# Spatial planning needed to drastically reduce nitrogen and phosphorus surpluses in China's agriculture

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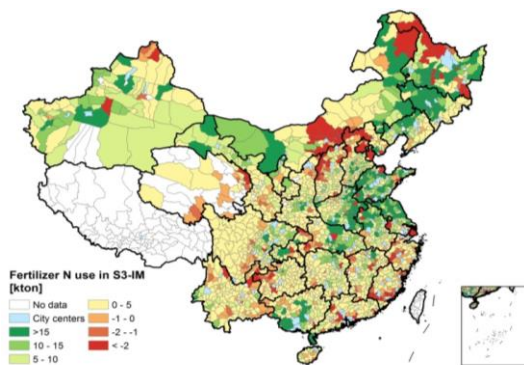* Corresponding authors: Zhaohai Bai zhbai@sjziam.ac.cn; Lin Ma malin1979@sjziam.ac.cn.

**Abstract:**

China's fertilization practices contribute greatly to the global biogeochemical nitrogen (N) and phosphorus (P) flows, which have exceeded the safe-operating space. Here, we quantified the potentials of improved nutrient management in the food chain and spatial planning of livestock farms on nutrient use efficiency and losses in China, using a nutrient flow model and detailed information of >2300 counties. Annual fertilizer use could be reduced by 26 Tg N and 6.4 Tg P following improved nutrient management. This reduction N and P fertilizer use would contribute 30% and 80% of the required global reduction, needed to keep the biogeochemical N and P flows within the planetary boundary. However, there are various barriers to make this happen. A major barrier is the transportation cost due to the uneven distributions of crop land, livestock and people with in the country. The amounts of N and P in wastes and residues are larger than the N and P demand of the crops grown in 30% and 50% of the counties, respectively. We argue that a drastic increase in the recycling and utilization of N and P from wastes and residues can only happen following re-location of livestock farms to areas with sufficient cropland.

46    **Graphic abstract:**



Fertilizer N demand in improved whole food system strategy

Fertilizer N use in S3-IM
[kton]

| | |
|---|---|
| No data | 0 - 5 |
| City centers | -1 - 0 |
| >15 | -2 - -1 |
| 10 - 15 | < -2 |
| 5 - 10 | |

47

48

## Introduction

Human pressures on the Earth-system have increased to unprecedented levels, with many of these pressures having severe impacts on the stability of Earth-system. Nine intrinsic biophysical processes that regulate the stability of the Earth-system have been identified, and four out of these nine have breached the boundaries. The biogeochemical flows of nitrogen (N) and phosphorus (P) have been considered to even reach a high-risk zone.[1-3] N and P are indispensable elements for all life on earth, and thus for food production. However, increasing inputs of N and P to agriculture have decreased the utilization efficiency of N and P in food production, and have led to increased losses of N and P to the environment and to pollution of surface waters and air.[2,4-7] It has been estimated that the total N and P fertilizer input to agriculture need to be reduced by at least 50% globally to be able to keep the global geochemical N and P flows within the suggested planetary boundaries.[3,8] Most of the environmental effects of N and P become visible on the local to regional range,[5] which increases the incentive to also perform measures at such spatial dimensions.

China will have an important role in achieving planetary boundaries for N and P flows, as China consumed around one third of global N and P fertilizers during the last decade,[9] and it faces serious water and air pollution due to low N and P use efficiencies.[10-11] The central government has set a 'zero increase target' for N and P fertilizer use between 2016 and 2020 to alleviate the environmental pollution.[12] Though a big step for farmers and industries, this target is far below the requirement to reduce N and P losses to acceptable levels. Several additional measures have been discussed, including more efficient fertilization,[13-15] improved livestock manure management, improved linking of crop production and livestock production,[16-17] diet manipulations and reduced food wastages[18-19]. Large potentials to reduce both N and P fertilizer inputs have been estimated. However, these measures focused only on certain sectors of the agro-food system, and neglected significant amounts of nutrients in the whole 'soil – crop – livestock – food processing – food consumption' chain,

that are potentially available for recycling. Earlier studies have shown that N and P use efficiency in the food chain was low, and that N and P losses were high in China.[20-21] This indicates that there is a need to consider the potential to recycle N and P from all wastes and residues of the food chain, and to estimate the potential N and P fertilizer savings.

It is well-known that not all N and P contained in recycled organic resources from the food chain are readily available to crops; for example, only 10% to 70% of the nitrogen in livestock manure is available following application to cropland, depending on the type of manure.[22-23] If synthetic fertilizer is replaced by manure without consideration of the bioavailability of the manure, there may be negative impacts on crop yield and possibly on food security. Hence, the bioavailability of nutrients in recycled organic resources has to be considered, also how the bioavailability is impacted by nutrient management practices, such as ammonia mitigation measures.[24] Such considerations have not been conducted yet in N and P fertilizer use projections for China.

Previous studies discussed the potentials to reduce fertilizer inputs at the national level, while ignoring the geographic disconnections between crop production, animal production and urban areas; the availability of organic resources, such as livestock manures and household residues, is often limited in rural areas, despite its abundance in and around urban areas. Other studies have pointed out that a subnational spatial linking of cropland and livestock agriculture are needed, combined with a strategy to replace mineral fertilizer by manure. [25-28] This indicates that the potentials for recycling of N and P from manures and wastes has to be examined at regional and local levels.

Here, we explored the potentials to recycle N and P from manure and wastes from the food chain in crop land at county level, and thereby the potentials to reduce N and P fertilizer use in China. The updated NUtrient flows in Food chains, Environment

108    Re-sources use (NUFER) county model was used, which contains data and

109    information of more than 2300 counties. [29-30] The potentials to recycle N and P from

110    manure and wastes from the food chain in crop land were examined at county level,

111    and national level; the difference between the two estimates indicates the current

112    geographic barriers for recycling N and P from manures and wastes, and for reducing

113    fertilizers input.

114

## Material and methods

116    **NUFER model**

117    The modified NUFER-county model was used to quantify the N and P flows in the

118    whole food chain.[29-30] The original NUFER model simulates the N and P flows in the

119    'soil – crop – livestock – food processing – food consumption' chain at the national

120    level in China,[19-20] but the county version is able to estimate the N and P flows in the

121    food chain at county level. Both model versions consider the food chain as a steady

122    state for one particular year. NUFER comprises an input sub-module (human activity,

123    agricultural production activity), a calculation module and an output module (different

124    type of nutrient losses, food export, nutrient accumulation in soil). The

125    NUFER-county model covers 2333 counties (including districts in the urban area), but

126    does not cover counties in Xinjiang, Tibet and Qinghai provinces, due to lack of

127    available data. These regions contribute <3.6% to the total crop production and

128    fertilizer use in China, and therefore have limited impacts on the results at the national

129    and county level. [31]

130

131    County-specific model input data were used, including (i) human activities in the food

132    chain, (ii) transformation and partitioning coefficients to match the data at county,

