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# 化肥氮对冬小麦氮素吸收的贡献和土壤氮库的补偿

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**摘要:**【目的】小麦对氮素的吸收消耗了土壤氮库，土壤中残留的化肥氮则可补偿土壤氮库的消耗，综合考虑这两方面的影响，核算施氮量和秸秆还田对小麦当季土壤氮库盈亏的影响。【方法】收集 1980 年以来国内报道的小麦 $^{15}$N 示踪试验的研究结果，分析化肥氮和土壤氮对小麦当季氮吸收的贡献，小麦当季氮吸收、化肥氮的去向、土壤氮库的盈亏分别与施氮量之间的关系，以及秸秆还田对小麦当季土壤氮库盈亏的影响。【结果】施氮量与化肥氮对小麦当季氮吸收的贡献之间呈显著正相关 ($P = 0.029$)，而与土壤氮的贡献之间呈显著负相关 ($P = 0.031$)。小麦当季氮素吸收源于土壤的比例约为 2/3，源于化肥的比例约为 1/3，追施氮对小麦氮吸收的贡献约是基施氮的 1.5 倍。施氮量与氮肥有效率 (氮肥利用率+氮肥残留率) 之间呈极显著负相关 ($P = 0.004$)，而与氮肥损失率之间呈极显著正相关 ($P < 0.001$)。在秸秆不还田和还田条件下，小麦季土壤氮库的盈亏均与施氮量之间呈极显著正相关 ($P \leqslant 0.001$)。【结论】在施氮量为 N 60～500 kg/hm$^2$ 时，小麦吸收的氮素 1/3 来自化肥，2/3 来自土壤。冬小麦季化肥氮的 3 个去向为：地上部吸收、土壤残留和损失，其所占比例分别约为 36%、33% 和 31%。在秸秆不还田和还田条件下，土壤氮库达到平衡的施氮量分别为 N 308 和 233 kg/hm$^2$。

**关键词:** 冬小麦；氮肥有效率；$^{15}$N 标记；土壤氮库盈亏；化肥氮去向

# Contributions of fertilizer N to winter wheat N uptake and compensation of soil N pool in farmland

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**Abstract:**【**Objectives**】This study investigated the effects of chemical fertilizer N and straw returning on the soil N balance in the wheat season, by considering the replenishing effect of residual fertilizer N and straw returning to soil N pool consumption by wheat.【**Methods**】This study collected the publications on $^{15}$N tracer experiments of winter wheat in China since 1980, and analyzed the contribution of chemical fertilizer N and soil N to N uptake by wheat, the relationship between N application rate and N uptake by wheat, the fate of fertilizer N and soil N pool budget, and also investigated the effect of straw returning on soil N pool budget in the wheat season through literature review.【**Results**】The N fertilizer application rate was significantly and positively related to the proportion of N uptake from fertilizer N in wheat ($P = 0.029$), but significantly and negatively related to the proportion of N from soil N ($P = 0.031$). The ratio of wheat N uptake derived from fertilizer N and

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soil N was about 1∶2, and the contribution of topdressing N to wheat N was 1.5 times of that of basal N. The N application rate showed significantly negative linear correlations with fertilizer N efficiency (N recovery + N residual rate, $P$ = 0.004), and significantly positive linear correlations with N loss rate ($P$ < 0.001). Without returning straw or with returning straw to field, there were the significantly positive correlation between soil N pool budget and N fertilizer application rate over the wheat season ($P$ ≤ 0.001).【**Conclusions**】Within the range of N 60–500 kg/hm$^2$, the applied fertilizer N in wheat season has three main fates, wheat uptake, soil residue and loss, with ratios in average of 36%, 33% and 31%, respectively. The contribution from chemical fertilizer in the nitrogen uptake of wheat is about 1/3, and that from soil is 2/3. The soil N pool could reach balance when N application rate is 308 kg/hm$^2$ without straw incorporation and 233 kg/hm$^2$ with straw incorporation, respectively.

**Key words:** winter wheat; fertilizer N efficiency; $^{15}$N labeling; soil N pool balance; fate of fertilizer N

在小麦生产中，肥料氮的去向受小麦品种[1]、施氮量[2-3]和施氮时期[4-5]的影响。一般情况下，随着施氮量增加，氮肥利用率和残留率降低，损失率增加[6-8]。大部分研究侧重于氮肥利用率的变化特征，而对土壤残留肥料氮对作物带走的土壤氮素消耗的补偿缺乏考虑[4, 6]。在解析传统氮肥利用率时，必须综合考虑施氮量、作物产量和土壤氮素肥力变化情况[6-8]。例如，通过降低氮肥施用量，可以很容易提高传统氮肥利用率，但不能维持高产和土壤氮素肥力[2-3, 6, 9]。因此，巨晓棠[6]提出了氮肥有效率应为作物氮肥利用率和土壤氮肥残留率之和，也就是说，肥料氮对土壤氮库消耗的补偿效应也是氮肥利用率的重要组成部分。

氮肥利用率一般以施氮区与未施氮区作物吸收氮素的差值即差值法来计算。但差值法不能区分作物吸收的氮素来源中肥料和土壤氮的比例，也无法明确土壤残留的肥料氮量和作物带走的土壤氮量，因此不能定量土壤氮库的盈亏量[4, 10-12]。$^{15}$N 示踪法可以区分作物吸收氮素的来源，因此，可以较好地解析施氮量对土壤氮库消耗的补偿效应[4, 6-8]。若土壤中残留的肥料氮量大于作物地上部带走的土壤氮量，土壤氮库为盈余，反之则亏损。

在华北平原等小麦主产区，秸秆还田是培肥土壤的重要措施[13]。秸秆的氮素转化及其对土壤氮素有效性的影响虽然有较多研究，但没有区分秸秆中氮素的来源及比例[14-15]。秸秆中只有源于肥料的氮量才可以补偿土壤氮库的消耗，以往的研究没有扣除秸秆中土壤来源的氮量[7-8]。小麦植株–土壤体系中肥料氮和土壤氮的转化也缺少分析，因此，对土壤氮库盈亏估算的准确性大打折扣。本研究通过汇总和分析中国农田小麦的$^{15}$N 示踪试验结果，揭示不同施氮量下化肥氮对小麦氮吸收的贡献、化肥氮的去向、土壤氮库的盈亏，以及秸秆还田对土壤氮库盈亏的影响，以期为我国小麦生产中的精确氮素管理、土壤氮素肥力提高和面源污染防控提供理论基础。

## 1 材料与方法

### 1.1 数据来源

利用中国知网检索关键词“$^{15}$N”和“小麦”，以及 Web of Science 数据库检索关键词“$^{15}$N”、“Wheat”和“China”，查阅了 1980 至 2018 年间我国小麦$^{15}$N 示踪相关的文献，通过以下 3 个标准对收集后的文献进行再次筛选：1)$^{15}$N 标记小麦以化肥氮方式施入土壤；2) 小麦氮吸收数据覆盖全生育期；3) 土壤氮库的盈亏基于田间小麦$^{15}$N 示踪结果。按照以上标准，最终筛选出 75 篇文献，其中 57 篇可用于核算化肥氮和土壤氮对小麦当季氮素吸收的贡献 (试验样本数为 95 个，表 1)，51 篇可用于核算化肥氮在小麦–土壤体系中的去向 (试验样本数为 101 个，表 2)，17 篇可用于核算秸秆还田和施氮量对小麦当季土壤氮库盈亏的影响 (试验样本数为 57 个，表 3)。

