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Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis

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7 **Title: Can knowledge-based N management produce more staple grain with**
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10 *Running head:* Effects of N management on Nr losses

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28

29 **Abstract:** Knowledge-based nitrogen (N) management, which is designed for a better
30 synchronization of crop N demand with N supply, is critical for global food security
31 and environmental sustainability. Yet, a comprehensive assessment on how these N
32 management practices affect food production, greenhouse gas emission (GHG) and N
33 pollution in China is lacking. We compiled the results of 376 studies (1166
34 observations) to evaluate the overall effects of seven knowledge-based N management
35 practices on crop productivity, nitrous oxide (N₂O) emission, and major reactive N
36 (Nr) losses (ammonia, NH₃; N leaching and runoff), for staple grain (rice, wheat and
37 corn) production in China. These practices included the application of
38 controlled-release N fertilizer, nitrification inhibitor (NI) and urease inhibitor (UI),
39 higher splitting frequency of fertilizer N application, lower basal N fertilizer (BF)
40 proportion, deep placement of N fertilizer, and optimal N rate based on soil N test.
41 Our results showed that, compared to traditional N management, these
42 knowledge-based N practices significantly increased grain yields by 1.3 to 10.0%,
43 which is attributed to the higher aboveground N uptake (5.1–12.1%) and N use
44 efficiency in grain (8.0–48.2%). Moreover, these N management practices overall
45 reduced GHG emission and Nr losses, by 5.4–39.8% for N₂O emission, 30.7–61.5%
46 for NH₃ emission (except for the NI application), 13.6–37.3% for N leaching and
47 15.5–45.0% for N runoff. The use of NI increased NH₃ emission by 27.5%
48 (9.0–56.0%), which deserves extra attention. The cost and benefit analysis indicated
49 that the yield profit of these N management practices exceeded the corresponding
50 input cost, which resulted in a significant increase of the net economic benefit by
51 2.9–12.6%. These results suggest that knowledge-based N management practice can
52 be considered an effective way to ensure food security and improve environmental
53 sustainability, while increasing economic return.

54 **Introduction**

55 Feeding the increasing population without devastating the environment is
56 challenging (Chen *et al.*, 2014). As the largest N fertilizer consumer in the world,

57 China plays a major role in global food security, but simultaneously contributes to
58 global greenhouse gas (GHG) emission and alters the nitrogen (N) cycle (Galloway *et al.*,
59 *et al.*, 2008; Oita *et al.*, 2016). About 27 Tg of fertilizer N was used annually for food
60 production during 2001–2010 in China, and more than 60% of that was applied for
61 staple grain (rice, wheat and corn) production (Yan *et al.*, 2014; Xia *et al.*, 2016).
62 However, around 20–50% of the fertilizer is lost to the environment as GHG (e.g.,
63 nitrous oxide, N₂O) and other reactive N species (e.g., ammonia, NH₃; N leaching
64 and runoff). This has created a cascade of environmental problems (e.g., global
65 warming, air pollution and eutrophication) that threaten ecosystems and human health
66 (Sutton *et al.*, 2011; Gu *et al.*, 2015). In 2015, the Ministry of Agriculture in China
67 announced a ‘Zero Increase Action Plan’ for national fertilizer use by 2020, which
68 aimed to reduce the environmental costs associated with food production (Liu *et al.*,
69 2015). This ‘Zero Increase’ plan highlights the need to adopt reasonable N
70 management to improve the nitrogen use efficiency (NUE), a key step to reduce the
71 unintended climate and environment changes induced by fertilizer N application
72 (Chen *et al.*, 2014).

73 To produce more grains while minimizing N₂O emission and major Nr losses,
74 knowledge-based N management practices were recommended, such as the use of
75 enhanced efficiency N fertilizers (controlled-release fertilizer, CRF; nitrification
76 inhibitors, NI; urease inhibitors, UI), and optimum N application methods (increasing
77 splitting frequency and deep placement) (Zhang *et al.*, 2011; Cui *et al.*, 2013a; Chen
78 *et al.*, 2014). Knowledge-based N management practices generally improve the NUE
79 by providing better synchronization of crop N demand with N supply, and therefore
80 have been adopted for increasing yield while decreasing N₂O emission and other Nr
81 losses (Ju *et al.*, 2009; Zhang *et al.*, 2012). While some knowledge-based N
82 management practices (e.g., NI application) increase yield (Abalos *et al.*, 2014), and
83 reduce one type of N loss (e.g., N₂O emission), they can increase N loss via other
84 pathways (e.g., NH₃ emission) (Lam *et al.*, 2016). Yet, a comprehensive assessment
85 on the agronomic and environmental impacts of these N management practices is
86 lacking.

87 Some knowledge-based N management practices (e.g., deep placement and NI
88 application) require additional economic input costs (Zhang *et al.*, 2012; Wang *et al.*,
89 2014). However, few studies have assessed the net economic benefit (NEB, balance
90 between the input cost and yield profit) of the knowledge-based N management
91 practices, which is the important factor for adopting the N practices (Wang *et al.*,
92 2014; Zhang *et al.*, 2015). We therefore conducted a comprehensive meta-analysis for
93 staple grain (rice, wheat and corn) production in China, and assessed the responses to
94 knowledge-based N management practice of crop productivity (yield; NUE;
95 aboveground N uptake), N₂O emission and major Nr losses (NH₃ emission, N
96 leaching and runoff) and economic indicators (input cost, yield profit and NEB). We
97 focused on seven knowledge-based N management practices, including the
98 applications of CRF, NI and UI, increasing splitting frequency of fertilizer N
99 application, lower basal N fertilizer (BF) proportion, deep placement of N fertilizer
100 and optimal N rate based on soil N test.

