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1 **Farm-scale practical strategies to increase nitrogen use efficiency and reduce nitrogen**
2 **footprint in crop production across the North China Plain**

3

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22

23 **Abstract:** Achieving a pathway for green development is a critically important challenge for
24 agriculture in China and beyond. The current study evaluates the effects of a range of management
25 interventions including planting, fertilizer nitrogen (N) rate optimization and increasing farm size
26 to promote agricultural green development across the North China Plain (NCP) based on large-

27 scale farm surveys. Our results showed that the mean annual N fertilizer rate for wheat-soybean
28 rotations was much lower than that of wheat-maize and wheat-peanut. Interestingly, our study
29 indicated strong pre-crop effects of summer soybean (*Glycine max* (Linn.) Merr.) on the following
30 winter wheat (*Triticum aestivum* Linn.) in N saving compared to summer maize (*Zea mays* Linn.)
31 and summer peanuts (*Arachis hypogaea* Linn.), the low N rate for summer soybean and its ‘legume’
32 carryover effects led to the low N rate, N surplus and N footprint, and high N use efficiency (NUE)
33 in wheat-soybean. The survey results showed that the optimal N rates for achieving maximum yield
34 of summer maize, summer peanuts and winter wheat were 229, 249 and 236-260 kg ha⁻¹ across the
35 NCP, respectively. Moreover, better N management is beneficial for reducing the N surplus and
36 leads to high a NUE and lower N footprint. Generally, large farms applied less N fertilizer than
37 small farms, thus leading to a lower N surplus and higher N partial factor productivity with the
38 same yield level. Here we show for the first time that the combinations of crop rotation design,
39 optimizing N rate application and increasing farm size are very efficient in reducing N fertilizer
40 applications and the N footprint with stable crop yields, which should play a more important role
41 in agricultural green development across the NCP and similar regions around the world.

42 **Keywords:** Crop rotations; Nitrogen use efficiency; Nitrogen footprint; Nitrogen surplus; North
43 China Plain

44

45 **1. Introduction**

46 Agriculture is a critically important contributor to China’s Carbon Peak and Carbon Neutral
47 Strategy (CPCNS) (P.R.C., 2021). Agricultural green development has been recognized as the
48 primary task during China’s agricultural transformation period throughout the 2010s that will
49 deliver to the CPCNS in terms of achieving high productivity with lower greenhouse gas emissions.
50 However, it remains challenging to achieve these goals and is the focus of much attention (MARA
51 2018). The North China Plain (NCP) is China’s largest area of agricultural production for wheat
52 and peanut, and the second largest for maize and soybean (NBSC 2019). The region is characterized

53 by excessive application of mineral fertilizer, particularly nitrogen (N) in order to secure higher
54 yields (Feng et al., 2020). The oversupply of N fertilizer has also led to reduced N use efficiency
55 (NUE) and enhanced N losses (i.e. gaseous emissions and leaching) (Hartmann et al., 2015;
56 Manevski et al., 2016). The current production methods of farmers can be largely optimized by
57 smallholders navigating a diverse array of personal and environmental demands (Jiang et al., 2021).
58 Furthermore, crop diversity has declined in the NCP due to increased maize production replacing
59 part of the soybean area resulting in massively increased consumption of N fertilizers (Zou et al.,
60 2019). These changes may threaten the agricultural green development in the region. The N
61 footprint of agricultural production has been used as an indicator for the waste of N resources and
62 environmental pressures (Einarsson and Cederberg, 2019; Leach et al., 2012). However, the N
63 footprint of crop production at the farm scale remains uncertain in the NCP due to the limited
64 samples (He, et al., 2021; Xu et al., 2020). Reducing this uncertainty is vital for developing
65 effective mitigation efforts and optimization tools to achieve agricultural green development across
66 the NCP and to realize the United Nations Sustainable Development Goals (SDGs).

67 The rotational design of cropping systems offers an efficient way to optimize N management
68 in agricultural production through alternative sequencing to ensure optimal resource use efficiency
69 (Rahman and Kazal, 2015). Previous studies in the NCP mainly focused on the N management of
70 single crops in wheat-maize rotation, but little attention has been given to system optimization for
71 wheat-peanut and wheat-soybean rotations (Cui et al., 2010; Liu et al., 2018). Generally, the
72 inclusion of legumes within crop rotations reduces synthetic N fertilizer use because of N inputs
73 by biological nitrogen fixation (BNF) (Jensen et al., 2020; Liu et al., 2011; Peoples et al., 2009). In
74 addition, previous studies have shown that yield benefits of legumes to the subsequent crops were
75 highest under low N fertilization, where mineral N could be reduced by about 60 kg N ha⁻¹ while
76 maintaining acceptable yields across Europe (i.e. Preissel et al., 2015). However, the N benefits of
77 BNF of legume crops and their pre-crop effects have not been fully used in agricultural production
78 across the NCP. Therefore, the extent to which synthetic N fertilizer for winter wheat can be

79 reduced following different summer legume crops compared to the traditional wheat-maize remains
80 uncertain in the NCP.

81 Generally, optimizing mineral N fertilizer inputs is another efficient way to increase NUE and
82 reduce N footprint (Zhang et al., 2021). For example, previous studies have shown that split
83 fertilization can be beneficial for increasing NUE and reducing N losses (Liu et al., 2019b).
84 Documenting the optimal N rate is crucial for recommending N application for farmers in
85 agricultural production. Field studies have shown that maximum yields of winter wheat, summer
86 maize, summer peanut and summer soybean in the NCP were achieved with the N application at
87 190-250 kg N ha⁻¹ (Lu et al., 2014; Ma et al., 2019), 185-280 kg N ha⁻¹ (Liu et al., 2019a; Zhou et
88 al., 2019), 150-225 kg N ha⁻¹ (Xia et al., 2020; Zhang et al., 2018a) and 60-150 kg N ha⁻¹ (Lv et al.,
89 2020; Zhang et al., 2018b), respectively, with variation depending on the local weather and soil
90 conditions. However, most field experiments were conducted for single crop seasons and the
91 optimal N application rate at the rotation scale are rarely studied (e.g., (Manevski et al., 2016)).
92 Previous surveys found that the mean N application rate for winter wheat and summer maize was
93 282 and 234 kg ha⁻¹, respectively, across NCP before 2014 (Huang et al., 2016; Ren et al., 2019).
94 Very limited information is available for the optimal N application rates to summer peanut and
95 summer soybean in the NCP (Hartmann et al., 2015; Liu et al., 2018; Ma et al., 2019). In addition,
96 large differences exist between the actual production and results from field experiments. This
97 highlights the importance of identifying the optimal rate and application time of N fertilizer for
98 individual crops and crop rotations at the rotation scale based on actual agronomic data across the
99 NCP.

100 Small farms have historically dominated agricultural production in the NCP, where the farm
101 size is generally smaller than 3 ha (Cui et al., 2018; Ju et al., 2016). The farm sizes is linked to the
102 degree of agricultural modernization, especially in using unified irrigation systems, pesticides and
103 large and effective machines (i.e. Wang et al., 2014). Previous study conducted in the NCP showed
104 that small farms cultivating wheat-maize rotation apply larger amounts of chemical N fertilizer (on

105 average 600 kg N ha⁻¹) compared to field experiments, which resulted in low NUE and high GHG
106 emissions (Feng et al., 2020). In recent years, an increasing number of large farms have been
107 established in the NCP (Wang et al., 2014), characterized by managers of large farms that have a
108 higher education level and find it easier to accept new agricultural technologies compared to
109 smallholder farmers. Such farmers will play a more important role in future agricultural production
110 (Wang et al., 2017). Increasing the farm scale might have benefits from the economic aspects and
111 at the national scale through reduced mineral N inputs (Ju et al., 2016). However, whether
112 increasing farm scale is beneficial for N management, thus promoting agricultural green
113 development in the NCP, needs further exploration.