133    provincial and national levels, and (iii) N and P contents and loss factors. Data on

134    human activities were derived from county statistical reports.[29-30] The NUFER-county

135    model was further improved by including crop yield dependent biological N fixation

136    for legume crops.[32]

137 $$N_{fixed} = N_{dfa} \times (Y \div NHI) \times BGN \tag{1}$$

138 where $N_{fixed}$ is the amount of N fixed by crops (kg N ha$^{-1}$ yr$^{-1}$), $N_{dfa}$ is the percentage

139 of N uptake derived from N fixation (%), Y is the harvested yield (expressed in kg N

140 ha$^{-1}$ yr$^{-1}$), NHI is the N harvest index (dimensionless), defined as the ratio of N in the

141 harvested material to the total N in above-ground production, and BGN is a

142 multiplicative factor taking into account the contribution to total $N_2$ fixation of

143 below-ground fixation associated with roots and nodules production as well as to

144 rhizodeposition via exudates and decaying root cells and hyphae (dimensionless).[32]

145

146 The N and P losses via surface runoff, erosion and leaching were estimated as

147 function of land use, precipitation, soil depth, soil type, temperature and soil texture

148 and soil organic matter content at the county scale. The detailed method has been

149 described in Zhao et al.[33] The data and parameters were derived from the Data Center

150 for Resources and Environmental Sciences, Chinese Academy of Sciences

151 (RESDC),[34] or estimated via the spatial interpolation methods applied by RESDC.

152

153

154 **Strategies to reduce synthetic N and P fertilizer use**

155 We developed two main strategies to reduce the required N and P fertilizer input: i)

156 Recycling of N and P from manures, wastes and residues in the food system, to

157 substitute the synthetic fertilizer; ii) Improved technologies to reduce nutrient losses

158 and to increase the bioavailability of N and P in recycled organic resources, and

159 reduce synthetic fertilizer towards matching crop needs.

160

161 Three levels of system boundaries have been considered: crop production,

162 crop-livestock production, and the whole 'soil-crop-livestock-food processing-food

163 consumption' chain. These system boundaries are represented in Fig 1a-c. For each

164 level of system boundaries in spatial optimization, two sets of technology have been

165 explored, one reflecting a business as usual situation, and one of improved

166 technologies. The resulting six strategies provide an illustrative comparison of

167 possible impacts to the base situation. Hence, no changes in crop and livestock

168 production yield and structure were assumed with respect to the reference year

169 situation of 2012. Also, there were no changes in feed and feed harvest from natural

170 areas within China, and imports of food and feed from other countries were also

171 assumed to remain constant (2012 level). All strategies were simulated for the

172 national and the county scales.

173

174 The year 2012 was used as reference year, because of the availability of data and

175 parameters. Possible changes in the recycling of N and P from manures and wastes in

176 the food chain, and the possible replacement of synthetic N and P fertilizers by

177 recycling N and P were also estimated for the year 2012.

178

179 **Description of strategies**

180 **Strategy S1:** Balanced N and P fertilization in crop production (Fig 1a). Balanced

181 fertilization was defined as 'total available N (or P) from synthetic fertilizers equals

182 total crop N (or P) uptake corrected by a crop N (or P) uptake factor'. The crop N (or

183 P) uptake factor reflects that not all applied fertilizer N (or P) can be taken up by the

184 crop effectively, also because there are always 'unavoidable' losses of N and P to the

185 wider environment. The crop N (or P) uptake factor was introduced to assure no

186 reduction of crop yields, and fits in the 'food security first' policy in China. The N and

187 P uptake factors of different crop species are listed in Table S1. The required synthetic

188 N (or P) fertilizer input was estimated as follows:

189 $Ic_{fertilizer} = \sum_{i=1}^{n} \left[ \left( Oc_{Main\,product,i} + Oc_{Straw,i} \right) \times UF_{crop,i} \right] + Oc_{Managed\,grass} \times UF_{Managed\,grass} -$

190 $Ic_{Soil\,mineralization}$     (2)

191 Where $Ic_{fertilizer}$ is the total input of synthetic N (or P) fertilizer, in kg N (or P);

192 $Oc_{Main\,product,i}$ and $Oc_{Straw,i}$ are the amounts of N (or P) in the main crop product and

193 straw per county, respectively, in kg N (or P); $Oc_{Managed\,grass}$ is the amount of N (or P)

194 in harvested grass from managed grassland per county, in kg N (or P); $UF_{crop,i}$ and

195 $UF_{Managed\,grass}$ are the uptake factors for crop species and grass, respectively

**8**

196      (dimensionless) (Table S1); $Ic_{Soilmineralization}$ is the net release of N (or P) from the

197      mineralization of soil organic matter per county, which were derived from maps from

198      the Ministry of Agriculture and Rural Affairs. The average net N (or P) mineralization

199      rate was dependent on the soil organic matter content and cropland area; soils with a

200      high soil organic matter content (>4.0%) may release 43 kg N per ha, while soils with

201      a medium (2.5%-4.0%) and low soil organic matter content (<2.5%) may release 27

202      and 11 kg N per ha per year, respectively.[35] Requirement for P addition was calculated

203      using soil Olsen-P content: At soils with high Olsen-P content (> 40 mg kg$^{-1}$), 100%

204      of crop uptake was considered to be replenished by fertilizer addition, while this value

205      increased to 110% and 120% of crop P uptake in soils with a medium (20-40 mg kg$^{-1}$)

206      and low (< 20 mg kg$^{-1}$) Olsen-P content, respectively. [36] Further, we assumed that

207      balanced fertilization reduced ammonia emission, runoff, erosion and leaching factors

208      by 40% relative to the reference situation.[37-38] Note that S1 does not consider other N

209      (or P) additions as from manure, seed or crop residue material, atmospheric deposition

210      or biological fixation, which all are being maintained constant. Hence significant

211      excess application still may occur.

212

213      **Strategy S2:** Balanced fertilization and improved nutrient accounting in the

214      crop-livestock production sector (Fig 1b). A number of recent studies emphasized the

215      need to recouple crop and livestock production. This would allow to increase nutrient

216      recycling, and hence reduce the external new nutrient input in the agricultural

217      system.[15,25,26] Here, we assumed that N (or P) inputs from animal manures,

218      atmospheric deposition, biological N$_2$ fixation, and irrigation were taken into account

219      in the N (or P) accounting. The required synthetic N (or P) fertilizer input was

220      estimated as follows:

221      $Ic_{fertilizer} = \sum_{i=1}^{n}[(Oc_{main\ product,i} + Oc_{straw,i}) \times UF_{crop,i}] + Oc_{managed\ grass} \times UF_{managed\ grass} -$

222      $Ic_{soil\ mineralization} - Ic_{deposition} - Ic_{BNF} - Ic_{irrigation} - \sum_{i=1}^{n}(Ic_{straw\ back\ to\ field,i} \times AF_{straw\ back\ to\ field,i}) -$

223      $\sum_{i=1}^{n}(Ic_{animal\ manure\ back\ to\ field,i} \times AF_{animalmanure\ back\ to\ field,i})$           (3)

224      Where, $Ic_{deposition}$ is the deposition of atmospheric N (kg N), $Ic_{BNF}$ is the N input via

225 biological N fixation (kg N), $Ic_{irrigation}$ is the N input via irrigation water (kg N),

226 $Ic_{straw\ back\ to\ field,i}$ is N (or P) input via crop straw return (kg N (or P)),

227 $Ic_{animal\_manure\_back\_to\_field,i}$ is the N (or P) input via animal manure (kg N (or P)).