101 **Materials and methods**

102 *Database compilation*

103 The Web of Science (<http://apps.webofknowledge.com/>) and China National
104 Knowledge Infrastructure database (<http://www.cnki.net/>) were employed to search
105 peer-reviewed studies published before March 2016. The following criteria were set
106 for a study to be included in the present analysis. First, only the field, pot and
107 lysimeter studies on rice, wheat or corn growth were included. The crop grain had to
108 be harvested and weighted at the physiological mature stage. Second, means and
109 samples size had to be reported with a minimum of three replicates. Third, the
110 application rates of agricultural materials had to be reported, such as fertilizers (N, P
111 and K) and inhibitors (NI and UI), for the consideration of the cost-benefit analysis. A
112 total of 1166 observations from 376 peer-reviewed studies were included in our
113 analysis (Supporting information, Fig. S1). All studies were divided into three groups:

114 (1) Enhanced efficiency N fertilizers: CRF application (332 observations), and
115 NI (151 observations) and UI application (80 observations). N fertilizer (e.g., urea)
116 application (control) was compared with N fertilizer treated with CRF (NI or UI)

117 application (treatment). The CRF mainly included those coated or encapsulated
118 fertilizers, such as sulfur-coated urea and polymer-coated urea. The NI mainly
119 included dicyandiamide (DCD), 3,4-dimethylpyrazole phosphate (DMPP) and
120 nitrapyrin (CP), while the UI mainly comprised hydroquinone (HQ) and N-(n-butyl)
121 thiophosphoric triamide (NBPT).

122 (2) Optimizing N fertilizer application method, including three aspects:
123 increasing splitting frequency of fertilizer N application (241 observations), reducing
124 BF proportion (92 observations) and employing deep placement (38 observations).
125 Using the method of Huang *et al.* (2016) for N split, N fertilizer treated with a higher
126 splitting frequency was set as the treatment, such as two split applications (treatment)
127 vs. a single application (control). For BF proportion reduction, N fertilizer treated
128 with a traditional proportion of BF (control) was compared with the BF proportion
129 reduction (treatment). The minimum percentage of BF reduction for ‘reducing BF
130 proportion’ was 10% in this study. For N placement, N fertilizer treated with surface
131 broadcast (control) was compared with deep placement (treatment). The minimum
132 depth of the deep placement of fertilizer N was 5 cm below the soil surface.

133 (3) Optimizing N rate (232 observations). Traditional N application rate (control)
134 was compared with optimal N rate (treatment). The optimal N rate refers to the N
135 application rate determined based on the soil N test, which was calculated by the
136 difference between crop N demand and soil N supply, i.e. the target crop N demand
137 minus the soil NH_4^+ and NO_3^- present in the root zone (Ju *et al.*, 2009; Huang *et al.*,
138 2013). On average, the optimal N rate was 28% lower than the traditional N rate of
139 the studies included in this meta-analysis. The optimal rates in some studies were
140 determined based on the recommendation of local agronomists (Cui *et al.*, 2013b; Yao
141 *et al.*, 2013) according to the results of ‘National Soil N Tests Project’ (Zhang *et al.*,
142 2012).

143 Treatment and control in above database, except for the ‘optimizing N rate’, have
144 identical N application rates. Effects of these knowledge-based N management
145 practices were evaluated by the following three categories with 10 variables,
146 including (1) crop productivity: yield, total aboveground N uptake and NUE; (2) N_2O

147 emission and other major Nr losses (NH₃ emission, N leaching and N runoff); (3)
148 economic indicators: input cost, yield profit and NEB. The NUE in this study refers to
149 the grain NUE, calculated by dividing the difference in the grain N uptake between
150 the treatments with and without fertilization by fertilizer N rate. In addition, the
151 effects of these practices were categorized, according to crop species (rice, wheat and
152 corn), soil organic carbon (SOC) content (≤ 10 , 10–20 and ≥ 20 , g kg⁻¹), soil TN
153 content (≤ 1 , 1–2 and ≥ 2 , g kg⁻¹), pH (≤ 6 , 6–8 and ≥ 8) and N application rate (≤ 200 ,
154 200–300 and ≥ 300 , kg N ha⁻¹). Due to the lack of data, the effects of UI application
155 on N leaching and runoff, reducing BF proportion on N₂O emission and N runoff, and
156 deep placement on N leaching were unable to be assessed in this study.

157 *Meta-analysis*

158 Impacts of knowledge-based N management practices on the values of variables
159 (X_t) were evaluated against their corresponding control (X_c) using the following
160 equation:

$$161 \quad \ln R = \ln \left(\frac{X_t}{X_c} \right), \quad (1)$$

162 where $\ln R$ represents the natural log of response ratio which is the effect size. The
163 results were presented as the percentage changes $((R-1) \times 100)$ under knowledge-based
164 N management practices. Positive percentage changes denote an increase due to N
165 managements whereas negative values indicate a decrease in the variables.

166 Effect sizes were weighted by the inverse of pooled variance (Yang *et al.*, 2016)
167 or replications (Lam *et al.*, 2012) in previous meta-analyses, depending on the
168 integrity of the reported standard deviations in the database. In this study, around 50%
169 studies did not report the standard deviations of the mean values. In addition, extreme
170 weights may be generated by variance-based weighting function but not for
171 replication-based one (Van Groenigen *et al.*, 2011). Therefore, the replication-based
172 weighting was adopted in the analysis using the following equation (Lam *et al.*,
173 2012):

$$174 \quad \text{weight} = \frac{n_t \times n_c}{n_t + n_c}, \quad (2)$$

175 where n_t and n_c represent the numbers of replicates of the treatment and control

176 groups, respectively.

177 Mean effect sizes and the 95% confidence intervals (CIs) were generated by a
178 bootstrapping procedure with 4999 iterations, using MetaWin 2.1 (Rosenberg *et al.*,
179 2000). Effects of knowledge-based N management practices were considered
180 significant if the 95% CIs did not overlap with zero. Means of categorical variables
181 were considered significantly different from each other if their 95% CIs did not
182 overlap.

183 *Cost-benefit analysis*

184 To evaluate whether the knowledge-based N management practices are
185 economically viable, a cost-benefit analysis was conducted by incorporating in this
186 analysis the input cost, yield profit and NEB. Input cost included the cost of
187 agricultural materials (fertilizers, NI and UI), and labor cost associated with fertilizer
188 application and the management practice (e.g., increasing splitting frequency, deep
189 placement and soil N test). Yield profit was the gross economic benefit from crop
190 grains. Price of fertilizers and labor cost were listed in the Supporting information
191 (Table S1). The NEB represented the net economic benefit, calculated by subtracting
192 the input cost from the yield profit.

