

1 **Nitrogen application rates need to be reduced for half of the rice paddy fields in**
2 **China**

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23

24 **ABSTRACT**

25 Increasing nitrogen (N) application to croplands in order to support growing food
26 demand is a major cause of environmental degradation. However, evaluations of
27 suitable N application rates based on environmental benefit have rarely been carried out
28 for paddy-rice at a national scale in China. To address this challenge, we investigated
29 the N application status in 1531 counties covering the main agroecological areas for
30 rice growing in 2008, and conducted 12 field experiments containing 3 rice cropping
31 systems with six N rates for 3 years (2011–2013). Results showed that the highest yields
32 for rice were 5.8–8.6 Mg ha⁻¹ with N rates of 209.4–289.8 kg N ha⁻¹. Compared with
33 the N rate for the highest yield (YHN), the environmentally optimal N rate (EnON) was
34 lower by 20–39% and the corresponding N loss was reduced by 21–45%, while
35 ensuring 95–99% of the highest crop yield. In China, the N inputs to paddy fields
36 exceeded the YHN and EnON rates by 10% and 45%, respectively. After adjusting the
37 N rate to paddy fields to the EnON rate, the N amount used in China and the
38 corresponding N lost would be reduced by 0.9 and 0.5 Tg N yr⁻¹, respectively, which
39 enable highly efficient production of food with the lowest N loss possible. Thus, we
40 suggest that N use rates for 45% of rice paddy fields in China, for which N application
41 rates exceed the EnON rate, need to be reduced to mitigate environmental damage, and
42 this can be done while still meeting China's food demand.

43 **Keywords:** Crop yield, rice, nitrogen rate threshold, nitrogen loss, food security,
44 environmental benefit, non-point source pollution

451. Introduction

46 To meet the food and fiber demands of an increasing and gradually wealthier
47 population, a series of policies were implemented to encourage synthetic fertilizer
48 production and use in China during the last three decades (Li et al., 2013). However,
49 nitrogen (N) fertilizer is substantially overused and misused in Chinese cropland, which
50 is causing a series of environmental problems (Ju et al., 2009; Lu et al., 2015), such as
51 greenhouse gas (GHG) emissions (Gu et al., 2012), eutrophication (Zhang et al., 2013),
52 soil acidification (Guo et al., 2010), and a loss of biodiversity (Humbert et al., 2016;
53 Zeng et al., 2016).

54 With the aggravation of environmental pollution, maintaining food production while
55 reducing the detrimental effects of anthropogenic N application is an urgent priority for
56 global food security and environmental sustainability (Erisman et al., 2011; Qiao et al.,
57 2015). Ultimately, there is a need to balance the benefits derived from N applications
58 with the associated environmental costs. The environmental cost assessment could
59 provide guidance for emerging policy priorities in mitigating certain Greenhouse Gas
60 (GHG) or reactive N (Nr) species, after quantifying both their release amounts and
61 damage costs to ecosystems (Chen et al., 2011; Gu et al., 2012). However, previous
62 studies have mostly focused on the optimal N rate to improve N use efficiency (NUE)
63 and increase yield to its maximum potential (Xu et al., 2014), such as by testing the soil
64 NO_3^- -N content in the root zone (Cui et al., 2010), developing fertilizer
65 recommendations based on soil testing, yield targets and crop responses (He et al., 2009)
66 and fertilizer effect function equations (Sonar and Babhulkar, 2002), etc. Few studies
67 have attempted to evaluate N input management and the associated environmental costs
68 from rice production (Xia et al., 2016).

69 Rice is an important staple crop in China, playing a crucial role in food security. The

70 global warming potential of GHG emissions and N loss from rice systems have been
71 found to be several times higher than from either wheat or maize (Linguist et al., 2012).
72 Thus, quantification of current N fertilization and improved N management practices
73 and policies in Chinese rice production regions is of national and global interest (Wu et
74 al., 2015). The rice planting area in China is extensive, with different crop rotations,
75 such as a single rice crop per year in Northeast China, rice-upland rotation in the
76 Yangtze River region, and double rice in South China. Furthermore, most Chinese farms
77 are very small, with large variation in N rates, which makes it hard to determine the
78 optimum N application rates for paddy-rice at a national scale in China (Zhang et al.,
79 2013).

80 In this study, we investigated the current status of N management in 1531 counties,
81 covering the primary agroecological regions of Chinese rice production in 2008, and
82 conducted 12 field experiments with different N level practices for 3 years (2011–2013).
83 The three questions we attempted to answer were: (i) What N rates achieve the highest
84 rice yield and the optimal economic/environmental benefit for the single rice, rice-
85 upland, double rice systems? (ii) What is the current level of N fertilizer application for
86 paddy rice across China based on the above N rates? and (iii) What is the potential for
87 reducing N application and N loss intensity using a reasonable management approach?

88

892. **Materials and methods**

90 *2.1. Study Areas*

91 The distribution of the 12 in-situ field sites is shown in Fig. 1. According to the
92 natural climatic conditions, cropping system used and cultivation history, the 12 sites
93 covered three types of rice cultivation: (i) single rice, mainly distributed in Northeast
94 China, which is dominated by a temperate monsoon climate with an average annual

95 temperature of 2.9–8.7°C and an annual precipitation of 350–700 mm; (ii) rice-upland
96 (wheat/rape/vegetable) rotation, mainly distributed in the Yangtze River Basin, which
97 is dominated by a subtropical monsoon climate with an average annual temperature of
98 14.8–17.3°C and an annual precipitation of 950–1500 mm; (iii) double rice, mainly
99 distributed in Southeast China, which is dominated by a subtropical monsoon climate
100 with an average annual temperature of 17–21°C and an annual precipitation of 1200–
101 2000 mm. The double rice cultivation consists of early and late rice with growing
102 seasons from April to July and from July to November, respectively.