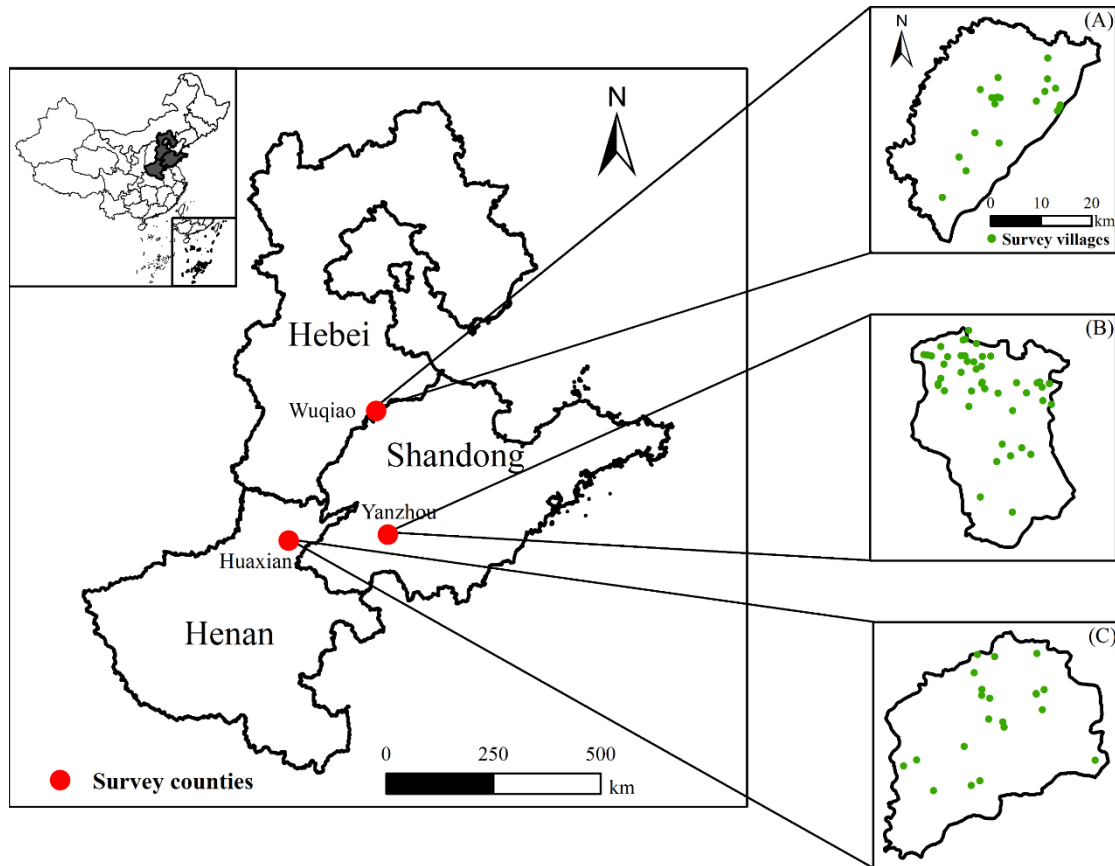
114 The objectives of the current study were therefore to 1) quantify the differences in N rate,
115 NUE, N surplus and N footprint in the major crop rotations and individual crops across the NCP,
116 2) evaluate the pre-crop effects of different summer crops on N rate, NUE, N surplus and N
117 footprint of the following winter wheat, 3) explore N management effects on NUE and N footprint
118 for each individual crop at the rotation scale, and 4) test if it is beneficial for increasing NUE and
119 reducing N footprint through increasing farm scale. These objectives were pursued through large-
120 scale field surveys conducted across the NCP.

121

122 **2. Materials and methods**

123 **2.1 Research area**

124 The study area was conducted in the NCP, mainly included the provinces of Hebei, Henan and
125 Shandong, municipalities of Beijing and Tianjin; an area with a warm and semi-humid continental
126 monsoon climate (Fig. 1). The annual mean annual temperature of the NCP is 8-15 °C, the
127 cumulative rainfall is 500-900 mm and more than 70% of which is concentrated in the summer
128 season (Ti et al., 2018). The agricultural soils are mainly calcareous and alluvial. Generally, the
129 pedo-climatic conditions allow double cropping with relative high yields, where wheat-maize was
130 the dominant cropping system, followed by wheat-peanut and wheat-soybean (Jiang et al., 2020).



131

132 **Fig. 1** Distributions of the surveyed counties and villages across the North China Plain (NCP).

133 Solid red circles represent the locations of survey counties, and the solid green circles show the
 134 distributions of survey villages in Wuqiao (A), Yanzhou (B) and Huaxian (C).

135

136 2.2 Data collection

137 The data were collected from surveys conducted in three representative counties across the
 138 NCP, namely Wuqiao in Hebei Province, Huaxian in Henan Province and Yanzhou in Shandong
 139 Province (Fig. 1). The counties were selected based on differences in climate, water resources, soil
 140 types, social economics and crop yield levels (Ti et al., 2018). For instance, Wuqiao is a county
 141 with high yields but low economic activity. Huxian is a county with high yields and moderate
 142 economic activity, and Yanzhou has high yields and high economic activity. Moreover, all counties
 143 have either high yield demonstration experiments or field experimental stations, which provides
 144 good opportunities for interactions with farmers. The questionnaire used in the study included three

145 major topics: 1) Basic farm information, including the types of crops, crop planting area and crop
146 yield; 2) Crop production information, including the amount of seeds, fertilizers, pesticides, and
147 diesel for agricultural machinery, electricity input for irrigation in the production process of
148 different crops; 3) N management information for crops, including the type of fertilizer used, time,
149 amount and method of fertilizer application, and the ratio of N, P and K in the fertilizer.

150 All major agricultural townships were visited in each county to thoroughly document
151 agricultural production. Afterwards, a stratified random sampling was used in each township to
152 select study villages, and four villages in each township were selected for field survey (Fig. 1). In
153 each village, we randomly selected 10-20 farm households based on the size of the village (Ti et
154 al., 2021; Yin et al., 2016), and we interviewed the household head and the manager of the
155 collective farm face to face. Generally, there were one to three large farms (or collective farms) in
156 each village in Wuqiao and Huaxian, and three to six large farms in most village in Yanzhou. All
157 questionnaires were conducted in July and August 2018, and the information for crop production
158 focused mainly on the year of 2017 and the previous 3 years. During the survey, we first asked the
159 interviewee whether they had grown either winter wheat, summer maize, summer soybean or
160 summer peanut in recent years, and interviewee continued only if answered affirmative. In total,
161 there were 805 households that participated in the survey, and we obtained 792 valid questionnaires
162 with full records from 91 villages across the NCP, with 289 surveys from Wuqiao, 245 from
163 Huaxian and 258 from Yanzhou. Generally, winter wheat was planted in all surveyed farms, and
164 the number of the farmers who planted summer maize, summer peanut and summer soybean were
165 743, 108 and 73, respectively.

166

167 2.3 Data analysis

168 2.3.1 Calculations of N use efficiency and N surplus

169 NUE was evaluated using N partial factor productivity (PFP) calculated as:

$$170 PFP = Y/N_{rate} \quad (1)$$

171 where Y represents crop yield after drying to the standard water content at the selling stage (about
172 12.5% for wheat, 14% for maize, 13% for soybean and 10% for peanut) (kg ha^{-1}), N_{rate} is the
173 amount of fertilizer (kg N ha^{-1}) applied to the crop. Specifically, the grain yield of peanut was
174 calculated as 0.71 of the pod weight (the mean ratio of kernel yield to pod yield) in the study (Gao
175 et al., 2015).

176 The N surplus calculation was according to Yin et al. (2020):

$$177 N_{surplus} = N_{input} - N_{output} \quad (2)$$

$$178 N_{input} = N_{rate} + N_{BNF} + N_{seed} + N_{deposition} \quad (3)$$

$$179 \begin{cases} N_{output} = Y \times N_{content} & \text{for wheat, maize and soybean} \\ N_{output} = P \times N_{content} + Straw \times N'_{content} & \text{for peanut} \end{cases} \quad (4)$$

180 where N_{input} (kg N ha^{-1}) is the total N inputs, N_{rate} is the mineral N applications, N_{BNF} is
181 the BNF of legume crops, N_{seed} is the N inputs from seed, and $N_{deposition}$ represents atmospheric
182 deposition, N_{output} was the amount of N exported by crop harvest, specifically, the N exported of
183 summer peanut include both pods (P) and straws ($Straw$). Generally, a positive surplus represents
184 higher N storage in the soil or reactive loss to the environment, while a negative surplus indicates
185 depletion of the soil total N pool (Yin et al., 2020).

186 All parameters used in calculating N surplus were obtained from the NCP: the BNF of summer
187 soybean was set to 57% of the N uptake from aboveground biomass (Guan et al., 2014; Lam et al.,
188 2012), and the BNF of summer peanut was 41% of N uptake of biomass (Zheng et al., 2019). The
189 harvest index of 0.40 and 0.41 was set for summer soybean and summer peanut, respectively (Ran
190 et al., 2021). The average N content for the biomass of summer soybean was 35 g kg^{-1} (Lam et al.,
191 2012). The average N content of pods and straws for summer peanut was 43 and 16 g kg^{-1} ,

192 respectively (Zhang et al., 2018a). The average N content for the grain of winter wheat, summer
 193 maize, summer soybean and summer peanut were 23, 12, 61 and 47 g kg⁻¹, respectively (Gao et al.,
 194 2015; Ma et al., 2019; Qin et al., 2018; Zhang et al., 2020). The N deposition was 23 and 35 kg ha⁻¹
 195 for the winter wheat and the summer crop growing season, respectively (Zhang et al., 2021).

196

197 2.3.2 Calculations of N footprint

198 The N footprint was calculated using the life cycle assessment (LCA) method proposed by
 199 ISO14044 (ISO 2006). Generally, the N footprint indicates the reactive (Nr) emissions and losses
 200 during the entire process of crop production from cradle to farm gate. The following calculation
 201 was used as described by Xue et al. (2016):

$$202 \quad NFs = indirectNF + NV_{NH_3} + NE_{N_2O} + NL_{NO_3^-} + NR_{NH_4^+} \quad (5)$$

203 where NFs is the N footprint per unit area (kg N-eq ha⁻¹), including both direct and indirect
 204 contributions, the former referring to the active N released into the environment during crop
 205 production, which mainly includes ammonia volatilization (NH₃, NV_{NH₃}) and nitrous oxide
 206 emissions (N₂O, NE_{N₂O}) released in the form of gases, and ammonium (NH₄⁺, NR_{NH₄}) and nitrate
 207 (NO₃⁻, NR_{NO₃}) that are lost through leaching. Previous studies have shown that nitrate leaching is
 208 the main form of N loss in agricultural production in the NCP (Xu et al., 2020), and ammonium
 209 leaching was ignored as it is typically very low. Therefore, Equation 5 can be simplified as:

$$210 \quad NFs = indirectNF + NV_{NH_3} + NE_{N_2O} + NL_{NO_3^-} \quad (6)$$

$$211 \quad indirectNF = \sum(Q_m \times f_m) \quad (7)$$

212 where *indirectNF* is the N footprint caused by substances input in the production. *Q_m* is the actual
 213 amount of each substance input in the production, and *f_m* is the coefficient of active N emission.
 214 The emission coefficients for different types of material inputs were the same as the most recent
 215 studies in the NCP (Chen et al., 2020; Xu et al., 2020). The emission coefficients of soybean and
 216 peanut seeds were used the same value as maize in the study due to the lack of recording in the

217 previous study.