228 $AF_{straw\ back\ to\ field,i}$ and $AF_{aniaml\_manure\_back\_to\_field,i}$ are the mineral fertilizer values of straw

229 and manure, respectively (dimensionless) (Table S2). Since manure P is almost 100%

230 available to crops, mineral fertilizer values for P in manure were assumed to be

231 constant (set at 1.0) for all strategies. Mineral fertilizer values of atmospheric N

232 deposition, BNF and N in irrigation were also set at 1.0.

233

234 **Strategy S3:** The whole food system strategy; balanced fertilization, improved

235 nutrient accounting in the crop-livestock sector, and improved nutrient accounting of

236 N (or P) inputs from the recycling of food waste and human excreta to crop land (Fig

237 1c). The required N (or P) fertilizer input was estimated as follows:

238 $Ic_{fertilizer} = \sum_{i=1}^{n}[(Oc_{main\ product,i} + Oc_{straw,i}) \times UF_{crop,i}] + Oc_{managed\ grass} \times UF_{managed\ grass} -$

239 $Ic_{soilmineralization} - Ic_{deposition} - Ic_{BNF} - Ic_{irrigation} - \sum_{i=1}^{n}(Ic_{straw\ back\ to\ field,i} \times AF_{straw\ back\ to\ field,i}) -$

240 $\sum_{i=1}^{n}(Ic_{animal\ manure\ back\ to\ field,i} \times AF_{animal\ manure\ back\ to\ field,i}) - Ic_{food\ byproduct} \times AF_{food\ byproduct} -$

241 $Ic_{human\ manure} \times AF_{human\ manure}$ (4)

242 Where $Ic_{food_{byproduct}}$ and $Ic_{human\_manure}$ are the N (or P) input via recycled food waste and

243 human excreta, $AF_{food_{byproduct}}$ and $AF_{human\_manure}$ are the mineral fertilizer values of the

244 treated (composted) food waste and human excreta (Table S2).

245

246 **Strategy S1-IM:** As S1, but with improved soil management and crop husbandry,

247 including soil fertility management, erosion control, crop rotation, green manuring

248 (Fig 1d). We assumed that these practices will lead to a considerable improvement of

249 soil fertility.[36] As a result, net soil N and P mineralization will increase.

250

251 **Strategy S2-IM:** As S2, but now with improved soil management and emission

252 mitigation in livestock production (Fig 1e). We assumed that ammonia emissions

253 from livestock production will be reduced by 50%, which is in agreement with the

254 recent target of the National Key Research and Development Program in China,[39]

through a combination of measures, including acidification of slurry, covering slurry storages, and closed manure composting technologies.[40-42] As a result, the mineral fertilizer value of the N in animal slurries and manure will be significantly improved (Table S2). At the same time, we assumed a strict ban on the discharge of manure to watercourses or landfill; hence, we assumed that all the livestock manure was collected and ultimately applied to crop land.

**Strategy S3-IM:** As S3, but now with improved soil management, emission mitigation in livestock production, and enhanced collection, sanitation and utilization of N (or P) in food waste and human excreta (Fig 1f).[11] A new system will be built to collect human excretions instead go to sewage treatment system, hence, the nutrients will be preserved and recycled. The estimated mineral fertilizer value of N in composts from food wastes and human excreta are presented in Table S2.

**Cumulative distribution of nutrient uptake and supply**

We define manure N (or P) loading as the ratio between total manure N (or P) excretions and total N (or P) withdrawal in harvested crop in a county (in kg). A low manure loading ratio refers to a low manure N (or P) excretion relative to the amounts of N and P in harvested crop within a county. A high manure loading ratio refers to a manure N (and/or P) surplus within a county. For a cumulative distribution curve, all counties were plotted in a graph along the X-axis in ascending order of their manure loading ratio, with either total N (or P) withdrawal with harvest crop, or manure N (or P) excretion, or fertilizer N (or P) application on the Y-axis.

## Results and Discussion

**Effects of improved nutrient accounting on synthetic fertilizer input reduction**

The total input of synthetic N and P fertilizers was 31 Tg N and 6.5 Tg P in 2012 (Fig 2). Balanced fertilization (S1) would reduce the total input of fertilizers to 28 Tg N and 5.5 Tg P, a reduction of 15% and 9%, respectively, compared to 2012 (Fig 2).

284    This will lead to strong reduction of N losses, especially from the crop production

285    (Fig 3). However, N and P use efficiencies in the whole food system did not change

286    much, as there were no improvements of nutrient management in the livestock, food

287    processing and consumption sectors (Fig 4). Note that 'balanced fertilization' in S1

288    does not account for inputs as BNF, atmospheric deposition and irrigation. It is a

289    simple first-step strategy, designed for local policy makers to implement at the county

290    level, as they have as yet little knowledge about nutrient management.[43]

291

292    There will be greater reductions of required synthetic N and P fertilizer inputs in the

293    integrated crop-livestock management strategy (S2). Accounting for the N and P in

294    animal manures, BNF, atmospheric deposition and irrigation reduces the total required

295    input of synthetic fertilizers to 16 Tg N and 3.4 Tg P, a reduction of 44% and 38%,

296    respectively, compared to S1 (Fig 2). The strong reduction in required synthetic

297    fertilizer input is mainly the result of accounting for the vast amounts of N and P in

298    animal manures, even though the mineral fertilizer value of recycled manure N and P

299    was assumed to be low due to its poor management.[16] In addition, there were

300    accountable inputs via the return of crop straw and residues from other crops,[44] and

301    atmospheric N deposition.[10]

302

303    Accounting for the N and P inputs from food waste and human excreta (S3) did not

304    further decrease the required synthetic N and P fertilizer inputs (Fig 2), as the N and P

305    from human excreta and food wastes were minimally returned to crop land in 2012.

306    Note that the required inputs of synthetic N and P fertilizers were lower when the

307    estimations were conducted at national scale than at county scale (Fig 2). The

308    estimations at county scale assumed that the recycled N and P from manures, crop

309    residues, food wastes and human excreta were recycled within the county where they

310    were produced, for all >2300 counties. The estimations at national scale assumed that

311    recycling occurred within the country, but without considerations of distances

312    between the sites of production and sites of utilization.

