A Global Meta-Analysis on the Impact of Management Practices on Net Global Warming Potential and Greenhouse Gas Intensity from Cropland Soils

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Abstract

Management practices, such as tillage, crop rotation, and N fertilization, may affect net global warming potential (GWP) and greenhouse gas intensity (GHGI), but their global impact on cropland soils under different soil and climatic conditions need further evaluation. Available global data from 57 experiments and 225 treatments were evaluated for individual and combined effects of tillage, cropping systems, and N fertilization rates on GWP and GHGI which accounted for CO2 equivalents from N2O and CH4 emissions with or without equivalents from soil C sequestration rate (ΔSOC), farm operations, and N fertilization. The GWP and GHGI were 66 to 71% lower with no-till than conventional till and 168 to 215% lower with perennial than annual cropping systems, but 41 to 46% greater with crop rotation than monocropping. With no-till vs. conventional till, GWP and GHGI were 2.6- to 7.4-fold lower when partial than full accounting of all sources and sinks of greenhouse gases (GHGs) were considered. With 100 kg N ha−1, GWP and GHGI were 3.2 to 11.4 times greater with partial than full accounting. Both GWP and GHGI increased curvilinearly with increased N fertilization rate. Net GWP and GHGI were 70 to 87% lower in the improved combined management that included no-till, crop rotation/perennial crop, and reduced N rate than the traditional combined management that included conventional till, monocropping/annual crop, and recommended N rate. An alternative soil respiration method, which replaces ΔSOC by soil respiration and crop residue returned to soil in the previous year, similarly reduced GWP and GHGI by 133 to 158% in the improved vs. the traditional combined management. Changes in GWP and GHGI due to improved vs. traditional management varied with the duration of the experiment and inclusion of soil and climatic factors in multiple linear regressions improved their relationships. Improved management practices reduced GWP and GHGI compared with traditional management practices and combined management practices were even more effective than individual management practices in reducing net GHG emissions from cropland soils. Partial accounting overestimated GWP and GHGI values as sinks or sources of net GHGs compared with full accounting when evaluating the effect of management practices.
Introduction

Agricultural management practices contribute from 6% of the total greenhouse gas (GHGs: CO₂, N₂O, and CH₄) emissions in the USA [1] to about 20% globally [2]. The impact of these GHGs in radiative forcing in earth’s atmosphere is quantitatively estimated by calculating net global warming potential (GWP) which accounts for all sources and sinks of CO₂ equivalents from farm operations, chemical inputs, soil C sequestration, and N₂O and CH₄ emissions [3, 4]. Another measure of GHGs’ impact is net greenhouse gas intensity (GHGI) which is expressed as net GWP per unit crop yield [4]. While soil C sequestration is the major sink and GHG emissions are sources of CO₂ in agroecosystems that are affected by soil and climatic conditions and management practices [4, 5], machinery and inputs used for growing crops, such as tillage, planting, harvesting, and applications of fertilizers, herbicides, and pesticides, can produce CO₂, thereby reducing the GHG mitigation potential [3, 6, 7]. The GWP and GHGI are typically controlled by the balance between soil C sequestration rate (ΔSOC), N₂O and CH₄ emissions, and crop yields [3, 4, 8].

Novel management practices that can mitigate GHG emissions and therefore GWP and GHGI include no-till, increased cropping intensity, diversified crop rotation, cover cropping, and reduced N fertilization rates [3, 4, 8]. No-till can increase soil organic C (SOC) compared with conventional till by reducing soil disturbance, residue incorporation, and microbial activity that lower CO₂ emissions [4, 9]. Diversified cropping systems, such as intensive cropping, crop rotation, and cover cropping, can increase SOC by increasing the quality and quantity of crop residue returned to the soil compared with less diversified systems, such as crop-fallow, monocropping, and no cover crop [4, 10]. Nitrogen fertilization typically stimulates N₂O emissions [3, 11], but can have a variable effect on CO₂ and CH₄ emissions [10, 12]. Because N₂O emissions play a major role in enhancing GWP and GHGI, practices that can reduce N fertilization rates without influencing crop yields can substantially reduce net GHG emissions [3, 4].

Management practices used for GHG mitigation sometime can have counter effects. For example, no-till can increase N₂O emissions compared with conventional till in humid regions by increasing soil water content and denitrification, thereby offsetting the GHG mitigation potential [13]. Incorporation of root residue can increase soil C sequestration, but root respiration and mineralization of crop residue and SOC can have negative impacts on GHG mitigation [10, 14]. Besides the direct effect of N fertilization on N₂O emissions, indirect effects, such as NH₄ volatilization, N-leaching, and urea hydrolysis in the soil can also counteract the mitigation potential [15]. All of these factors should be considered while calculating net GWP and GHGI, regardless of management practices [3, 4, 16].

Several methods have been employed to calculate GWP and GHGI by using the SOC method which considers ΔSOC as CO₂ sink. Some have used the sum of CO₂ equivalents of N₂O and CH₄ emissions [17, 18, 19], while others [20, 21] have included CO₂ equivalents of all three GHGs. Still others have used CO₂ equivalents of N₂O and CH₄ emissions and ΔSOC [22, 23, 24]. A full accounting of all sources and sinks of GHGs to calculate net GWP and GHGI includes CO₂ equivalents from farm operations, N fertilization, and other inputs in addition to above parameters [3, 4, 8, 16, 25, 26, 27, 28, 29, 30]. Some have excluded N₂O and CH₄ emissions, but used CO₂ equivalents of all other sources and sinks [7]. An alternative method (hereby called the soil respiration method) of calculating GWP and GHGI includes substituting ΔSOC by soil respiration and the amount of previous year’s crop residue returned to the soil [4, 27, 28, 29, 30, 31]. Each method has its own advantages and drawbacks which will be explored in detail by comparing GWP and GHGI values below.

Information on the effects of soil and crop management practices on GHG emissions in croplands is available [17, 32, 33, 34]. Relatively, little is known about the influence of management practices on GWP and GHGI. The objectives of this study were to: (1) conduct a meta-
analysis of global data available in the literature on the individual and combined effects of tillage, cropping systems, and N fertilization rates on GWP and GHGI calculated by the SOC method in cropland soils using partial or full accounting of all sources and sinks of GHGs, (2) relate GWP and GHGI with the duration of the experiment and soil and climatic conditions, (3) compare GWP and GHGI values calculated by the SOC and soil respiration methods, and (4) identify improved management practices that can reduce net GWP and GHGI.

**Materials and Methods**

**Data collection and management**

Data on GWP and GHGI were pulled from the available literature from 57 experiments and 225 treatments from national and international regions and grouped by individual and combined management practices that included tillage, cropping systems, and N fertilization rates (Tables 1, 2, 3, 4 and 5) using all available resources (e.g. Web of Science, Google Scholar, SCOPUS, etc.).

| Location                  | Soil type          | Annual precip. | Study duration | Mean air temp. | Tillage† | GWP‡ | GHGI‡ | Parameters used to calculate GWP/GHGI | Reference |
|---------------------------|--------------------|----------------|----------------|----------------|----------|------|------|--------------------------------------|-----------|
| Colorado, USA             | Clay loam          | 382            | 5              | 10.6           | NT       | -15  | 18   | N₂O, CH₄, ΔSOC, farm operation, inputs | [26]      |
|                           |                    |                |                |                | CT       | 1479 | 143  |                                      |           |
|                           |                    |                |                |                | NT       | -516 | -60  |                                      | [4]       |
|                           |                    |                |                |                | CT       | 1071 | 93   |                                      |           |
| Queensland, Australia     | Clay               | 728            | 4              | 17.2           | NT       | 403  | 158  | N₂O, CH₄, ΔSOC                          | [23]      |
|                           |                    |                |                |                | CT       | 495  | 195  |                                      |           |
| Michigan, USA             | Sandy loam, loam   | 890            | 1              | 9.7            | NT       | 2870 | -    | -                                    | [21]      |
|                           |                    |                |                |                | CT       | 11500| -    | CO₂, CH₄, N₂O                          |           |
|                           |                    |                |                |                | NT       | -500 | -32  |                                      | [24]      |
|                           |                    |                |                |                | CT       | 2900 | 172  |                                      |           |
|                           |                    |                |                |                | NT       | 140  | -    | N₂O, CH₄, ΔSOC, farm operation, inputs | [16]      |
|                           |                    |                |                |                | CT       | 1140 | -    |                                      |           |
| Hyderabad, India          | Clay               | 1520           | 20             | 25.0           | NT       | 8930 | -    | N₂O, CH₄, ΔSOC, farm operation, inputs | [16]      |
|                           |                    |                |                |                | CT       | 10250| -    |                                      |           |
| Colorado, USA             | Clay loam          | 890            | 1              | 10.6           | NT       | -1253| -    | N₂O, CH₄, ΔSOC, farm operation, inputs | [8]       |
|                           |                    |                |                |                | CT       | 2264 | -    |                                      |           |
| North Dakota, USA         | Sandy loam         | 373            | 4              | 5.2            | NT       | 887  | 420  | N₂O, CH₄, ΔSOC, farm operation, inputs | [29]      |
|                           |                    |                |                |                | CT       | 1287 | 655  |                                      |           |

