indirect $N_2O$ emissions was as follows [22]:

$$Q_{N_2O\ (Indirect)}= [(F_{SN} \times Frac_{GASF} \times EF_4+(F_{SN} +F_{CR}) \times Frac_{LEACH-(H)} \times EF_5] \times 44/28 \qquad (S4)$$

where $Q_{N_2O\ (Indirect)}$ is the total indirect $N_2O$ emissions (kg $N_2O$ year$^{-1}$); $F_{SN}$ is the annual amount of synthetic N fertilizer applied to soils (kg N year$^{-1}$); $F_{CR}$ is the annual amount of N in crop residues (kg N year$^{-1}$); $Frac_{GASF}$ is the fraction of synthetic N fertilizer that volatilizes as $NH_3$ and $NO_x$, kg N volatilized (kg of N applied)$^{-1}$; $EF_4$ is the emission factor for $N_2O$ emissions from atmospheric deposition of N on soils and water surfaces, kg N–$N_2O$ (kg $NH_3$–N+$NO_x$–N volatilized)$^{-1}$, with the value of 0.01; $Frac_{LEACH-(H)}$ is the fraction of all N added to, or mineralized in, managed soils in regions where leaching or runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$; and $EF_5$ is the emission factor for $N_2O$ emissions from N leaching and runoff, kg $N_2O$–N (kg N leached and runoff)$^{-1}$, with the value of 0.011.

**Table S5.** Emission factors of reactive N from N fertilization and P loss in the field.

| Loss pathways | Unit | Emission factors | | Reference |
|---|---|---|---|---|
| | | Rice | Wheat | |
| Direct $N_2O$ | kg N kg$^{-1}$ | 0.005 | 0.01 | [22] |
| NOx | kg N kg$^{-1}$ | 0.000047 | 0.00392 | [23] |
| N leaching | kg N kg$^{-1}$ | 0.018 | 0.035 | [25] |
| N runoff | kg N kg$^{-1}$ | 0.027 | 0.073 | [25] |
| $NH_3$ volatilization | kg N kg$^{-1}$ | 0.182 | 0.055 | [24] |
| P leaching | kg P kg$^{-1}$ | 0.002 | 0.0033 | [26,27] |
| P runoff | kg P kg$^{-1}$ | 0.0149 | 0.0191 | [28] |

**Table S6**. Normalization reference value and weight coefficient of world per-capita environmental impact for 2010.

| Impact category | Units | Reference value [34] | Weight |
|---|---|---|---|
| Global warming | kg $CO_2$ eq | 7990.41 | 0.113 |
| Fine particulate matter formation | kg PM2.5 eq | 25.57 | 0.063 |
| Terrestrial acidification | kg $SO_2$ eq | 40.98 | 0.081 |
| Freshwater eutrophication | kg P eq | 0.65 | 0.143 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 15200.31 | 0.129 |
| Freshwater ecotoxicity | kg 1,4-DCB | 25.17 | 0.134 |
| Human carcinogenic toxicity | kg 1,4-DCB | 10.30 | 0.109 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 31251.84 | 0.087 |
| Fossil resource scarcity | kg oil eq | 569.90 | 0.057 |
| Water consumption | $m^3$ | 266.64 | 0.084 |