103 The number of study sites in each cropping system was mainly determined by the
104 total rice planting area and the heterogeneity of environmental factors and management
105 practices. Accordingly, 1, 8 and 3 field sites were set up for the single rice, rice-upland
106 rotation and double rice systems, respectively. The planting areas of the above three
107 systems in China were 4.6, 11.1 and 10.9 million ha, respectively (NBS, 2014).
108 Compared with the latter two systems, the single rice system is commonly concentrated
109 over relatively small areas with little variation in climatic conditions and soil type.
110 Therefore, only one representative field site was chosen for the single rice system in
111 this study. In view of the large variations in climatic conditions in the rice-upland crop
112 growing regions and different crops (wheat/rape/vegetable) used for rotation with rice,
113 8 field sites were chosen for the study.

114

115 -----

116 Fig. 1

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119 2.2. *Field measurements*

120 The experiments were conducted over a three crop cycle during 2011–2013, with a
121 total of 211 site-year observations across China. The experiments included a total of six
122 fertilization treatments: zero N-fertilizer (CK), local farmers’ practice (FT), and another
123 four treatments with 50, 67, 83, and 133% of FT. Although each site had 6 treatments,
124 the local farmers’ practice treatment (FT) included a range of fertilization rates due to
125 variations in the local practice among various regions. Consequently, the rates for the
126 treatments with 50, 67, 83, and 133% of the local FT rates also varied. Prior to rice
127 transplantation, soil was irrigated and plowed for better separation and homogeneity,
128 followed by basal fertilization. Based on local farmers' practices, some sites also
129 applied tillering topdressing and anthesis topdressing fertilization. Basic information
130 about climate, soil properties, and fertilization for each site is shown in Tables S1–2. At
131 each experiment site, the plots (20–40 m² in area) were arranged following a
132 randomized complete block experimental design with three replicates. At maturity,
133 grain yield and above-ground biomass were sampled and measured for each plot, with
134 five replicate plants being randomly taken and mixed together for each plot. Their N
135 concentrations were determined using the Kjeldahl procedure (Peng et al., 2011).

136

137 2.3. *Survey of N used*

138 Representative farmers were selected for a face-to-face, questionnaire-based
139 household survey in the First National Pollution Census Program of China in 2008. A
140 total of 15,310 farmers (1531 counties) were selected for surveying of the N rate and
141 planting area, which covered the main agroecological areas for rice in 18 provinces
142 across China. In each province, 10 to 152 counties that covered the main planting region
143 were selected, and 10 individual farmers were randomly surveyed in each county. All
144 of these in-house surveys were conducted by agricultural extension staff. The rice

145 planting area for each county was provided by the local agricultural bureaus, which had
 146 a good knowledge of local production data. Before the survey informed consent was
 147 obtained from each farmer.

148

149 2.4. Calculations

150 The N surplus and PFP_N (N partial factor productivity, in kilograms of grain per
 151 kilogram of N applied) were calculated as following equation:

$$152 \quad N_{surplus} = N_{input} - N_{uptake} \quad (1)$$

$$153 \quad PFP_N = Yield / N_{input} \quad (2)$$

154 where $N_{surplus}$ is the N surplus (kg N ha⁻¹), N_{input} is the N fertilizer application rate (kg
 155 N ha⁻¹), N_{uptake} is the aboveground N uptake by rice (kg N ha⁻¹), PFP_N is the kilograms
 156 of grain per kilogram of N applied (kg kg⁻¹ N), $Yield$ is the rice yield under N_{input} .

157 The N losses (NH₃ volatilization, N₂O emission, N runoff and leaching) were
 158 calculated using the following equations (Chen et al., 2014; Wang et al., 2018):

$$159 \quad N_{NH3} = 0.0002 \times N_{input}^2 + 0.1319 \times N_{input} + 8.9249 \quad (3)$$

$$160 \quad N_{N2O} = 0.74e^{(0.011 \times N_{surplus})} \quad (4)$$

$$161 \quad N_{runoff} = 8.69e^{(0.0077 \times N_{surplus})} \quad (5)$$

$$162 \quad N_{leaching} = 6.03e^{(0.0048 \times N_{surplus})} \quad (6)$$

$$163 \quad N_{total\ loss} = N_{NH3} + N_{N2O} + N_{runoff} + N_{leaching} \quad (7)$$

164 where N_{NH3} is the NH₃ volatilization loss (kg N ha⁻¹), N_{N2O} is the N₂O emission loss (kg
 165 N ha⁻¹), N_{runoff} is the N runoff loss (kg N ha⁻¹), $N_{leaching}$ is the N leaching loss (kg N ha⁻¹),
 166 $N_{total\ loss}$ is the total N loss from paddy soil through the above mechanisms (kg N ha⁻¹).

167 The N loss ratio was calculated using the following equation:

$$168 \quad R_N = \frac{C_N - C_0}{N} \times 100\% \quad (8)$$

169 where R_N is the N loss ratio (%), C_N is the total N loss at each non-zero N application

170 rate (kg N ha^{-1}), C_0 is the total N loss at the zero N application rate (kg N ha^{-1}), and N
171 is N fertilizer application rate (kg N ha^{-1}).