218 The calculation of the active emissions from volatilization (NH₃), nitrous oxide (N₂O) and
219 leaching (NO₃⁻) are shown in Equations (8-10):

$$220 \quad NV_{NH_3} = F_{N-input} \times \emptyset \times \frac{17}{14} \times 0.883 \times 1000 \quad (8)$$

$$221 \quad NE_{N_2O} = F_{N-input} \times \varepsilon \times \frac{44}{28} \times 0.476 \times 1000 \quad (9)$$

$$222 \quad NL_{NO_3^-} = F_{N-input} \times \delta \times \frac{62}{14} \times 0.238 \times 1000 \quad (10)$$

223 where $F_{N-input}$ is the amount of nitrogen fertilizer input, \emptyset , ε , and δ are the emission factors
224 for NH₃, N₂O and NO₃⁻, respectively (Tables S1). The eutrophication potential factors for NH₃ (kg
225 N-eq ha⁻¹ of NH₃), N₂O (kg N-eq ha⁻¹ of N₂O), NO₃⁻ (kg N-eq ha⁻¹ of NO₃⁻) were obtained from the
226 CML2002 methodology, and the values were 0.833, 0.476 and 0.238, respectively (Guinee et al.,
227 2002).

228 NF_y represents N footprint for crop grain yield (g N-eq kg⁻¹), which was calculated as follows:

$$229 \quad NF_y = NF_s/Y \quad (11)$$

230

231 2.3.3 Optimal nitrogen rate

232 Generally, linear plateau models, quadratic plateau models, quadratic models and exponential
233 models have been the most widely used methods to determine the optimal nitrogen application rate
234 in agricultural production (Bullock and Bullock 1994; Cerrato and Blackmer 1990; Wang et al.,
235 2020). Previous studies have shown that the linear plateau model performed best in determining
236 the optimal N application rate for winter wheat across the NCP (Cui et al., 2010). Therefore, the
237 linear plateau model was adopted in this study to explore the relationship between crop yield and
238 fertilization rate based on the survey database across the NCP.

$$239 \quad \begin{cases} Y = a + b * x & (x \leq x_1) \\ Y = c & (x > x_1) \end{cases} \quad (12)$$

240 where Y means crop yield, x means N rate, b is the coefficient, x_1 is the amount of N fertilizer

241 when the maximum yield is reached, c is the intercept.

242 Our preliminary analysis showed that soybean did not reach the maximum yield due to a low
243 fertilization rate. A linear equation was used to fit the relationship between N rate and yield.

244 Generally, winter wheat was divided into three types depending on the previous summer crops
245 in the study, including winter wheat following summer maize (MWW), winter wheat following
246 summer peanut (PWW), and winter wheat following summer soybean (SWW).

247

248 **2.3.4 Statistical analyses**

249 In general, the Kruskal-Wallis test was first used to test the differences in N rate, PFP, N
250 surplus and N footprint between individual crops, crop rotations and farm scales (large vs. small
251 farms). Afterwards, the pairwise comparisons were applied to evaluate the differences between
252 each group with p-value adjusted according to the Benjamini & Hochberg method for multiple
253 comparisons. Subsequently, a linear regression model was used to evaluate the relationship between
254 N surplus, PFP and N footprint. All analyses were undertaken using R 4.0.2 ([R Core Team, 2015](#)),
255 the spatial distribution of survey counties was displayed using ArcGIS 10.4 ([Environmental
256 Systems Research Institute, Inc., Redlands, CA, USA](#)).

257

258 **2.3.5 Scenario analysis**

259 Four types of scenario analysis were carried out to explore the effects of proportion of crops
260 grown, N optimization and increasing farm size on the N application, N footprint and crop yield
261 for wheat-maize and wheat-soybean across the NCP. Scenario 1 (S1) only considered the crop
262 proportion that mainly focused on the changes of the summer maize and summer soybean cropping
263 area without changing farm size and N management; S1-1 represented a ratio of the cropping area
264 of soybean and maize of 1:5, and S1-2 represents a ratio of 1:11 according to agricultural situation
265 in NCP. Scenario 2 (S2) considered optimizing N management without changing farm size and
266 cropping structure; S2-1 used the optimal N application rate based on previous experimental results

267 applied to all crops, and S2-2 used the optimal N application rate determined in this study and
268 applied to all crops. Scenario 3 (S3) considered the changes of farm size without modifying
269 cropping structure and N management; S3-1 represented large farms, and S3-2 small farms.
270 Scenario 4 (S4) considered the combinations of farm size, crop proportion adjustment and N
271 optimization, assuming all farms were large and that the ratio of the cropping area of summer
272 soybean and summer maize was 1:5. The optimal N rate from experiments was applied for each
273 crop in this scenario.

274 The parameters used in the scenario analysis were as follows: The planting areas of winter
275 wheat, summer maize and summer soybean in the NCP were derived from statistical data. The ratio
276 of large farms to small farms was estimated based on the area ratio observed in the survey. Based
277 on previous experiments, the optimal N application rates for winter wheat and summer maize were,
278 respectively, 220 and 230 kg ha⁻¹ (Liu et al., 2019b; Lu et al., 2014; Ma et al., 2019; Zhou et al.,
279 2019), and the corresponding NFs were 71.6 and 64.8 kg N-eq ha⁻¹, and yields are 8.3 and 9.3 Mg
280 ha⁻¹, respectively. The optimal N application rate and yield of winter wheat, summer maize and
281 summer soybean based on the summary of this investigation were described in Section 3.3, and the
282 corresponding N footprints were 84.2, 64.4 and 18.8 kg ha⁻¹. Due to the large uncertainties of the
283 optimal N rate for maximum summer soybean yield level from field experiments in the NCP, only
284 the surveyed N rate and yield for soybean was applied in the scenario analysis.

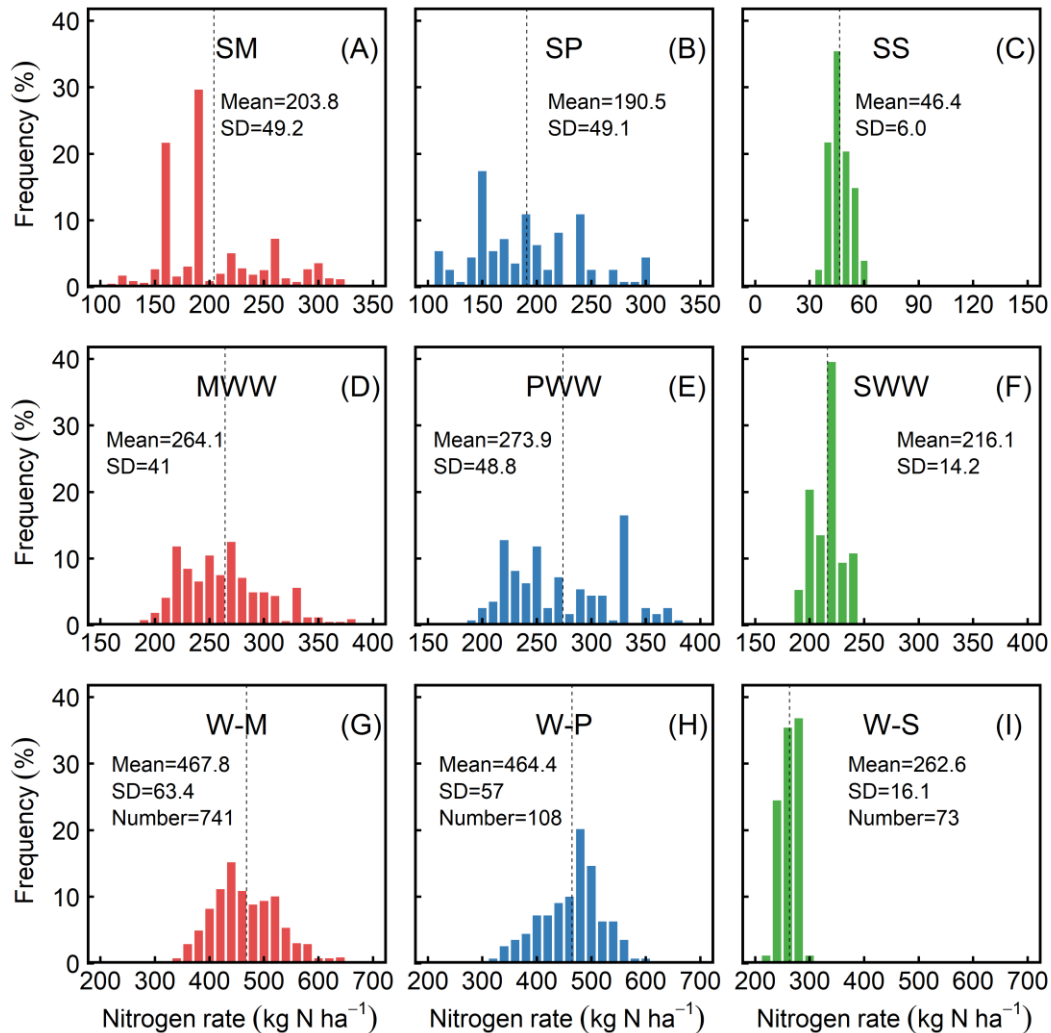
285

286 **3. Results**

287 **3.1 N managements in crop production across the NCP**

288 Our results showed that the N fertilizer rate differed significantly between the summer crops
289 grown across the NCP. Specifically, the mean annual N rate was 204, 191 and 46 kg N ha⁻¹ for
290 summer maize, summer peanut and summer soybean, respectively (Fig. 2 A-C). More than 50% of
291 farmers applied less than 200 kg ha⁻¹ N to summer maize, while the 71% of N application was
292 concentrated in 150-240 kg ha⁻¹. Similar trends were observed for summer peanut (Fig. 2B). In