### 1.2 数据分类方法

遵循如下思路对$^{15}$N 示踪相关的数据进行归纳整理：1) 小麦氮素吸收来源分为土壤氮和化肥氮，吸收的化肥氮又分为基施氮和追施氮 (表 1)；2) 化肥氮的去向分为籽粒及秸秆吸收、土壤残留和损失 (表 2)；3) 设置秸秆不还田和还田两种方式，分别整理籽粒吸收的土壤氮量，秸秆中来源于化肥和土壤的氮量，及土壤中残留肥料氮量，核算秸秆还田和施氮量对土壤氮库盈亏的影响 (表 3)。

### 1.3 氮肥有效率和土壤氮库盈亏量的计算公式

1.3.1 氮肥有效率　氮肥有效率指氮肥利用率和土

**表 1　化肥氮和土壤氮对小麦氮素吸收的贡献 (%)**

**Table 1　Contribution of fertilizer- and soil-derived N to N uptake by wheat**

| 施氮量 ($kg/hm^2$) N application rate | 肥料氮 Fertilizer N | | | 土壤氮 Soil N | 参考文献 Reference |
|---|---|---|---|---|---|
| | 基肥 Basal | 追肥 Topdressing | 总 Total | | |
| 100 | | | 8.3 | 91.7 | [16] |
| 276 | | | 33.3 | 66.6 | [17] |
| 191 | | | 31.7 | 68.3 | [18] |
| 141 | | | 41.2 | 58.8 | [19] |
| 60 | | | 23.6 | 76.4 | [20] |
| 120 | | | 38.7 | 61.9 | [20] |
| 180 | | | 42.7 | 57.3 | [20] |
| 230 | | | 41.9 | 58.1 | [21] |
| 150 | | | 51.5 | 48.5 | [22] |
| 230 | | | 22.1 | 78.0 | [23] |
| 225 | | | 38.1 | 61.9 | [24] |
| 75 | | | 14.0 | 86.0 | [25] |
| 150 | | | 21.5 | 78.5 | [25] |
| 225 | | | 25.2 | 74.5 | [25] |
| 327 | | | 35.3 | 64.7 | [26] |
| 75 | | | 13.2 | 86.8 | [27] |
| 150 | | | 20.1 | 80.0 | [27] |
| 225 | | | 25.7 | 74.4 | [27] |
| 190 | | | 41.9 | 58.1 | [28] |
| 425 | | | 56.4 | 43.6 | [29] |
| 75 | | | 29.0 | 71.0 | [30] |
| 278 | | | 41.1 | 58.9 | [31] |
| 75 | | | 15.6 | 84.4 | [32] |
| 150 | | | 22.3 | 77.7 | [32] |
| 225 | | | 26.5 | 73.5 | [32] |
| 300 | | | 26.8 | 73.2 | [32] |
| 188 | | | 66.8 | 33.4 | [33] |
| 314 | | | 21.1 | 78.9 | [34] |
| 240 | 19.9 | 27.4 | 47.3 | 52.7 | [10] |
| 298 | | | 15.3 | 84.7 | [35] |
| 100 | | | 33.3 | 66.7 | [36] |
| 150 | | | 40.4 | 59.6 | [36] |
| 120 | | | 35.1 | 64.9 | [37] |
| 240 | | | 45.6 | 54.4 | [37] |
| 360 | | | 53.0 | 47.0 | [37] |
| | | | 30.8 | 69.2 | [38] |

续表 1 Table 1 continued

| 施氮量 (kg/hm²) N application rate | 肥料氮 Fertilizer N | | | 土壤氮 Soil N | 参考文献 Reference |
|---|---|---|---|---|---|
| | 基肥 Basal | 追肥 Topdressing | 总 Total | | |
| 112 | | | 24.1 | 75.9 | [39] |
| 187 | | | 28.1 | 71.9 | [39] |
| 225 | | | 29.8 | 70.2 | [39] |
| 168 | 8.0 | 12.1 | 20.0 | 80.0 | [40] |
| 240 | 6.5 | 15.2 | 21.7 | 78.3 | [40] |
| 120 | | | 36.0 | 64.0 | [5] |
| 240 | | | 55.2 | 44.8 | [5] |
| 90 | | | 19.0 | 81.0 | [41] |
| 180 | | | 23.6 | 76.5 | [41] |
| 270 | | | 35.3 | 64.7 | [41] |
| 168 | 7.2 | 13.7 | 20.9 | 79.1 | [42] |
| 240 | 8.3 | 17.3 | 25.6 | 74.4 | [42] |
| 120 | 10.0 | 14.7 | 24.7 | 75.3 | [43] |
| 240 | 10.8 | 14.9 | 25.7 | 74.3 | [43] |
| 278 | | | 10.3 | 89.7 | [44] |
| 168 | 7.2 | 13.7 | 20.9 | 79.1 | [45] |
| 240 | 8.4 | 17.5 | 25.9 | 75.1 | [45] |
| 75 | | | 25.0 | 75.0 | [46] |
| 150 | | | 45.8 | 54.3 | [46] |
| 225 | | | 59.1 | 41.0 | [46] |
| 300 | | | 61.6 | 38.4 | [46] |
| 210 | 8.8 | 20.8 | 29.6 | 70.4 | [47] |
| 150 | 22.1 | 16.0 | 38.1 | 61.9 | [9] |
| 210 | 17.1 | 32.0 | 49.1 | 50.9 | [9] |
| 270 | 15.7 | 37.4 | 53.1 | 46.9 | [9] |
| 120 | 9.4 | 10.1 | 19.4 | 80.6 | [48] |
| 168 | 8.5 | 13.6 | 22.1 | 78.0 | [48] |
| 195 | 8.7 | 15.1 | 23.8 | 76.2 | [48] |
| 240 | 10.7 | 17.2 | 28.0 | 72.0 | [48] |
| 180 | | | 26.6 | 73.4 | [49] |
| 200 | | | 33.6 | 66.4 | [49] |
| 240 | | | 27.3 | 72.7 | [49] |
| 150 | | | 33.7 | 66.3 | [13] |
| 300 | | | 23.8 | 76.2 | [13] |
| 165 | | | 43.4 | 56.5 | [50] |
| 379 | | | 25.0 | 75.0 | [51] |
| 139 | | | 37.8 | 62.3 | [52] |

续表 1　Table 1 continued

| 施氮量 (kg/hm²) N application rate | 肥料氮 Fertilizer N | | | 土壤氮 Soil N | 参考文献 Reference |
|---|---|---|---|---|---|
| | 基肥 Basal | 追肥 Topdressing | 总 Total | | |
| 300 | | | 25.7 | 74.3 | [52] |
| 180 | | | 40.5 | 59.5 | [53] |
| 240 | 17.9 | 25.9 | 44.0 | 66.0 | [53] |
| 113 | | | 29.1 | 70.9 | [54] |
| 225 | | | 39.4 | 60.6 | [54] |
| 338 | | | 46.4 | 53.6 | [54] |
| 60 | | | 15.6 | 84.5 | [3] |
| 150 | | | 26.8 | 73.2 | [3] |
| 240 | | | 33.8 | 66.2 | [3] |
| 60 | | | 33.5 | 66.5 | [2] |
| 150 | | | 51.0 | 49.0 | [2] |
| 240 | | | 58.1 | 41.9 | [2] |
| 250 | | | 53.9 | 46.1 | [55] |
| 250 | 26.6 | 30.6 | 57.2 | 42.8 | [4] |
| 467 | | | 12.9 | 87.1 | [56] |
| 150 | 11.3 | 12.8 | 24.1 | 75.9 | [57] |
| 210 | 12.2 | 14.1 | 26.2 | 73.8 | [57] |
| 270 | 11.5 | 13.5 | 25.0 | 75.0 | [57] |
| 201 | 12.1 | 18.4 | 32.8 | 67.4 | 平均值 Average value |
| 200 | 10.4 | 15.2 | 29.4 | 70.7 | 中位数 Median value |
| | 5.4 | 7.4 | 12.9 | 12.9 | 标准差 SD |

