Nitrogen (N) is essential for life on Earth, but excess N causes pollution — in the form of nitrous oxide and ammonia in the atmosphere and nitrate in the water — that has a major impact on human and ecosystem health. Annual damages from N pollution are estimated to exceed $200 billion in the U.S.\(^1\) and up to $500 billion in Europe.\(^2\)

N losses to the environment are invisible and have historically been difficult to measure and monitor. N balance — the difference between N inputs to and N outputs from a field over the course of a year or crop rotation — overcomes those challenges. It provides a user-friendly, scientifically robust way to assess environmental results.
Previous methods of measuring N losses

Over the years, Environmental Defense Fund has assessed and tried many approaches to helping farmers and supply chain companies measure progress in reducing N pollution at scale. Time and again, we found that existing ways to measure excess N are expensive, inaccurate and difficult to scale.

Direct measurement

Directly measuring changes in emissions of nitrous oxide to air and nitrate to water is prohibitively expensive to do at the scale needed. For nitrous oxide, the fact that most is emitted at highly variable "hot spots" and "hot moments" means that a dense network of continuously running sensors would need to be installed. For nitrate, in-stream monitoring can aggregate losses across many fields, meaning that fewer sensors are needed than for nitrous oxide, but legacy or time lag effects may make it difficult to discern the signal of present-day changes from the background of historic losses.

Practices as proxy

Because of the downsides of direct measurement, public and private entities have tended to rely on a "practices as proxy" approach to tracking N losses. This approach assumes that a given agricultural conservation practice has a fixed effect on nitrous oxide or nitrate losses. Thus, it would be possible to estimate total impacts on N losses by counting the acres on which those practices have been adopted.

Unfortunately, the scientific literature shows that the impact of a practice on N losses is highly variable over space and time, depending on soil type, weather, landscape position and previous management history. A practice that reduces nitrous oxide or nitrate losses in one field in one year may increase them in the next year, reduce them in one field while increasing them in an adjacent field, or have opposite effects on different N loss pathways.

Complex models

Faced with the highly variable and unpredictable relationship between conservation practices and N losses, EDF and others have explored the use of complex "process-based" biophysical models to track changes in N losses. These models — for example DayCent for nitrous oxide emissions and the Soil and Water Assessment Tool for nitrate losses — can be incredibly powerful when used properly.

The models are most effective when used at local scales where large amounts of input data are available. Relying on these models at a supply chain scale, however, is fraught with difficulties. The models have rarely been calibrated and validated for the array of cropping systems, soil types and climates that are represented in even a simple supply chain, and the local input data needed to make the models run properly is usually lacking.

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1. Sobota et al., 2015.
2. Van Grinsven et al., 2013.
4. Puckett et al., 2011.
6. Tonitto et al., 2018; Ehrhardt et al., 2019; Olander, 2013.
Scientific consensus that N balance is a better approach

N balance is widely accepted by scientists as the preferred metric for measuring the risk of N losses to the environment, reflecting impacts on both climate and water quality.

EDF brought together scientists and agriculture sector stakeholders for a 2017 workshop to consider a different approach to measuring N losses, one that would improve upon the challenges related to direct measurement, practice as proxy and biophysical models.

Our criteria were that the approach had to be:

1. Scientifically robust (i.e., linked strongly to N losses to the environment).
2. Easy to implement in the supply chain context (i.e., capable of being aggregated at a large scale, across multiple soil types, climates and cropping systems and using very limited input data).
3. Meaningful to farmers (i.e., based on N input variables that are within farmers’ control and helpful for showing the connection between management changes and N losses at the field and farm scale).

The outcome of that workshop was agreement that N balance was a promising approach. The next step was to review the evidence showing a relationship between N balance and N losses to the environment.

EDF convened a wide array of scientists from across North America and Europe in 2019 to do just that. We discovered numerous peer-reviewed publications in which scientists reported on this relationship over a wide array of cropping systems and climates in Europe, North America and Asia. Participating scientists agreed that the existing science showed a consistent relationship between N balance and N losses (Figure 1).

In addition, we learned that in Europe, where farmers have significantly reduced their N balance scores over the past 25 years, improvements in N balance led to improvements in water quality — average nitrate levels in groundwater and loads in rivers have declined — at regional and national scales.

This body of evidence has led to a scientific consensus that the relationship between N balance and N losses to the environment is robust at a variety of scales.

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7 Attendees represented: Agricultural Retailers Association, American Society of Agronomy, Cornell University, The Fertilizer Institute, Field to Market, International Plant Nutrition Institute, Iowa Soybean Association, Iowa State University, Michigan State University, National Association of Wheat Growers, National Corn Growers Association, The Nature Conservancy, Nebraska Corn Board, NC State University, Soil Health Partnership, United Soybean Board, US Agency for International Development, US Department of Agriculture, University of California-Davis, University of Illinois, University of Maryland, University of Minnesota, University of Missouri, University of Nebraska-Lincoln, University of Wisconsin, and World Wildlife Fund.