172 The economic and environmental benefits were calculated using the following
173 equations:

$$174 \quad ECB = Y \times Y_p - AI \quad (9)$$

$$175 \quad ENB = Y \times Y_p - AI - NrDC \quad (10)$$

176 Where ECB is the economic benefit (¥ ha^{-1}), ENB is the environmental benefit (¥ ha^{-1}), Y is the rice yield under each individual N application rate (kg ha^{-1}), Y_p is the price of rice (¥ ha^{-1}), AI is the agricultural input (fertilizer, labor, seed, diesel oil and pesticides, ¥ ha^{-1}), NrDC is damage cost due to Nr losses (¥ ha^{-1}). Data from Xia *et al.*,
180 (2016) was used to assess the environmental costs (¥) of N loss. The prices of food
181 products and various agricultural inputs are shown in Table S3.

182

183 2.5. Scenario analysis

184 Excessive amounts of N fertilizers are being used in paddy fields, which increases
185 production costs and causes environmental degradation (Deng *et al.*, 2011; Chen *et al.*,
186 2014). In order to predict the potential for reducing N consumption and N loss intensity,
187 we conducted a scenario analysis with three N management approaches: YHN (N
188 application rate to achieve highest yield), EcON (economically optimal N application
189 rate) and EnON (environmentally optimal N application rate).

190 Scenario YHN would involve reducing the N application rate to the YHN rate in
191 regions where it is currently higher than YHN. Scenario EcON would involve reducing
192 the N application rate to the EcON rate in regions where it is currently higher than
193 EcON. Scenario EnON would involve reducing the N application rate to the EnON rate
194 in regions where it is currently higher than EnON.

195

196 2.6. Statistical analysis

197 The statistical data analyses and graphs were prepared using SPSS 19.0 statistical
198 software (SPSS China, Beijing, China) and Origin 8.5 software (Origin Lab Ltd.,
199 Guangzhou, China) packages. Spearman's correlation coefficients were used to test for
200 significant correlations between N application rate and rice yield, total N loss, N surplus,
201 economic benefit and environmental benefit. A p value less than 0.05 was considered
202 to be statistically significant.

203

2043. Results

205 3.1. Yield response to N application rate

206 Based on the 12 experimental sites, the N rate response curves for both N surplus and
207 N loss induced by N fertilizer fitted concave quadratic models ($P < 0.001$, $R^2 = 0.85$ –
208 0.99) (Fig. S1–2), and the response curves for the rice yield, economic benefit and
209 environment benefit induced by N fertilizer fitted convex quadratic models ($P < 0.001$ –
210 0.05, $R^2 = 0.15$ –0.84) (Fig. S3–5).

211 The highest rice yields for the single rice, rice-upland crop rotation, and double rice
212 (early and late rice) were 8.64, 8.64, 5.81 (early rice) and 7.67 (late rice) Mg ha^{-1} ,
213 respectively, with N application rates ranging between 209.4 and 289.8 kg N ha^{-1} (Fig.
214 2). Among the three rice-cropping systems, the YHN rate was highest for the rice-
215 upland crop, and lowest for single rice. Furthermore, the N losses at the YHN rate were
216 66.7–116.1 kg N ha^{-1} , accounting for 23–34% of the N input. Compared with the YHN
217 rate, the EcON rate was 6–17% lower, without reducing production. This corresponded
218 to a 6–25% reduction in N loss. If the environment remediation costs of N pollution are
219 taken into account, the EnON rate and corresponding N losses would further decrease.

220 The EnON rate achieved 95–99% of the yield potential with a rate 20–39% lower than
221 the YHN rate. At the EnON rate the total N losses from paddy soil were reduced 20–
222 45%.

223

224 -----

225 Fig. 2

226 -----

227

228 3.2. N application rates at county level

229 The results of the county-level investigations showed that the total amount of N
230 applied to rice paddy fields in the whole country was 5.3 Mt in 2008, accounting for
231 19% of China's total N fertilizer consumption. The average N application rate was
232 192.3 kg N ha⁻¹ (189.6–195.2 kg N ha⁻¹) (Fig. 3), and those of single rice, rice-upland,
233 early rice and late rice were 176.0, 216.2, 165.7 and 185.8 kg N ha⁻¹, respectively.
234 Among the provinces, the variation in N rate was very large, varying from 136.5 kg N
235 ha⁻¹ to 376.9 kg ha⁻¹. The highest N inputs were observed in Jiangsu and Hainan
236 provinces, up to 376.9 and 358.3 kg ha⁻¹, respectively. For Heilongjiang, Guizhou,
237 Sichuan and Chongqing provinces, the N inputs were less than 160 kg N ha⁻¹ (Table
238 S4). In China, the N rate for 10% of the paddy fields exceeded the YHN rate, and for
239 45% exceeded EnON (Fig. 4a). It is clear that N fertilizer application far exceeded the
240 YHN rate in the Southern Area of Northeast China and in the lower reaches of the
241 Yangtze River.