**表 2　化肥氮在小麦–土壤系统中的去向 (%)**

**Table 2　Fate of fertilizer-derived N in wheat–soil system**

| 施氮量 (kg/hm²) N application rate | 地上部回收率 Recovery in shoot | | | 土壤残留 Soil residual | 氮肥有效率 Fertilizer N efficiency | 损失 Loss | 参考文献 Reference |
|---|---|---|---|---|---|---|---|
| | 籽粒 Grain | 秸秆 Straw | 总 Total | | | | |
| 100 | | | 45.1 | | 45.1 | | [16] |
| 186 | | | 46.3 | 22.5 | 68.8 | 31.2 | [58] |
| 276 | 51.5 | 5.4 | 56.9 | 23.2 | 80.1 | 19.9 | [17] |
| 120 | | | 47.1 | 31.3 | 78.4 | 22.2 | [59] |
| 141 | 36.4 | 18.1 | 54.4 | | | | [19] |
| 207 | | | 38.8 | 35.7 | 74.5 | 25.6 | [20] |
| 414 | | | 36.4 | 37.4 | 73.8 | 26.2 | [20] |
| 621 | | | 25.9 | 34.5 | 60.4 | 40.4 | [20] |
| 75 | 57.1 | 16.8 | 73.9 | | | | [60] |
| 113 | 50.8 | 15.1 | 65.9 | | | | [60] |
| 150 | 47.2 | 14.9 | 62.1 | | | | [60] |

续表 2 Table 2 continued

| 施氮量 (kg/hm²) N application rate | 地上部回收率 Recovery in shoot | | | 土壤残留 Soil residual | 氮肥有效率 Fertilizer N efficiency | 损失 Loss | 参考文献 Reference |
|---|---|---|---|---|---|---|---|
| | 籽粒 Grain | 秸秆 Straw | 总 Total | | | | |
| 188 | 48.5 | 12.8 | 61.3 | | | | [60] |
| 225 | 43.9 | 10.6 | 54.5 | | | | [60] |
| 263 | 40.1 | 9.2 | 49.3 | | | | [60] |
| 95 | | | 40.9 | 32.4 | 73.2 | 26.7 | [61] |
| 230 | | | 35.6 | 16.7 | 52.4 | 48.0 | [21] |
| 150 | | | 52.4 | 29.8 | 82.1 | 17.9 | [22] |
| 230 | 31.3 | 13.4 | 44.6 | 26.3 | 70.9 | 29.1 | [23] |
| 225 | 27.6 | 7.4 | 35.0 | 24.7 | 59.7 | 40.3 | [24] |
| 75 | | | 45.1 | 6.9 | 52.0 | 48.0 | [25] |
| 150 | | | 46.1 | 28.2 | 74.3 | 25.7 | [25] |
| 225 | | | 41.1 | 13.2 | 54.3 | 45.7 | [25] |
| 327 | 29.2 | 8.7 | 37.8 | 38.3 | 76.1 | 23.9 | [26] |
| 204 | | | 43.7 | 16.2 | 59.8 | 40.2 | [62] |
| 337 | | | 47.7 | 16.7 | 64.4 | 35.6 | [62] |
| 75 | 25.8 | 12.7 | 38.5 | 31.3 | 69.8 | 30.2 | [27] |
| 150 | 22.2 | 10.1 | 32.3 | 31.1 | 63.4 | 36.6 | [27] |
| 225 | 13.6 | 8.8 | 22.4 | 46.3 | 68.7 | 31.2 | [27] |
| 190 | 14.1 | 3.4 | 17.5 | | | | [28] |
| 265 | | | 7.7 | 70.0 | 77.6 | 22.4 | [63] |
| 425 | 11.2 | 6.0 | 17.2 | 45.8 | 63.0 | 37.0 | [29] |
| 275 | 19.7 | 3.5 | 23.2 | 18.3 | 41.5 | 58.5 | [30] |
| 278 | | | 24.5 | | | | [31] |
| 75 | 36.7 | 9.3 | 46.0 | 14.3 | 60.3 | 39.7 | [32] |
| 150 | 34.4 | 8.0 | 42.4 | 20.4 | 62.8 | 37.2 | [32] |
| 225 | 27.3 | 7.3 | 34.6 | 25.6 | 60.2 | 39.8 | [32] |
| 300 | 22.1 | 8.6 | 30.6 | 19.8 | 50.4 | 49.6 | [32] |
| 188 | | | 37.3 | 21.1 | 58.4 | 41.6 | [33] |
| 314 | | | 28.5 | 29.6 | 58.1 | 41.9 | [34] |
| 120 | | | 44.4 | 45.3 | 89.7 | 10.3 | [10] |
| 360 | | | 23.8 | 20.9 | 44.7 | 55.3 | [10] |
| 225 | 31.8 | 8.2 | 40.1 | 34.3 | 74.3 | 25.7 | [64] |
| 240 | | | 24.5 | 16.5 | 40.9 | 51.9 | [65] |
| 100 | 18.3 | 17.6 | 35.9 | 33.1 | 69.0 | 31.0 | [36] |
| 150 | 16.9 | 16.8 | 33.8 | 30.5 | 64.3 | 35.7 | [36] |
| 120 | 30.3 | 15.0 | 45.3 | 45.3 | 90.6 | 9.4 | [37] |
| 240 | 19.6 | 10.4 | 30.0 | 24.0 | 54.0 | 45.9 | [37] |
| 360 | 14.2 | 9.0 | 23.2 | 20.9 | 44.1 | 55.9 | [37] |