8 Attendees represented Cornell University, International Plant Nutrition Institute, MyFarms, Planterra, Purdue University, University of California – Davis, University of Guelph, University of Illinois, University of Maryland, University of Nebraska – Lincoln, Wageningen University.
Environmental models measure environmental outcomes at scale

EDF developed two empirical models that enable supply chain companies, policymakers and others to translate aggregated\textsuperscript{10} field-level changes in N balance into improvements in environmental outcomes, specifically reductions in nitrous oxide emissions and nitrate leaching.

Working with scientists from Cornell University and the University of Nebraska, we published preliminary models for the relationship between N balance, nitrous oxide and nitrate for corn grown with synthetic fertilizer on silt loam soils in the Corn Belt.\textsuperscript{11}

Since then, we have collaborated with scientists from land-grant universities, government agencies and other institutions across North America\textsuperscript{12} to refine the models using additional data from more diverse cropping systems, soils, regions and N sources.\textsuperscript{13}

As a result, we have developed a refined model for the relationship between N balance and nitrous oxide emissions, which can be used broadly across all cropping systems in temperate climates, regardless of soil type and N source. This model was published in a peer-reviewed journal in September 2020.\textsuperscript{14} A similar generalized model representing the relationship between N balance and nitrate leaching has also been submitted for peer review, with publication expected in early 2021.

To account for the impacts of annual weather variability, we recommend monitoring changes in N balance and modelled environmental outcomes over a three-to-five-year moving average to best understand progress toward environmental goals.

EDF and partners will continue to refine these environmental models over time to meet the ever-increasing demand for their implementation across crops and regions within and beyond North America. We are confident that food supply chain companies, agricultural stakeholders and policymakers will embrace N balance as a scientifically robust, easy to implement way of measuring progress, improving water quality and reducing greenhouse gas emissions.

\textsuperscript{9} Hansen et al., 2017; Windolf et al., 2012.

\textsuperscript{10} Our models are statistically robust when data are aggregated across hundreds of fields, for example across a grain company’s sourcing region.

\textsuperscript{11} McLellan et al., 2018.

\textsuperscript{12} EDF scientists collaborated with scientists from Purdue University, University of California-Davis, University of Illinois, University of Maryland, University of Nebraska, as well as Agriculture and Agri-Food Canada and the International Plant Nutrition Institute.

\textsuperscript{13} We refined the models with data from: 1) additional cropping systems — barley, canola, corn-grain, corn-silage, oilseed rape, sugar beet, and wheat — 2) additional soil types — clay, clay loam, fine sandy loam, loam, loamy sand, sand, sandy clay loam, sandy loam, silty clay loam and silt loam — 3) additional regions — eastern and central Canada, eastern and central U.S. and Europe — and 4) additional N sources — ammonia nitrate, anhydrous ammonia, calcium ammonium nitrate, cattle manure, hog manure, polymer-coated urea, SuperU, UAN and urea

\textsuperscript{14} Eagle and McLellan, et al. 2020
References


How to Calculate Nitrogen Balance

Nitrogen balance, or N balance, is the difference between nitrogen added to a farm field minus nitrogen removed during harvest. The remaining N is vulnerable to being lost to the environment as nitrous oxide and nitrate.

This guide explains how to calculate N balance when N is added as synthetic fertilizer, manure or legumes, and when N is removed via a cash crop harvest or as crop residue such as straw or stover.

Throughout, equations use imperial U.S. units, and sample calculations are provided in both imperial and metric units. Be sure to double-check all units and unit conversions.
The **N balance** equation

N balance is calculated by:

\[
\text{N balance} \left( \frac{\text{lbs. N}}{\text{acre}} \right) = \text{Total\_N\_Applied} \left( \frac{\text{lbs. N}}{\text{acre}} \right) - \text{N\_Removed} \left( \frac{\text{lbs. N}}{\text{acre}} \right)
\]

Details on how to determine N\_Removed and Total\_N\_Applied, as well as sample N balance calculations, are provided below.

### How to determine N\_Removed

The amount of N\_Removed at harvest is calculated by:

\[
\text{N\_Removed} \left( \frac{\text{lbs. N}}{\text{acre}} \right) = \left[ \text{Grain\_N} \left( \frac{\text{lbs. N}}{\text{bu grain}} \right) \times \text{Crop\_Yield} \left( \frac{\text{bu grain}}{\text{acre}} \right) \right]
+ 0.5 \times \left[ \text{Grain\_N} \left( \frac{\text{lbs. N}}{\text{bu grain}} \right) \times \text{Crop\_Yield} \times \%\text{Stover\_Removed} \right]
\]

where N\_Removed is the total N\_Removed in the crop grain and stover, Grain\_N is the concentration of N in the crop (e.g., the amount of N in each metric ton or bushel of grain) and Crop\_Yield is the grain yield at standard moisture content (e.g., at 15.5% moisture for corn grain). To calculate the amount of N\_Removed in stover (if applicable), the N harvest index of 0.5\(^1\), Grain\_N, Crop\_Yield and %Stover\_Removed are multiplied.