313

**Effects of improved nutrient management on synthetic fertilizer input reduction**

There are strong differences in required synthetic N and P fertilizer inputs between the current situation and following enhanced nutrient management strategies (Fig 2), as technologies are implemented to increase solid and liquid manure collection, transportation, and application to crops according to the nutrient demand. Also, this strategy assumes that technology has been installed that allows to collect and treat the sewage water, which then enables recycling of nutrients to cropland. Our estimates suggest that the required inputs of synthetic N and P fertilizers could be reduced ultimately to 5.0 Tg N and 0.16 Tg P (S3-IM) for the national scale analysis.

Clearly, improved nutrient management in crop-livestock production (S2-IM vs S2) and in the whole food chain (S3-IM vs S3) greatly reduces the required input of synthetic N and P fertilizer. The differences are larger for P than for N, because P losses from crop-livestock production and from the whole food chain may be reduced more easily through improved collection and emission mitigation than N losses.[45-46] The estimated reductions in required synthetic N and P fertilizer inputs strongly depend on the mineral fertilizer value of the recycled nutrient resources (Table S2). There is greater uncertainty in estimated mineral fertilizer value in the short term than in the long-term; overestimation of the short-term mineral fertilizer value will increase the risk of crop yield declines.[22-23]

Improved nutrient management greatly reduces the losses of N and P from the food chain to the environment (Fig 3). The effects are notably large for P in crop-livestock production (S2-IM vs S2) and in the whole food chain (S3-IM vs S3), because of the strong decrease in discharges to surface waters or landfills (Fig 3). Conversely, N losses from the food chain are more diffuse and basically all strategies contribute to a reduction in N losses. Our estimates suggest that N losses may be reduced ultimately by ~70% and P losses ultimately by ~90%. However, these are likely overestimates, because the estimations are based on national scale analyses.

344    Improved nutrient management increases the N and P use efficiency in crop

345    production, crop-livestock production and in the whole food chain (Fig 4). Increases

346    are larger for P use efficiency than for N use efficiency. Interestingly, not all strategies

347    increase N use efficiency equally well; small decreases reflect that highly available

348    synthetic N fertilizer was replaced by inputs of moderately available N from recycled

349    resources. Relative increases in N and P use efficiency were larges for the whole food

350    chain and least in crop production. The N use efficiency in crop production increased

351    from 29% in the reference year 2012 to a maximum of about 42% in S3, which is a

352    modest increase. However, this modest increase hides that the N input sources have

353    greatly altered from highly available synthetic N fertilizer to moderately available N

354    in composts and residues. Basically, the N use efficiency in S1 is overestimated,

355    because various possible N sources are not accounted for in the calculations.

356    Evidently, the N and P accounting is most complete for the food chain system, and as

357    a result the relative increases in N and P use efficiency are largest for the whole food

358    system.

359

360    Human excreta were a main source of N (4.7 Tg) and P (0.5 Tg), but these were not

361    used effectively in 2012 (Fig S1). Discharge of sewage water was found to be one of

362    the main sources of N and P in watercourses in 2010.[47] The central government has

363    invested around 21 billion US $ in sewage treatment plants since 2014 to treat 49

364    billion m$^3$ sewage water per year.[9] These sewage treatment plants were built nearby

365    urban areas (Fig S2), and 'remove' about 26% of the nutrients through treatment,

366    while the rest ends up in watercourses.[48-49] Recycling of household waste and human

367    excreta in crop land was common practice before the 1980s, but has largely vanished

368    because of concerns about the fecal-oral transmission and fecal-body transmission of

369    communicable diseases and pathogens. Currently, there are no institutions and

370    markets anymore for recycling of household wastes and human excreta as composts in

371    agricultural land.

372

373    Furthermore, it has been estimated that around 20% of grains and 50% of fruits and

374    vegetables are wasted or lost before reaching the dining table.[21, 50] Though some of

375    these wastes are being used as animal feeds, most of the food wastes ends up in

376    garbage burning installations or landfill sites.[51] These wastes contain approximately

377    0.9 Tg N and 0.3 Tg P (Fig S1).

378

379    Largest underutilized nutrient resources were animal manures in 2012. Approximately

380    12.2 Tg N and 2.1 Tg P were lost from the manure management chain in 2012 (Fig

381    S1). A combination of improved manure collection and storage, appropriate emission

382    mitigation measures and targeted application of manure to crop land may greatly

383    increase manure nutrient utilization and decrease N and P losses from the manure

384    chain.[16]

385

386    **Spatial disconnection of nutrient supply and demand**

387    There is a big divide between estimations of the nutrient recycling potentials at

388    national scale and at county scale. The nutrient recycling potentials and hence the

389    fertilizer input reduction potentials in the S2 and S3 strategies were much smaller

390    when the estimations were made at county scale than at country scale. For example,

391    the required N fertilizer input in the S3-IM strategy was about 5.0 Tg when based on

392    national-scale analyses and about 9.0 Tg when based on county-scale analyses. The

393    difference is even bigger for P, the county-aggregated demand of P fertilizer was 1.1

394    Tg, which was more than 5 times that of the national-scale analysis in the S3-IM

395    strategy. The main difference between the county and national scale analyses is that

396    the county analysis excludes cross-county border transportation of nutrient resources.

397    Though this is a gross simplification of reality, especially along borders of counties,

398    this analysis accounts for the barriers involved with long-distance transport of wastes

399    such as the high transportation cost and the risk of the transmission of pathogens. For

400    example, the average profit of pig production ranged between 12 and 24 US $ head[-1]

401    during July 2017 to January 2018, which was before the outbreak of African Swine

402    Fever. [52] Each slaughtered pig produced around 1 ton of manure, for which the

403    average transportation cost was around 0.30 US $ km[-1]. Transport of manure to farms

40-80 km away will neutralize all profits of pig production, a distance typically still within the county border. [52] The provincial level results are showed in Fig S3, and are not in-depth described here.

The main reasons for the large differences between county and national level analysis in nutrient recycling potentials is due to the uneven distributions of productive crop land, livestock and human population in China. The total amounts of N in livestock manure and human excreta distributed on arable systems exceeded the total uptake by crops in many counties in 2012 in the S3-IM strategy, especially in the Yangtze River Basin, which covers Sichuan, Chongqing, Hunan, Jiangxi and Zhejiang provinces (Fig 5a). These provinces are mountainous and have a high density of watercourses. Livestock farms are often near villages and urban areas, and spatially disconnected from cropland by mountains and water courses, which hinders the transport of the voluminous livestock manures to crop land. The mismatch between demand and supply is even larger for P in some counties; the supply of P in livestock manures exceeds crop demand in the Yangtze River Basin, the Pearl River Delta and Fujian province (Fig 5b). Further differences were introduced by excluding Xinjiang, Gansu and Tibet from the calculations, for which county level data was unavailable. As their contributions were relatively small (<3.5% of total crop N or P uptake at the national level), and as the livestock and crop production are evenly distributed in these provinces, with grassland based ruminant animal production systems, the lack of data will likely not strongly affect the overall result.[31]

For the S3-IM strategy, the mean manure N and P loadings per county are presented in Figure 6 in ascending order on the x-axis, while the cumulative manure N and P loadings are presented on the y-axis. Manure N (or P) loading is defined here as the ratio of mean N (or P) supply via livestock manure and demand by the crop. A ratio of < 1 means that total supply is lower than total demand within a county. About one-third of the number of counties had a manure surplus. The cumulative surplus was 3.1 Tg N and 1.0 Tg P for the counties with a surplus (Fig 6). This indicates that

434    these amounts of manure N and P cannot be used effectively as a substitutes for

435    synthetic N and P fertilizers, because of the spatial disconnect between supply and

436    demand. Surprisingly, the counties with a manure surplus used about 1/3 of the N

437    fertilizer in 2012. This reflects overuse of both manure N and fertilizer N (Fig 6a).