续表 2 Table 2 continued

| 施氮量 (kg/hm²) N application rate | 地上部回收率 Recovery in shoot | | | 土壤残留 Soil residual | 氮肥有效率 Fertilizer N efficiency | 损失 Loss | 参考文献 Reference |
|---|---|---|---|---|---|---|---|
| | 籽粒 Grain | 秸秆 Straw | 总 Total | | | | |
| 112 | 29.0 | 13.6 | 42.6 | | | | [39] |
| 187 | 23.9 | 11.3 | 35.2 | | | | [39] |
| 225 | 18.8 | 11.0 | 29.8 | | | | [39] |
| 100 | | | 32.5 | | | | [66] |
| 168 | | | 45.3 | 29.3 | 74.6 | 25.7 | [42] |
| 240 | | | 39.7 | 23.3 | 63.0 | 37.3 | [42] |
| 90 | | | 37.9 | 41.7 | 79.7 | 20.3 | [41] |
| 180 | | | 35.6 | 38.1 | 73.7 | 26.3 | [41] |
| 270 | | | 28.3 | 24.5 | 52.7 | 47.3 | [41] |
| 150 | | | 11.5 | | | | [67] |
| 84 | | | 25.3 | 15.1 | 40.4 | 40.4 | [68] |
| 100 | | | 46.7 | 34.1 | 80.8 | 19.1 | [69] |
| 200 | | | 46.8 | 32.7 | 79.5 | 20.5 | [69] |
| 278 | | | 44.0 | 36.6 | 80.6 | 19.4 | [44] |
| 100 | | | 21.8 | | | | [70] |
| 84 | 20.4 | 14.4 | 34.8 | | | | [71] |
| 210 | 35.2 | 4.1 | 39.3 | 27.8 | 67.1 | 32.9 | [47] |
| 120 | | | 44.5 | 45.3 | 89.8 | 10.3 | [5] |
| 360 | | | 23.8 | 50.1 | 73.9 | 26.1 | [5] |
| 75 | | | 47.6 | 33.6 | 81.2 | 18.9 | [72] |
| 150 | | | 49.8 | 26.8 | 76.5 | 23.5 | [72] |
| 225 | | | 45.4 | 35.6 | 81.0 | 19.1 | [72] |
| 300 | | | 37.5 | 39.9 | 77.3 | 22.7 | [72] |
| 150 | 11.5 | 2.9 | 14.4 | | | | [46] |
| 150 | 38.0 | 7.5 | 45.5 | 40.5 | 86.0 | 13.5 | [9] |
| 210 | 40.5 | 7.5 | 48.0 | 27.0 | 75.0 | 24.5 | [9] |
| 270 | 38.0 | 6.5 | 44.5 | 26.5 | 71.0 | 28.5 | [9] |
| 180 | | | 32.4 | 56.3 | 88.7 | 11.3 | [49] |
| 200 | | | 30.1 | 43.3 | 73.4 | 27.6 | [49] |
| 240 | | | 22.1 | 29.6 | 51.7 | 48.3 | [49] |
| 417 | | | 32.9 | | | | [73] |
| 150 | | | 38.4 | 19.4 | 57.8 | 42.2 | [13] |
| 300 | | | 34.9 | 16.4 | 51.3 | 48.8 | [13] |
| 379 | | | 28.2 | 33.4 | 61.6 | 37.2 | [51] |
| 139 | | | 18.2 | 69.3 | 87.5 | 12.5 | [52] |
| 300 | | | 34.8 | 39.2 | 74.0 | 26.0 | [52] |
| 278 | | | 20.0 | 41.2 | 61.1 | 38.9 | [74] |

续表 2 Table 2 continued

| 施氮量 (kg /hm²) N application rate | 地上部回收率 Recovery in shoot | | | 土壤残留 Soil residual | 氮肥有效率 Fertilizer N efficiency | 损失 Loss | 参考文献 Reference |
|---|---|---|---|---|---|---|---|
| | 籽粒 Grain | 秸秆 Straw | 总 Total | | | | |
| 180 | | | 40.5 | 26.3 | 66.8 | 32.2 | [53] |
| 240 | | | 37.9 | 27.4 | 65.3 | 34.7 | [53] |
| 113 | | | 32.3 | 54.0 | 86.3 | 13.7 | [54] |
| 225 | | | 25.1 | 46.5 | 71.6 | 28.4 | [54] |
| 338 | | | 16.7 | 38.4 | 55.1 | 44.9 | [54] |
| 60 | 26.8 | 6.3 | 33.1 | 46.8 | 79.9 | 20.2 | [3] |
| 150 | 19.7 | 7.0 | 26.7 | 38.0 | 64.7 | 35.4 | [3] |
| 240 | 17.7 | 7.2 | 24.9 | 30.7 | 55.6 | 45.5 | [3] |
| 60 | 31.0 | 6.6 | 37.5 | 54.0 | 91.5 | 8.4 | [2] |
| 150 | 28.7 | 6.7 | 35.3 | 57.2 | 92.5 | 7.4 | [2] |
| 240 | 25.5 | 6.5 | 32.0 | 41.5 | 73.5 | 26.6 | [2] |
| 250 | 29.0 | 3.0 | 32.0 | 29.0 | 61.0 | 39.0 | [55] |
| 250 | 29.1 | 7.4 | 36.5 | 28.6 | 65.1 | 33.9 | [4] |
| 150 | | | 33.2 | 47.4 | 80.6 | 19.4 | [57] |
| 210 | | | 31.2 | 44.8 | 76.0 | 24.0 | [57] |
| 270 | | | 22.2 | 45.0 | 67.2 | 32.8 | [57] |
| 206 | 29.2 | 9.5 | 36.4 | 33.1 | 68.3 | 31.1 | 平均值 Average value |
| 204 | 28.8 | 8.6 | 35.9 | 31.3 | 69.0 | 30.6 | 中位数 Median value |
| | 11.4 | 4.1 | 11.8 | 12.4 | 12.9 | 12.2 | 标准差 SD |

**表 3 秸秆还田对不同施氮量小麦当季土壤氮库盈亏的影响 (N kg/hm²)**

**Table 3 Balance of indigenous soil N in wheat season under different N application rates affected by straw incorporation**

| 施氮量 N application rate (N kg/hm²) | 籽粒中的土壤氮 Soil N in grain | 秸秆中的土壤氮 Soil N in straw | 地上部的土壤氮 Soil N in shoot | 秸秆中肥料氮 Fertilizer N in straw | 土壤残留的肥料氮 Residual fertilizer N in soil | 土壤氮盈亏 Soil N balance | | 参考文献 Reference |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 秸秆还田 With straw incorporation | 秸秆不还田 Without straw incorporation | |
| 291 | 160.2 | 34.7 | 194.9 | 9.8 | 87.3 | –63.1 | –107.6 | [75] |
| 120 | 70.0 | 18.2 | 88.2 | 14.6 | 54.3 | –1.1 | –33.9 | [76] |
| 240 | 50.6 | 20.7 | 71.3 | 22.4 | 57.7 | 29.5 | –13.6 | [76] |
| 360 | 45.6 | 15.4 | 61.0 | 30.8 | 75.3 | 60.5 | 14.3 | [76] |
| 75 | 88.8 | 18.3 | 107.1 | 6.8 | 24.3 | –57.7 | –82.8 | [10] |
| 150 | 73.8 | 17.4 | 91.2 | 14.3 | 40.1 | –19.4 | –51.1 | [10] |
| 225 | 54.5 | 15.5 | 70.0 | 21.9 | 78.1 | 45.5 | 8.1 | [10] |
| 300 | 47.7 | 15.6 | 63.3 | 25.3 | 121.9 | 99.5 | 58.6 | [10] |
| 100 | | | 69.3 | | 31.8 | | –37.5 | [36] |
| 150 | | | 73.4 | | 43.8 | | –29.6 | [36] |
| 75 | 93.0 | 26.0 | 119.0 | 7.7 | 32.3 | –53.0 | –86.7 | [77] |
| 225 | 67.2 | 12.2 | 79.4 | 24.1 | 68.1 | 25.0 | –11.3 | [77] |