242

243 -----

244 Fig. 3 and Fig. 4

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246

247 *3.3. Potential for reducing N loss and N application*

248 The total amount of N lost from paddy fields was estimated at 2.0 Tg N yr⁻¹, derived
249 from the investigation data in China, which accounted for 38% of the total N input to
250 rice fields (Fig 4b and Fig. 5). NH₃ volatilization was the main pathway for N loss from
251 paddy fields, and accounted for 58% of the total lost. The N lost through N runoff, N
252 leaching and N₂O emission accounted for 28, 8 and 6%, respectively. The N
253 management approach of applying N at the YHN value, if adopted in the regions that
254 N rate exceeded this value, could reduce N fertilizer use by more than 0.3 Tg per year.
255 Compared with the current situation, applying N at the YHN value would reduce annual
256 N loss by 17% (Fig 4c). Of this, the amount of N lost through NH₃ emission, N runoff,
257 N leaching and N₂O emission would be reduced by 9, 32, 1 and 62%, respectively.
258 Further, if the N rate applied to the paddy fields was adjusted to the EnON rate, the
259 amount of N fertilizer used would reduce by 0.9 Tg N yr⁻¹, and the subsequent N loss
260 would reduce by 0.5 Tg N yr⁻¹ (Fig 4d), through NH₃ emission, N runoff, N leaching
261 and N₂O emission reductions of 19, 41, 1 and 70%, respectively.

262

263 -----

264 Fig. 5

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266

2674. Discussion

268 *4.1. Rice yield*

269 Grain yields at the same N application rate resulted in great temporal and spatial

270 variation, and the yield ranges were -57% to 35% and -24% to 33% over time and
271 space, respectively (Zhang et al., 2015). Although the highest yields of early (5.8 Mg
272 ha^{-1}) and later (7.7 Mg ha^{-1}) rice in the double cropping system were lower, the highest
273 yields (8.6 Mg ha^{-1}) in the single rice and rice-upland systems were achieved at the
274 YHN rate, and were comparable to yield potentials in areas of the world with the most
275 favorable conditions and intensive agronomic management, for example 9 Mg ha^{-1} in
276 California (USA) (Grassini et al., 2013). However, high N surplus ($36.3\text{--}176.1 \text{ kg N}$
277 ha^{-1}) and low PFP_N ($20.7\text{--}41.3 \text{ kg kg}^{-1} \text{ N}$) were found when achieving maximum yields
278 at the YHN rate (Table 1), indicating that inefficiency and environmental damage are
279 associated with attempts to increase yields by increasing N inputs.

280

281 -----

282 Table 1

283 -----

284

285 Numerous studies have shown that the response of grain yield to N input fits a linear-
286 plateau or convex quadratic model (Chen et al., 2011; Cui et al., 2013a; Zhang et al.,
287 2015). Thus, a small decrease in the theoretical maximum achievable yield caused by
288 reduction of N application rate will not severely reduce the grain yield in practice. For
289 instance, no significant differences were observed in grain yield under N fertilizer
290 application rates between $135\text{--}270 \text{ kg N ha}^{-1}$ (Qiao et al., 2012). Through improved in-
291 season root zone N management the required N rate was reduced from 300 to 160 kg N
292 ha^{-1} without any yield losses (Lu et al., 2015). Our experiments demonstrated that the
293 rice yield using the EnON rate achieved $95\text{--}99\%$ of the highest rice yield potential, by
294 reducing the amount of N applied by $20\text{--}39\%$ compared with the YHN rate. More

295 importantly, for all rice crops except early rice, when the EnON rate was used the N
296 surplus dropped steeply by 39–79%, and PFP_N increased to 43.4–50.6 kg kg⁻¹ N. These
297 N use efficiencies are comparable to those of most ‘ecologically intensive’ systems
298 worldwide (Chen et al., 2014).

299 With population and economic growth, demand for rice in China is expected to reach
300 218 Mt by 2030, by which time China’s population is expected to have stabilized (Chen
301 et al., 2014). If farmers could achieve 95–99% of the highest rice yield potential using
302 the EnON rate and using the same planting area as in 2008, by 2030 total production of
303 rice would reach 221 Mt; exceeding the demand for direct human consumption. Such
304 results imply that a substantial reduction in N input based on minimizing environmental
305 damage would not significantly affect the rice yield.

306

307 *4.2. Environmental effects*

308 The Nr losses and GHG emissions from agriculture contribute substantially to
309 atmospheric and water pollution in China and elsewhere (Chen et al., 2014). Using
310 established empirical models, we evaluated total Nr losses and gas emissions per unit
311 area (expressed as kilograms of N per hectare), and they showed a quadratic relationship
312 with increasing N application rate. This showed that a decrease in N rate could reduce
313 N loss. Our results demonstrated that the amount of N lost when the EnON rate was
314 used was reduced by 21–45% from 74.8–112.3 kg N ha⁻¹ to 59.1–70.4 kg N ha⁻¹,
315 compared with the YHN rate. A root-zone N management strategy was also shown to
316 reduce the required N application rate from 325 kg N ha⁻¹ to 128 kg N ha⁻¹, while the
317 intensity of Nr losses and GHG emissions was reduced by 80% and 77%, respectively
318 (Cui et al., 2013b). This suggests that reducing N input is the most convenient and
319 effective way to mitigate the environmental pollution derived from chemical fertilizer

320 application.

321 Under current practice total Nr losses combined with gaseous emissions could be as
322 high as 2.0 Tg yr⁻¹. If the EnON rate is widely adopted in the regions with a higher N
323 rate, above the EnON rate, the N lost could be reduced by more than 0.5 Tg per year
324 across China (Fig. 5), which would be equal to 10% of the total N input to rice fields.
325 Enabling highly efficient production of food with the lowest possible environmental
326 damage, the EnON rate can be used as a tool to guide use of N fertilizer for growing of
327 rice.