438    Situations were even worse for P (Fig 6b).

439

440    Similar but less extreme situations have been found at country level in a global study.

441    Lassaletta et al.[53] found that increasing trade of animal feed has contributed to

442    decoupling of crop production and livestock production; livestock manure is rarely

443    transferred back from feed importing countries to feed exporting countries.[27] In the

444    Baltic Sea drainage basin in Europe, a high ammonia emission intensity occurred in

445    regions with both high mineral fertilizer N and manure N applications, suggesting that

446    animal manures were disposed of on cropland near farms and that mineral fertilizer N

447    applications were not much corrected for the manure N input.[54-55] An exception is

448    perhaps the Netherlands, where the surplus manure P produced (about 25% of total P

449    excretion) has to be exported, [56] mostly to neighboring countries (Germany and

450    France), but also to far-distance countries including Ukraine, South Korea, and China.

451    Far-distance transport increases the cost of the processed manure products and its use

452    is restricted therefore to niche markets.

453

454    **Required synthetic N and P fertilizer input at the county level**

455    The required synthetic fertilizer input per county and strategy is presented in Fig 7 for

456    synthetic N fertilizer and in Fig S5 for synthetic P fertilizer, and the mean values per

457    hectare of cropland are presented in Fig S6-7. These maps provide total and means

458    per county, and could be easily used by local governments as targets at the county

459    level. However, additional field level guidance is needed for crop type and field

460    specific recommendations; these should be based also on results of soil testing.[57-61]

461    Largest inputs are required in the Northeast Plain, North China Plain, and the middle-

462    and down- stream of the Yangtze River (Fig 7, S4). These are major grain, vegetable

463    and fruits producing areas.[31] The relatively large required synthetic fertilizer input in

464    the Northeast Plain and southwest Xinjiang is partly due to its large area of cropland

465    per county.[31]

466

467    Interestingly, around 30% of the counties appear to have no need for synthetic N

468    fertilizer input, and 50% of the counties appear to have no need for P fertilizer input in

469    S3-IM, because the supply of N and P from livestock manure, crop residues and

470    human excreta exceeds on average the N and P demand by the growing crops in these

471    counties (Fig 7, S4). The N and P surpluses in these counties also indicate a large

472    pressure on the environment, especially water quality. These regions either have to

473    invest in manure treatment and manure export to other regions, or will have to

474    re-locate livestock farms to other regions. There are several technologies for manure

475    treatment, but economic costs are often high, such as the produce the struvite,

476    incineration and closed continuous composting technologies.[45-46, 62]

477

478    The main uncertainty originated from the mineral fertilizer value of livestock manures

479    and organic wastes, which were estimated to range from 0.10-1.0 (Table 1). The

480    manures and wastes provide huge amounts of N and P compared with the N and P

481    withdrawal with harvested crop (Fig 6), but the fraction of total N that is available for

482    crops is highly uncertain, because the mineral fertilizer value is highly sensitive to

483    weather conditions, crop type and cropping system (single and doubling cropping

484    systems), and soil properties. [22-23,35] Hence, small changes of the mineral fertilizer

485    value of manures and wastes have large impacts on the availability of manure and

486    waste N to growing crops, and also had a large impact on the results of our study. Due

487    to lack of data, estimates of the mineral fertilizer value were partly derived from

488    Chinese data [63] and partly from European studies. [22-23]

489

490    **Suggestions for further steps**

491    The required input of synthetic fertilizer N and P strongly depends on strategy; the

492    required input decreases in the order S1> S1-IM > S2 > S3 > S2-IM > S3-IM (Fig 2).

493    The planetary boundaries for biogeochemical N and P flows at the global level have

been estimated a 62 Tg year$^{-1}$ for N and 6.2 Tg year$^{-1}$ for P.[3] The total global inputs in 2012 were 150 Tg for N and 14 Tg for P.[9] If all the required reduction would have to come from synthetic fertilizers, the total N and P fertilizer inputs need to be reduced by 88 Tg and 7.8 Tg, respectively. In the best strategy (S3-IM), China could save as much as 26 Tg synthetic fertilizer N and 6.4 Tg synthetic fertilizer P by 2030, which is equivalent to around 30% and 80% of the estimated required N and P fertilizer reduction to keep biogeochemical N and P flows within the suggested planetary boundaries at the global scale. However, only a fraction of this potential reduction in fertilizer input can be achieved at short notice, as there are major barriers for such drastic reductions. Our study indicates that improved spatial planning of livestock production is key to fully utilize the potential to recycle livestock manures and wastes.

Based on the results of this study, we formulated two complementary recommendations for policy makers in China to achieve the potential improvements in the recycling of N and P from manures, wastes and residues, and to drastically reduce the inputs of synthetic fertilizers simultaneously. First, improvement of nutrient management in the food system as suggest by the results of the six strategies. There are large opportunities for improving nutrient management practices and for reducing nutrient losses to the environment, but these improvements require investments in knowledge, technology, and institutions. Above all, it requires training of farmers and their advisors. A series of technologies and polices are needed to efficiently recycle manure.[16,25,61] Recently, demonstration programs have been established in 100 counties to boost manure recycling, and there are plans for another 200 counties.[62] In addition, zoonotic diseases problems of livestock manure need to carefully considered to avoid spread of African Swine Fever or other diseases. The estimated investment needed for building the recycling system for human excreta is comparable to the investment needed to build and manage sewage treatment plants.[11] However, additional treatment will be needed to prevent and control the transmission of communicable diseases and pathogens, which are major health concerns in the recycling of livestock and human excreta.