†Tillage are CT = conventional till, NT = no-till.
‡Positive values indicate source and negative values sink of CO₂.
Table 2. Effect of cropping systems on net global warming potential (GWP) and greenhouse gas intensity (GHGI) calculated by using the soil organic C method in various regions with different soil and climatic conditions.

| Location, USA | Soil type, USA | Annual precip. | Mean air temp | Study duration | Cropping system† | GWP‡ | GHGI‡ | Parameters used to calculate GWP/GHGI | Reference number |
|---------------|----------------|----------------|---------------|----------------|------------------|------|-------|--------------------------------------|-----------------|
| Colorado, USA Clay loam | 382 | 10.6 | 5 | C | 222 | 65 | N₂O, CH₄, ΔSOC, farm operation, inputs | [26] |
| Colorado, USA Clay loam | 382 | 10.6 | 3 | C | -557 | -64 | N₂O, CH₄, ΔSOC, farm operation, inputs | [4] |
| Michigan, USA Sandy loam, loam | 890 | 9.7 | 1 | G | -3500 | - - - | CO₂, CH₄, N₂O, | [21] |
| Michigan, USA Sandy loam, loam | 890 | 9.7 | 1 | W-W | 578 | - - - | N₂O, ΔSOC, farm operation | [47] |
| Michigan, USA Sandy loam, loam | 890 | 9.7 | 1 | C-W-S | 640 | - - - | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [8] |
| Colorado, USA Clay loam | 382 | 10.6 | 1 | C-W-F | 254 | - - - | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [8] |
| Colorado, USA Clay loam | 382 | 10.6 | 1 | C | -498 | - - - | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [8] |
| Colorado, USA Clay loam | 382 | 10.6 | 1 | C-S | 1020 | 102 | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [25] |
| Saskatchewan, Canada Loam, silt loam | 250 | 5.2 | 3 | W-W | 578 | - - - | N₂O, ΔSOC, farm operation | [47] |
| Saskatchewan, Canada Loam, silt loam | 250 | 5.2 | 3 | W-L | 396 | - - - | N₂O, ΔSOC, farm operation | [47] |
| Nebraska, USA Silty clay loam | 600 | 11.0 | 1.5 | C | 690 | 48 | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [25] |
| Nebraska, USA Silty clay loam | 600 | 11.0 | 1.5 | C-S | 1020 | 102 | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [25] |
| Central North Dakota, USA Silt loam | 407 | 6.0 | 1.5 | W-F | 1654 | - - - | N₂O, CH₄, and ΔSOC | [52] |
| Western North Dakota, USA Sandy loam | 373 | 5.2 | 4 | B | 971 | 300 | N₂O, CH₄, ΔSOC, farm operation, irrigation | [29] |
| Western North Dakota, USA Sandy loam | 373 | 5.2 | 4 | B-P | 771 | 250 | N₂O, CH₄, ΔSOC, farm operation, irrigation | [29] |
| Western Montana, USA Silt loam | 453 | 6.2 | 2 | W | 5074 | 730 | N₂O, CH₄, ΔSOC, farm operation, inputs | [28] |
| Western Montana, USA Silt loam | 453 | 6.2 | 2 | W-P/B-F | 5191 | 1065 | N₂O, CH₄, ΔSOC, farm operation, inputs | [28] |

† Crops are A = alfalfa, B = barley, C = corn, F = fallow, Fx = flax, G = grass, P = pea, PO = poplar, L = lentil, S = soybean. Letters joined by hyphenation indicates crop rotation, e.g. W-F = wheat-fallow rotation.
‡ Positive values indicate source and negative values sink of CO₂.

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Table 3. Effect of N fertilization rate on net global warming potential (GWP) and greenhouse gas intensity (GHGI) calculated by using the soil organic C method in various regions with different soil and climatic conditions.

| Location          | Soil type | Annual precip. | Mean air temp. | Study duration | Crop          | N rate | GWP † | GHGI † | Parameters used to calculate GWP/ GHGI | Reference |
|-------------------|-----------|----------------|----------------|----------------|---------------|--------|-------|--------|----------------------------------------|-----------|
| Colorado, USA     | Clay loam | 382            | 10.6           | 5              | Corn, soybean | 0      | 472   | 77     | N₂O, CH₄, ΔSOC, farm operation, inputs | [26]      |
|                   |           |                |                |                |               | 134    | 542   | 45     |                                        |           |
|                   |           |                |                |                |               | 246    | 1197  | 102    |                                        |           |
| Colorado, USA     | Clay loam | 382            | 10.6           | 3              | Corn, soybean | 0      | -77   | -19    | N₂O, CH₄, ΔSOC, farm operation, inputs | [4]       |
|                   |           |                |                |                |               | 134    | 449   | -32    |                                        |           |
|                   |           |                |                |                |               | 246    | 500   | 37     |                                        |           |
| Queensland, Australia | Clay    | 728            | 17.2           | 4              | Wheat         | 0      | 324   | 139    | N₂O, CH₄, ΔSOC                           | [23]      |
|                   |           |                |                |                |               | 90     | 575   | 214    |                                        |           |
| California, USA   | Clay      | 368            | 15.0           | 2              | Rice          | 0      | 3965  | 861    | N₂O, CH₄                                 | [19]      |
|                   |           |                |                |                |               | 80     | 4789  | 544    |                                        |           |
|                   |           |                |                |                |               | 140    | 5437  | 463    |                                        |           |
|                   |           |                |                |                |               | 200    | 5395  | 410    |                                        |           |
|                   |           |                |                |                |               | 260    | 5507  | 445    |                                        |           |
| California, USA   | Clay      | 368            | 15.0           | 1              | Corn, soybean | 0      | -311  | -       | N₂O, CH₄, ΔSOC, farm operation, inputs | [9]       |
|                   |           |                |                |                |               | 134    | 629   | -       |                                        |           |
|                   |           |                |                |                |               | 202    | 595   | -       |                                        |           |
| California, USA   | Clay      | 368            | 15.0           | 3              | Rice          | 0      | 658   | 156    | N₂O, CH₄                                 | [18]      |
|                   |           |                |                |                |               | 50     | 816   | 120    |                                        |           |
|                   |           |                |                |                |               | 100    | 712   | 91     |                                        |           |
|                   |           |                |                |                |               | 150    | 1491  | 188    |                                        |           |
|                   |           |                |                |                |               | 200    | 1541  | 190    |                                        |           |
| California, USA   | Clay      | 368            | 15.0           | 3              | Rice          | 0      | 5061  | 844    | N₂O, CH₄                                 | [18]      |
|                   |           |                |                |                |               | 50     | 6012  | 772    |                                        |           |
|                   |           |                |                |                |               | 100    | 6768  | 687    |                                        |           |
| Arkansas, USA     | Silt loam | 1200           | 12.5           | 3              | Rice          | 0      | 1068  | 278    | N₂O, CH₄                                 | [18]      |
|                   |           |                |                |                |               | 112    | 2018  | 265    |                                        |           |
|                   |           |                |                |                |               | 168    | 2069  | 257    |                                        |           |
|                   |           |                |                |                |               | 224    | 2238  | 286    |                                        |           |
| North Dakota, USA | Sandy loam| 373            | 5.2            | 4              | Barley, pea   | 0      | 926   | 617    | N₂O, CH₄, ΔSOC, farm operation, inputs | [29]      |
|                   |           |                |                |                |               | 101    | 1248  | 383    |                                        |           |
| Montana, USA      | Loam      | 350            | 6.2            | 4              | Barley, pea   | 0      | 635   | 453    | N₂O, CH₄, ΔSOC, farm operation, inputs | [30]      |
|                   |           |                |                |                |               | 80     | 185   | 105    |                                        |           |

(Continued)
PRISMA (Preferred Reporting Items for System Review and Meta-Analysis) guidelines (Fig 1) have been followed for collection and meta-analysis of data. In each management group, GWP and GHGI values were listed based on soil and climatic conditions, cropping systems, duration of study in each location, and parameters used for calculations. In some studies where two or more treatments were arranged in split-plot arrangements to evaluate the effects of individual and combined management practices on GWP and GHGI, values for main and split-plot treatments were used as individual management practices and their interactions as combined management practices when data are significantly different among treatments and interactions using General Linear Model (GLM) and mean separation tests. For experiments with unbalanced treatments, main treatment was considered as individual management practice when data were analyzed using the orthogonal contrast test and other mixed treatments as combined management practices when analyzed using GLM and mean separation tests, provided that differences among treatments are significant. When main treatments cannot be separated in a combination of various treatments, such treatments were considered as combined management practices and data were analyzed as above.