续表 3 Table 3 continued

| 施氮量 N application rate (N kg/hm$^2$) | 籽粒土壤氮量 Soil N in grain | 秸秆土壤氮量 Soil N in straw | 地上部土壤氮量 Soil N in shoot | 秸秆肥料氮量 Fertilizer N in straw | 土壤残留肥料氮量 Residual fertilizer N in soil | 土壤氮盈亏 Soil N balance | | 参考文献 Reference |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 秸秆还田 With straw incorporation | 秸秆不还田 Without straw incorporation | |
| 375 | 45.9 | 6.1 | 52.0 | 27.3 | 155.0 | 136.4 | 103.0 | [77] |
| 105[a] | 217.6 | 51.1 | 268.7 | 6.9 | 21.3 | –189.4 | –247.4 | [78] |
| 195[a] | 199.9 | 50.6 | 250.4 | 12.0 | 42.3 | –145.5 | –208.1 | [78] |
| 240[a] | 190.9 | 48.3 | 239.1 | 14.0 | 69.4 | –107.5 | –169.8 | [78] |
| 105[b] | 191.1 | 41.6 | 232.7 | 7.4 | 20.2 | –163.6 | –212.6 | [78] |
| 195[b] | 185.6 | 45.0 | 230.6 | 11.0 | 40.6 | –134.0 | –190.0 | [78] |
| 240[b] | 183.4 | 44.0 | 227.4 | 13.6 | 67.2 | –102.7 | –160.2 | [78] |
| 75 | 88.5 | 17.4 | 105.9 | 5.0 | 26.0 | –57.5 | –79.9 | [79] |
| 150 | 67.1 | 14.7 | 81.8 | 12.6 | 40.2 | –14.3 | –41.6 | [79] |
| 225 | 53.2 | 12.5 | 65.7 | 18.3 | 82.2 | 47.3 | 16.5 | [79] |
| 300 | 47.5 | 14.5 | 62.0 | 22.8 | 117.2 | 92.5 | 55.2 | [79] |
| 105 | 214.4 | 48.6 | 263.0 | 7.5 | 19.3 | –187.6 | –243.7 | [42] |
| 168 | 231.9 | 54.7 | 286.6 | 11.8 | 45.5 | –174.6 | –241.1 | [42] |
| 120 | | | 94.8 | | 54.4 | | -40.4 | [5] |
| 360 | | | 69.5 | | 180.4 | | 110.9 | [5] |
| 150[c] | 102.0 | 20.4 | 122.4 | 10.6 | 66.5 | –24.9 | –55.9 | [9] |
| 210[c] | 96.8 | 17.6 | 114.4 | 15.4 | 53.9 | –27.5 | –60.5 | [9] |
| 270[c] | 78.8 | 15.2 | 94.1 | 18.8 | 74.5 | 14.4 | –19.6 | [9] |
| 150[d] | 102.8 | 19.8 | 122.6 | 12.2 | 55.0 | –35.6 | –67.6 | [9] |
| 210[d] | 88.1 | 19.9 | 107.9 | 19.1 | 59.2 | –9.7 | –48.7 | [9] |
| 270[d] | 91.9 | 19.7 | 111.6 | 22.3 | 70.8 | 1.2 | –40.8 | [9] |
| 139 | 117.7 | 22.4 | 140.1 | 6.3 | 54.4 | –57.0 | –85.7 | [80] |
| 300 | 73.3 | 16.7 | 90.0 | 8.9 | 208.0 | 143.6 | 118.0 | [80] |
| 180 | 68.3 | 34.9 | 103.2 | 19.4 | 47.3 | –1.6 | –55.9 | [53] |
| 240 | 74.1 | 37.3 | 111.4 | 28.5 | 65.8 | 20.2 | –45.6 | [53] |
| 60[e] | 85.9 | 19.3 | 105.2 | 4.5 | 25.8 | –55.6 | –79.4 | [3] |
| 150[e] | 79.8 | 23.3 | 103.1 | 12.2 | 52.7 | –14.9 | –50.4 | [3] |
| 240[e] | 83.4 | 29.0 | 112.4 | 22.1 | 75.0 | 13.7 | –37.4 | [3] |
| 60[f] | 88.7 | 22.6 | 111.3 | 3.1 | 30.3 | –55.3 | –81.0 | [3] |
| 150[f] | 93.2 | 23.3 | 116.5 | 8.9 | 61.0 | –23.3 | –55.5 | [3] |
| 240[f] | 87.0 | 28.7 | 115.7 | 12.6 | 67.2 | –7.2 | –48.5 | [3] |
| 60[g] | 32.4 | 8.1 | 40.5 | 4.1 | 30.7 | 2.4 | –9.8 | [2] |
| 150[g] | 38.3 | 9.2 | 47.5 | 8.5 | 84.9 | 55.1 | 37.4 | [2] |
| 240[g] | 42.5 | 9.7 | 52.2 | 15.1 | 88.3 | 60.9 | 36.1 | [2] |
| 60[f] | 36.8 | 9.2 | 46.0 | 3.7 | 34.1 | 1.0 | –11.9 | [2] |

续表 3 Table 3 continued

| 施氮量 N application rate (N kg/hm²) | 籽粒土壤氮量 Soil N in grain | 秸秆土壤氮量 Soil N in straw | 地上部土壤氮量 Soil N in shoot | 秸秆肥料氮量 Fertilizer N in straw | 土壤残留肥料氮量 Residual fertilizer N in soil | 土壤氮盈亏 Soil N balance | | 参考文献 Reference |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 秸秆还田 With straw incorporation | 秸秆不还田 Without straw incorporation | |
| 150[f] | 39.4 | 11.4 | 50.8 | 11.2 | 86.7 | 58.5 | 35.9 | [2] |
| 240[f] | 42.7 | 12.7 | 55.4 | 15.7 | 110.9 | 83.9 | 55.5 | [2] |
| 113 | | | 80.7 | | 61.0 | | –20.0 | [54] |
| 225 | | | 103.6 | | 105.0 | | 1.0 | [54] |
| 338 | | | 81.1 | | 130.0 | | 48.5 | [54] |
| 250[h] | 61.7 | 7.7 | 69.4 | 7.4 | 72.2 | 17.9 | 2.8 | [55] |
| 250[i] | 75.3 | 9.8 | 85.1 | 7.5 | 115.4 | 47.6 | 30.3 | [55] |
| 150 | 105.1 | 51.9 | 157.0 | 15.8 | 71.1 | –18.2 | –85.9 | [57] |
| 210 | 125.1 | 59.0 | 184.1 | 21.1 | 94.1 | –9.9 | –90.0 | [57] |
| 270 | 121.2 | 58.5 | 179.7 | 19.5 | 121.5 | 19.8 | –58.2 | [57] |
| 平均值 Average value | 96.0 | 25.2 | 116.4 | 14.0 | 69.6 | –14.7 | –46.8 | |
| 中位数 Median value | 84.7 | 19.8 | 103.2 | 12.6 | 65.8 | –8.5 | –41.6 | |
| 标准差 SD | 53.5 | 15.2 | 63.9 | 7.1 | 38.8 | 77.5 | 84.5 | |

注（Note）：a—高肥力土壤 High fertility soil; b—低肥力土壤 Low fertility soil; c—低灌溉 Light irrigation; d—高灌溉 Heavy irrigation; e—分期施肥 Split fertilization; f—带状施肥 Banded fertilization; g—撒播 Broadcast seeding; h—秸秆不还田 No straw returning; i—秸秆还田 Straw returning.