328

329 *4.3. Potentials for mitigation and management*

330 Good infrastructure and readily available and relatively inexpensive N fertilizer
331 facilitate application and promote overuse in China (Sutton and Bleeker, 2013). During
332 the last decade, the global N fertilizer consumption increased by 22%, of which, a
333 quarter (about 4.7 Mt) was attributed to China (FAO, 2017). Based on our survey, the
334 average N application rate for rice production was not high, ca. 192 kg ha⁻¹, compared
335 with the YHN rate (209–290 kg ha⁻¹) or the EnON rate (169–199 kg ha⁻¹). However,
336 the average rice N surplus was 68 kg N ha⁻¹, which showed that farmers in China
337 typically applied much more N than required by rice plants.

338 The differences in rice cropping systems and farmers' differing habits bring about
339 large variations in regional N application rate, ranging from <100 to more than 400 kg
340 ha⁻¹ (Fig. 3). In China, 10% and 45% of paddy fields received a rate of N application
341 exceeding the YHN and EnON rates, respectively. Generally, the average N application
342 to rice-upland crops was higher than the others, especially in the lower reaches of the
343 Yangtze River (Fig. 4a). This region is widely recognized as a high N input area with
344 farmers having strong agricultural material consumption capacity. The other high N

345 input region was the Southern Area of Northeast China, in which the optimal N
346 application rate to achieve the highest yield was less than in other regions due to high
347 soil fertility. Although the average N input of this region was 176.0 kg N ha⁻¹, there
348 were many fields for which the N input exceeded the YHN rate. More importantly, there
349 has been poor synchrony between crop N demand and N supply, because most farmers
350 still believe that more fertilizer and higher grain yield are synonymous (Meng et al.,
351 2016). The yield gap in these regions was much larger, and increased agronomic inputs
352 cannot close this gap, because it already has gone past a point of diminishing returns,
353 in the case of fertilizer applications in particular (Cui et al., 2016). For these regions,
354 the Chinese government should adopt appropriate management measures and
355 interventions to limit the amounts of chemical fertilizer used and regulate farmers'
356 production behavior, such as reducing fertilizer subsidies, providing technical
357 assistance, and implementing incentive programs (Good and Beatty, 2011).

358 On the other hand, for the 5% of regions for which the N input is lower than 100 kg
359 N ha⁻¹, achieving 90% of the highest rice yield potential, government policies in China
360 could provide fertilizer recommendations for higher yields. In summary, to achieve
361 reasonable N management goals for chemical fertilizer use in rice fields, site-specific
362 recommendations for N application are required.

363

3645. **Conclusions**

365 Our results demonstrated that the economically optimal rice N application rate was
366 169–199 kg N ha⁻¹. Compared with highest yield N application, the N input for
367 economically optimal rice N management would be lower by 20–39% and the
368 corresponding reduction in N loss would be 21–44%, while ensuring 95–99% of
369 maximum crop yield. This provides evidence for making policies and protection

370 measures to reduce N application in order to produce higher agronomical benefits and
371 lower environmental losses. Based on the above N rate threshold, 45% of rice fields in
372 China have received excess N. Using the above practice, the amount of N fertilizer used
373 and the corresponding N lost would reduce by 0.9 and 0.5 Tg N yr⁻¹, respectively. This
374 indicates that a negligible reduction in rice production would enable highly efficient
375 production of food with the lowest N loss possible.

376

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382

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470

Table 1 Nitrogen surplus, PFP_N and N loss ratio under three scenarios for YHN, EcON and EnON

Cropping system	Site No.	YHN			EcON			EnON		
		N surplus (kg N ha ⁻¹)	PFP _N (kg kg N ⁻¹)	N loss ratio (%)	N surplus (kg N ha ⁻¹)	PFP _N (kg kg N ⁻¹)	N loss ratio (%)	N surplus (kg N ha ⁻¹)	PFP _N (kg kg N ⁻¹)	N loss ratio (%)
Single rice	1	36.3	41.1	23.1	27.8	43.7	22.5	7.8	50.6	21.1
Rice-upland	8	123.3	29.7	30.3	84.6	35.5	26.9	35.4	46.3	22.4
Double rice										
Early rice	3	20.7	20.7	34.3	155	22.6	32.6	108	28.2	28.6
Late rice	3	30.3	30.3	33.9	136	32.9	25.5	80.2	43.4	24.6

471 Note: YHN, EcON and EnON represent the N application rates to achieve the highest yield, optimal economic benefit and optimal

472 environmental benefit, respectively. Nitrogen partial factor productivity (PFP_N) is kilograms of grain per kilogram of N applied (Chen, et al.,

473 2014).

474 **Figure legend**

475

476 **Fig. 1 Geographical distribution of the 12 monitoring sites in China.** Double rice
477 was subdivided into early and late rice.

478

479 **Fig. 2 Relationships between N fertilizer rate and rice yield, economic benefit or**
480 **environmental benefit in the rice growing regions in China based on data from the**
481 **12 experimental sites.** (a) Single rice; (b) Rice-upland crop; (c) Double rice (Early
482 crop); and (d) Double rice (Late crop). The black points on the curves represent the
483 highest rice yield, and corresponding yields for optimal economic and environmental
484 benefits, and the red points represent the corresponding total N losses. The intersections
485 of color thin-dash lines with the X axis indicate the corresponding N application rates.

486

487 **Fig. 3 Distribution of N application rate in rice fields across China.** Data is
488 derived from the county-level investigations in 2008. County-rotation represents the
489 total number of rotation systems in all counties under a certain range of N application
490 rate. Most counties had more than one rotation system, so the total number of county-
491 rotations (n value) was 2910 instead of 1531, which is the number of counties.