193 **Results**

194 *Grain yield*

195 Overall, grain yield was significantly increased by 8.0% for CRF application
196 (Fig.1a), 10.0% for NI application (Fig.1b), 7.1% for UI application (Fig.1c), 5.9% for
197 increasing splitting frequency of fertilizer N application (Fig.2a), 4.1% for reducing
198 BF proportion (Fig.2b), 6.9% for deep placement (Fig.2c), and 1.3% for optimizing N
199 rate (an average N rate reduction of 28%) based on soil N test (Fig.3a). The effect of
200 NI application on grain yield was stronger in wheat (12.1%) than corn (6.5%), and
201 that of increasing splitting frequency of fertilizer N application was stronger in rice
202 (8.1%) than wheat (4.0%) and corn (4.5%) (Fig.1 and Fig.2). The effect of reduction
203 of BF proportion on grain yield became non-significant if the reduction rate was
204 larger than 60% (Table S6). N application rates and soil properties (e.g., SOC, TN and
205 pH) also changed the yield responses to the knowledge-based N management

206 practices to some extent (Table S10).

207 *Aboveground N uptake and NUE*

208 On average, the aboveground N uptake was significantly reduced by 5.6% when
209 the optimum N rate was used (Fig.3), but increased by other N management practices,
210 ranging from 5.1% (increasing splitting frequency of fertilizer N application) to 12.1%
211 (NI application) (Fig.1 and Fig.2). The NUE was also significantly improved by
212 employing these N management practices by 26.5% (NI application) to 48.2%
213 (optimizing N rate), except for the practice of reducing BF proportion (Fig.1, Fig.2
214 and Fig.3) which led to a non-significant increase (8.0%) in NUE (Fig.2b). Responses
215 of aboveground N uptake and NUE were in general similar for various crops, N
216 application rates and soil properties (Table S10).

217 *NH₃ emission*

218 NI application overall significantly increased NH₃ emission by 27.5% (Fig.4b),
219 but other knowledge-based N management practices significantly reduced the
220 emission by 30.7% (optimizing N rate) to 61.5% (reducing BF proportion) (Fig.3,
221 Fig.4 and Fig.5). Applying CRF in rice and corn showed stronger effect on reducing
222 NH₃ emission than wheat (Fig.4a). The effect of CRF on NH₃ emission also varied
223 significantly with SOC and TN contents, and N application rate (Table S2 and Table
224 S10), and that of deep placement on NH₃ emission varied significantly with crops, TN
225 content and pH (Table S7 and Table S10). For other N management practices, similar
226 responses of NH₃ emission were observed for different crops, N rates and soil
227 properties (Table S10).

228 *N₂O emission*

229 Averaged across all studies, N₂O emission was significantly reduced by 38.3%
230 for CRF application, 39.8% for NI application, 27.8% for UI application and 31.2%
231 for optimizing N rate (Fig.3, Fig.4 and Fig.5). Increasing splitting frequency of
232 fertilizer N application and employing deep placement also reduced N₂O emission by
233 5.4% and 14.6%, respectively, albeit not significantly (Fig.5). A higher reduction in
234 N₂O emission was observed in rice (50.4%) than corn (25.3%) for CRF application
235 (Fig.4a), in rice (51.0%) than wheat (31.8%) for NI application (Fig.4b), and in corn

236 (37.0%) than wheat (11.9%) for UI application (Fig.4c), and in wheat (20.4%) than
237 rice (4.0%) for higher splitting frequency of fertilizer N application (Fig.5a). In
238 general, the responses of N₂O emission to these N managements were not affected by
239 soil properties (Table S10).

240 *N leaching and runoff*

241 N leaching was significantly reduced by 17.3% for CRF application, 37.3% for
242 NI application, 24.7% for increasing splitting frequency of fertilizer N application,
243 13.6% for reducing BF proportion and 35.3% for optimizing N rate (Fig.3, Fig.4 and
244 Fig.5). N runoff was also significantly decreased by these N management practices,
245 by 31.7% for CRF application, 45.0% for NI application, 36.5% for increasing
246 splitting frequency of fertilizer N application, 15.5% for deep placement and 27.6%
247 for optimizing N rate. A higher reduction in N leaching was observed in corn (45.8%)
248 than wheat (26.4%) for optimizing N rate (Fig.3a), while a stronger reduction in N
249 runoff was shown in rice (45.7%) than wheat (24.5%) for increasing splitting
250 frequency of fertilizer N application (Fig.5a). Responses of N leaching and runoff
251 were in general similar for different soil properties (Table S10).

252 *Cost-benefit analysis*

253 The input cost was significantly reduced (by 3.2%) when the optimum N rate
254 was used, but was not affected by reducing BF proportion (Table 1). Other N
255 management practices significantly increased the input cost, ranging from 6.4% for
256 CRF application to 21.4% for increasing splitting frequency of fertilizer N application,
257 due to the additional financial cost associated with deep placement, extra topdressing
258 and the higher price of enhanced efficiency N fertilizers than traditional fertilizers
259 (Table S1). All these N management practices significantly improved the yield profit,
260 ranging from 1.3% (optimizing N rate) to 10.0 % (NI application). Likewise, these N
261 management practices significantly increased the NEB by 2.9% for optimizing N rate
262 to 12.6% for NI application.

263 **Discussion**

264 *Crop productivity and N loss to environment*

265 The global population is projected to reach 9 billion by 2050, with food demand

266 likely to be doubled (Tilman *et al.*, 2011). Can the increase in food production be
267 achieved on the existing farmland? Based on the meta-analysis of 376 studies, we
268 found that the application of single knowledge-based N management practice
269 significantly increased staple grain production (1.3–10%) in China (Fig.6). Moreover,
270 applying combination of these N management practices would result in much higher
271 (18–35%) increase in the grain yield, as reported by Chen *et al.* (2014). This increase
272 in yield was largely attributed to greater plant N uptake and higher NUE (Fig.6),
273 because the knowledge-based N management practice generally resulted in a better
274 synchronization between crop N demand and N supply throughout the crop growing
275 season (Ju *et al.*, 2009; Yang *et al.*, 2012). For instance, a lower BF proportion
276 reduces N rate applied to early growth stage of crop, and satisfies the N requirements
277 for the rapid growth stages (e.g., stem elongation of wheat and expanded leaf stage of
278 maize), thus improving N uptake and NUE (Zhang *et al.*, 2012). Nonetheless, there
279 was no significant improvement in grain yield when BF was reduced by more than
280 60%, which deserves additional attention. This was likely because the insufficient N
281 supply could damage the healthy root growth at the early stage of crop growth (Cui *et*
282 *al.*, 2008).