293 general, N application to summer soybean was between 40 and 60 kg ha⁻¹ (Fig. 2C). N management
294 varied considerably in summer crops across the NCP, and most farmers applied mineral N in
295 summer maize, summer peanut and summer soybean production at one time during crop growing
296 season (Table 1). Specifically, 67% of farmers applied all N fertilizer before summer maize sowing,
297 and 31% applied both basal fertilizer and top dressings during the summer maize growing season.
298 For summer peanut, 36% of farmers applied all N fertilizer before sowing and 42% applied all N
299 fertilizer during the flowering stage. Split applications were made by 22% of farmers during the
300 summer peanut growing season. Most farmers applied all N before the summer soybean sowing.
301 Interestingly, farmers who split the N application always used more N fertilizer compared to single
302 applications for all three summer crops (Table 1).



303

304 **Fig. 2** Frequency of nitrogen applications in (A) summer maize (SM), (B) summer peanut (SP), (C)
 305 summer soybean (SS), (D) winter wheat following maize (MWW), (E) winter wheat following
 306 peanut (PWW), (F) winter wheat following soybean (SWW), (G) wheat-maize rotation (W-M), (H)
 307 wheat-peanut rotation (W-P) and (I) wheat-soybean rotation (W-S) across the NCP.

308

The N applications were much lower in SWW compared to MWW or PWW, and the mean N
 309 application value was 264, 274 and 216 kg ha⁻¹ for MWW, PWW and SWW, respectively (Fig. 2
 310 D-F). Generally, all farmers used two N applications in wheat production (Table 1). Our results
 311 showed that the annual N rate was much lower in winter wheat-soybean compared with wheat-
 312 maize and wheat-peanut rotations. The mean annual values were 468, 464 and 263 kg ha⁻¹ for

313 wheat-maize, wheat-peanut and wheat-soybean, respectively (Fig. 2 G-I). Moreover, the high
 314 frequency of annual N application for wheat-maize, wheat-peanut and wheat-soybean was mainly
 315 focused on the ranges of 360-580, 340-560 and 220-300 kg ha⁻¹ (Fig. 2 G-I).

316 **Table 1** The amount of base and latter fertilizer of different crops and the proportion of the
 317 number of farmers

| Crop | BF (kg N ha ⁻¹) | TD (kg N ha ⁻¹) | TF (kg N ha ⁻¹) | Pro. (%) |
|------|-----------------------------|-----------------------------|-----------------------------|----------|
| | 181.3±33.3 | — | 181.3±33.3 | 67.3 |
| SM | 156.1±43.5 | 94.8±41.2 | 250.9±44 | 31.1 |
| | — | 234±44.9 | 234±44.9 | 1.6 |
| | 189.2±53.9 | — | 189.2±53.9 | 36.1 |
| SP | 93.5±38.4 | 128.3±41.8 | 221.9±46.1 | 22.2 |
| | — | 174.9±38.2 | 174.9±38.2 | 41.7 |
| | 45.8±6.0 | — | 45.8±6.0 | 86.3 |
| SS | 35.6±5.9 | 16.7±1.2 | 52.4±5.6 | 6.8 |
| | — | 48.4±2.8 | 48.4±2.8 | 6.8 |
| MWW | 122.1±24.1 | 141.9±36.7 | 264.1±41 | 100 |
| PWW | 127.1±22.9 | 146.9±43.5 | 273.9±48.8 | 100 |
| SWW | 114.5±11.6 | 101.6±13.5 | 216.1±14.2 | 100 |

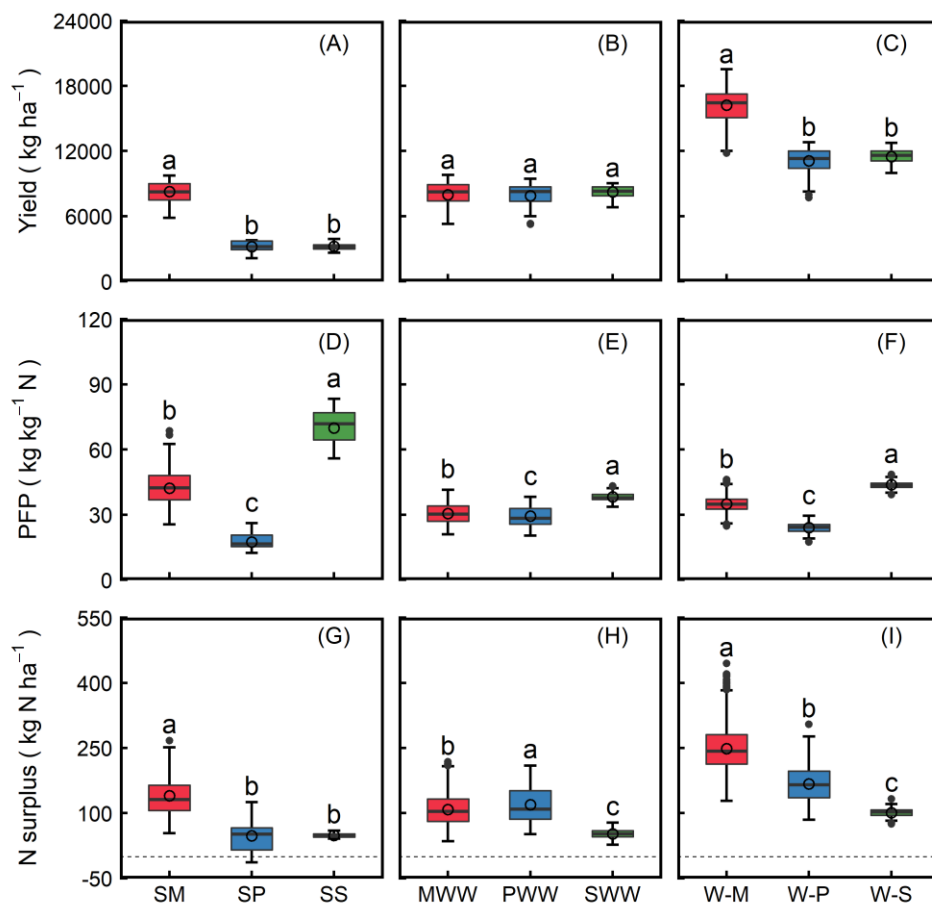
318 Note: BF means base fertilizer (kg N ha⁻¹), TD means top dressing (kg N ha⁻¹), TF means total
 319 fertilizer (kg N ha⁻¹), Pro. means proportion (%). SM is summer maize, SP is summer peanut, SS
 320 is summer soybean, MWW is winter wheat after maize, PWW is winter wheat after peanut, and
 321 SWW is winter wheat after soybean.

322

323 3.2 Crop yield, PFP, N surplus and N footprint

324 Summer maize yields were about 5 Mg ha⁻¹ higher than those of peanut and soybean (Fig. 3A).
 325 Significant differences were observed for PFP between the three summer crops and the mean PFP
 326 for summer soybean, summer maize and summer peanut, which were 70, 42 and 18 kg kg⁻¹ N,