壤中氮肥残留率之和[6]，即氮肥有效率 (%) = 氮肥利用率 (%) + 土壤中氮肥残留率 (%)。

1.3.2 土壤氮库盈亏量 秸秆不还田条件下，土壤氮输出为地上部带走的土壤氮量，土壤氮输入为土壤中残留肥料氮量[7-8]，土壤氮库盈亏量 (N kg/hm²)= 土壤中残留的肥料氮量 – 地上部吸收的土壤氮量；秸秆还田条件下，土壤氮输出为籽粒带走的土壤氮量，土壤氮输入为土壤和秸秆中源于肥料的氮量[7-8]，土壤氮库盈亏量 (N kg/hm²)=土壤中残留肥料氮量 + 秸秆吸收的肥料氮量 – 籽粒吸收的土壤氮量。

### 1.4 统计方法

采用 Microsoft Excel 2013 软件完成数据整理和作图。小麦氮素吸收中不同来源氮的比例、化肥氮的去向及土壤氮库的盈亏分别与施氮量之间的关系运用线性模型进行拟合，相关分析及方差分析采用 SPSS 17.0 版软件完成。

## 2 结果与分析

### 2.1 化肥氮和土壤氮对小麦氮素吸收的贡献

对我国小麦 $^{15}N$ 示踪相关的文献汇总分析 (表 1) 发现，小麦季氮肥用量平均为 N 200 kg/hm²，冬小麦当季的氮素吸收主要源于土壤氮，约占 2/3，来自化肥氮仅占 1/3。追肥氮对小麦氮素吸收的贡献约是基施化肥氮的 1.5 倍，其中追肥氮对小麦氮素吸收的贡献平均值约为 18%，基肥氮的贡献约为 12%。

化肥氮对小麦氮吸收的贡献与施氮量之间呈显著正相关 ($P = 0.029$，图 1-a)，而与土壤氮的贡献之间呈显著负相关 ($P = 0.031$，图 1-b)，这表明小麦氮素吸收源于化肥氮的比例随施氮量增加呈升高趋势，而来自于土壤氮的比例则表现相反趋势。

由于施氮量与化肥氮对小麦氮吸收的贡献呈显著正相关 (图 1-a)，与土壤氮对小麦氮吸收的贡献呈显著负相关 (图 1-b)，因此本研究进一步分析不同施氮水平下小麦氮素不同来源比例的差异。结果表明，在低氮水平 (≤ 150 kg/hm²)，小麦氮吸收来源于肥料氮的比例为 28.8%，源于土壤氮的比例为 71.3% (图 2-a)；而在中氮 (150～250 kg/hm²) 和高氮 (250～500 kg/hm²) 水平，肥料氮对小麦氮吸收的贡献上升到 33.9%～35.3%，而土壤氮的贡献下降到 64.9%～66.1%(图 2-b、c)。

### 2.2 化肥氮在冬小麦–土壤系统中的去向

化肥氮施入小麦–土壤系统后主要被植株吸收、

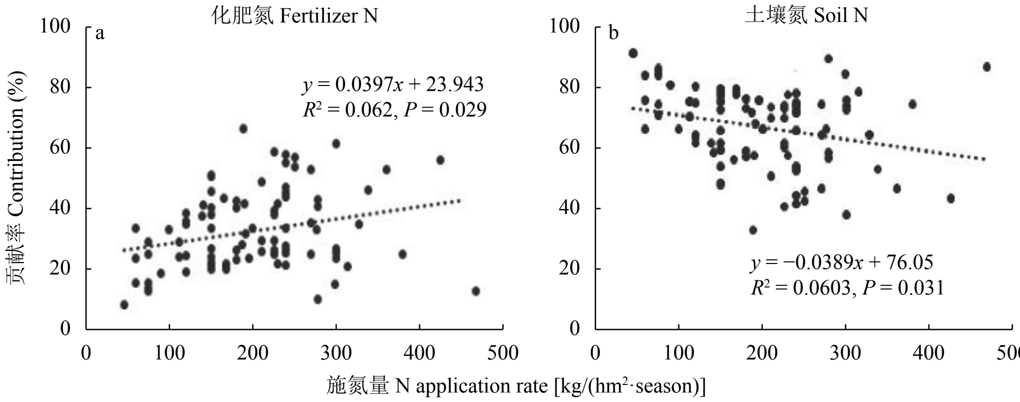


**图 1　化肥氮和土壤氮对小麦氮吸收的贡献及其与施氮量之间的关系**

**Fig. 1　N application rate dependent relationship between contributions of fertilizer N and soil N to wheat N uptake**

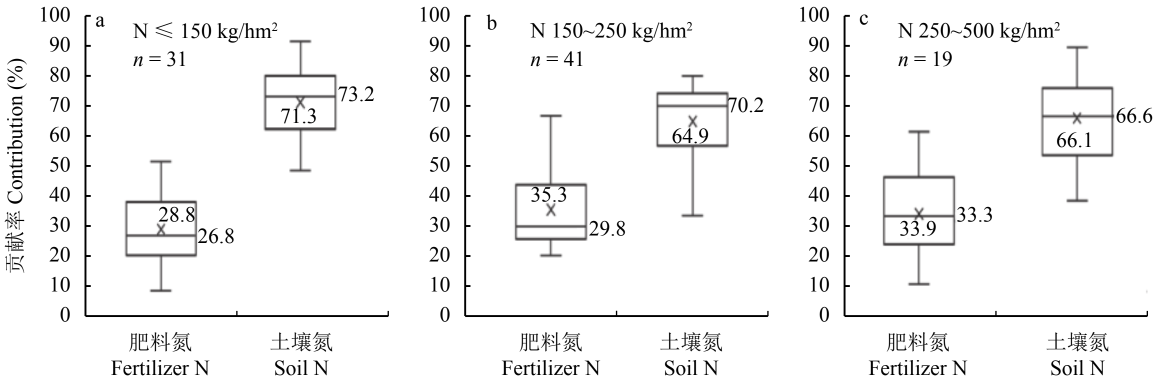


**图 2　不同施氮水平下化肥氮和土壤氮对小麦氮吸收的贡献**

**Fig. 2　Contributions of fertilizer N and soil N to wheat N uptake under different N application rates**

[注（Note）：*n*—样本数 Sample number; 箱式图中的水平线为中位数值，叉号表示平均值
The horizontal lines and cross marks in the box plots represent the median and average values, respectively.]

在土壤中残留以及各种途径的损失。对我国小麦化肥$^{15}$N 去向的有关文献整合分析 (表 2) 发现，化肥氮在地上部吸收、土壤中残留和损失的比例约为 1 : 1 : 1，其中地上部对化肥氮的回收率平均为 36.4%，籽粒的回收率约是秸秆的 3 倍。

小麦收获后约 33% 的化肥氮残留在土壤中，仅有约 30% 的化肥氮损失到环境中，氮肥有效率 (地上部回收率+土壤残留率) 约为 70% (表 2)。施氮量与氮肥有效率之间呈极显著负相关 ($P = 0.004$, 图 3-a)，与氮肥损失率之间呈极显著正相关 ($P < 0.001$, 图 3-b)，这说明随施氮量增加，化肥有效率呈降低趋势，而氮肥损失率则相反。

由于化肥氮在小麦–土壤系统各去向与施氮量之间呈显著线性关系 (图 3)，因此进一步分析在不同施氮水平下化肥氮去向的差异 (图 4)。结果表明，在低施氮水平 (≤ 150 kg/hm²)，化肥氮被地上部吸收、土壤中残留和损失的比例分别约为 40%、36% 和 24%。在中施氮水平 (150～250 kg/hm²)，与低施氮相比，氮肥损失率上升到 33%，氮肥有效率下降到 67%，地上部对氮肥的回收率保持基本稳定 (42.5%)，而氮肥残留率降低约 15% (约为 30%)。在高施氮水平 (250～500 kg/hm²)，氮肥损失率上升到 37%，地上部对氮肥的回收率下降到 31%，而氮肥残留率保持基本稳定 (约为 33%)。