283 Because of the traditional belief that higher fertilizer N rates increase yield,
284 farmers often use excessive N fertilizer to pursue high yield profits, particularly in
285 China (Ju *et al.*, 2009). However, N losses will be substantial when the availability of
286 N in the soils exceeds crop N demand (Cui *et al.*, 2013a). Our study indicated that the
287 use of knowledge-based N management practice largely reduced various N losses
288 while increasing grain yield (Fig.6). Through better synchronizing crop N demand
289 with N supply (Linguist *et al.*, 2013), applying CRF application and optimizing N rate
290 reduced all the N loss pathways targeted in this study (Fig.6). Through reducing urea
291 hydrolysis (Huang *et al.*, 2016), UI application decreased NH₃ emission by 50.0% in
292 this study (Fig.4c). In contrast to Akiyama *et al.* (2010)'s study, we found that N₂O
293 emission was significantly reduced when UI was applied for staple grain production
294 in China, which is likely due to the difference in the targeted crop species and
295 agricultural systems between these two studies.

296 Nitrification inhibitors suppress the conversion of NO_3^- from NH_4^+ (Chen *et al.*,
297 2008), and decrease the N_2O emission, N leaching and runoff (Fig.4b). However,
298 more NH_4^+ may retain in soils under NI application, which may stimulate NH_3
299 emission (Lam *et al.*, 2016). The increase in NH_3 emission under NI application
300 observed in this study (27.5%) is slightly higher than that reported by others (13–20%)
301 (Qiao *et al.*, 2015; Yang *et al.*, 2016). Previous studies have demonstrated that the
302 majority of Nr losses (e.g., NH_3 emission, N leaching and runoff) occurred at the
303 early growth stage of crops when N uptake by roots is limited (Chen *et al.*, 2011).
304 Reducing BF proportion and increasing splitting frequency of fertilizer N application
305 avoid over basal N fertilization and increased N uptake along crops growth (Zhang *et*
306 *al.*, 2012), thus reducing NH_3 emission, N leaching and runoff (Fig.5a,b). These N
307 losses could also be minimized through the deep placement of N fertilizer (Fig.5c),
308 which decreases the concentrations of NH_4^+ or NO_3^- in the flooded water (paddy) or
309 surface soils (upland system) (Linguist *et al.*, 2013; Xu *et al.*, 2013).

310 Overall, the use of knowledge-based N management practice is effective in
311 decreasing various N losses to the environment while increasing grain yield (Fig.6).
312 However, it should be noted that soil properties and crop species might affect the
313 responses of yield and N losses to these practices (Table S10). For instance, the effect
314 of increasing splitting frequency of fertilizer N application on grain yield was stronger
315 in rice than wheat and corn (Fig.2). The effects of enhanced efficiency N fertilizers on
316 N_2O mitigation and grain yield also varied with crop species and certain soil
317 properties (e.g., pH) (Fig.4 and Table S10). More studies are needed to uncover the
318 underlying mechanisms before applying these N management practices to a large
319 scale.

320 *Implication of the cost-benefit analysis*

321 By taking the costs of various agricultural inputs (e.g., fertilizers and labors) into
322 consideration, we conducted a preliminary assessment of the NEB associated with the
323 application of the knowledge-based N management practices. Although grain yields
324 were significantly enhanced by these N management practices, the input cost
325 increased accordingly (Table 1). In contrast, the input cost of optimizing N rate based

326 on soil N test was lower, because the cost saved from N fertilizer reduction
327 outweighed that associated with the soil N test. Overall, the yield profit exceeded the
328 corresponding input cost, and therefore resulted in a significant increase in the NEB
329 (Fig.6). The NEB would be even greater if the environmental benefits achieved by the
330 reduction of N loss were included in the cost-benefit analysis (Gu *et al.*, 2012; Qiao *et*
331 *al.*, 2015).

332 Despite their positive NEB, these knowledge-based N management practices are
333 not popular in China. Why are these practices not adopted by the Chinese farmers?
334 Most of the farms in China are tiny, making the large-scale mechanization of these N
335 practices impractical (Zhang *et al.*, 2013). In addition, farmers often have part-time
336 jobs in urban areas to source additional income (Ju *et al.*, 2009). Therefore, in most
337 instances the opportunity cost (e.g. labor, time and education/training costs) of
338 implementing these N practices is very high. Farmers are mostly risk-averse when
339 faced with new agricultural management practices (Wang *et al.*, 2014), but more
340 importantly it is the opportunity cost that impedes the popularity of these new N
341 technologies. To change this situation, national subsidy programs should be
342 established to provide an incentive for farmers to gradually adopt these N practices,
343 such as the 'Carbon Farming Initiative' in Australia (Lam *et al.*, 2013). Farmers are
344 reluctant to increase the input cost without realizing the effectiveness of the
345 knowledge-based N practices (Wang *et al.*, 2014; Xia *et al.*, 2014). More
346 demonstration trials should be conducted in the major areas of staple grain production
347 in China (e.g., North China Plain and Taihu Lake region) to convince farmers of the
348 economic viability of these N practices (Zhang *et al.*, 2012; Zhang *et al.*, 2013).

349 Extra attention should be paid on the NI application, since it considerably
350 increased NH₃ emission. Nonetheless, this problem can be likely solved by the
351 combining NI application with other N management practices (e.g., UI application)
352 (Zhang *et al.*, 2012). The use of the NI dicyandiamide has been reported to result in
353 the contamination of milk power in New Zealand (Lucas, 2013). Therefore, the effects
354 of NI (UI) application on staple food security in China should also be taken into
355 consideration in future studies. The effects of these N management practices on the

356 global warming potential (an overall consideration of methane emission, N₂O
357 emission and soil organic carbon change) should be fully assessed, but the current
358 assessment was restricted to N₂O emission due to data deficiency (Fig.6). Despite this
359 limitation, we demonstrated that knowledge-based N management practice can be
360 considered an effective way to ensure food security and improve environmental
361 sustainability, while increasing economic return.