492

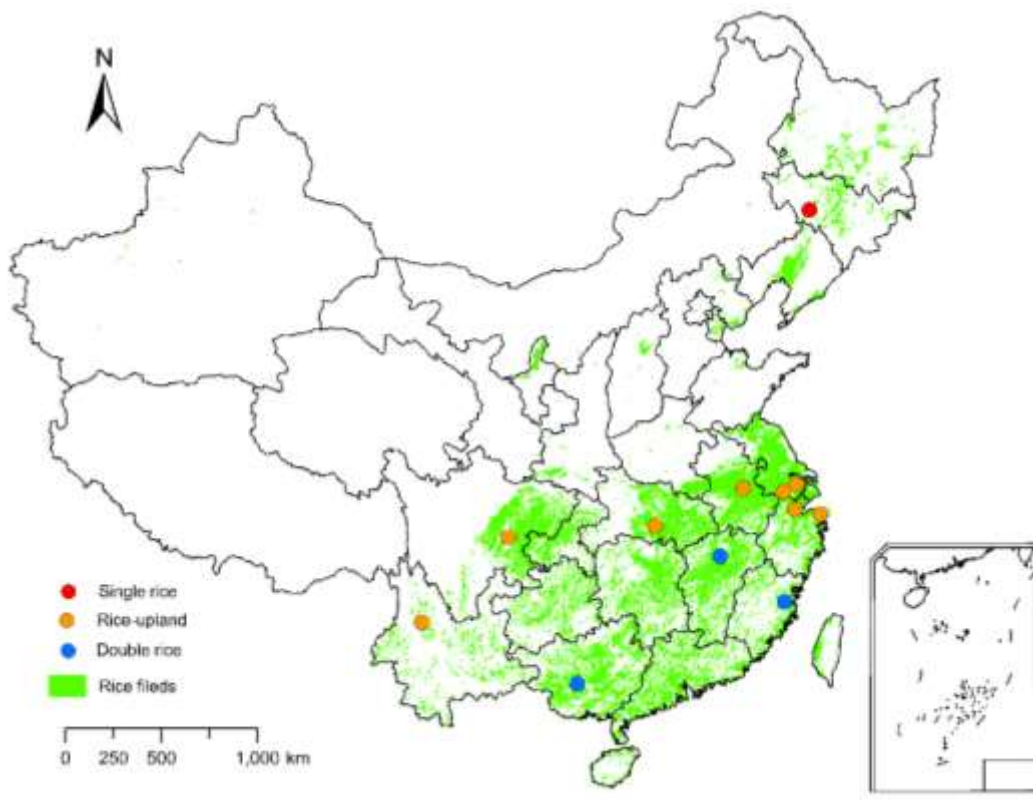
493 **Fig. 4 Geographical distribution of N application and N loss from rice fields**
494 **under different scenarios.** (a) N application; (b) N loss at current situation; (c) N loss
495 at YHN scenarios; and (d) N loss at EnON scenarios. Data is derived from the county-
496 level investigations in 2008. YHN represents the N application rate to achieve highest
497 yield, EcON represents the N application rate to achieve optimal economic benefit and
498 EnON represents the N application rate to achieve optimal environmental benefit.

499

500 **Fig. 5 N loss from rice under different scenarios.** "Current" represents the N loss
501 in the current situation. "YHN" represents the N application rate to achieve the highest
502 yield, "EcON" represents the N application rate to achieve the optimal economic benefit
503 and EnON represents the N application rate to achieve the optimal environmental
504 benefit.