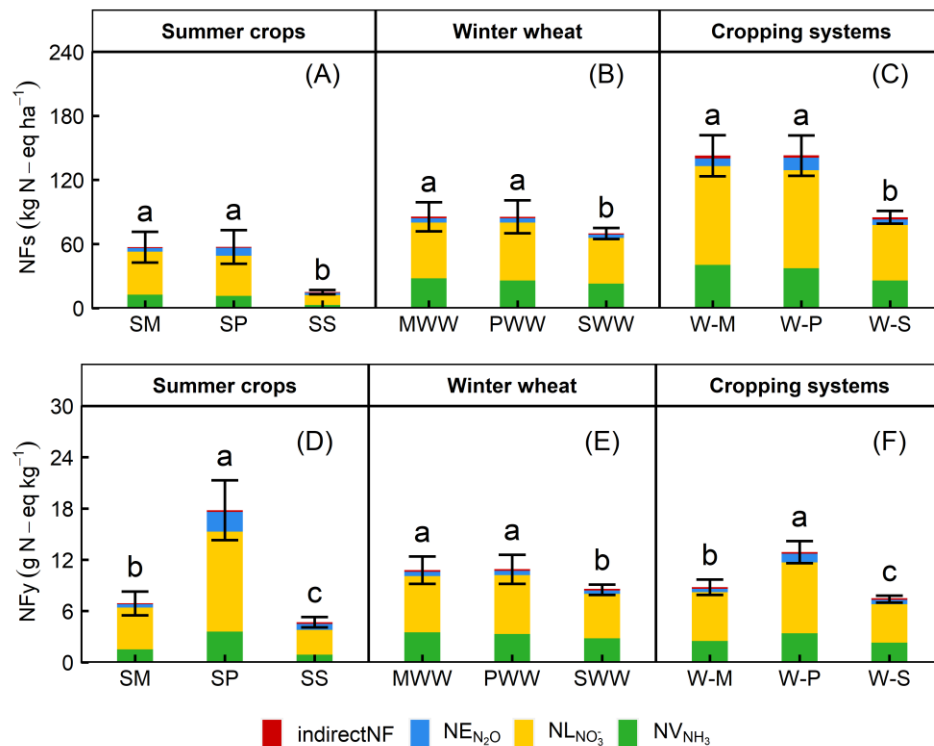
327 respectively (Fig. 3D). The N surplus was highest in summer maize and lowest in summer peanut,
 328 with a mean N surplus of 140, 48 and 49 kg N ha⁻¹ for summer maize, summer peanut and summer
 329 soybean, respectively (Fig. 3G). NFs were much lower in summer soybean compared to summer
 330 maize and summer peanut, and the mean values were 57, 57 and 15 kg N-eq ha⁻¹ for summer maize,
 331 summer peanut and summer soybean, respectively (Fig. 4A). The NFy was lowest in summer
 332 soybean and highest in summer peanut, and the mean NFys were 4.7, 6.9 and 17.8 g N-eq kg⁻¹ for
 333 summer soybean, summer maize and summer peanut, respectively (Fig. 4D).



334
 335 **Fig. 3** Distributions of crop yield (A, B, C), nitrogen partial factor productivity (PFP) (D, E, F) and
 336 N surplus (G, H, I) for summer maize (SM), summer peanut (SP), summer soybean (SS), winter
 337 wheat following maize (MWW), winter wheat following peanut (PWW), winter wheat following

338 soybean (SWW), wheat-maize rotation (W-M), wheat-peanut rotation (W-P) and wheat-soybean
 339 rotation (W-S) across the NCP. The dashed line corresponds to the Y axis equal to 0.

340 There were no differences between the yields of MWW, PWW and SWW, that were estimated
 341 at about 8 Mg ha⁻¹ (Fig. 3B). Interestingly, significant differences were found for the PPF of winter
 342 wheat following different summer crops in the study, and the mean the PFP value was 38, 31 and
 343 29 kg kg⁻¹ N for SWW, MWW and PWW, respectively (Fig. 3E). The N surplus showed a different
 344 pattern to PFP (Fig. 3H), where the mean N surplus was 52, 109 and 120 kg N ha⁻¹ for SWW,
 345 MWW and PWW, respectively. Both NFs and NFy of SWW were much lower than those of MWW
 346 and PWW (Fig. 4B & E). Our results showed that N leaching was the largest contributor to NFs
 347 and NFy, followed by ammonia volatilization and nitrous oxide emissions. The NFs and NFy
 348 caused by N leaching accounts for 60-70% (Fig. 4 A-B and D-E).



349
 350 **Fig. 4** Ranges of NFs (N footprint per hectare) (A, B, C) and NFy (N footprint per kg yield) (D, E,
 351 F) of summer maize (SM), summer peanut (SP), summer soybean (SS), winter wheat following
 352 maize (MWW), winter wheat following peanut (PWW), winter wheat following soybean (SWW),

353 wheat-maize rotation (W-M), wheat-peanut rotation (W-P) and wheat-soybean (W-S) across the
354 NCP. The red color represents the indirect NF, the blue color represents the NF caused by released
355 N₂O, the yellow color represents the NF caused by NH₃ volatilization, and the green color
356 represents the NF caused by NO₃⁻ leaching.

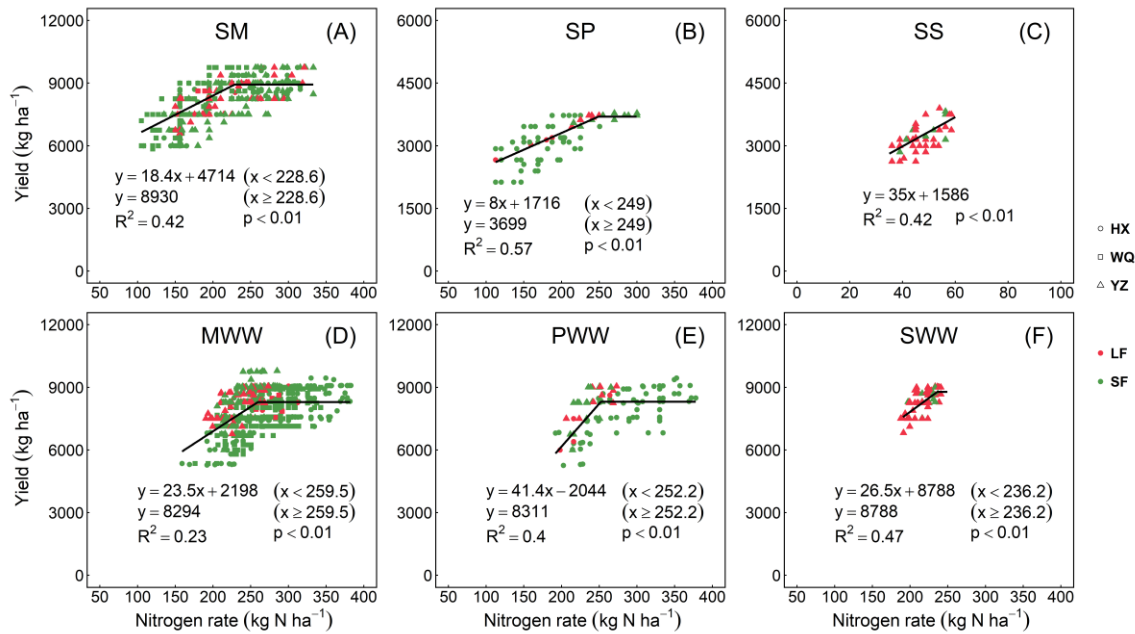
357 Generally, the annual grain yield was highest in wheat-maize rotation and lowest in wheat-
358 peanut rotation, with mean values of 16.2, 11.0 and 11.5 Mg ha⁻¹ for wheat-maize, wheat-peanut
359 and wheat-soybean rotations, respectively (Fig. 3C). Our results showed that PFP was highest for
360 the wheat-soybean and lowest in the wheat-peanut rotations across NCP, and the mean PFP value
361 was about 44, 35 and 24 kg N⁻¹ for wheat-soybean, wheat-maize and wheat-peanut, respectively
362 (Fig. 3F). The N surplus was highest in wheat-maize, followed by wheat-peanut and wheat-soybean,
363 with mean values of 250, 168 and 101 kg N ha⁻¹, respectively (Fig. 3I). In general, the NFs of
364 wheat-soybean were much lower than those of wheat-maize and wheat-peanut rotations, with
365 means of 143, 143 and 85 kg N-eq ha⁻¹ for the respective systems (Fig. 4C). On the other hand,
366 NFy was lowest in wheat-soybean and highest in wheat-peanut, with means of 7.4, 8.8 and 12.9 g
367 N-eq kg⁻¹ for wheat-soybean, wheat-maize and wheat-peanut, respectively (Fig. 4F).

368

369 **3.3 N management effects on crop yield and N footprint**

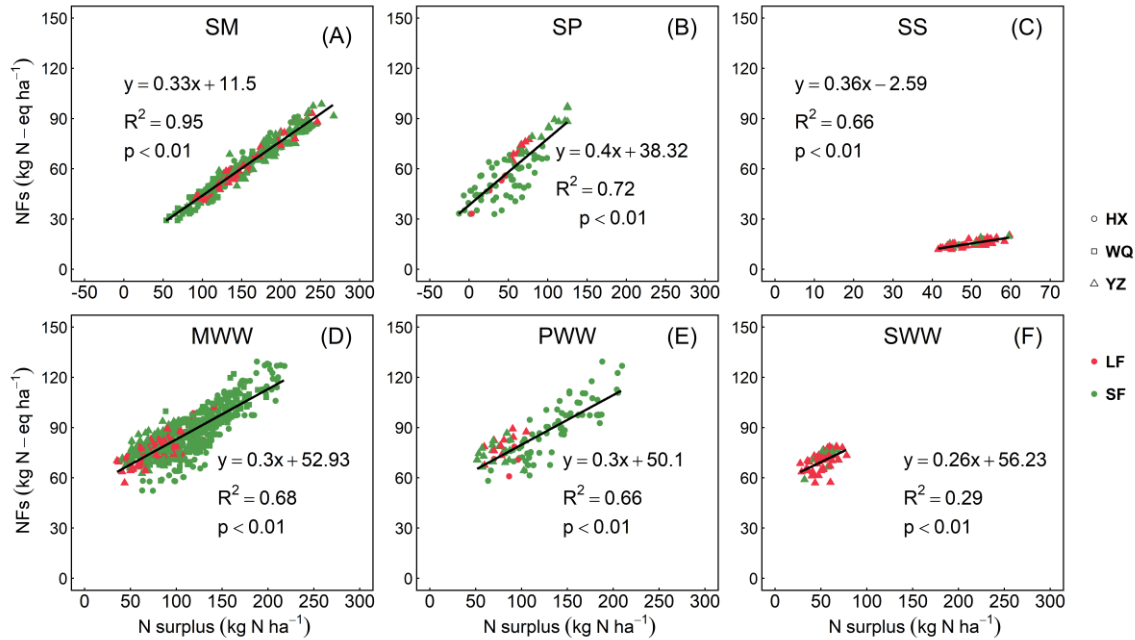
370 Our results identified the threshold N application rate for maize, peanut and winter wheat
371 across the NCP based on the basis of actual production data. The regression model results showed
372 that a kg ha⁻¹ increase of N applied would lead to 18.4 kg ha⁻¹ increase of summer maize yield when
373 the N rate ranges from 100 to 229 kg ha⁻¹ (Fig. 5A). The threshold N rate for summer peanut was
374 249 kg ha⁻¹, where a 1 kg ha⁻¹ increase of N rate would lead to 8 kg ha⁻¹ increase of summer peanut
375 yield below the threshold value (Fig. 5B). The threshold N rate for summer soybean production
376 was not determined but a 1 kg ha⁻¹ increase of N rate would lead to 35 kg ha⁻¹ increase of summer
377 soybean yield under the current N application range (Fig. 5C). The threshold of N rate for winter
378 wheat varied between different previous summer crops, which were 260, 252 and 236 kg ha⁻¹ for