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370 **References**

- 371 Abalos D, Jeffery S, Sanz-Cobena A, Guardia G, Vallejo A (2014) Meta-analysis of
372 the effect of urease and nitrification inhibitors on crop productivity and
373 nitrogen use efficiency. *Agriculture, Ecosystems & Environment*, **189**,
374 136-144.
- 375 Akiyama H, Yan X, Yagi K (2010) Evaluation of effectiveness of enhanced-efficiency
376 fertilizers as mitigation options for N₂O and NO emissions from agricultural
377 soils: meta-analysis. *Global Change Biology*, **16**, 1837-1846.
- 378 Chen D, Suter H, Islam A, Edis R, Freney J, Walker C (2008) Prospects of improving
379 efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced
380 efficiency fertilisers. *Soil Research*, **46**, 289-301.
- 381 Chen X, Cui Z, Vitousek PM *et al.* (2011) Integrated soil-crop system management
382 for food security. *Proceedings of the National Academy of Sciences*, **108**,
383 6399-6404.
- 384 Chen X, Cui Z, Fan M *et al.* (2014) Producing more grain with lower environmental
385 costs. *Nature*, **514**, 486-489.

- 386 Cui Z, Chen X, Miao Y *et al.* (2008) On-Farm Evaluation of the Improved Soil
387 N-based Nitrogen Management for Summer Maize in North China Plain.
388 *Agronomy Journal*, **100**, 517-525.
- 389 Cui Z, Yue S, Wang G *et al.* (2013a) Closing the yield gap could reduce projected
390 greenhouse gas emissions: a case study of maize production in China. *Global*
391 *Change Biology*, **19**, 2467-2477.
- 392 Cui Z, Yue S, Wang G, Zhang F, Chen X (2013b) In-season root-zone N management
393 for mitigating greenhouse gas emission and reactive N losses in intensive
394 wheat production. *Environmental Science & Technology*, **47**, 6015-6022.
- 395 Galloway JN, Townsend AR, Erisman JW *et al.* (2008) Transformation of the nitrogen
396 cycle: recent trends, questions, and potential solutions. *Science*, **320**, 889-892.
- 397 Gu B, Ge Y, Ren Y *et al.* (2012) Atmospheric reactive nitrogen in China: Sources,
398 recent trends, and damage costs. *Environmental Science & Technology*, **46**,
399 9420-9427.
- 400 Gu B, Ju X, Chang J, Ge Y, Vitousek PM (2015) Integrated reactive nitrogen budgets
401 and future trends in China. *Proceedings of the National Academy of Sciences*,
402 **112**, 8792-8797.
- 403 Huang S, Lv W, Bloszies S, Shi Q, Pan X, Zeng Y (2016) Effects of fertilizer
404 management practices on yield-scaled ammonia emissions from croplands in
405 China: A meta-analysis. *Field Crops Research*, **192**, 118-125.
- 406 Huang T, Gao B, Christie P, Ju X (2013) Net global warming potential and
407 greenhouse gas intensity in a double-cropping cereal rotation as affected by
408 nitrogen and straw management. *Biogeosciences*, **10**, 13191-13229.
- 409 Ju X, Xing G, Chen X *et al.* (2009) Reducing environmental risk by improving N
410 management in intensive Chinese agricultural systems. *Proceedings of the*
411 *National Academy of Sciences*, **106**, 3041-3046.
- 412 Lam SK, Chen D, Norton R, Armstrong R, Mosier AR (2012) Nitrogen dynamics in
413 grain crop and legume pasture systems under elevated atmospheric carbon
414 dioxide concentration: A meta-analysis. *Global Change Biology*, **18**,
415 2853-2859.

- 416 Lam SK, Chen D, Mosier AR, Roush R (2013) The potential for carbon sequestration
417 in Australian agricultural soils is technically and economically limited.
418 *Scientific Reports*, **3**.
- 419 Lam SK, Suter H, Mosier AR, Chen D (2016) Using nitrification inhibitors to mitigate
420 agricultural N₂O emission: a double-edged sword? *Global Change Biology*.
421 doi: 10.1111/gcb.13338
- 422 Linquist BA, Liu L, Van Kessel C, Van Groenigen KJ (2013) Enhanced efficiency
423 nitrogen fertilizers for rice systems: Meta-analysis of yield and nitrogen
424 uptake. *Field Crops Research*, **154**, 246-254.
- 425 Liu X, Vitousek P, Chang Y, Zhang W, Matson P, Zhang F (2015) Evidence for a
426 historic change occurring in China. *Environmental Science & Technology*, **50**,
427 505-506.
- 428 Lucas G (2013) Dicyandiamide contamination of milk powders. *Sri Lanka Journal of*
429 *Child Health*, **42**, 63-64.
- 430 Oita A, Malik A, Kanemoto K, Geschke A, Nishijima S, Lenzen M (2016) Substantial
431 nitrogen pollution embedded in international trade. *Nature Geoscience*, **9**,
432 111-115.
- 433 Qiao C, Liu L, Hu S, Compton JE, Greaver TL, Li Q (2015) How inhibiting
434 nitrification affects nitrogen cycle and reduces environmental impacts of
435 anthropogenic nitrogen input. *Global Change Biology*, **21**, 1249-1257.
- 436 Rosenberg MS, Adams DC, Gurevitch J (2000) *MetaWin: statistical software for*
437 *meta-analysis*, Sinauer Associates Sunderland, Massachusetts, USA.
- 438 Sutton MA, Oenema O, Erisman JW, Leip A, Van Grinsven H, Winiwarter W (2011)
439 Too much of a good thing. *Nature*, **472**, 159-161.
- 440 Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable
441 intensification of agriculture. *Proceedings of the National Academy of*
442 *Sciences*, **108**, 20260-20264.
- 443 Van Groenigen KJ, Osenberg CW, Hungate BA (2011) Increased soil emissions of
444 potent greenhouse gases under increased atmospheric CO₂. *Nature*, **475**,
445 214-216.