The GWP using the SOC method [3, 4, 29, 30] to compare the effect of management practices in data analysis included the following options for calculations:

Partial accounting data:

\[
GWP = CO_2 \text{ equivalents from (N}_2O + CH_4) \text{ emissions with or without } CO_2 \text{ equivalent from } \Delta SOC. 
\]

Full accounting data:

\[
GWP = CO_2 \text{ equivalents from (N}_2O + CH_4) \text{ emissions} + CO_2 \text{ equivalents from (farm operations + N fertilization + other inputs)} - CO_2 \text{ equivalent from } \Delta SOC
\]

### Table 3. (Continued)

| Location          | Soil type | Annual precip. | Mean air temp. | Study duration | Crop       | N rate | GWP†   | GHGI†   | Parameters used to calculate GWP/ GHGI | Reference |
|-------------------|-----------|----------------|----------------|----------------|------------|--------|--------|---------|---------------------------------------|-----------|
| Beijing, China    | Loam      | 600            | 10.0           | 6              | Corn, wheat| 0      | 2702   | 369     | \(N_2O, CH_4, \Delta SOC, \) farm operation, inputs, irrigation | [54]      |
|                   |           |                |                |                |            |        | 247    | 255     |                                       |           |
|                   |           |                |                |                |            |        | 280    | 350     |                                       |           |
| Nanjing, China    | Silt loam | 1107           | 15.4           | 2              | Amaranth, Tug choy, Bok choy, Coriander | 0      | -2347  | -139    | \(N_2O, CH_4, \Delta SOC, \) farm operation, inputs | [55]      |
|                   |           |                |                |                |            |        | 1475   | -1650   | 5                                                   |           |
|                   |           |                |                |                |            |        | 1967   | 7700    | 109                                                |           |
| Nanjing, China    | Silt clay | 1107           | 15.4           | 2              | Rice, wheat| 0      | 5700   | 740     | \(N_2O, CH_4, \Delta SOC\)                                    | [56]      |
|                   |           |                |                |                |            |        | 360    | 7210    | 500                                                |           |
|                   |           |                |                |                |            |        | 432    | 6660    | 410                                                |           |
|                   |           |                |                |                |            |        | 480    | 8360    | 580                                                |           |

† Positive values indicate source and negative values sink of \(CO_2\).

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Table 4. Effect of combined management practices (tillage, cropping system, and N fertilization) on net global warming potential (GWP) and greenhouse gas intensity (GHGI) calculated by using the soil organic C method in various regions with different soil and climatic conditions.

| Location          | Soil type | Annual precip. | Mean air temp. | Study duration | Combined management practices | GWP† | GHGI† | Parameters used to calculate GWP/GHGI | Reference |
|-------------------|-----------|----------------|----------------|----------------|--------------------------------|------|------|--------------------------------------|-----------|
| Colorado, USA     | Clay loam | 382            | 10.6           | 5              | CT-CC-N0‡                       | 709  | 108  | N₂O, CH₄, ΔSOC, farm operation, inputs | [26]      |
|                   |           |                |                |                |                                |      |      |                                      |           |
|                   |           |                |                |                | CT-CC-N1‡                       | 1545 | 136  |                                      |           |
|                   |           |                |                |                | CT-CC-N2‡                       | 2184 | 185  |                                      |           |
|                   |           |                |                |                | NT-CC-N0‡                       | 234  | 46   |                                      |           |
|                   |           |                |                |                | NT-CC-N1‡                       | -459 | -47  |                                      |           |
|                   |           |                |                |                | NT-CC-N2‡                       | 210  | 19   |                                      |           |
|                   |           |                |                |                | NT-CB-N0‡                       | 33   | 6    |                                      |           |
|                   |           |                |                |                | NT-CB-N2‡                       | 963  | 113  |                                      |           |
|                   |           |                |                | 3              | CT-CC-N0‡                       | 80   | 13   | N₂O, CH₄, ΔSOC, farm operation, inputs | [4]       |
|                   |           |                |                |                |                                |      |      |                                      |           |
|                   |           |                |                |                | CT-CC-N1‡                       | 1333 | 117  |                                      |           |
|                   |           |                |                |                | CT-CC-N2‡                       | 1800 | 150  |                                      |           |
|                   |           |                |                |                | NT-CC-N0‡                       | -233 | -50  |                                      |           |
|                   |           |                |                |                | NT-CC-N1‡                       | -436 | -53  |                                      |           |
|                   |           |                |                |                | NT-CC-N2‡                       | -880 | -77  |                                      |           |
| Queensland,       | Clay      | 728            | 17.2           | 4              | CT-SB-N0§                       | 277  | 117  | N₂O, CH₄, ΔSOC                        | [23]      |
| Australia         |           |                |                |                |                                |      |      |                                      |           |
|                   |           |                |                |                | CT-SB-N90§                      | 710  | 272  |                                      |           |
|                   |           |                |                |                | CT-SR-N0§                       | 338  | 148  |                                      |           |
|                   |           |                |                |                | CT-SR-N90§                      | 654  | 243  |                                      |           |
|                   |           |                |                |                | NT-SB-N0§                       | 329  | 136  |                                      |           |
|                   |           |                |                |                | NT-SB-N90§                      | 534  | 202  |                                      |           |
|                   |           |                |                |                | NT-SR-N0§                       | 350  | 153  |                                      |           |
|                   |           |                |                |                | NT-SR-N90§                      | 401  | 140  |                                      |           |
| Nebraska, USA     | Silty clay loam | 600       | 11.0           | 1.5            | CC-F1¶                         | 540  | 39   | N₂O, CH₄, ΔSOC, farm operation, inputs | [25]      |
|                   |           |                |                |                |                                |      |      |                                      |           |
|                   |           |                |                |                | CC-F2¶                         | 840  | 56   |                                      |           |
|                   |           |                |                |                | CB-F1¶                         | 1020 | 104  |                                      |           |
|                   |           |                |                |                | CB-F2¶                         | 1020 | 99   |                                      |           |
| Colorado, USA     | Clay loam | 382            | 10.6           | 1              | CT-CC-N0‡                       | 1647 | -    | N₂O, CH₄, ΔSOC, farm operation, inputs | [8]       |
|                   |           |                |                |                |                                |      |      |                                      |           |
|                   |           |                |                |                | CT-CC-N1‡                       | 2383 | -    |                                      |           |
|                   |           |                |                |                | CT-CC-N2‡                       | 2763 | -    |                                      |           |
|                   |           |                |                |                | NT-CC-N0‡                       | -1766| -    |                                      |           |
|                   |           |                |                |                | NT-CC-N1‡                       | -1125| -    |                                      |           |
|                   |           |                |                |                | NT-CC-N2‡                       | -815 | -    |                                      |           |
|                   |           |                |                |                | NT-CB-N0‡                       | -942 | -    |                                      |           |
|                   |           |                |                |                | NT-CB-N2‡                       | -164 | -    |                                      |           |

(Continued)
| Location                  | Soil type                  | Annual precip. | Mean air temp. | Study duration | Combined management practices | GWP† | GHGI† | Parameters used to calculate GWP/ GHGI | Reference |
|--------------------------|----------------------------|----------------|----------------|----------------|-------------------------------|------|------|--------------------------------------|-----------|
| Minnesota, USA           | Loam, silty, clay loam, clay loam | 645            | 4.3            | 3              | BAU#                          | 5000 | 1094 | N₂O, CH₄, ΔSOC, farm operation, inputs | [27]      |
|                          |                            |                |                |                |                               |      |      |                                       |           |
|                          |                            |                |                |                |                               |      |      |                                       |           |
|                          |                            |                |                |                |                               |      |      |                                       |           |
| North Dakota, USA        | Sandy loam                 | 373            | 5.2            | 4              | IR-CT-B-NF††                   | 1607 | 450  | N₂O, CH₄, ΔSOC, farm operation, inputs, irrigation | [29]      |
|                          |                            |                |                |                |                               |      |      |                                       |           |
|                          |                            |                |                |                |                               |      |      |                                       |           |
| Eastern Montana, USA     | Loam                       | 350            | 6.2            | 4              | CT-BF-N0†‡                    | 1153 | 836  | N₂O, CH₄, ΔSOC, farm operation, inputs | [30]      |
|                          |                            |                |                |                |                               |      |      |                                       |           |
|                          |                            |                |                |                |                               |      |      |                                       |           |
| Western Montana, USA     | Silt loam                  | 453            | 5.5            | 2              | HA-A§§                        | 927  | 150  | N₂O, CH₄, ΔSOC, farm operation, inputs | [28]      |
|                          |                            |                |                |                |                               |      |      |                                       |           |
|                          |                            |                |                |                |                               |      |      |                                       |           |