379 MWW, PWW and SWW, respectively. Specifically, the regression results indicated that an increase
 380 of N rate in PWW and SWW contributed more to yield increase than that of summer maize (Fig. 5
 381 D-F). According to the optimal N application rate determined in this study, the proportion of
 382 farmers in this area with excessive N application rates for winter wheat, maize and peanut was 49%,
 383 27%, and 12%, respectively (Figs. 2 & 5).



384
 385 **Fig. 5** Responses of crop yield to N fertilizer application of (A) summer maize (SM), (B) summer
 386 peanut (SP), (C) summer soybean (SS), (D) winter wheat after maize (D), (E) winter wheat after
 387 peanut (PWW) and (F) winter wheat after soybean (SWW) across the NCP considering different
 388 farm scales. LF means large farms, SF means small farms, HX, WQ and YZ represents Huxian,
 389 Wuqiao and Yanzhou, respectively.

390 The results showed that the increased N surplus led to lower PFP (Fig. S1), and decreased PFP
 391 led to a higher N footprint (Fig. S2). Thus an increased N surplus resulted in a higher N footprint
 392 (Fig. 6). For all crops, the R² of each regression equation was relatively high and P value was
 393 smaller than 0.01. Thus, N surplus provides a good indicator of PFP and NFs.

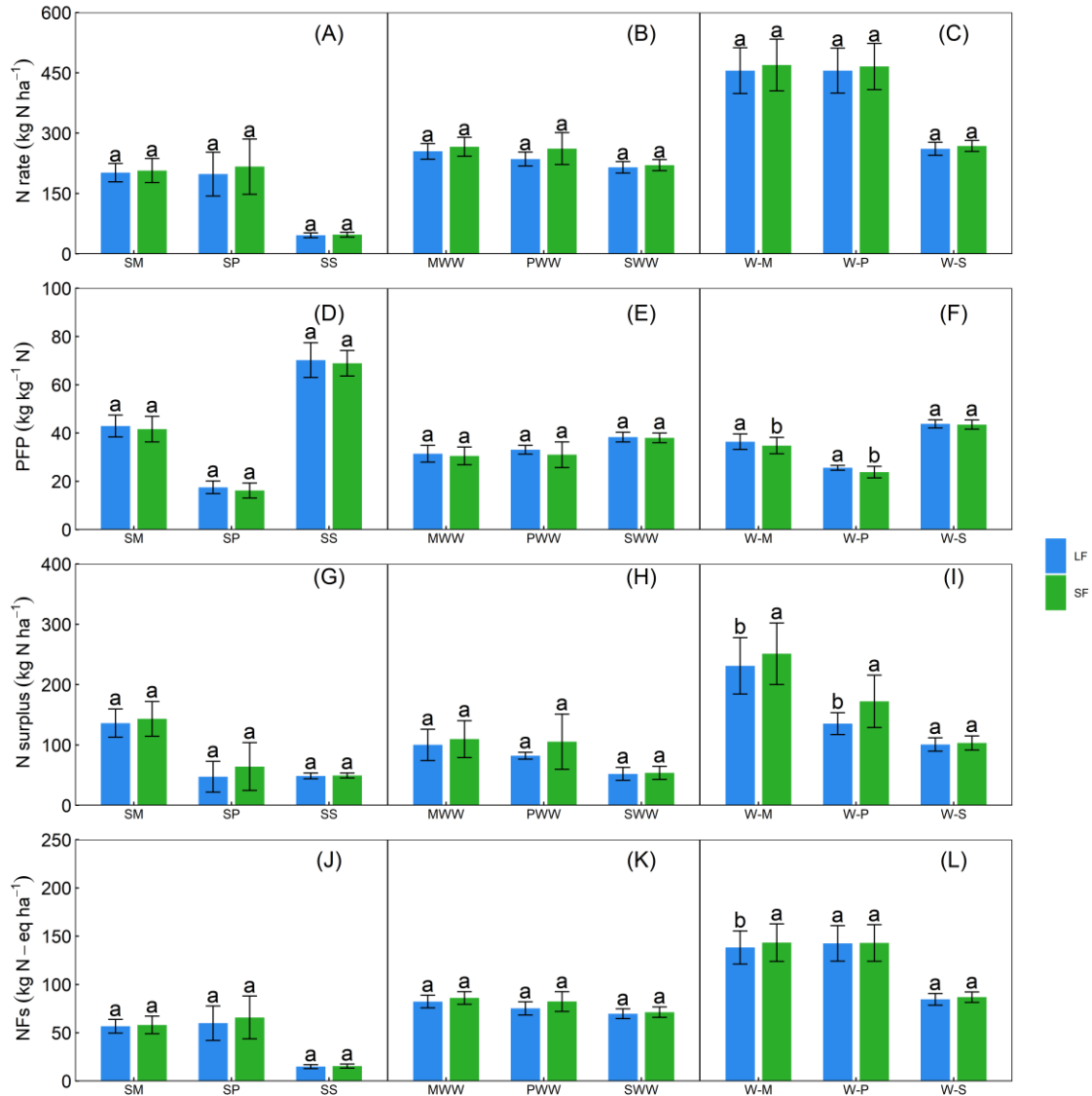


394
 395 **Fig. 6** Influences of N surplus on N footprint of (A) summer maize (SM), (B) summer peanut (SP)
 396 and (C) summer soybean (SS), (D) winter wheat after maize (MWW), (E) winter wheat after peanut
 397 (PWW) and (F) winter wheat after soybean (SWW) across NCP. LF means large farms, SF means
 398 small farms, HX, WQ and YZ represents Huxian, Wuqiao and Yanzhou, respectively.

399

400 3.4 Farm size effects

401 The average N fertilizer rate was slightly lower for large compared to small-scale farming for
 402 each crop (Fig. 7A-B), and PFP was slightly higher for large than small farms for all individual
 403 crops in the study (Fig. 7D-E) whereas the N surplus was much lower for large than small farms
 404 (Fig. 7G-H). Moreover, large farms had smaller NFs for summer maize, summer peanut, summer
 405 soybean, and MWW, PWW and SWW (Figs. 7J-K). Similar patterns were found for large and small
 406 farms for three rotations in the study (Fig. 7C, F, I&L).



407

408 **Fig. 7** Effects of farm scale on N rate, PFP, N surplus, NFs of summer maize (SM), summer peanut

409 (SP), summer soybean (SS), winter wheat after maize (MWW), winter wheat after peanut (PWW),

410 winter wheat after soybean (SWW), wheat-maize rotation (W-M), wheat-peanut rotation (W-P) and

411 wheat-soybean rotation (W-S) in NCP. LF and SF represents the large farms and small farms,

412 respectively. Different lowercase letters denote significant differences at $p < 0.05$.

413

414 **3.5 Scenarios analysis**

415 The estimated total N application and N footprint for the major crop rotations (wheat-soybean
 416 and wheat-maize) in the NCP was 4.7 million tons 4 million tons of N-eq in 2017, respectively The
 417 corresponding production of winter wheat, maize and soybean was 82.6, 82.5 and 1.7 million tons
 418 of grain yield (Table 2). The scenario analysis showed that adjusting the proportion of soybean in
 419 the rotations would be the most efficient way of reducing the N rate and N footprint in wheat-
 420 soybean and wheat-maize rotations across the NCP (Table 2). The current proportion of soybean
 421 to maize was 1:18, and if the ratio increased to 1:5, the total N rate and N footprint would be reduced
 422 to considerably 4.4 and 1.4 million tons, respectively. On the other hand, the soybean production
 423 would increase to 5.6 million tons, and wheat production would increase by 0.4 million tons due to
 424 the positive pre-crop effects of soybean. Optimizing N rate and increasing farm size would also
 425 reduce N applications and the N footprint, which according to the scenario study would increase
 426 maize and soybean production. Compared to the baseline, increasing the proportion of soybean in
 427 combination with optimization of N fertilizer rates and greater farm size would efficiently reduce
 428 N rate and NF, as well as increasing soybean and wheat production in the NCP (Table 2).