## 2.3　秸秆还田和施氮量对小麦当季土壤氮库盈亏的影响

对国内田间小麦$^{15}$N 示踪结果进行汇总，分析地上部带走的土壤氮量、秸秆中化肥来源的氮量以及土壤中残留化肥氮量，核算秸秆还田对小麦季土壤氮库盈亏的影响。结果表明，秸秆中化肥来源的氮量为 14.0 kg/hm²，与秸秆不还田相比，秸秆还田的土壤氮素亏损量降低了 70% (表 3)。

在秸秆不还田和还田条件下，土壤氮库盈亏量与施氮量之间均呈极显著正相关 ($P \leqslant 0.001$，图 5)，

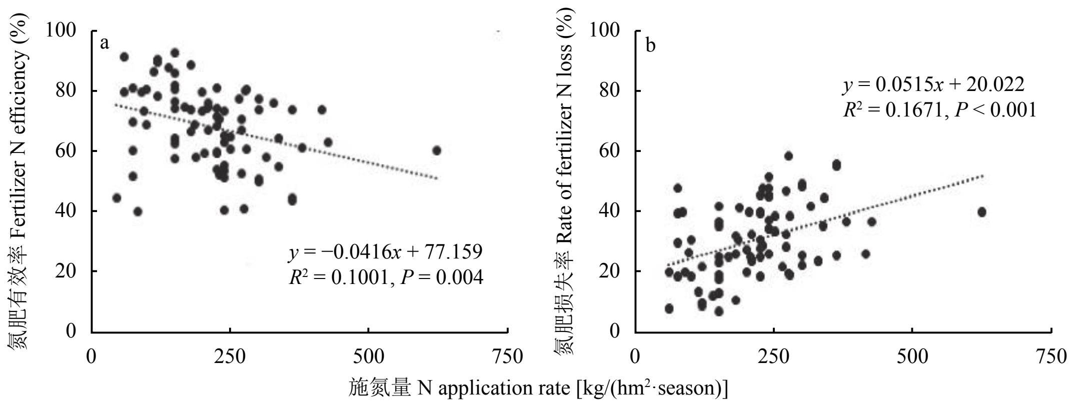


图 3 氮肥有效率和损失率随施氮量的变化

**Fig. 3 Changes of fertilizer nitrogen efficiency and loss with N application rates**

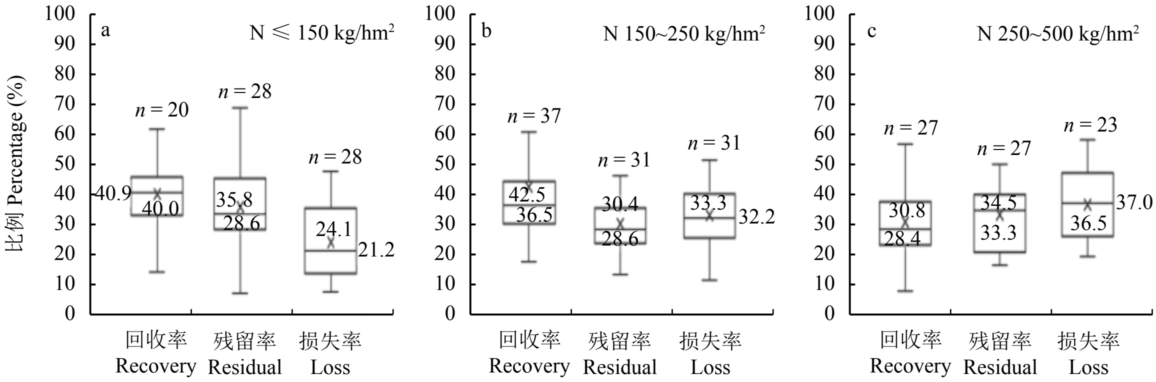


图 4 不同施氮水平下化肥氮的回收率、残留率和损失率比例

**Fig. 4 Percentage of fertilizer N in recovery, residual and loss under different N application rates**

[注（Note）：*n*—样本数 Sample number; 箱式图中的水平线为中位数值，叉号表示平均值 The horizontal lines and cross marks in the box plots represent the median and average values, respectively.]

当施氮量低于平衡点时，土壤氮库处于亏损状态，且亏损量随着施氮量的升高而降低；当高于平衡点时，土壤氮库处于盈余状态，且盈余量随着施氮量的升高而升高。在秸秆不还田下，土壤氮库达到平衡点的施氮量为 N 308 kg/hm² 时，即地上部带走的土壤氮量等于土壤中残留的肥料氮量 (图 5-a)；与秸秆不还田相比，在秸秆还田条件下，由于秸秆中化肥来源的氮量对土壤氮库消耗的补充，导致土壤氮库达到平衡点的施氮量降低约 25% (为 N 233 kg/hm²)，即籽粒带走的土壤氮量等于土壤残留和还田秸秆中的肥料氮量总和 (图 5-b)。

## 3 讨论

### 3.1 小麦氮素吸收自化肥氮和土壤氮的比例

小麦植株氮素吸收主要有两个来源，化肥氮和土壤氮[2-3, 55]。本研究对国内肥料$^{15}$N 示踪结果进行整合分析发现，小麦氮素吸收来自土壤氮的比例高达 2/3，而来自肥料氮的比例仅占 1/3。在表 1 的大多数研究中，土壤氮对小麦氮吸收的贡献高于化肥氮，这个趋势在表 1 的比例高达 87%，并且小麦吸收的化肥氮的比例随施氮量升高而升高 (图 1-a)，而吸收的土壤氮的比例则相反 (图 1-b)。例如，当施氮量从低氮水平 ( ≤ 150 kg/hm²) 升高到高氮水平 (250～500 kg/hm²)，化肥氮对小麦氮吸收的贡献由 29% 增加到 34%，相反，土壤氮的贡献由 71% 降低到 66% (图 2-a、c)。这是由于化肥氮施入土壤后，化肥氮与土壤氮并存，稀释了土壤本身来源的无机氮库，化肥氮可部分替代土壤无机氮被作物吸收，减少作物对土壤来源无机氮的吸收比例[81]。但是，当施氮量达到一定程度，提高施氮量只增加化肥氮的吸收比例，但不能提高小麦植株氮吸收量，这也是过量施氮不能提高小麦产量的原因[2-3, 55]。

无论施肥量多高，土壤氮对小麦氮吸收的贡献一般在 50% 以上 (表 1)，这主要有两个可能原因：1)