**19**

524

525   The second recommendation relates to improved spatial planning: livestock

526   production must be spatially reconnected again with crop production, to be able to

527   recycle manure nutrients effectively and efficiently. Recently, there has been a

528   re-location of pig farms from south to north, to solve water pollution problems in the

529   south, which has been not without side-effects.[64] Spatial planning of livestock

530   production areas must be considered from environmental, social and economic points

531   of view. In any case, excessively high densities of livestock production should be

532   avoided. The regional self-sufficiency of animal-source food production was recently

533   emphasized by the Ministry of Agricultural and Rural Affairs.[65] The cost of

534   implementing changes considering spatial planning of livestock maybe very low after

535   the wide outbreak of African Swine Fever. This was because around 22% of pig

536   production had to be closed down, and it is easy to regulate geographic site and

537   manure treatment facilities of the newly constructed pig farms, which will with lower

538   additional cost when compare with completely shut down farms in one region and

539   build new one in another region. A new 3-years plan was launched to recover the pig

540   production from the decline through the incidence of African swine fever. The plan

541   proposes a strict spatial planning of pig production away from water courses, but

542   includes the target that >70% of the pork consumption must be produced locally.[65] We

543   argue that additional restrictions are needed related to a maximum pig density per unit

544   of surface area. In addition, major investments are needed in knowledge, technology

545   and institution to be able to achieve the suggested reductions in fertilizer use through

546   enhanced manure and waste recycling.

547

548   **Supporting Information:**

549   The supplementary information (13 pages) contains the brief description about the

550   definition of nutrient use efficiency, key parameters and reference list. Moreover, the

551   SI includes graphs which illustrate the N and P flow of food chain in 2012, the

552   distribution of sewage treatment plant, and required N and P input at the county level.

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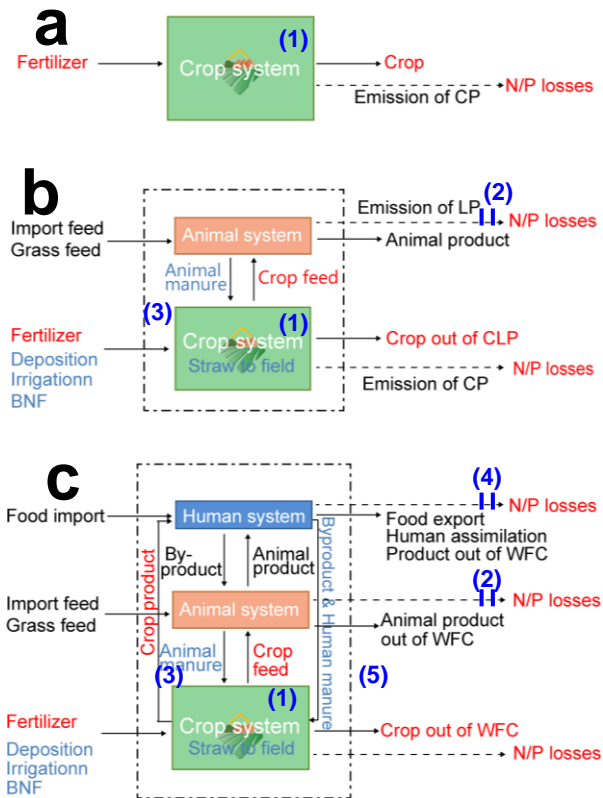
Fig 1. The system boundaries for the different strategies considered in this study: S1 and S1-IM (a), S2 and S2-IM (b) and S3 and S3-IM (c).

*Note: S1: Balanced fertilization in crop production; S2: S1 + integrated nutrient accounting in crop-livestock production; S3: S2 + integrated nutrient accounting in the whole food chain; S1-IM: S1 + improved soil management; S2-IM: S2 + improved soil management + emission mitigation control; S3 -IM: S3 + improved soil management + emission mitigation control + improved recycling.*

*CP, crop production; LP, livestock production; CLP, crop-livestock production system; WFC, whole food chain; BNF, biological nitrogen fixation.*

*The values with brackets are representing the improvement of nutrient management of different system. (1) Increasing of soil fertility; (2) Improved livestock manure management with low ammonia emission; (3) Abandon discharge of manure and increase recycling of livestock manure; (4) Improve nutrient management of human excretions with low ammonia emission; (5) New system to recycle human excretion and food waste.*

794
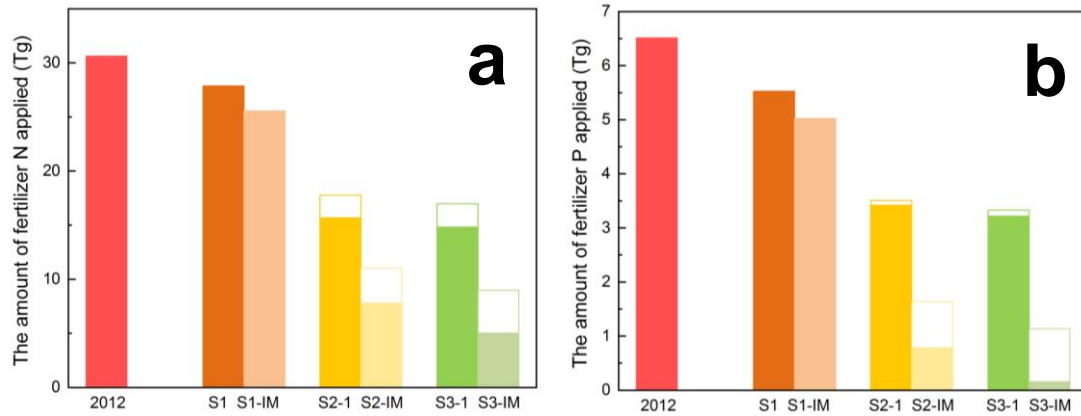
Fig 2. Inputs of synthetic nitrogen (N) fertilizer (a) and phosphorus (P) fertilizer (b) to
Chinese agriculture in 2012, and the required inputs of synthetic N and P fertilizers
for various strategies. The solid (filled) bars represent the required synthetic N and P
fertilizer inputs, following assumptions and estimations at the national level. The
blank top-up bars represent the estimated required inputs following assumptions and
estimations at county level.