- 446 Wang W, Koslowski F, Nayak DR *et al.* (2014) Greenhouse gas mitigation in Chinese
447 agriculture: Distinguishing technical and economic potentials. *Global*
448 *Environmental Change*, **26**, 53-62.
- 449 Xia L, Wang S, Yan X (2014) Effects of long-term straw incorporation on the net
450 global warming potential and the net economic benefit in a rice-wheat
451 cropping system in China. *Agriculture, Ecosystems & Environment*, **197**,
452 118-127.
- 453 Xia L, Ti C, Li B, Xia Y, Yan X (2016) Greenhouse gas emissions and reactive
454 nitrogen releases during the life-cycles of staple food production in China and
455 their mitigation potential. *Science of the Total Environment*, **556**, 116-125.
- 456 Xu J, Liao L, Tan J, Shao X (2013) Ammonia volatilization in gemmiparous and early
457 seedling stages from direct seeding rice fields with different nitrogen
458 management strategies: A pots experiment. *Soil and Tillage Research*, **126**,
459 169-176.
- 460 Yan X, Ti C, Vitousek P, Chen D, Leip A, Cai Z, Zhu Z (2014) Fertilizer nitrogen
461 recovery efficiencies in crop production systems of China with and without
462 consideration of the residual effect of nitrogen. *Environmental Research*
463 *Letters*, **9**, 095002.
- 464 Yang M, Fang Y, Sun D, Shi Y (2016) Efficiency of two nitrification inhibitors
465 (dicyandiamide and 3, 4-dimethylpyrazole phosphate) on soil nitrogen
466 transformations and plant productivity: a meta-analysis. *Scientific Reports*, **6**.
- 467 Yang Y, Zhang M, Li Y, Fan X, Geng Y (2012) Controlled release urea improved
468 nitrogen use efficiency, activities of leaf enzymes, and rice yield. *Soil Science*
469 *Society of America Journal*, **76**, 2307-2317.
- 470 Yao Z, Zheng X, Wang R *et al.* (2013) Greenhouse gas fluxes and NO release from a
471 Chinese subtropical rice-winter wheat rotation system under nitrogen fertilizer
472 management. *Journal of Geophysical Research: Biogeosciences*, **118**,
473 623-638.
- 474 Zhang F, Cui Z, Fan M, Zhang W, Chen X, Jiang R (2011) Integrated soil-crop
475 system management: reducing environmental risk while increasing crop

476 productivity and improving nutrient use efficiency in China. *Journal of*
477 *Environmental Quality*, **40**, 1051-1057.

478 Zhang F, Cui Z, Chen X *et al.* (2012) Integrated nutrient management for food
479 security and environmental quality in China. *Advances in Agronomy*, **116**,
480 1-40.

481 Zhang F, Chen X, Vitousek P (2013) Chinese agriculture: An experiment for the world.
482 *Nature*, **497**, 33-35.

483 Zhang X, Mauzerall DL, Davidson EA, Kanter DR, Cai R (2015) The economic and
484 environmental consequences of implementing nitrogen-efficient technologies
485 and management practices in agriculture. *Journal of Environmental Quality*,
486 **44**, 312-324.

487 **Supporting Information**

488 Additional Supporting Information may be found in the online version of this article:
489 **Figure S1.** Regional distribution of study sites included in this meta-analysis.

490 **Table S1.** Price of fertilizers, NI and UI products, crop grains and labor costs used in
491 this meta-analysis.

492 **Table S2.** Effects of CRF application on changes of crop productivity and N losses
493 under different categories with 95% bootstrap CI.

494 **Table S3.** Effects of NI application on changes of crop productivity and Nr losses
495 under different categories with 95% bootstrap CI.

496 **Table S4.** Effects of UI application on changes of crop productivity and Nr losses
497 under different categories with 95% bootstrap CI.

498 **Table S5.** Effects of increasing splitting frequency of fertilizer N application on
499 changes of crop productivity and Nr losses under different categories with 95%
500 bootstrap CI.

501 **Table S6.** Effects of reducing BF proportion on changes of crop productivity and Nr
502 losses under different categories with 95% bootstrap CI.

503 **Table S7.** Effects of fertilizer N deep placement on changes of crop productivity and
504 Nr losses under different categories with 95% bootstrap CI.

505 **Table S8.** Effects of optimizing N rate on changes (%) of crop productivity and Nr
506 losses under different categories with 95% bootstrap CI.

507 **Table S9.** Changes of input costs, yield profit and NEB induced by the application of

508 various knowledge-based N management practices with 95% bootstrap CI.

509 **Table S10.** Effects of knowledge-based N management practices on between group
510 heterogeneity (Qb) for each variable.

511 **Data S1.** Source references of all datasets used in this meta-analysis.

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517 **Table 1** Changes (%) in the input cost, yield profit and net economic benefit (NEB)

518 induced by the application of knowledge-based N management practices

Knowledge-based N practice ^a	Input cost		Yield profit		NEB	
	mean	95% CI	mean	95% CI	mean	95% CI
CRF application	6.4	4.9–7.8	7.7	6.5–8.8	7.8	6.3–9.2
NI application	9.8	8.1–11.5	10.0	8.2–12.1	12.6	9.0–17.1
UI application	7.1	5.5–8.7	7.1	5.5–8.9	5.9	2.2–9.3
Increasing splitting frequency	21.4	20.1–22.8	5.8	4.8–6.8	3.6	2.4–4.7
Reducing BF proportion	0	0	4.1	2.7–5.4	5.0	3.5–6.7
Applying deep placement	8.2	7.5–9.0	6.6	4.7–8.9	6.1	3.8–8.6
Optimizing N rate	-3.2 ^b	-(4.6–1.9)	1.3	0.3–2.3	2.9	1.4–4.5

519 ^aCRF, controlled-release fertilizer; NI, nitrification inhibitor; UI, urease inhibitor; BF,
520 basal N fertilizer. ^bThe negative value denotes that optimizing N rate reduced the
521 input cost by 3.2 (95% CI: 1.9–4.6).