429 **Table 2** Effects of the combinations of planting, N rate application and increasing farm size on N
 430 rate, N footprint and crop yeild for winter wheat (WW), summer maize (SM) and summer
 431 soybean (SS) under different scenarios across the NCP.

| | N appl (Mt) | NF (Mt N-eq) | Yield (Mt) | | | Total yield (Mt) | Area (Mha) | | |
|----------|----------------|-----------------|------------|-------|------|------------------------|------------|------|------|
| | | | WW | SM | SS | | WW | SM | SS |
| Baseline | 4.68 | 1.43 | 82.62 | 82.47 | 1.73 | 166.82 | 10.41 | 9.87 | 0.54 |
| S1-1 | 4.45 | 1.36 | 83.00 | 72.49 | 5.55 | 161.04 | 10.41 | 8.67 | 1.73 |
| S1-2 | 4.62 | 1.41 | 82.73 | 79.74 | 2.78 | 165.25 | 10.41 | 9.54 | 0.87 |
| S2-1 | 4.59 | 1.40 | 86.39 | 91.77 | 1.95 | 180.11 | 10.41 | 9.87 | 0.54 |
| S2-2 | 4.98 | 1.52 | 86.66 | 87.83 | 1.95 | 176.44 | 10.41 | 9.87 | 0.54 |
| S3-1 | 4.65 | 1.42 | 82.39 | 82.89 | 1.73 | 167.01 | 10.41 | 9.87 | 0.54 |

| | | | | | | | | | |
|------|------|------|-------|-------|------|--------|-------|------|------|
| S3-2 | 4.81 | 1.47 | 83.48 | 80.92 | 1.73 | 166.13 | 10.41 | 9.87 | 0.54 |
| S4 | 4.39 | 1.34 | 86.39 | 80.67 | 6.25 | 173.31 | 10.41 | 8.67 | 1.73 |

432 Note: Baseline represents the current situation based on the farmer survey, the detailed descriptions
433 of each scenario was shown in the materials and methods section. .

434

435 4. Discussion

436 4.1 Effects of proportion of maize, soybean and peanut grown

437 4.1.1 Comparisons of N rate, PFP, N surplus and N footprint between crops and rotations

438 Our results showed that the mean annual N fertilizer rate of wheat-soybean was about 200 kg
439 ha⁻¹ lower than that of wheat-maize and wheat-peanut rotations (Fig. 2), where the lowest N rate in
440 wheat-soybean led to the highest PFP and the lowest N surplus. This means that increasing the
441 proportion of soybean in rotation with wheat would be beneficial for N management in the NCP.
442 A similar conclusion was reached in a study recently by (Zhang *et al.* 2021) who showed that
443 inclusion of soybean into wheat maize rotations in the NCP contributed to high NUE whilst
444 reducing the overall C footprint. Previous studies have mainly focused on the N fertilizer
445 management in wheat-maize rotations across the NCP without considering the pre-crop effects of
446 grain legumes in the wheat-peanut and wheat-soybean systems (Cui *et al.*, 2010; Liu *et al.*, 2018;
447 Michalczyk *et al.* 2020). Our results showed that the annual mean N applied to wheat-maize
448 rotations was 468 kg ha⁻¹, which was in the lower range of that previous reported N of 410-588 kg
449 ha⁻¹ (Feng *et al.*, 2020; Ju *et al.*, 2009). Generally, the annual N rate for winter wheat of 220-260
450 kg N ha⁻¹ was consistent with the results of a recent study (Ren *et al.*, 2019). On the other hand, the
451 surveyed annual N rate for summer maize was also in the range of previous reported annual N
452 application rates of 172-417 kg ha⁻¹ across the NCP based on farmer surveys (Huang *et al.*, 2016).
453 This is mainly because previous studies were conducted before 2015, and the application of the
454 “Action Plan for the Zero Increase of Fertilizer and Pesticides Use (APZIFPS)” policy in 2015
455 promoted the reduction of N rate in crop production across NCP.

456 Both NFs and NFy were lowest for wheat-soybean among the three major crop rotations in
457 the NCP, thus suggesting smaller environmental costs of wheat-soybean compared to the other
458 rotational systems. On the other hand, even though there was no significant difference for the NFs
459 between wheat-maize and wheat-peanut, the NFy of wheat-peanut was much higher compared to
460 wheat-maize, indicating a higher environmental risk of wheat-peanut due to lower yields of summer
461 peanut compared to summer maize. Nitrate leaching, and ammonia volatilization were the major
462 contributors to the N footprint at the rotational level (Fig. 4; Xu et al., 2020), which implies better
463 management in reducing nitrate leaching and ammonia volatilization would be beneficial for
464 reducing the N footprint.

465

466 **4.1.2 Pre-crop effects on winter wheat of different summer crops**

467 Our study indicated the benefits of soybean on the following winter wheat in improving NUE,
468 reducing the N surplus and N footprint without influencing wheat yield (Figs. 3 & 4). Generally,
469 the lower N rate in wheat-soybean rotations was not only because of the low N inputs in the soybean
470 growing season, but also the pre-crop effects of soybean. Legume-based rotations have been widely
471 used in tightening the field N cycle by adding N to the soil in crop residues (i.e. Mawois et al., 2019;
472 Yigezu et al., 2019), and the positive effects of soybean as the pre-crop on increasing yield and
473 NUE of the subsequent crops have been observed in various studies (Espinoza et al., 2020; Preissel
474 et al., 2015). For example, previous studies indicated that N applications for winter wheat can be
475 reduced by about 60 kg N ha⁻¹ following legume crops compared to that following cereal crops
476 without influencing yield (Preissel et al., 2015; Yin et al., 2020). The effects of BNF of legume
477 crops in reducing N application has been widely recognized in legume-based rotations (Liu et al.,
478 2011; Peix et al., 2015; Peoples et al., 2009). Moreover, due to the higher N concentrations and
479 lower C:N ratio, in addition to the nitrogen rhizodeposition of legumes, compared to cereal residues,
480 the inclusion of legume crops in crop rotations would not only contribute to reduce the use of
481 external N inputs, but also improve the soil N cycling (Guinet et al., 2020).

482 However, the pre-crop effects of peanut on the PWW rotation were not documented in the
483 study. This is probably because farmers applied large amounts of mineral N in peanut production
484 to pursue high yield thus neglecting the BNF of the legume crop (Fig. 2). The advantage of BNF
485 for legume crops disappear with N application rates in excess of 150 kg ha⁻¹ (Cernay et al., 2017),
486 and the high N rate applied to peanut in the NCP probably restrained the BNF process, including
487 the amount of N exudates from roots. Moreover, peanut is generally grown in sandy soils, which
488 have relatively low soil fertility and higher needs for mineral N fertilization. On the other hand,
489 peanut residue contains a relatively large amount of N, and its effective recycling can reduce the
490 input of fertilizer N to support sustainable agricultural production (Cui et al., 2021). However, the
491 peanut straw was also harvested from the farmland as feed for animals, resulting in higher needs
492 for N application in the PWW rotation (Zhang et al., 2018a; Zhang et al., 2019).

493

494 **4.2 Optimizing N application to increase NUE and reduce N footprint**

495 **4.2.1 N rates in crop production**

496 It's widely recognized that the increase of N inputs will improve crop yield below the optimal
497 N rate, followed by stable yields with N inputs exceeding the threshold value (Cui et al., 2010; Lu
498 et al., 2014). Our results showed that the optimal N rate for summer maize was 229 kg ha⁻¹ across
499 the NCP (Fig. 5), in line with the reported optimal N rate for maize from field experiments of 185-
500 280 kg ha⁻¹ (Liu et al., 2019a; Zhou et al., 2019). Our results showed that the optimal N rate for
501 winter wheat was 230-260 kg ha⁻¹, which was slightly higher than the previously reported optimal
502 rate of 190-250 kg ha⁻¹ (Lu et al., 2014; Ma et al., 2019). This is mainly because previous studies
503 were all based on field experiments using precise N management strategies, such as water-nitrogen
504 coupling, soil testing and formula fertilization, which contributed improved NUE compared to the
505 farmer's situation (Cui et al., 2010).

506 Previous studies have shown that the mean annual BNF of soybean and peanut from the
507 atmosphere can reach 137 and 103 kg ha⁻¹, respectively (Peoples et al., 2009). The BNF contributes

508 23–65% and 33–51% of total aboveground N accumulation in soybean and peanut, respectively,
509 thus additional N supply, possibly through fertilizer, is needed to achieve their optimum yields
510 (Cordova et al., 2019; Zheng et al., 2019). However, previous studies reported optimal N rates for
511 a high soybean yield of 50-150 kg ha⁻¹ with large uncertainties (i.e. Lv et al., 2020; Zhang et al.,
512 2018b). Our results showed that soybean yield always increased when the N application rate was
513 below 60 kg ha⁻¹, and that no definite optimal N rate could be identified. On the other hand, the
514 BNF effects of peanut were not found in the study as the optimal N rate for peanut was 249 kg ha⁻¹
515 (Fig. 5B), which was slightly higher than the reported optimal N rate of peanut from field
516 experiments of 150-225 kg ha⁻¹ (Xia et al., 2020; Zhang et al., 2018a). It is known that additional
517 N fertilizer reduces the activity of rhizobia on grain legumes and thus inhibits BNF (Lyu et al.,
518 2019). Therefore, further research to estimate the optimal N input for peanut and soybean across
519 the NCP is required..