† Positive values indicate source and negative values sink of CO₂.
‡ CT = conventional till, NT = no-till, CC = continuous corn, CB = corn-soybean rotation, N₀ = 0 kg N ha⁻¹, N₁ = 134 kg N ha⁻¹, and N₂ = 56–246 kg N ha⁻¹.
§ CT = conventional till, NT = no-till, SB = stubble burned, SR = stubble retained in the soil, N₀ = 0 kg N ha⁻¹, N₀ = 90 kg N ha⁻¹.
¶ CC = continuous corn, CB = corn-soybean, F₁ = 130–140 kg N ha⁻¹, 0 kg P ha⁻¹, 0 kg K ha⁻¹; F₂ = 230–310 kg N ha⁻¹, 45 kg P ha⁻¹, 85 kg K ha⁻¹.
# BAU = conventional till corn-soybean rotation with 143 kg N ha⁻¹, 17 kg P ha⁻¹, and 0 kg K ha⁻¹; MAXC = strip till corn-soybean-wheat/alfalfa-alfalfa rotation with 89 kg N ha⁻¹, 32 kg P ha⁻¹, and 28 kg K ha⁻¹; OGCB = strip till corn-soybean-wheat/alfalfa-alfalfa rotation with 0 kg N ha⁻¹, 0 kg P ha⁻¹; and 0 kg K ha⁻¹.
†† IR = irrigated, NIR = nonirrigated, CT = conventional till, NT = no-till, B = malt barley, BP = malt barley-pea rotation, NO = 0 kg K ha⁻¹, and NF = 67–134 kg K ha⁻¹.
‡‡ CT = conventional till, NT = no-till, B = malt barley, BF = malt barley-fallow rotation, BP = malt barley-pea rotation, N₀ = 0 kg K ha⁻¹, N₈₀ = 0 kg K ha⁻¹.
§§ HA = herbicide application for weed control, SHG = sheep grazing for weed control, A = alfalfa, W = wheat, WP/BF = wheat-pea/barley mixture fallow rotation.

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Table 5. Soil respiration method of calculating net global warming potential (GWP) and greenhouse gas intensity (GHGI) in various regions with different soil and climatic conditions as affected by combined management practices (tillage, cropping system, and N fertilization).

| Location         | Soil type | Annual precip. | Mean air temp. | Study duration | Combined management practices | GWP† | GHGI† | Parameters used to calculate GWP/GHGI | Reference |
|------------------|-----------|----------------|----------------|----------------|------------------------------|------|------|-------------------------------------|-----------|
| Colorado, USA    | Clay loam | 382            | 10.6           | 3              | CT-CC-N0‡                    | 1953 | 133  | Soil respiration, N₂O, CH₄, crop residue, farm operation, inputs | [4]       |
|                  |           |                |                |                | CT-CC-N1‡                    | -1367| -45  |                                |           |
|                  |           |                |                |                | CT-CC-N2‡                    | -1743| -162 |                                |           |
|                  |           |                |                |                | NT-CC-N0‡                    | -833 | -217 |                                |           |
|                  |           |                |                |                | NT-CC-N1‡                    | -2990| -310 |                                |           |
|                  |           |                |                |                | NT-CC-N2‡                    | -4300| -390 |                                |           |
|                  |           |                |                |                | NT-CB-N0‡                    | 9495 | 1340 |                                |           |
|                  |           |                |                |                | NT-CN-N2‡                    | 9850 | 865  |                                |           |
| Arkansas, USA    | Silt loam | 1200           | 14.5           | 4              | NIR-CT§                      | -1351| -     | N₂O, CH₄, crop residue, farm operation, inputs | [31]      |
|                  |           |                |                |                | IR-CT§                       | 951  | -     |                                |           |
|                  |           |                |                |                | NIR-SO                       | -455 | -     |                                |           |
|                  |           |                |                |                | IR-SO§                       | -965 | -     |                                |           |
|                  |           |                |                |                | NIR-S§                       | -301 | -     |                                |           |
|                  |           |                |                |                | IR-R§                        | -4   | -     |                                |           |
|                  |           |                |                |                | NIR-W§                       | 6632 | -     |                                |           |
| Minnesota, USA   | Loam, silt, clay loam | 645    | 4.3            | 3              | BAU¶                         | 500  | 109  | N₂O, CH₄, crop residue, farm operation, inputs | [27]      |
|                  |           |                |                |                | MAXC¶                        | 9100 | 2542 |                                |           |
|                  |           |                |                |                | OGGP¶                        | 1220 | 361  |                                |           |
| North Dakota, USA| Sandy loam| 373            | 5.2            | 4              | IR-CT-B-NF#                  | -7793| -1950| Soil respiration, N₂O, CH₄, crop residue, farm operation, inputs | [29]      |
|                  |           |                |                |                | IR-CT-B-NO#                  | -1495| -490 |                                |           |
|                  |           |                |                |                | IR-NT-BP-NF#                 | -9169| -2490|                                |           |
|                  |           |                |                |                | IR-NT-B-NF#                  | -8112| -2150|                                |           |
|                  |           |                |                |                | IR-NT-B-NO#                  | -117 | -10  |                                |           |
|                  |           |                |                |                | NIR-CT-B-NF#                 | -7050| -2270|                                |           |
|                  |           |                |                |                | NIR-CT-B-NO#                 | -1752| -670 |                                |           |
|                  |           |                |                |                | NIR-NT-BP-NF#                | -6618| -2920|                                |           |
|                  |           |                |                |                | NIR-NT-B-NF#                 | -6243| -1920|                                |           |
|                  |           |                |                |                | NIR-NT-B-NO#                 | -1281| -510 |                                |           |
| Eastern Montana, USA | Loam  | 350            | 6.2            | 4              | CT-BF-N0††                    | 114  | 83   | Soil respiration, N₂O, CH₄, crop residue, farm operation, inputs | [30]      |
|                  |           |                |                |                | CT-BF-N80††                   | -292 | -203 |                                |           |
|                  |           |                |                |                | NT-BP-N0††                    | -1902| -1156|                                |           |

(Continued)
All data: GWP = CO2 equivalents calculated both from partial and full accounting data. The purpose of using all data option in the analysis was to compare them with partial and full accounting data options and to examine if the relationships of GWP and GHGI with management practices can be improved when the all data option was used compared with using only partial and full accounting data options.

In the soil respiration method \[4, 29, 30, 31\], GWP was calculated as:

\[
GWP = \text{CO}_2\text{ equivalents from} \left(\text{CO}_2\text{ [excluding root respiration]} + N_2O + \text{CH}_4\right)\text{ emissions} + \text{CO}_2\text{ equivalents from} \left(\text{farm operations} + N\text{ fertilization} + \text{other inputs}\right) - \text{CO}_2\text{ equivalent from previous year’s crop residue returned to the soil}\n\] (3)

The GHGI in the SOC or the soil respiration method was calculated as:

\[
GHGI = \frac{GWP (SOC \text{ or soil respiration method})}{\text{grain or biomass yield}}.\n\] (4)

Although data from 60 experiments and 255 treatments were collected, only data from 57 experiments and 225 treatments were selected for meta-analysis which meets the specific criteria shown below:

Table 5. (Continued)

| Location | Soil type       | Annual precip. | Mean air temp. | Study duration | Combined management practices | GWP† | GHGI† | Parameters used to calculate GWP/GHGI | Reference |
|----------|-----------------|-----------------|----------------|----------------|------------------------------|------|------|---------------------------------------|-----------|
|          |                 | mm             | °C             | yr             |                              | kg CO₂ eq. ha⁻¹ yr⁻¹ | kg CO₂ eq. Mg⁻¹ grain or biomass |                                      |           |
| Western Montana, USA | Silt loam | 453 | 5.5 | 2 | HA-A†† | 4970 | 780 | Soil respiration, N₂O, CH₄, crop residue, farm operation, inputs | [28] |
|          |                 | 8740 | | | HA-W†† | 1180 | | | | |
|          |                 | 5894 | | | HA-WP/BF†† | 1040 | | | | |
|          |                 | 7030 | | | SHG-A†† | 650 | | | | |
|          |                 | 8574 | | | SHG-W†† | 1440 | | | | |
|          |                 | 8868 | | | SHG-WP/BF†† | 1860 | | | | |