*Note: S1: Balanced fertilization in crop production; S2: S1 + integrated nutrient accounting in*
*crop-livestock production; S3: S2 + integrated nutrient accounting in the whole food chain; S1-IM: S1*
*+ improved soil management; S2-IM: S2 + improved soil management + emission mitigation control;*
*S3 -IM: S3 + improved soil management + emission mitigation control + improved recycling.*
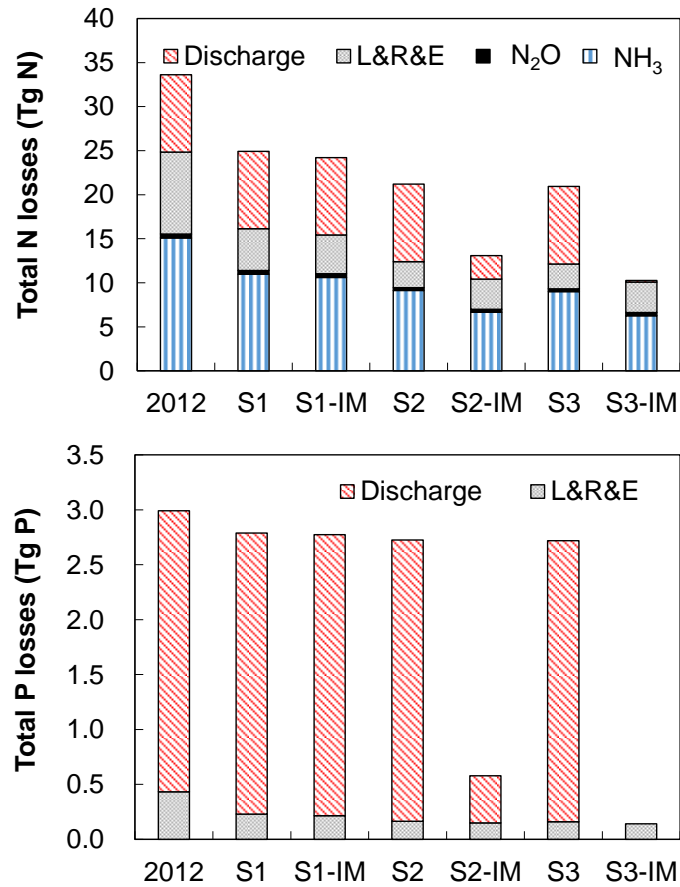
Fig 3. Total nitrogen (N) and phosphorus (P) losses from the whole food chain of different strategies at the national level in 2012.
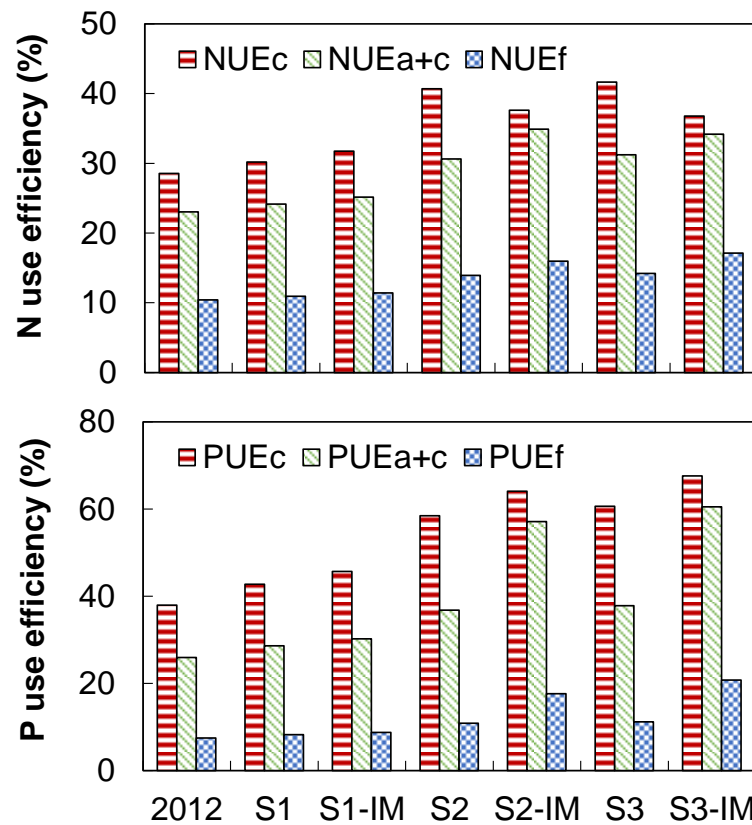
*Note: L&R&E is the leaching, runoff and erosion losses.*

*S1: Balanced fertilization in crop production; S2: S1 + integrated nutrient accounting in crop-livestock production; S3: S2 + integrated nutrient accounting in the whole food chain; S1-IM: S1 + improved soil management; S2-IM: S2 + improved soil management + emission mitigation control; S3 -IM: S3 + improved soil management + emission mitigation control + improved recycling.*

813

814 Fig 4. Nitrogen (N) and phosphorus (P) use efficiency in crop production (NUEc and

815 PUEc, respectively), in crop-livestock production (NUEa and PUEa, respectively),

816 and in the food chain (NUEf and PUEf, respectively) in 2012 and in 2050 for different

817 strategies.

818 *Note: S1: Balanced fertilization in crop production; S2: S1 + integrated nutrient accounting in*

819 *crop-livestock production; S3: S2 + integrated nutrient accounting in the whole food chain; S1-IM: S1*

820 *+ improved soil management; S2-IM: S2 + improved soil management + emission mitigation control;*

821 *S3 -IM: S3 + improved soil management + emission mitigation control + improved recycling.*
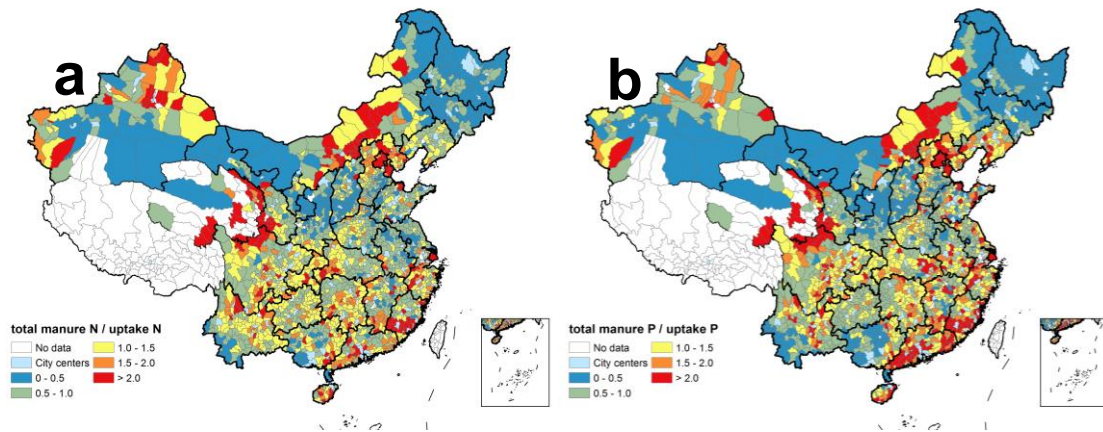
Fig 5. Map of the distribution of the manure N loading (a) and manure P loading (b) at county level in 2012. The manure N (or P) loading is defined as the ratio of the total excretions of N (or P) by livestock and humans and the N (or P) withdrawal with harvested crops.