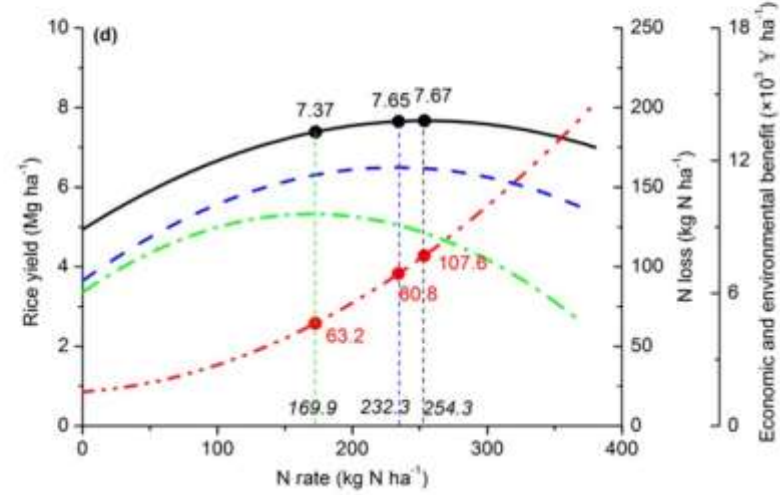
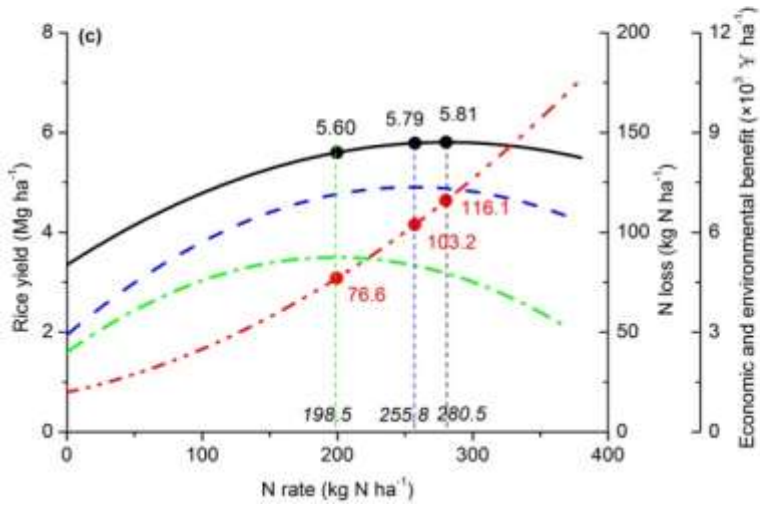
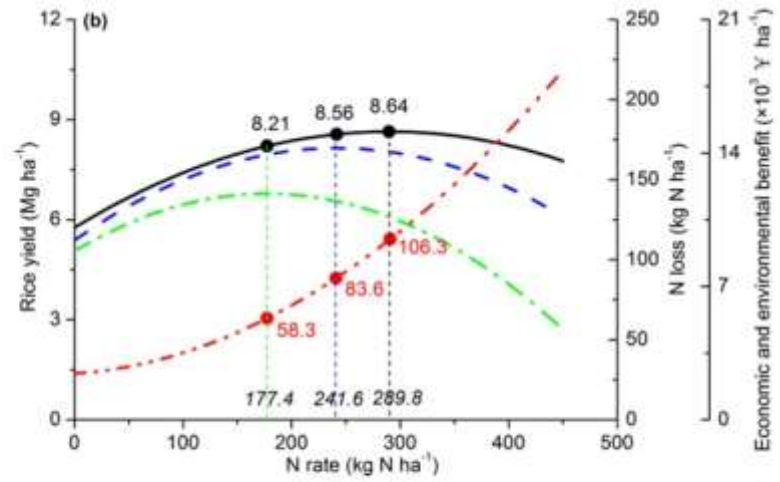
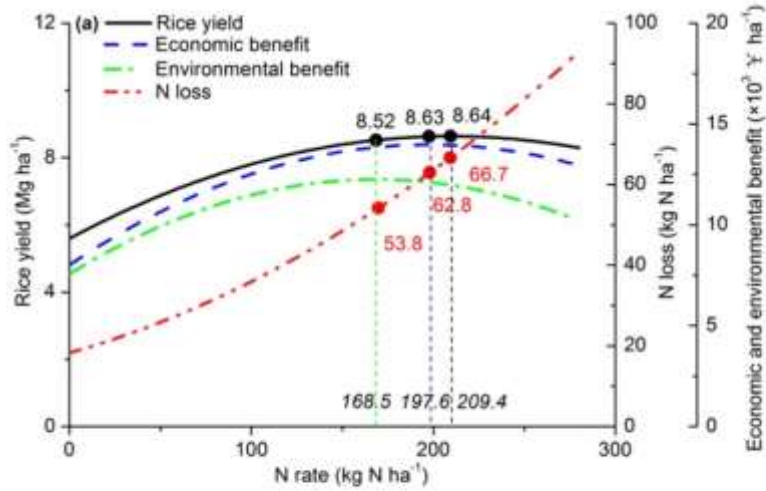
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506 Fig. 1