† Positive values indicate source and negative values sink of CO₂.
‡ CT = conventional till, NT = no-till, CC = continuous corn, CB = corn-soybean rotation, N0 = 0 kg N ha⁻¹, N1 = 134 kg N ha⁻¹, and N2 = 56–246 kg N ha⁻¹.
§ IR = irrigated, NIR = nonirrigated, C = corn, CT = cotton, SO = sorghum, S = soybean, R = rice, and W = wheat.
¶ BAU = conventional till corn-soybean rotation with 143 kg N ha⁻¹, 17 kg P ha⁻¹, and 0 kg K ha⁻¹; MAXC = strip till corn-soybean-wheat/alfalfa-alfalfa rotation with 89 kg N ha⁻¹, 32 kg P ha⁻¹, and 28 kg K ha⁻¹; OGCB = strip till corn-soybean-wheat/alfalfa-alfalfa rotation with 0 kg N ha⁻¹, 0 kg P ha⁻¹; and 0 kg K ha⁻¹.
# IR = irrigated, NIR = nonirrigated, CT = conventional till, NT = no-till, B = malt barley, BP = malt barley-pea rotation, NO = 0 kg K ha⁻¹, and NF = 67–134 kg K ha⁻¹.
†† CT = conventional till, NT = no-till, B = malt barley, BF = malt barley-fallow rotation, BP = malt barley-pea rotation, N0 = 0 kg K ha⁻¹, N80 = 0 kg K ha⁻¹.
‡‡ CT = conventional till, NT = no-till, B = malt barley, BF = malt barley-fallow rotation, N0 = 0 kg K ha⁻¹, N80 = 0 kg K ha⁻¹.

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1. All experiments should be conducted in croplands in the field. Croplands included both uplands and lowlands under all agricultural irrigated and dryland crops. Number of crops grown in a year should be two or less. Data on GWP and GHGI estimated by models were excluded for analysis.

2. Treatments in the experiments should be replicated, randomized, and arranged in a proper experimental design.
3. For GWP and GHGI calculated by using the SOC method, soil C sequestration should have occur to a depth of 20 cm from the initiation of the experiment to the end of GHG measurement period. In the soil respiration method, experiments should have started in the previous year where the amount of crop residue returned to the soil was known.

4. Measurement of GHG emissions should occur at regular events, including close measurements during episodic events, such as immediately following precipitation, irrigation, tillage, fertilization, and snow melts.

5. A time horizon of 100 yr should be used to calculate the CO₂ equivalents of N₂O and CH₄ emissions which have 298 and 25 times, respectively, more global warming potential than CO₂ [35].

6. Carbon dioxide emissions associated with use of farm equipment for irrigation, tillage, fertilization, planting, herbicide and pesticide application, and harvest as well as manufacture and application of fertilizers and other chemical inputs should be either calculated based on the number of hours the equipment were used multiplied by CO₂ emissions per liter of fuel or estimated as shown by various researchers [7, 36, 37].

7. For comparing the effects of individual and combined management practices on GWP and GHGI, the SOC method was used to calculate these parameters. Because of the limited availability of data, the soil respiration method was used only to evaluate the effect of combined management practice on GWP and GHGI.

**Statistical analysis of data**

Meta-analysis of data was conducted by using procedure as suggested by various researchers [38, 39, 40, 41]. Those data where excessive levels of GHGs were reported, such as due to high rates of N fertilization, were discarded for analysis. A paired t-test was used for data analysis to compare the effects of individual and combined treatments of improved vs. traditional management practices on GWP and GHGI by evaluating significant difference between practices [42]. Individual improved management practices included no-till, crop rotation, increased cropping intensity, perennial crops, and reduced N fertilization rates. Individual traditional management practices included conventional till, monocropping, reduced cropping intensity, annual crops, and recommended N fertilization rates. Combined improved or traditional management practices included combinations of two or more of these practices. Comparisons included no-till vs. conventional till, crop rotation vs. monocropping, annual vs. perennial crop, and combined improved vs. combined traditional management practice that included a combination of these practices with or without cropping intensity and N fertilization rates. For cropping intensity and N fertilization rates, regression analysis were conducted to determine their relationships with GWP and GHGI [42]. For comparison of combined improved vs. combined traditional management practice, appropriate combination of individual treatments with lower and higher GWP and GHGI, respectively, were selected.

Regression analysis was used to relate changes in GWP and GHGI due to improved vs. conventional management with duration of the experiment to examine if the changes vary with time [42]. Multiple linear regressions were conducted to include soil and climatic factors (total annual precipitation and mean air temperature) in these analyses to determine if the relationships can be improved. For analysis of the soil factor, soil texture was assigned to a numerical value: coarse = 0, medium = 1, and fine = 2; where coarse refers to sand, loamy sand, and sandy loam; medium refers to loam, silt, silt loam, sandy clay, and sandy clay loam; and fine refers to clay, silty clay, clay loam, and silty clay loam [39].
Results and Discussion

Effect of tillage

A meta-analysis of nine experiments (Table 1) on the effect of tillage, when other practices, such as cropping systems, fertilization, and farm activities were similar between tillage systems, showed that no-till reduced GWP by 66% and GHGI by 71% compared with conventional till when the all data option of the SOC method of calculating GWP and GHGI was used (Table 6). Using the full accounting data option, no-till reduced GWP by 55% and GHGI by 58% compared with conventional till. With the partial accounting data option, the reductions in GWP and GHGI due to no-till vs. conventional till were 81 and 73%, respectively. Differences in crop yields among cropping systems and variations in soil and climatic conditions among regions resulted in different proportion of reductions in GWP and GHGI due to no-till vs. conventional till. Variability in GWP and GHGI were high, with coefficient of variation ranging from 19 to 91%.

It is not surprising to obtain high variability in GWP and GHGI due to management practices because of extreme variations in GHG values caused by large fluxes from episodic events.

Table 6. Effect of various management practices on net global warming potential (GWP) and greenhouse gas intensity (GHGI) based on the meta-analysis. Values for difference between practices are denoted as mean (± standard error).

| Management practice                           | GWP                                      | GHGI                                      |
|----------------------------------------------|------------------------------------------|-------------------------------------------|
|                                              | N†                                       | Difference between practices              | N                                       | Difference between practices |
|                                              |                                          | kg CO₂ eq. ha⁻¹ yr⁻¹                       | kg CO₂ eq. Mg⁻¹ grain or biomass         |
| Tillage (NT vs. CT)‡                         |                                          |                                           |                                         |
| All data                                     | 9                                        | 1212–3598 = -2386* (±874)                | 6                                        | 292–1008 = -716 (±566)          |
| Full accounting data                         | 6                                        | 1362–2915 = -1553* (±430)                | 3                                        | 126–297 = -171* (±33)           |
| Partial accounting data                      | 3                                        | 924–4965 = -4041 (±2485)                 | 3                                        | 458–1719 = -1261 (±1142)        |
| Cropping system§                             |                                          |                                           |                                         |
| Crop rotation vs. monocrop                   | 11                                       | 987–674 = 313** (±84)                    | 11                                       | 304–215 = 89 (±34)              |
| Corn-soybean vs. continuous corn             | 4                                        | 270–(-234) = 504* (±1114)               | 4                                        | 68–16 = 52 (±52)                |
| Small grain-legume vs. continuous small grain| 3                                        | 649–834 = -185** (±8)                    | 3                                        | - - - -#                        |
| Cropping intensity (1.00 vs. 0.67)          | 11                                       | 827–1319 = -492 (±301)                   | 6                                        | 225–572 = -347** (±64)          |
| Cropping intensity (1.00 vs. 0.50)          | 11                                       | 827–853 = -26 (±426)                    | 6                                        | - - - - -                      |
| Cropping intensity (0.67 vs. 0.50)          | 11                                       | 1319–853 = 466 (±21)                    | 6                                        | - - - - -                      |
| Perennial vs. annual crop                   | 11                                       | (-604)– 885 = -1489*** (±278)            | 6                                        | (-298)– 260 = -558** (±138)     |
| Combined management practice¶               |                                          |                                           |                                         |
| Improved vs. traditional (SOC method)       | 9                                        | 297–2474 = -2177* (±671)                 | 8                                        | 174–582 = -408* (±154)          |
| Improved vs. traditional (Respiration method)| 6                                        | (-1909)– 5741 = -7650** (±1720)          | 5                                        | (-620)– 1068 = -1688** (±315)   |

*Significant at P ≤ 0.05
**Significant at P ≤ 0.01
***Significant at P ≤ 0.001.
† Number of experiments included in the meta-analysis.
‡ Tillage is CT, conventional tillage; and NT, no-tillage. Full accounting data denotes calculation of GWP and GHGI by accounting all sources and sinks of GHGs (N₂O and CH₄ emissions, farm operations, inputs, and soil C sequestration). Partial accounting data denotes partial accounting of sources and sinks (N₂O and CH₄ emissions and/or soil C sequestration). All data denotes inclusions of both full and partial accounting.
§ Small grains include wheat and barley. Cropping intensity was calculated based on number of crops grown in a year.
¶ Combined management practices include combinations of tillage, cropping system, and N fertilization. Improved and traditional management practices were treatments with lowest and highest GWP and GHGI that were calculated by the soil organic C (SOC) and soil respiration method, respectively.
# Insufficient data.