**Table S7.** Economic profit analysis of rice-wheat rotation with different N-fertilizer treatment (2021–2022).

| Treatment | Seed CNY $ha^{-1}$ | N fertilizer CNY $ha^{-1}$ | P fertilizer CNY $ha^{-1}$ | K fertilizer CNY $ha^{-1}$ | Pesticide CNY $ha^{-1}$ | Field management CNY $ha^{-1}$ | Cost CNY $ha^{-1}$ | Revenue [a] CNY $ha^{-1}$ | Profit [b] CNY $ha^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| R0W0 | 1980 | 0 | 2861 | 1256 | 353 | 8255 | 14705 | 17225 | 2519 |
| R0W180 | 1980 | 1023 | 2861 | 1256 | 353 | 8255 | 15728 | 27544 | 11816 |
| R0W240 | 1980 | 1364 | 2861 | 1256 | 353 | 8255 | 16069 | 31527 | 15459 |
| R0W300 | 1980 | 1705 | 2861 | 1256 | 353 | 8255 | 16410 | 29898 | 13489 |
| R0W360 | 1980 | 2045 | 2861 | 1256 | 353 | 8255 | 16751 | 29192 | 12441 |
| R180W0 | 1980 | 1023 | 2861 | 1256 | 353 | 8255 | 15728 | 25859 | 10131 |
| R180W180 | 1980 | 2045 | 2861 | 1256 | 353 | 8255 | 16751 | 32587 | 15836 |
| R180W240 | 1980 | 2386 | 2861 | 1256 | 353 | 8255 | 17091 | 36489 | 19397 |
| R180W300 | 1980 | 2727 | 2861 | 1256 | 353 | 8255 | 17432 | 35433 | 18000 |
| R180W360 | 1980 | 3068 | 2861 | 1256 | 353 | 8255 | 17773 | 33883 | 16109 |
| R240W0 | 1980 | 1364 | 2861 | 1256 | 353 | 8255 | 16069 | 30615 | 14546 |
| R240W180 | 1980 | 2386 | 2861 | 1256 | 353 | 8255 | 17091 | 37054 | 19962 |
| R240W240 | 1980 | 2727 | 2861 | 1256 | 353 | 8255 | 17432 | 40583 | 23150 |
| R240W300 | 1980 | 3068 | 2861 | 1256 | 353 | 8255 | 17773 | 39385 | 21612 |
| R240W360 | 1980 | 3409 | 2861 | 1256 | 353 | 8255 | 18114 | 37717 | 19602 |
| R300W0 | 1980 | 1705 | 2861 | 1256 | 353 | 8255 | 16410 | 34789 | 18379 |
| R300W180 | 1980 | 2727 | 2861 | 1256 | 353 | 8255 | 17432 | 40814 | 23381 |
| R300W240 | 1980 | 3068 | 2861 | 1256 | 353 | 8255 | 17773 | 43634 | 25860 |
| R300W300 | 1980 | 3409 | 2861 | 1256 | 353 | 8255 | 18114 | 41932 | 23818 |
| R300W360 | 1980 | 3750 | 2861 | 1256 | 353 | 8255 | 18455 | 39816 | 21361 |
| R360W0 | 1980 | 2045 | 2861 | 1256 | 353 | 8255 | 16751 | 32181 | 15431 |
| R360W180 | 1980 | 3068 | 2861 | 1256 | 353 | 8255 | 17773 | 38657 | 20884 |
| R360W240 | 1980 | 3409 | 2861 | 1256 | 353 | 8255 | 18114 | 40715 | 22601 |
| R360W300 | 1980 | 3750 | 2861 | 1256 | 353 | 8255 | 18455 | 38824 | 20369 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| R360W360 | 1980 | 4091 | 2861 | 1256 | 353 | 8255 | 18796 | 37446 | 18650 |
| R420W0 | 1980 | 2386 | 2861 | 1256 | 353 | 8255 | 17091 | 31144 | 14052 |
| R420W180 | 1980 | 3409 | 2861 | 1256 | 353 | 8255 | 18114 | 36977 | 18863 |
| R420W240 | 1980 | 3750 | 2861 | 1256 | 353 | 8255 | 18455 | 39137 | 20682 |
| R420W300 | 1980 | 4091 | 2861 | 1256 | 353 | 8255 | 18796 | 37047 | 18251 |
| R420W360 | 1980 | 4432 | 2861 | 1256 | 353 | 8255 | 19137 | 35753 | 16616 |

[a] The price of rice and wheat was 2.6 CNY and 2.3 CNY per kilogram, according to National Development and Reform Commission of the People's Republic of China (https://www.ndrc.gov.cn/).