522

523 Figure captions

524 Fig. 1. Changes in grain yield, total aboveground N uptake and nitrogen use efficiency
525 (NUE) induced by the applications of controlled-release fertilizer (a), nitrification
526 inhibitor (b) and urease inhibitor (c). Numbers of experimental observation are in
527 parentheses.

528

529 Fig.2. Changes in grain yield, total aboveground N uptake and nitrogen use efficiency
530 (NUE) induced by the applications of increasing splitting frequency of fertilizer N
531 application (a), reducing basal N fertilizer proportion (b) and deep placement of N
532 fertilizer (c). Numbers of experimental observation are in parentheses.

533

534 Fig.3. Changes in grain yield, total aboveground N uptake and nitrogen use efficiency
535 (NUE) (a), and various Nr losses (b) induced by the application of optimizing N rate.
536 Numbers of experimental observation are in parentheses.

537

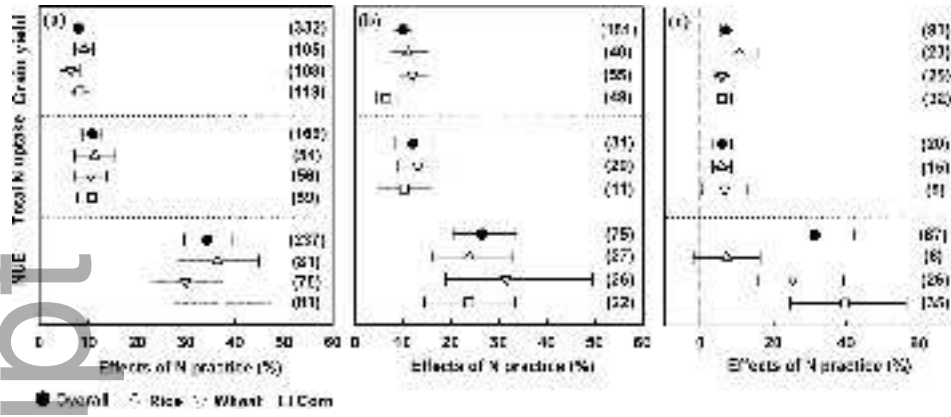
538 Fig.4. Changes in various N losses induced by the applications of controlled-release
539 fertilizer (a), nitrification inhibitor (b) and urease inhibitor (c). Numbers of
540 experimental observation are in parentheses.

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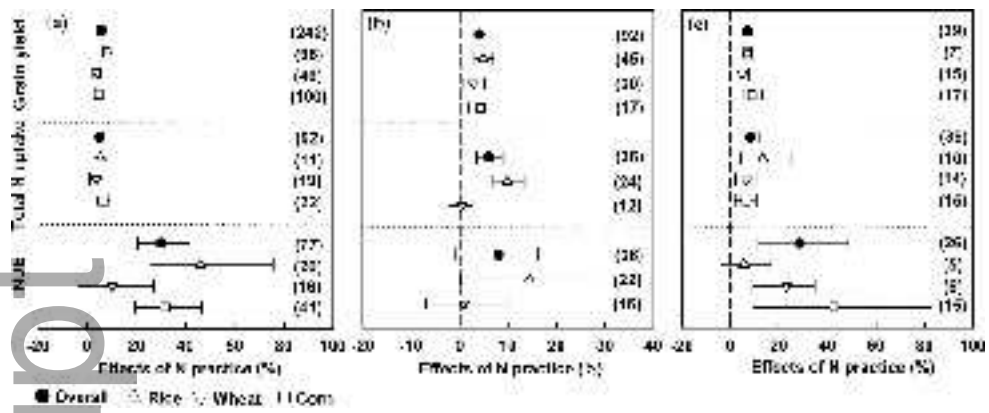
542 Fig.5. Changes in various N losses induced by the applications of increasing splitting
543 frequency of fertilizer N application (a), reducing basal N fertilizer proportion (b) and
544 deep placement of N fertilizer (c). Numbers of experimental observation are in
545 parentheses.

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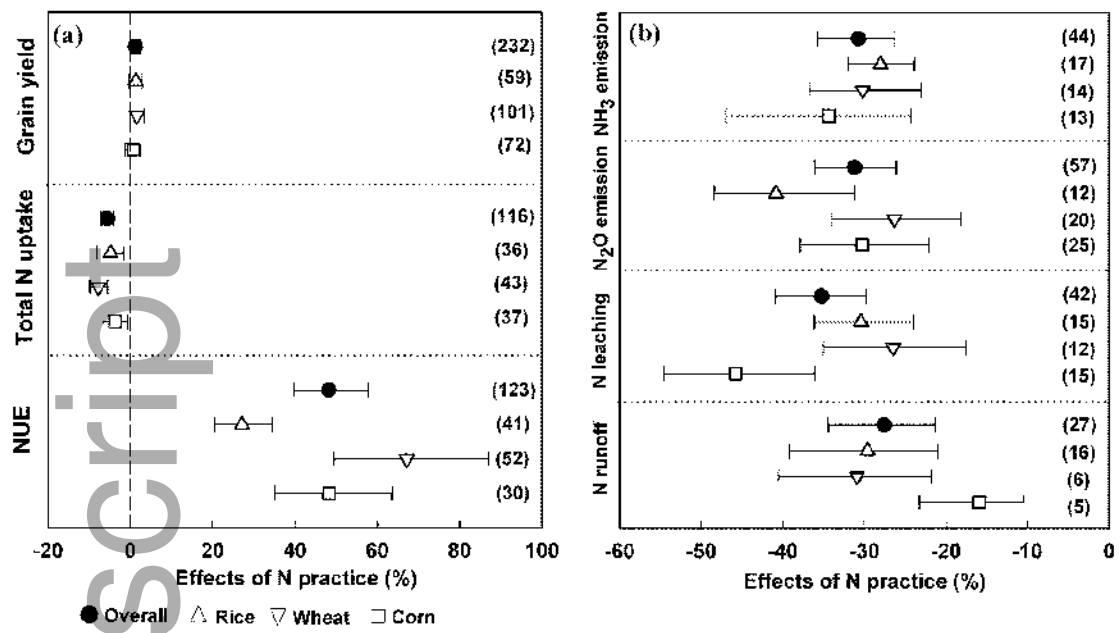
547 Fig.6. Effects of knowledge-based N management practices on crop productivity,
548 greenhouse gas (GHG) emission, major Nr losses and economic return. TN uptake,
549 total aboveground N uptake; NUE, nitrogen use efficiency; NEB, net economic
550 benefit; SOC, soil organic carbon. The percentage closed to the arrow with same
551 colour denotes the effect of N management practice on the variable in which the
552 arrow points. The arrows also reflect the reasons that promoted the changes of the
553 variables.