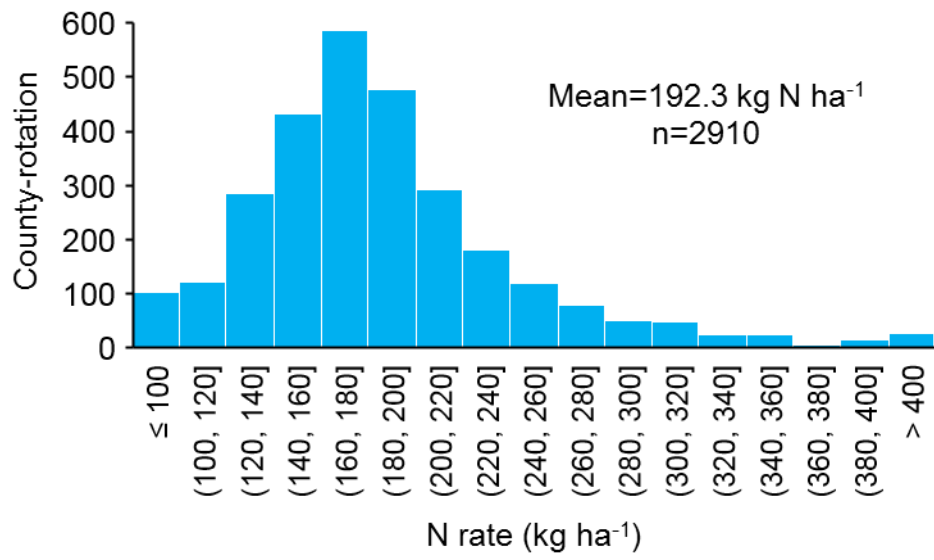


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Fig. 2



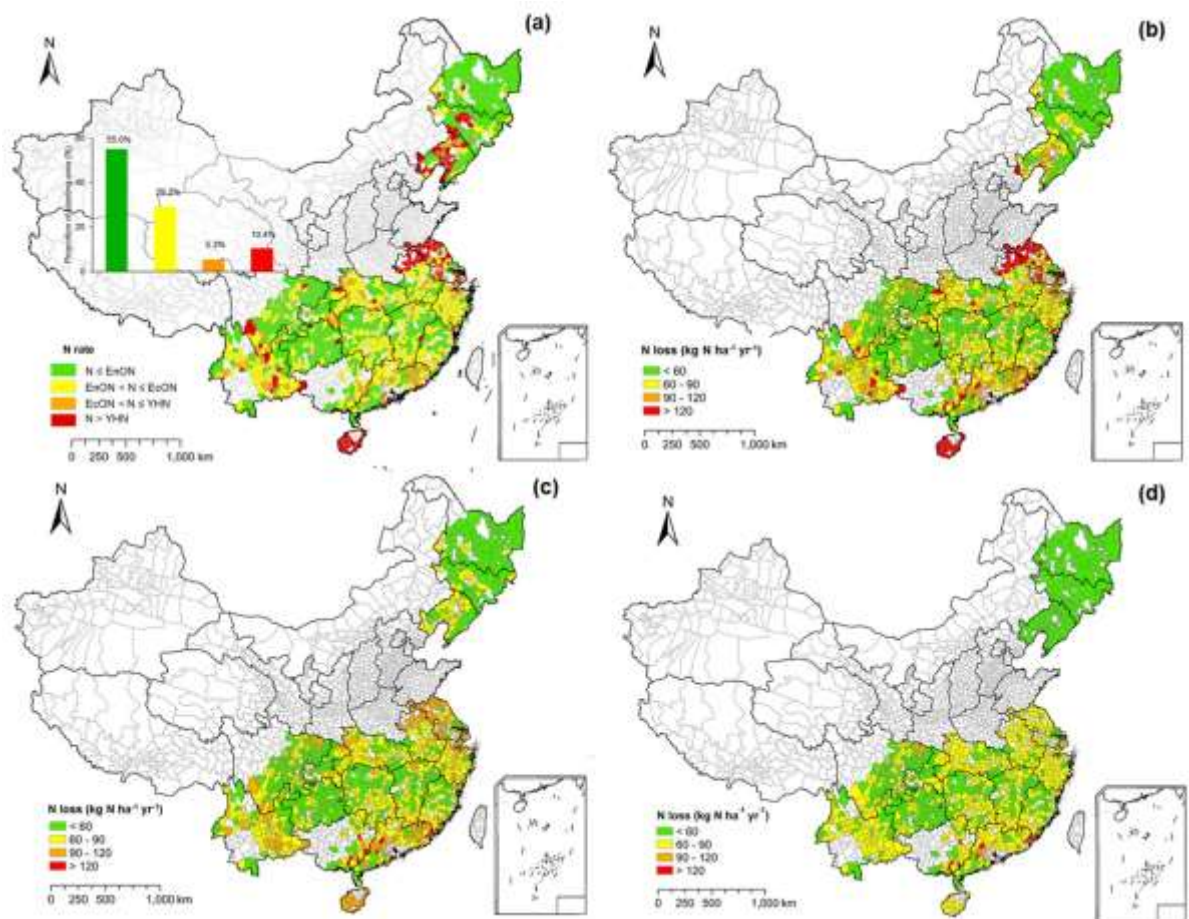
510 Fig. 3



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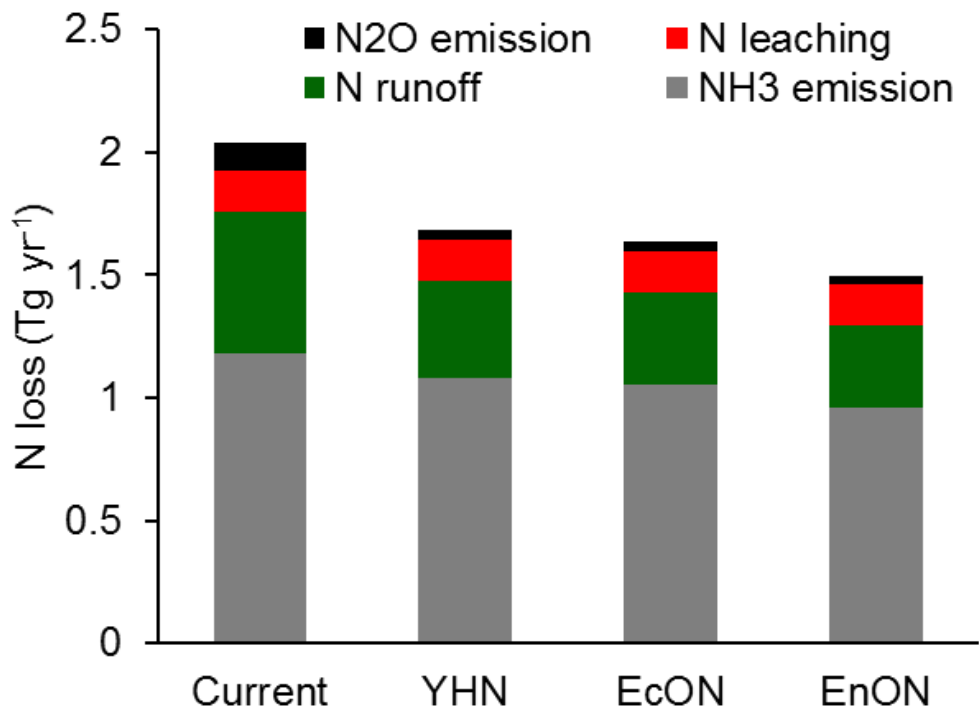
513 Fig. 4



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516 Fig. 5



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