[b] Profit = Revenue - Cost

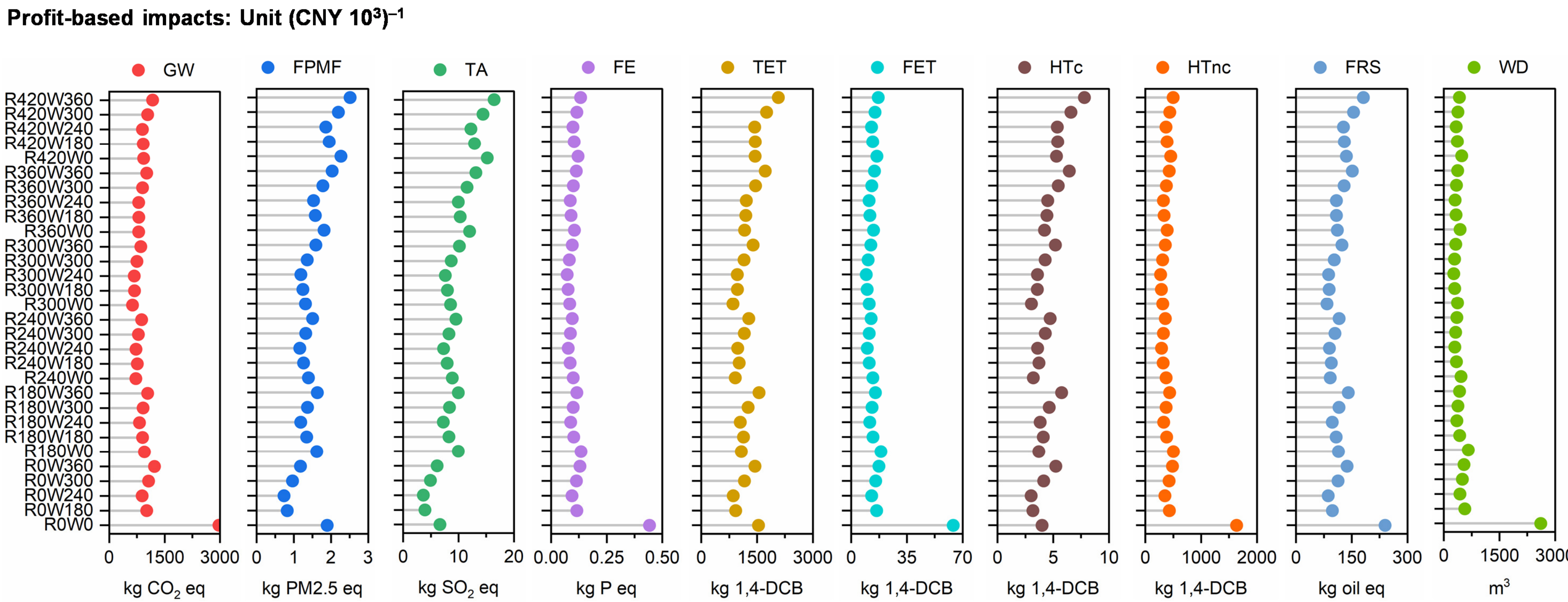


**Figure S1.** Environmental impacts per CNY $10^3$ economic profit of rice-wheat rotation system with different fertilization modes.

**Table S8.** Uncertainty analysis of environmental impacts for rice-wheat rotation (Treatment: R300W240).

| Impact category | Unit | Mean | Median | SD | CV (%) | 2.5% | 97.5% |
|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq $ha^{-1}$ | 17493.60 | 17438.58 | 839.93 | 4.80 | 16017.17 | 19313.31 |
| Fine particulate matter formation | kg PM2.5 eq $ha^{-1}$ | 30.74 | 30.66 | 1.45 | 4.73 | 28.19 | 33.88 |
| Terrestrial acidification | kg $SO_2$ eq $ha^{-1}$ | 196.96 | 196.87 | 7.37 | 3.74 | 183.04 | 210.99 |
| Freshwater eutrophication | kg P eq $ha^{-1}$ | 1.86 | 1.74 | 0.51 | 27.26 | 1.36 | 3.14 |
| Terrestrial ecotoxicity | kg 1,4-DCB $ha^{-1}$ | 25142.90 | 22911.96 | 10219.66 | 40.65 | 12893.78 | 49496.51 |
| Freshwater ecotoxicity | kg 1,4-DCB $ha^{-1}$ | 246.12 | 220.46 | 87.68 | 35.62 | 179.52 | 476.05 |
| Human carcinogenic toxicity | kg 1,4-DCB $ha^{-1}$ | 94.23 | 72.49 | 181.10 | 192.19 | 36.46 | 267.39 |
| Human non-carcinogenic toxicity | kg 1,4-DCB $ha^{-1}$ | 7023.14 | 6055.48 | 3291.09 | 46.86 | 4559.93 | 15637.86 |
| Fossil resource scarcity | kg oil eq $ha^{-1}$ | 2270.79 | 2230.05 | 358.09 | 15.77 | 1685.34 | 3086.56 |
| Water demand [a] | $m^3$ $ha^{-1}$ | 297.08 | 305.19 | 403.08 | 135.68 | 104.30 | 1031.56 |

[a] Water demand here exclude the irrigation water during the crop cultivation stage.

## Reference


22. IPCC. N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2019. pp. 1–48. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (accessed on 6 January 2024). Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html

23. Liu, S.; Lin, F.; Wu, S.; Ji, C.; Sun, Y.; Jin, Y.; Li, S.; Li, Z.; Zou, J. A meta-analysis of fertilizer-induced soil NO and combined NO+$N_2O$ emissions. *Glob. Chang. Biol.* **2017**, *23*, 2520–2532. https://doi.org/10.1111/gcb.13485.

24. Xie, Z.; Fan, P.; Wu, H.; Cheng, K.; Pan, G. Deriving volatile factors and estimating direct ammonia emissions for crop cultivation in China. *Huanjing Kexue Xuebao/Acta Sci. Circumstantiae* **2020**, *40*, 4180–4188. https://doi.org/10.13671/j.hjkxxb.2020.0183.

25. Xia, Y. Q.; Yang, W. X.; Shi, W. M.; Yan, X. Y. Estimation of nitrogen occurrence from non-point sources in intensive planting industry in China. *J. Ecol. Rural Environ*. **2018**, *34*, 782–787.

26. Han X.F.; Xie D.T.; Gao M.; Wang Z.F.; Chen C. Effects of reduced-phosphorus fertilizer and combinations of organic fertilizers on phosphorus leaching in purple paddy soil with conventional paddy-upland rotation tillage. *Acta Ecol. Sin*. **2017**, *37*, 3525–3532.

27. Gong, R.; Liu, Q.; Rong, X.; Zhang, Y. Effects of phosphorus fertilizer reduction on leaching loss of different phosphorus forms in upland land of central And Southern China. *J. Soil Water Conserv*. **2015**, *29*, 106–110.

28.. Wang, R.; Min, J.; Kronzucker, H. J.; Li, Y.; Shi, W. N and P runoff losses in China’s vegetable production systems: Loss characteristics, impact, and management practices. *Sci. Total Environ*. **2019**, *663*, 971–979.

34. Sleeswijk, A.W.; van Oers, L.F.; Guinée, J.B.; Struijs, J.; Huijbregts, M.A. Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. *Sci. Total Environ*. **2008**, *39*, 227–240.