520

521 **4.2.2 N application time in crop production**

522 Previous studies have shown that split fertilization is more efficient than base fertilization,
523 typically around sowing, based on the N requirement of the cereal crop growth, which is beneficial
524 for increasing crop yield and NUE (i.e. Liu et al., 2019b). However, our results showed that a split
525 fertilizer application was linked to greater N applications compared to single fertilizer application
526 (Table 1). Furthermore, split fertilization has higher labour and economic costs for farmers, which
527 may prevent farmers from adopting this practice. Nevertheless, very limited information is
528 available on split fertilization for peanut and soybean across the NCP, and further documentation
529 on benefits of this practice is therefore needed. The practice of splitting N application for winter
530 wheat into two applications was probably linked to irrigation, which is normally conducted at the
531 jointing stage and the top N dressing is applied before irrigation. In addition, N uptake in the early
532 stage of winter wheat growth is relatively small, and too much basal fertilizer application will
533 enhance N losses (Cui et al., 2010). However, the amount of basal fertilizer and top dressing by

534 farmers is almost equal in this study, to a previous study which reported that the ratio of basal
535 fertilizer and top dressing as 1:1.3 increased NUE(Jia et al., 2011).

536

537 **4.2.3 N management effects on N footprint**

538 Our study confirmed that optimizing N management is beneficial for improving NUE and
539 reducing the N footprint (Figs. 5-6). Significant and linear relationships between NFs, PFP and N
540 surplus were observed for all crops included in the study, which means that a larger N surplus is
541 linked to a smaller PFP (Fig. S1) and higher NFs (Fig. 6), probably because both N surplus and the
542 N footprint are directly linked to N fertilizer inputs (Table S1). Our results showed that the values
543 of NFs and NFy for the three summer crops in the study were in line with previous studies (He et
544 al., 2021; Xu et al., 2020). The NFy of winter wheat was slightly larger than previously reported,
545 which mainly because of the different calculations of nitrate leaching, for instance Xu et al. (2020)
546 used crop model to calculate it, whereas this study used an empirical approach. Generally, N
547 leaching is the major source of the N footprint, with previous studies showing that the increase of
548 the N surplus is linked to larger amounts of N leaching (De Notaris et al., 2018; Peng et al., 2017).
549 In the NCP, N leaching mainly occurs in the summer crop as about 70% of rainfall is concentrated
550 in this period(Jia et al., 2014). Our results showed that N surplus was lowest in the summer soybean
551 and winter wheat-soybean rotations, which means the lowest N leaching risks are found in wheat-
552 soybean compared to wheat-maize and wheat-peanut rotations.

553

554 **4.3 Farm size effects on increasing NUE and reducing N footprint**

555 Farm size is generally increasing in the NCP, which strongly changes the agricultural
556 production and management in the region. Generally, farmer responses to available production
557 inputs, policies and technical training are highly related to farm scale (Cui et al., 2018). Our results
558 showed that crop yield is not affected by farm scale, which has also been reported earlier (Yan et
559 al., 2015). Furthermore, our results indicated that large farms have greater NUE and lower N surplus

560 and NF. Specifically, the N rate was generally lower for large farms compared to small-holder
561 farms for each individual crop included in the study, and the lower N rate in large farms led to
562 higher PFP and lower N surplus (Fig. 7). Similar trends were observed for wheat-maize, wheat-
563 peanut and wheat-soybean rotations (Fig. 7). Generally, the household head of large farms was
564 younger and with a higher education level than smallholders, which made them more responsive to
565 new information and technologies. Moreover, agricultural technology demonstrations were
566 implemented to a greater extent on large farms, and large farms had better farm equipment for N
567 application. Both aspects promoted the household head of large farms to better target and reduce N
568 rates in crop production. Furthermore, agro-economic benefits play a dominant driver for the
569 household of large farms reducing N rate. A previous study showed that increasing the scale of
570 production reduced the total fertilizer input for crop production, which was highly related to N
571 fertilizer prices and related policies that have subsidized fertilizer inputs to enhance production (Ju
572 et al., 2016). However, the reduction of N rate for large farms led to lower NFs and NFy compared
573 to small farms. These showed that large farms would play an important role in contributing to
574 agricultural green development in the NCP.

575

576 **4.4 Perspectives and implications**

577 An LCA-based method was used to calculate the N footprint in the study, which was mainly
578 based on empirical formulae and large-scale field surveys, that can relatively well reflect the
579 environmental effects of N application in agricultural production across the NCP (Qin et al., 2011;
580 Shibata et al., 2017). Empirical formulas based on experiments were used to estimate the amount
581 of N volatilization (NH_3), nitrous oxide (N_2O) and nitrate leaching (NO_3^-) in the study (Table S1),
582 which performed well in calculating N footprint across the NCP (Bellarby et al., 2018). In this
583 study, the N surplus calculation considered all N inputs in crop production, including fertilizer N,
584 the BNF of soybean and peanut, N decomposition and the N inputs of seeds, which can adequately
585 reflect the N status in the major crop rotations in the NCP. Due to the lack of direct measured data,

586 the calculations of BNF were mainly based on the experiments in the NCP to minimize
587 uncertainties as shown in the materials and methods section. Furthermore, the N decomposition
588 value considered both wet and dry decomposition that was measured in the NCP (Zhang et al.,
589 2021).

590 The CPCNS has raised the requirements for the green development of agriculture across the
591 NCP (P.R.C., 2021). High crop yield and resource use efficiency with low environmental impact
592 are the basic goals for agricultural production in China as well in the NCP. It is impossible to realize
593 this goal using one single technology, and more integrated strategies, like climate-smart agriculture,
594 should be adopted. Our study provided evidence to promote agricultural green development
595 considering the composition of the crop rotations by enhancing the area of soybean and optimizing
596 N management, supported by increasing farm size. Our results showed that growing more soybean
597 to replace maize is an efficient way of reducing N applications and enhancing soybean production
598 in the region. If the soybean cropping area was increased to 20% of the current maize area, and
599 farmers adopt optimal N rate and management, crop production would increase with reduced N
600 applications and N footprint. Soybean production could then reach 5.6 million tons with a slight
601 reduction of maize production in the NCP (Table 2).

602 Generally, crop production was different in each county included in the study, which was
603 highly related to the local soil and climatic conditions and agricultural management. For instance,
604 the lowest N rate for wheat-maize in Wuqiao was probably related to the technological
605 demonstration of the Wuqiao Experimental Stations. Our results show that farmers in Huaxian and
606 Wuqiao applied less N to both summer maize and summer peanut compared to those in Yanzhou,
607 while higher N rates were used in the winter wheat production in Huaxian and Wuqiao compared
608 to Yanzhou (Table S2). The high N surplus in summer maize and summer peanut in Yanzhou can
609 be explained by the lower N application in winter wheat, which was supported by the N transfer
610 from the previous crop (Liu et al. 2018). Our results showed that the N rate for summer soybean
611 was about 200 kg ha⁻¹ lower than that of summer maize and summer peanut. The N rate for SWW

612 was still about 23 kg ha⁻¹ lower than that of MWW and PWW in Yanzhou, and there were no
613 differences in the yields of winter wheat with the different pre-crops (Table S2). This strongly
614 demonstrates the pre-crop effects of soybean on reducing the N rate and increasing NUE for the
615 subsequent winter wheat. Since the wheat-soybean rotation was mainly concentrated in Yanzhou
616 in our survey, this may have caused some bias at the region level. Moreover, the high N rates in
617 winter wheat may hide the pre-crop effects of soybean, which should be stronger when the N
618 application was smaller than 150 kg N ha⁻¹ in the winter wheat season as demonstrated in our field
619 experiment in the region. It shows a large room was existed to reduce N application in winter wheat
620 production in the NCP.

621

622 5. Conclusions

623 This is the first study that systematically evaluated the effects of a range of management
624 interventions including crop rotation design, fertilizer nitrogen (N) rate optimization and increasing
625 farm size to promote agricultural green development across the NCP based on large-scale farm
626 surveys. Our results showed that the mean annual N rate of the wheat-soybean rotations was much
627 lower than that of wheat-maize and wheat-peanut, specifically, the mean N fertilizer rate was 204,
628 191, 46, 264, 274 and 216 kg ha⁻¹ for maize, peanut, soybean, and MWW, PWW and SWW,
629 respectively, in the NCP. On most farms, N fertilizer was applied twice during the winter wheat
630 season, and once for summer crops. The low N fertilizer requirement of soybean, coupled with
631 strong pre-crop effects on N supply for the following winter wheat contributed to the low N
632 fertilizer rate of the wheat-soybean rotations, and thus induced high PFP, a lower N surplus and the
633 lowest N footprint of the three rotations. This highlights the importance of adjusting crop rotations
634 by expanding the planting area of wheat-soybean rotations in the region. The management of N
635 fertilizers has improved in recent years, and the survey results showed that optimal N rates
636 corresponding to the maximum yield of summer maize, summer peanut, and MWW, PWW and
637 SWW were 229, 249, 260, 252 and 236 kg ha⁻¹, respectively. Better N management is beneficial

638 for reducing the N surplus, which is correlated with higher PFP and a lower N footprint. Moreover,
639 the results showed that large farms used less N fertilizer than small farms without compromising
640 crop yield and thus leading to higher PFP, a lower N surplus and lower N footprint. The scenario
641 analysis showed that the combinations of crop rotations with soybean, optimal N rate and increased
642 farm size would increase NUE and reduce the N footprint at the regional level, which is also
643 beneficial for enhancing soybean production. The approach used in this study could be applied in
644 other agricultural regions dominated by smallholder farmers and characterized by a diversity of
645 crops and crop rotations.

646

647 **Authors' contributions**

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654

655 **Declaration of Competing Interest**

656 The authors declare that they have no known competing financial interests or personal
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658

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