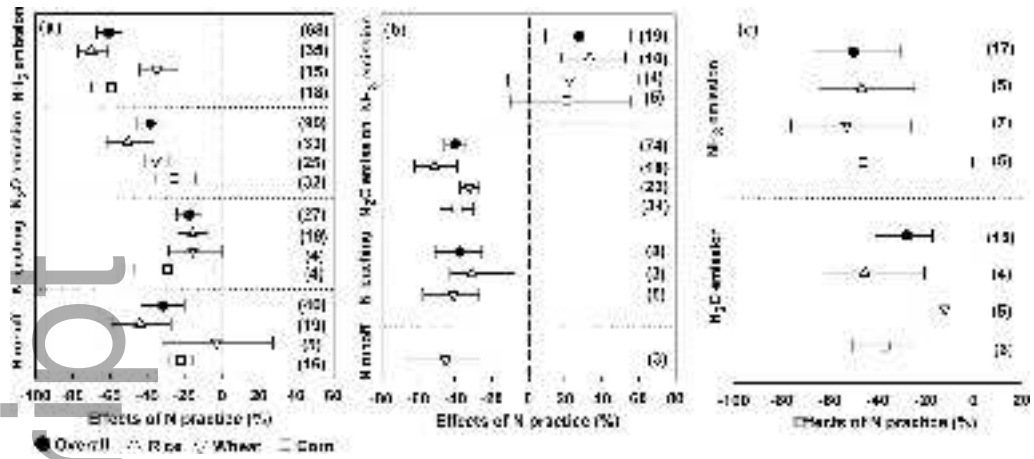
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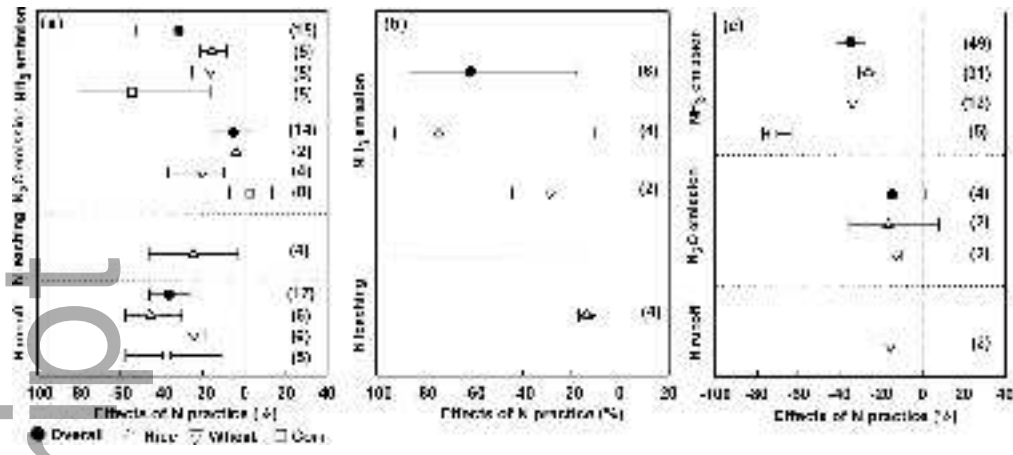
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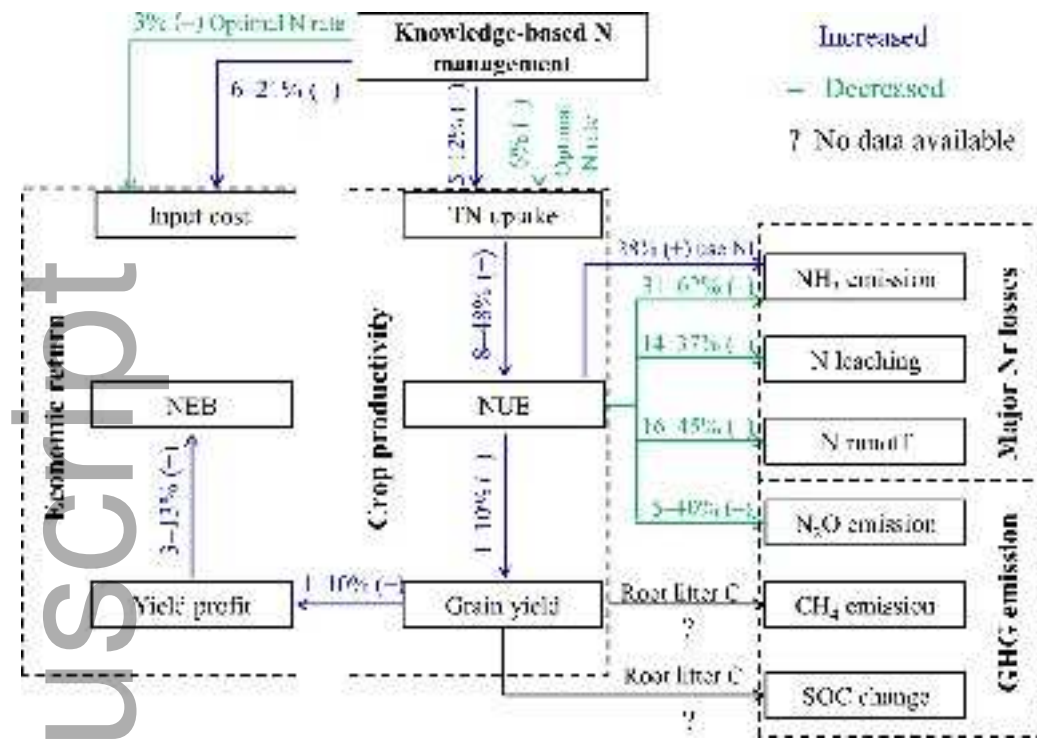
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