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of tillage, fertilization, precipitation, and snow melt, while variations from farm operations, N fertilization, and other inputs are low [3, 4, 8, 29, 30]. As a result, variability in GWP and GHGI calculated by the partial accounting data option (62 to 91%) was higher than calculated by the full (19 to 28%) accounting data option. The GHG emissions vary not only from one region to another due to differences in soil and climatic conditions, but also by diurnally, seasonally, and annually due to changes in soil temperature and water content in the same region [8, 16, 43]. Reductions in GWP and GHGI in no-till compared with conventional till, regardless of the option used for calculation, showed that increased C sequestration due to reduced soil disturbance and C mineralization reduced GWP and GHGI in no-till [3, 16, 44]. Conventional till increases crop residue incorporation and microbial activity, thereby reducing C sequestration, but increasing GWP and GHGI compared with no-till [8, 45].

Lower GWP and GHGI values due to no-till vs. conventional till in the partial than the full accounting data shows that the partial accounting data calculated greater GHG sink due to the effect of tillage than the full accounting data. This is because CO₂ equivalents from farm operations, N fertilization, and other inputs were not accounted in the partial accounting data. Because all other farming operations were similar, the difference between no-till and conventional till was the use of several tillage operations to prepare a seed bed in conventional till, while soil was not disturbed in no-till. As a result, CO₂ emissions associated with burning of fossil fuel for tractor operation was higher in conventional till than in no-till. Also, ΔSOC was lower in conventional till than no-till. The result was greater differences in GWP and GHGI values between no-till and conventional till in the partial than the full accounting data. It was not surprising that GWP and GHGI values due to no-till vs. conventional till calculated by the all data option were between full and partial accounting data options. Therefore, CO₂ emissions associated with farm operations, N fertilization, and other chemical inputs should be taken into account in addition to those from GHG emissions and soil C sequestration while calculating net GWP and GHGI from agroecosystems.

Changes in GWP and GHGI due to no-till vs. conventional till with experiment duration were linear to curvilinear for all and full accounting data, but linear for partial accounting data (Fig 2). Availability of limited data resulted in fewer data points for GWP and GHGI in the partial accounting data. Both GWP and GHGI increased from 0 to 12 yr of experiment duration and then declined for all and full accounting data, but increased with increased duration of experiment for partial accounting data. This could be explained by several factors: (1) no-till can some time increases N₂O emissions due to increased soil water content and denitrification compared with conventional till, especially in the humid region, thereby increasing GWP and GHGI [13, 16, 44], (2) the potential for soil C sequestration using no-till decreases and reaches a steady state as the duration of the experiment increases [44, 46], and (3) there is a high uncertainty in spatial and temporal variability in GHG emissions within and among regions due to variations in soil and climatic conditions and management practices [8, 16, 29, 30]. As C sequestration rate decreases due to increased C saturation with increased duration of the experiment [40, 44], GWP and GHGI may increase. When soil and climatic conditions, such as soil texture, annual precipitation, and average air temperature of the experimental sites were included in the multiple linear regressions, the relationships were dramatically improved (as indicated by higher R² and lower P values) (Tables 7 and 8). While air temperature had a negative effect on GWP and GHGI, the effect of soil texture varied. As increased air temperature can increase GHG emissions due to accelerated mineralization of SOC, it is likely that increased temperature enhanced rate of SOC mineralization more than the rate of GHG emissions. As a result, temperature had a negative effect on GWP and GHGI. The potentials for reducing GWP and GHGI using no-till compared with conventional till, however, exist after 12 year. This is similar to that found by Six et al. [43] who reported that the benefit of no-till in
reducing GWP and GHGI compared with conventional till was achieved only after 10 yr. Nevertheless, more long-term experiments are needed to relate the effect of tillage with duration of experiment on GWP and GHGI.

Effect of cropping system

An evaluation of eleven experiments on cropping system containing small and large grain crops showed that crop rotation increased GWP by 46% and GHGI by 41% compared with monocropping (Tables 2 and 6). This was especially true for large grain crops, such as corn (Zea mays L.) and soybean (Glycine max L.), where GWP and GHGI were 215 and 325%,
respectively, greater under corn-soybean than continuous corn (Table 6). In contrast, for small grain crops, such as barley (*Hordeum vulgare* L.) and pea (*Pisum sativum* L.), GWP was 22% lower under barley-pea than continuous barley. As cropping intensity increased, GWP and GHGI reduced (Table 6, Fig 3). Both GWP and GHGI were 168 and 215%, respectively, lower with perennial than annual cropping systems. Lack of sufficient data on crop yields prevented for comparison of some treatments for GHGI.

Increased ΔSOC due to greater crop residue returned to the soil reduced GWP and GHGI under continuous corn than corn-soybean rotation, although N fertilization rate to produce sustainable yield was higher in continuous corn [4, 8, 25, 26]. In contrast, greater N₂O emissions following soybean increased GWP and GHGI in corn-soybean rotation [4, 8, 25, 26]. Under small grain crops, however, several researchers [29, 30, 43, 44, 47] have found that including legumes, such as pea and lentil (*Lens culinaris* L.), in rotation with nonlegumes, such as wheat (*Triticum aestivum* L.) and barley, reduced GWP and GHGI compared with continuous nonlegumes. They observed this because (1) no N fertilizer was applied to legumes compared with nonlegumes which required large amount of N fertilizers to sustain yields, as N fertilizer stimulates N₂O emissions and (2) legumes supplied greater amount of N to succeeding crops due to higher N concentration when above- and belowground residues were returned to the soil and reduced N fertilization rate than nonlegumes. Sainju et al. [29, 30] also found that legume-nonlegume rotation increased ΔSOC because of increased turnover rate of plant C to soil C compared with continuous nonlegume. Greater number of experiments and magnitude of changes, however, resulted in higher GWP and GHGI with monocropping than crop rotation under large than small grain crops when values were averaged across experiments during data analysis.

Greater crop residue returned to the soil and increased ΔSOC reduced GWP and GHGI when cropping intensity was increased [28, 29]. Enhanced C sequestration with increased compared with reduced cropping intensity in the semiarid regions with limited precipitation has been well known [48, 49]. Several researchers [8, 28, 29] have found that fallowing or crop-fallow rotation increased GHG emissions and therefore GWP and GHGI compared with continuous cropping due to increased soil temperature and water content that enhanced microbial activity and absence of crops to utilize mineralized N during fallow. Perennial crops can reduce GWP and GHGI due to higher root biomass production [50, 51] and increased C sequestration [12, 45] compared with annual crops [8, 21, 28]. Perennial crops are not usually tilled or applied with fertilizers, herbicides, and pesticides, which reduce GHG emissions compared with annual crops [3].

Changes in GWP and GHGI due to crop rotation vs. monocrop, corn-soybean vs. continuous corn, and perennial vs. annual crop decreased with increased duration of experiment (Fig 3). This suggests that GWP and GHGI can be reduced in the long term by using improved cropping systems, such as crop rotation, intensive cropping, and perennial crops compared with monocropping, crop-fallow, and annual crops. Although corn-soybean increased GWP and GHGI compared with continuous corn in the short term (Table 6), increased C sequestration rate in the long-term may reduce GWP and GHGI with corn-soybean with increased duration of the experiment. It may be possible that duration of obtaining C saturation may be shorter in continuous corn due to higher C sequestration rate than corn-soybean [40]. The relationships were further strengthened, especially for GWP, when soil and climatic conditions were accounted in the multiple linear regressions of GWP and GHGI with the duration of the experiment (Tables 7 and 8). Soil texture had a positive effect on GWP and GHGI for cropping intensity, but negative effect on GWP for crop rotation vs. monocrop and perennial vs. annual crop. The trend was opposite for mean air temperature while annual precipitation had small effect. Because the magnitude of ΔSOC is lower and time for C saturation is longer for cropping
system than for tillage [44, 46], reduced GWP and GHGI for increased cropping intensity, crop rotation vs. monocrop, and perennial vs. annual crop with increased duration of experiment was probably due to increased C sequestration. The results showed that coarse texture soil can enhance GWP and GHGI compared with fine texture when cropping intensity was increased, but reduce GWP when crop rotation instead of monocropping or perennial instead of annual crop were used. The reverse was true in regions with higher than lower air temperature.