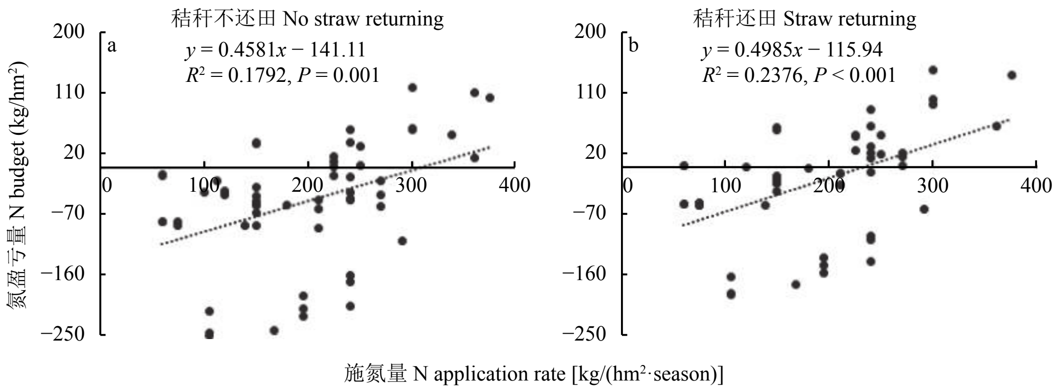


**图 5 施氮量与土壤氮库盈亏的关系**

**Fig. 5 The relationship between the N application rate and the budget of soil N**

肥料氮替换土壤氮被微生物固定，释放土壤来源的无机氮被作物吸收[82]；2) 由于土壤氮库很大，30 cm 土体一般为 N 3000～5000 kg/hm²，通过肥料施入的氮量相对较小 (小麦季 N 100～300 kg/hm²)，因此，肥料氮对土壤氮库的稀释程度有限，土壤氮占总可利用无机氮库的比例依然很大[10]。但是，从长期土壤氮平衡来看，土壤中残留肥料氮对于补充土壤氮素消耗、维持土壤氮肥力及土壤氮素供应具有重要意义。

本研究对 22 个小麦基肥和追肥 $^{15}$N 示踪数据源汇总分析，发现追肥氮对小麦氮吸收的贡献均高于基肥氮，平均贡献提高了 50% (表 1)。这可能由于：1) 在播种期施基肥，由于小麦处于苗期，根系小，根系对氮素的吸收能力不强，土壤中绝大部分肥料氮被微生物固定，所以土壤固持的肥料氮相对也较多一些；2) 在小麦旺盛生长期追肥，土壤氮素供应与小麦快速生长对氮的大量需求同步，提高了小麦对肥料氮的吸收利用[5, 45, 78]。因此，未来适当氮肥后移或增加追肥比例可能会提高肥料利用率。

### 3.2 化肥氮的去向

小麦籽粒吸收肥料氮的多少决定了氮肥的经济利用效率[49]。本研究对国内小麦 $^{15}$N 示踪结果整合分析发现，籽粒吸收的肥料氮约是秸秆的 3 倍，表明地上部吸收的肥料氮优先分配于籽粒中。小麦对肥料氮的回收率一般随施氮量的增加而减少，但取决于施氮水平[2-3, 7, 45]。例如当施氮水平从低氮水平 ( ≤ 150 kg/hm²) 增加到中氮水平 (150～250 kg/hm²)，小麦对肥料氮的利用率仅发生较小变化 (肥料氮的回收率由 40% 变为 43%)，而当增加到高氮水平 (250～500 kg/hm²)，肥料氮的回收率发生较大变化，降低到约 31%。这是由于尽管施氮量升高可以增加小麦对肥料氮的吸收比例 (图 2) 和绝对量 (表 3)，但是传统氮肥利用率是通过当季作物吸收的肥料氮量除以施用量计算得到，因此氮肥利用率变化还取决于施氮量的多少[6]。巨晓棠[6]分析了国内小麦 $^{15}$N 示踪试验资料，认为我国现有农田管理水平的氮肥损失率很高 (在 40%～50%)，氮肥有效率在 50%～60%，而本研究发现仅有约 30% 的化肥氮损失到环境，氮肥有效率高达 70%，因此，通过优化氮肥管理与综合农艺管理相结合，我国未来将氮肥有效率提高至 70% 以上是可以实现的[6]。

### 3.3 土壤氮库的盈亏

本研究施氮量与土壤氮库盈亏之间呈极显著正相关 (图 5)，土壤氮库盈亏取决于土壤中肥料来源的氮量是否可以补偿土壤本身氮素的消耗，这个趋势与倪玉雪等[7]建立华北地区小麦施氮量与土壤氮库盈亏的关系类似。在秸秆不还田和还田两种情况下，土壤氮库达到平衡时的施氮量分别是 N 308 kg/hm² 和 233 kg/hm²，秸秆不还田下这个数值远高于我国目前小麦的推荐施氮量 (N 150～250 kg/hm²)[83]，这是由于测试或平衡计算的推荐施氮方法，是通过测定土壤中贮存有效氮供应量以及从作物氮素需求中减去土壤供氮量来计算施氮量，往往田块过去的施氮量过高，而在下季要利用这部分氮素，很少考虑土壤氮的消耗是怎么补偿的[6]，因此，一般推荐量低于本研究基于小麦当季氮收支平衡计算的结果；如果地块长期保持合理施氮水平，从施氮量中减去测定土壤有效氮供氮量，就会导致土壤氮素肥力下降[6-8]。倪玉雪等[7]报道，秸秆 50% 及 100% 还田条件下施氮量分别为 N 192 和 166 kg/hm² 时，以及在秸秆不还田下施氮量为 N 245 kg/hm²[6]时，冬小麦季土壤氮库达到平衡，低于本研究达到土壤氮库平衡时的施氮

量。这种差异的原因可能是建立施氮量与土壤氮库盈亏量之间的小麦$^{15}$N示踪结果的数据库不同，本研究在倪玉雪等[7]的基础上又整合了近5年发表的国内小麦$^{15}$N示踪试验结果。

土壤氮素平衡受秸秆还田措施影响较大，本研究秸秆带走的土壤氮量为N 25 kg/hm$^2$，肥料氮量为N 14 kg/hm$^2$，因此秸秆还田措施可以补充当季被小麦吸收消耗的土壤氮量N 39 kg/hm$^2$ (表3)。根据施氮量与氮肥有效率之间的关系 $y=-0.0416x+77.159$ (图3-a) 以及与损失率之间关系 $y=0.0515x+20.022$ (图3-b)，当施氮量为N 308、233和500 kg/hm$^2$时，氮肥有效率分别为64%、68%和56%，损失率分别为36%、32%和46%。因此，在秸秆不还田和还田条件下，种植一季冬小麦后，当施氮范围分别在N 308～500和233～500 kg/hm$^2$，土壤氮素肥力氮得以维持或提高，小麦季氮肥有效率和损失率分别在56%～68%和32%～46%。

## 4 结论

1) 对于小麦整个生育期，在施氮量为N 60～500 kg/hm$^2$时，植株积累的氮素有2/3来自于土壤氮，1/3来自肥料氮，说明小麦当季氮素积累主要取决于对土壤氮的吸收，因此，从长期土壤氮素平衡来看，土壤中残留的肥料氮对于补充土壤氮素消耗、维持土壤氮肥力及土壤氮素供应具有重要意义。

2) 在小麦旺盛生长期追肥，植株对氮素的大量需求与土壤氮素供应同步，因此，追肥氮对小麦氮吸收的贡献约是基肥氮的1.5倍，未来适当氮肥后移或增加追肥比例可能会提高肥料利用率。

3) 化肥氮在冬小麦季的去向与施氮量之间呈显著线性关系，在低施氮水平 (≤ 150 kg/hm$^2$) 表现为吸收量 > 残留量 > 损失量，而在施氮水平为250～500 kg/hm$^2$时为损失量 > 残留量 > 吸收量。

4) 随着施氮量的增加，小麦吸收的肥料氮增加，吸收的土壤氮减少，土壤残留的肥料氮增加；在秸秆不还田和还田条件下，施氮量分别高于N 308和233 kg/hm$^2$时，土壤氮素平衡由亏缺转为盈余。土壤氮素平衡受秸秆还田措施影响较大，秸秆还田措施可以补充小麦当季消耗的土壤氮量N 39 kg/hm$^2$。

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