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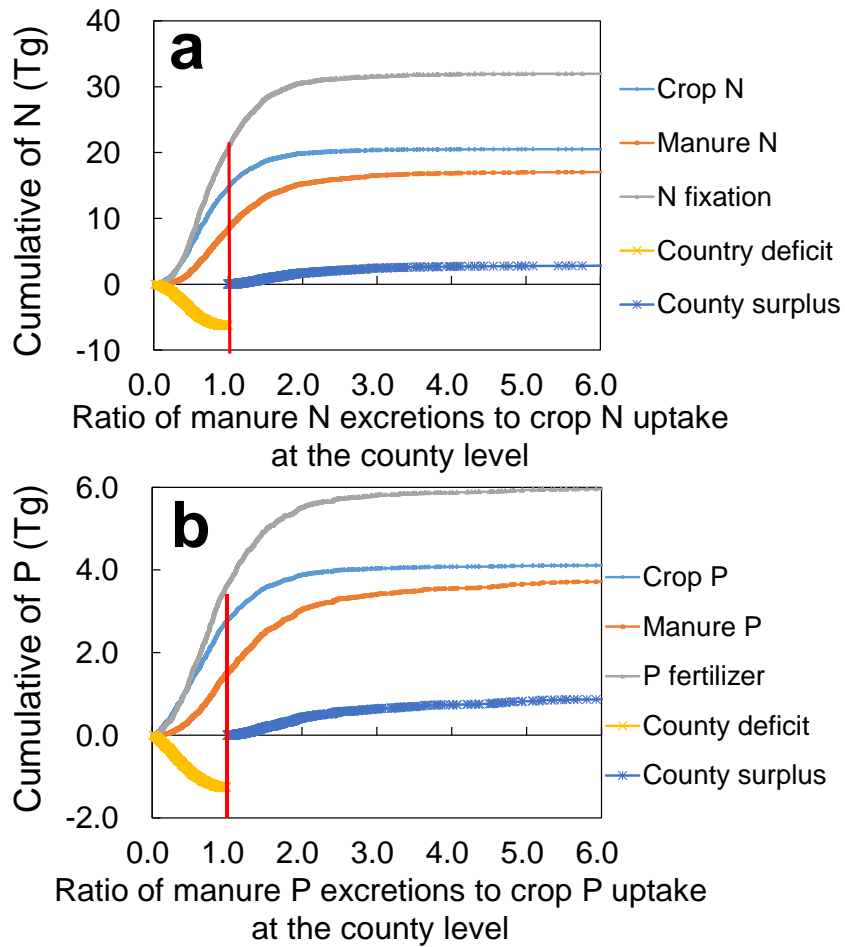
Fig 6. Cumulative distribution curves of N (or P) withdrawal in harvested crops, livestock N (or P) excreta, use of N (or P) fertilizer, and the surplus (or deficit) livestock N (or P) relative to the N (or P) withdrawal in harvest crops of counties in 2012.

*Note: N, nitrogen; P, phosphorus. All the counties were put into the X-axis in the ascending order of their manure N (or P) loading capacity, and their cumulative contributions to the total production or use were showed in the Y-axis.*

*County surplus is the cumulative positive differences between total livestock N or P excretions and crop uptake; County deficit is the cumulative negative differences between livestock N or P excretions and crop uptake.*

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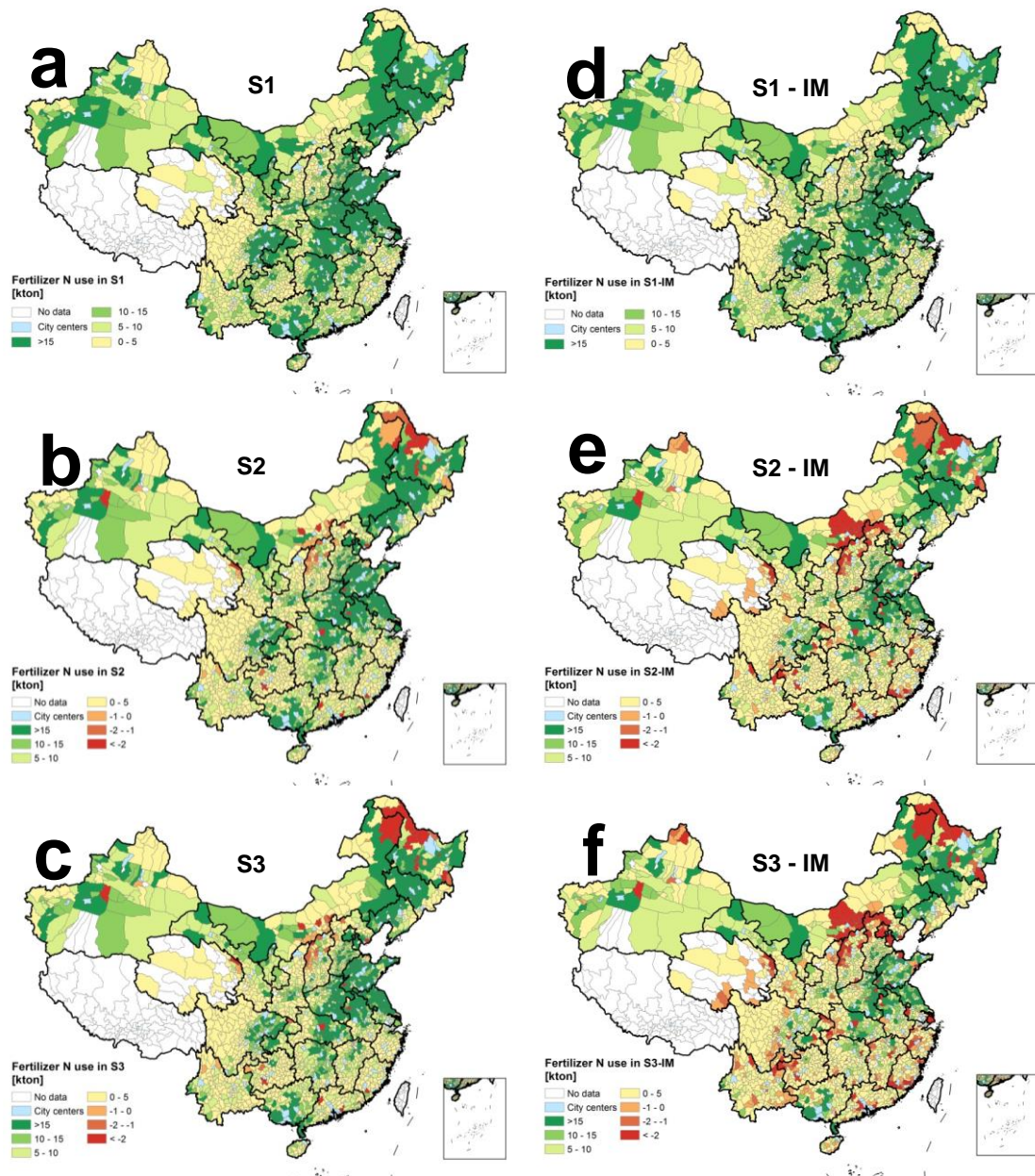
Fig 7. Mineral fertilizer (N) demand at the county level under the respective strategies (see Fig. 1 for definitions). Blue shades (negative numbers) designate areas where availability manure N already exceeds plant requirements.

*Note: there might be negative values for the requirement of synthetic N and P fertilizers at the national and county level, due to high available of N and P in the recycled nutrients.*

*S1: Balanced fertilization in crop production; S2: S1 + integrated nutrient accounting in crop-livestock production; S3: S2 + integrated nutrient accounting in the whole food chain; S1-IM: S1 + improved soil management; S2-IM: S2 + improved soil management + emission mitigation control; S3 -IM: S3 + improved soil management + emission mitigation control + improved recycling.*