**Effect of nitrogen fertilization**

The GWP decreased from 0 to ≤ 88 kg N ha⁻¹ and then increased with increased N fertilization rate for full and partial accounting data as well as all data option (Table 3, Fig 4). Similarly, GHGI decreased from 0 to ≤ 213 kg N ha⁻¹ and then increased with increased N rate for full and partial accounting and all data options. At lowest GWP and GHGI, N rates for the full accounting data were 88 and 145 kg N ha⁻¹ compared with 45 and 213 kg N ha⁻¹, respectively, for the partial accounting data.

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**Table 7. Multiple linear regression analysis of net global warming potential (GWP) with management practices, duration of the experiment, total annual precipitation, mean annual air temperature, and soil texture from various locations.**

| Management practice                      | Intercept | Cropping intensity | N fertilization rate | Duration of the experiment | Total annual precipitation | Mean annual air temperature | Soil texture | R²  | P    |
|------------------------------------------|-----------|--------------------|----------------------|-----------------------------|----------------------------|-----------------------------|--------------|-----|------|
| Tillage (NT vs. CT)†                    |           |                    |                      |                             |                            |                             |              | 0.89| 0.031|
| All data                                 | -680      | -2                 |                      | 302                         | -2                         | -339                        | 3185         | 0.89| 0.031|
| Full accounting data                     | -359      | -2                 |                      | 278                         | -2                         | -94                         | -336         | 0.97| 0.012|
| Partial accounting data                  |           |                    |                      |                             |                            |                             |              |      |      |
| Cropping system‡                         |           |                    |                      |                             |                            |                             |              |      |      |
| Cropping intensity                       | 2619      | -2924              |                      | 343                         | 13                         | -1143                       | 2751         | 0.86| 0.003|
| Crop rotation vs. monocrop               | 281       | -119               |                      | -2                          | 144                        | -96                         | 0.79         | 0.019|
| Corn-soybean vs. corn                    | 1604      | -113               |                      | -2                          | 144                        | -96                         | 0.79         | 0.019|
| Small grain-legume vs. small grain       |           |                    |                      |                             |                            |                             |              | 0.90| 0.005|
| Perennial vs. annual crop                | 5127      | -4824              |                      | -1                          | 328                        | -757                        | 0.99         | 0.002|
| N fertilization rate (kg N ha⁻¹)†        |           |                    |                      |                             |                            |                             |              |      |      |
| All data                                 | -599      | 7.6                |                      | -188                        | 0.06                       | 175                         | 528          | 0.75| 0.011|
| Full accounting data                     | -2872     | 3.2                |                      | 94                          | 106                        | -107                        | -292         | 0.93| 0.0001|
| Partial accounting data                  | 8043      | 7.2                |                      | -3513                       | -5.7                       | 932                         | -2765        | 0.84| 0.0001|
| Combined management practice§            |           |                    |                      |                             |                            |                             |              | 0.85| 0.043|
| Improved vs. traditional (SOC method)    | -7695     | -188               |                      | 757                         | 7                          | -68                         | 381          | 0.85| 0.043|
| Improved vs. traditional (Soil respiration method) | -4753 | 59 | 4 | -52 | -1122 | 0.82 | 0.049 |

† Tillage is CT, conventional tillage; and NT, no-tillage. Full accounting data denotes calculation of GWP and GHGI by accounting all sources and sinks of CO₂ (N₂O and CH₄ emissions, farm operations, inputs, and soil C sequestration). Partial accounting data denotes partial accounting of sources and sinks (N₂O and CH₄ emissions and/or soil C sequestration). All data denotes inclusions of full and partial accounting data.
‡ Small grains include wheat and barley. Cropping intensity was calculated based on number of crops grown in a year.
§ Combined management practices include combinations of tillage, cropping system, and N fertilization. Improved and traditional management were treatments with lowest and highest GWP and GHGI that were calculated by the soil organic C (SOC) or soil respiration method.

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Regardless of the data option used for calculating GWP and GHGI, results showed that increasing N rates to a certain level actually decreased GWP and GHGI, a case similar to that reported by various researchers [4, 18, 29, 30, 52, 53]. These N rates probably corresponded to crop N demand when crops used most of the soil available N, leaving little residual N in the soil that reduced N₂O emissions and therefore GWP and GHGI. When N rates further increased, GWP and GHGI also increased, suggesting that excessive application of N fertilizers can induce net GHG emissions. Therefore, GWP and GHGI can be reduced if N fertilization rate can be decreased without affecting crop yields. Several researchers [3, 4, 29, 30] have reported that N rates to crops can be decreased to reduce GWP and GHGI without influencing crop yields. One practice is to use legume-nonlegume crop rotation where legume can reduce N rate to succeeding nonlegume by supplying more N compared with continuous nonlegume.

Table 8. Multiple linear regression analysis of net greenhouse gas intensity (GHGI) with management practices, duration of the experiment, total annual precipitation, mean annual air temperature, and soil texture from various locations.

| Management practice | Intercept | Cropping intensity | N fertilization rate | Duration of the experiment | Total annual precipitation | Mean annual air temperature | Soil texture | R² | P   |
|---------------------|-----------|---------------------|----------------------|---------------------------|---------------------------|-----------------------------|--------------|-----|-----|
| Tillage (NT vs. CT)† | All data  | 1259                | - - - - - -            | -80                       | 2                         | -17                         | -1147        | 0.80 | 0.045 |
|                     | Full accounting data | 1638                | - - - - - -            | 32                        | -44                       | 5                           | - - -         | 0.94 | 0.015 |
|                     | Partial accounting data | 9428                | - - - - - -            | -126                      | -6                        | -                           | - - -         | 0.74 | 0.075 |
| Cropping system‡    | Cropping intensity | 2385                | -1015                 | 37                        | 1                         | -328                        | 757          | 0.94 | 0.0002 |
|                     | Crop rotation vs. monocrop | -                  | - - - - - -            | -                         | -                         | -                           | - - -         | -    | -    |
|                     | Corn-soybean vs. corn | -                  | - - - - - -            | -                         | -                         | -                           | - - -         | -    | -    |
|                     | Small grain-legume vs. small grain | -        | - - - - - -            | -                         | -                         | -                           | - - -         | -    | -    |
|                     | Perennial vs. annual | -                  | - - - - - -            | -                         | -                         | -                           | - - -         | -    | -    |
|                     | N fertilization rate (kg N ha⁻¹)† | All data  | -1335                | - - - - - -            | 27                        | 15                         | 625                      | -377 | 0.76  | 0.079 |
|                     | Full accounting data | 33.0                | - - - - - -            | 40                        | 0.81                      | -57                        | 146          | 0.82 | 0.002 |
|                     | Partial accounting data | 1034                | - - - - - -            | 0.33                      | 373                       | -0.60                      | 104          | -336 | 0.73  | 0.0002 |
| Combined management practice§ | Improved vs. traditional (Regular method) | -1335                | - - - - - -            | 27                        | 15                         | 625                      | -377 | 0.76  | 0.079 |
|                     | Improved vs. traditional(Alternative method) | -                  | - - - - - -            | -                         | -                         | -                           | - - -         | -    | -    |

† Tillage is CT, conventional tillage; and NT, no-tillage. Full accounting data denotes calculation of GWP and GHGI by accounting all sources and sinks of CO₂ (N₂O and CH₄ emissions, farm operations, inputs, and soil C sequestration). Partial accounting data denotes partial accounting of sources and sinks (N₂O and CH₄ emissions and/or soil C sequestration). All data denotes inclusions of full and partial accounting data.
‡ Small grains include wheat and barley. Cropping intensity was calculated based on number of crops grown in a year.
§ Combined management practices include combinations of tillage, cropping system, and N fertilization. Improved and traditional management were treatments with lowest and highest GWP and GHGI that were calculated by the soil organic C (SOC) or soil respiration method.

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Fig 3. Changes in net global warming potential (GWP) and greenhouse gas intensity (GHGI) due to various cropping systems with the duration of the experiment using the soil organic C method. Because of the lack of sufficient data, only the all data option method of calculating GWP and GHGI were used for meta-analysis.

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Sainju et al. [29] have reported that N rate to dryland malt barley can be reduced by half by adopting malt barley-pea rotation compared while continuous malt barley while maintaining malt barley yield and quality. At 100 kg N ha$^{-1}$ rate, GWP and GHGI were lower with the full accounting data (259 kg CO$_2$ eq. ha$^{-1}$ yr$^{-1}$ and 119 kg CO$_2$ eq. Ma$^{-1}$ grain or biomass, respectively) than the partial accounting data (2948 kg CO$_2$ eq. ha$^{-1}$ yr$^{-1}$ and 371 kg CO$_2$ eq. Ma$^{-1}$ grain or biomass, respectively). This is in contrast to the effect of tillage where GWP and GHGI were higher with full than partial accounting data. This suggests that, as with tillage comparison, GWP and GHGI values calculated by using the partial accounting data were overestimated and that CO$_2$ equivalents associated with farm operations, N fertilization, and other chemical inputs should be accounted in addition to those from GHG emissions and ΔSOC when calculating net GWP and GHGI [21, 23, 24].
The relationships between GWP, GHGI, and N rate were further improved when duration of the experiment and soil and climatic factors were taken into account in the multiple linear regression (Tables 7 and 8). Duration of experiment and annual precipitation had positive effects, but air temperature and soil texture had negative effects on GWP when the full accounting data was used. With the partial accounting data, only air temperature had positive effect on GWP, but other factors had negative effects. For GHGI, the factors having negative effects were air temperature using the full accounting data and soil texture using the partial accounting data. Annual precipitation had minor effect on GWP and GHGI, a case similar to that observed for the effect of tillage.

**Effect of combined management practice**

Using the all data option, the improved combined management practice that included no-till, diversified cropping system (crop rotation, increased cropping intensity, and perennial crop), and reduced N rate decreased GWP and GHGI by 70 to 88% compared with the traditional combined practice that included conventional till, less diversified cropping system (monocropping, crop-fallow, and annual crop), and recommended N rate (Tables 4 and 6). When compared with individual management practices, these reduction values were greater, such as 66 to 71% reductions for GWP and GHGI obtained with no-till vs. conventional till or -46 to -41% reductions with crop rotation vs. monocrop. Using the soil respiration method, reductions in GWP and GHGI were even higher, representing 133 to 158% reductions with the improved combined management practice compared with the traditional combined management practice (Tables 5 and 6).

These results clearly showed that the improved management practice can reduce GWP and GHGI compared with the traditional management practice, regardless of the methods used for calculating GWP and GHGI. Further reduction in the magnitudes of GWP and GHGI showed that the combined management practices may be more effective in reducing net GHG emissions than the individual practices, a case similar to those reported by various researchers [4, 8, 26, 29, 30]. The results also suggest that the soil respiration method may show greater GHG sink values for comparison of management practices than the SOC method [4, 28, 29, 30].

Using the SOC method, changes in GWP due to improved vs. traditional combined management practice increased from 0 to 3.5 yr of experiment duration and then decreased (Fig 4). Changes in GHGI, however, increased with increased duration of the experiment. In contrast, changes in GWP and GHGI using the soil respiration method were either not affected by or declined with the duration of the experiment. The relationships were further improved by including soil and climatic factors in the multiple linear regressions (Tables 7 and 8). As with the effect of individual management practices, some of the possible reasons for increased GWP and GHGI for improved vs. traditional combined management with increased duration of the experiment using the SOC method are: (1) high spatial and temporal variations of GHG emissions due to differences in soil and climatic conditions and management practices, (2) reduced potential for soil C sequestration with increasing duration of the experiment, (3) use of full or partial accounting data option for calculating GWP and GHGI, and (4) uncertainty in the methods of measuring GHG emissions, such as variations in type and size of static chambers, placement of chamber in the plot (row vs. inter-row or including vs. excluding plants in the chamber), time of GHG measurement during the day, and calculation of GHG fluxes (linear or nonlinear emissions with time). Results, however, indicate that GWP and GHGI can be reduced in the long term as duration of the experiment is increased, regardless of the method used. As a result, more long-term experiments may be needed to properly evaluate the effect of combined management practices on GWP and GHGI.
Comparison of the methods of measurement

Both GWP and GHGI using SOC and soil respiration methods were lower with the improved combined management practice than the traditional combined management practice (Table 6). The GWP and GHGI measured with the soil respiration method were three to four times lower than those with the SOC method. Furthermore, changes in GWP and GHGI due to combined improved vs. combined traditional management practice were either not affected or decreased with the duration of experiment with the soil respiration method, but increased with the SOC method (Fig 5). This indicates that improved management practices may act more towards GHG sink than the traditional management practices using the soil respiration method compared with the SOC method. Similar results have been reported by various researchers [4, 28, 29, 30] who observed that most treatments were sources (or positive values) of GWP and GHGI when measured by using the SOC method, but sinks (or negative values) when measured by the soil respiration method. It is difficult to examine with the limited amount of data at present about which method provides efficient and accurate measurement of GWP and GHGI because of limitations, such as high variability in GHG emissions, slow changes in soil organic C levels, and differences in crop yields from year to year due to climatic conditions. More studies, however, are needed to accurately evaluate the effectiveness of each method on GWP and GHGI as affected by management practices.

Several researchers [4, 8, 29, 30] have reported that GWP and GHGI calculated by the soil respiration method had more variability than those calculated by the SOC method due to
differences in CO₂ emissions and crop residue production from year to year. This was against the results obtained in this study where coefficient of variations were 22% for GWP and 19% for GHGI calculated by the soil respiration method compared with 31 and 38%, respectively, calculated by the SOC method for combined management practices (Table 6). The SOC method is also subjected to high spatial variability due to interference from soil inorganic C, besides variability in GHG emissions [4, 8, 29, 30].

There are several benefits and drawbacks of each method. The soil respiration method may provide quick results for GWP and GHGI compared with the SOC method, since only two years of experimentation are required when the amount of crop residue returned to the soil in the previous year is known. Information on C contributions from roots and rhizodeposit from previous crop can further reduce GWP and GHGI calculated by this method [29, 30]. Such factors, however, are not usually measured in most experiments. Loss of previous crop residue due to the actions of wind and water or crop failure due to drought, especially in dryland cropping systems, can contribute significant errors in the calculation of GWP and GHGI in this method. Other needed information is soil respiration where the value of root respiration is excluded. Although the SOC method is a standard method and requires fewer parameters for calculating GWP and GHGI, it may take long time to measure these parameters using this method, because the process of C sequestration is slow and ΔSOC depends on soil and climatic conditions. In some cases, the benefits of management practices, such as no-till compared with conventional till, in reducing GWP and GHGI by the SOC method may not be realized after 10 yr [44]. While soil respiration and the amount of crop residue returned to the soil were the driving factors for GWP and GHGI in the soil respiration method, N₂O emissions were the dominant factor in the SOC method. This study showed that GWP and GHGI calculated by the soil respiration method have potentials to decrease with increased duration of the experiment, which are in contrast to those obtained by the SOC method (Fig 5).

The notion that the soil respiration method showed greater reductions in GWP and GHGI than the SOC method may sometime provide false conclusions, especially during dry years when crop yields can be lower and GHG emissions can be higher, resulting in net CO₂ source [29, 30]. During years with above-average precipitation, crop yields and the amount of crop residue returned to the soil can be greater, resulting in lower GWP and GHGI as measured by this method. In contrast, C sequestration is largely controlled by soil and climatic conditions among regions in the SOC method, although C input from crop residue can influence ΔSOC. Carbon sequestration rate can be higher in fine than in coarse-textured soil [29, 30]. Similarly ΔSOC can be greater in cold than in warm regions or higher in irrigated than dryland cropping systems. These factors add uncertainty in the measurements of GWP and GHGI in the SOC method. Both methods, however, showed that improved management practices, such as no-till continuous cropping with optimum N fertilization rate, can reduce GWP and GHGI compared with traditional practices, such as conventional till with crop-fallow and recommended N fertilization rate, a case similar to that reported by various researchers [4, 29, 30].

Conclusions

Analysis of available global data revealed that improved management practices, such as no-till, diversified cropping systems, and reduced N fertilization rate, either as individually or in combination, reduced GWP and GHGI compared with traditional management practices, such as conventional till, less diversified cropping system, and recommended N rate. Changes in GWP and GHGI due to tillage practices were greater than changes due to cropping systems and N rates. Improved combined management practices further reduced GWP and GHGI compared with improved individual management practices. Adopting improved management practices
for a longer period can further reduce GWP and GHGI. The GWP and GHGI values can be overestimated when indirect GHG emissions due to farm operations, N fertilization, and other chemical inputs were not accounted for. Both soil respiration and SOC methods showed similar results of measuring GWP and GHGI as affected by management practices. Although the soil respiration method may provide quick results for GWP and GHGI which can be higher for improved management practices than measured by the SOC method, greater variability in GHG measurements and crop yields from year to year suggest that more long-term studies are needed to accurately measure the effect of management practices on GWP and GHGI using both methods.

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Author Contributions

Conceived and designed the experiments: UMS. Performed the experiments: UMS. Analyzed the data: UMS. Contributed reagents/materials/analysis tools: UMS. Wrote the paper: UMS.

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