Grain\_N can be measured by testing a sample of grain for N content or by using the standard nutrient removal estimates from the International Plant Nutrition Institute (IPNI)\(^2\).

### How to determine Total\_N\_Applied

Total\_N\_Applied includes N from fertilizer, manure or legumes\(^3\), depending on which sources are added to a farm field:

\[
\text{Total\_N\_Applied} = \text{Fertilizer\_N} \left( \frac{\text{lbs. N}}{\text{acre}} \right) + \text{Manure\_N} \left( \frac{\text{lbs. N}}{\text{acre}} \right) + \text{Legume\_Fixed\_N} \left( \frac{\text{lbs. N}}{\text{acre}} \right)
\]

where Fertilizer\_N is total N added in fertilizer, Manure\_N is total N added in manure\(^4\) and Legume\_Fixed\_N is N converted from the air into a plant-useable form by rhizobia on the legume roots, also known as biological N fixation (BNF).

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1 Nitrogen harvest index = ratio of Stover\_N to Grain\_N (e.g., for each bushel of corn grain, IPNI estimates 0.33 lbs. Stover\_N and 0.67 lbs. Grain\_N) = 0.5.
2 See Appendix A.
3 This method of incorporating manure and/or legumes is based on the best available science. EDF is continuing to advance this research, and we expect that the methodology will continue to be refined as the science progresses.
4 To simplify N balance calculations and account for all N sources, we use manure total N, rather than available N. One reason why is that manure application rate determinations generally also consider the proportion of Manure\_N from current and prior years available in the current year.
**Example calculations with synthetic fertilizer:**

Data needed: **Fertilizer_N** (required), **Crop_Yield** (required), **Grain_N** (optional), **%Stover_Removed** (optional)

**Example 1 (imperial units)**
- 195 lbs. N fertilizer per acre (**Total_N_Applied = Fertilizer_N**)
- 200 bu per acre corn grain, at 15.5% moisture (**Crop_Yield**)
- 50% stover removed from field at harvest

\[ N_{\text{Removed}} = N_{\text{Removed}} \text{ in grain} + N_{\text{Removed}} \text{ in stover} \]
\[ = [0.67 \text{ lbs. N/bu corn} \times 200 \text{ bu/acre}] + [0.5 \times 0.67 \text{ lbs. N/bu corn} \times 200 \text{ bu/acre} \times 50\%] = 168 \text{ lbs. N/acre} \]

**N balance** = 195 lbs. N/acre — 168 lbs. N/acre = **27 lbs. N/acre**

**Example 2 (metric units)**
- 200 kg N fertilizer per hectare (**Total_N_Applied = Fertilizer_N**)
- 12.5 t/hectare corn grain, at 15.5% moisture (**Crop_Yield**)

\[ N_{\text{Removed}} = 12 \text{ kg N/t corn} \times 12.5 \text{ t/hectare} = 150 \text{ kg N/hectare} \]

**N balance** = 200 kg N/hectare — 150 kg N/hectare = **50 kg N/hectare**

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**Manure_N**

**Manure_N** depends on both the amount of manure applied (**Manure_Applied**) and its N content (**Manure_Test_N**, e.g., “as is” laboratory values that account for moisture content):\(^6\)

\[ \text{Manure_N} = \frac{\text{Manure Test N}}{\text{acres}} \times \text{Manure Applied} \]

**Example calculations with manure:**

Data needed: **Fertilizer_N** (required), **Crop_Yield** (required), **Grain_N** (optional), **Manure_Applied** (required), **Manure_Test_N** (required), and **Manure_Dry_Matter** (if **Manure_Test_N** is % of dry matter instead of “as is”).

**Example 1 (imperial units)**
- 75 lbs. N fertilizer per acre (**Fertilizer_N**)
- 4,000 lbs. (2 tons) poultry litter per acre (**Manure_Applied**), 50 lbs. N/ton “as is” (**Manure_Test_N**)
- 200 bu per acre corn grain, at 15.5% moisture (**Crop_Yield**)

\[ N_{\text{Removed}} = 0.67 \text{ lbs. N/bu corn} \times 200 \text{ bu/acre} = 134 \text{ lbs. N/acre} \]

\[ \text{Manure N} = 50 \text{ lbs. N/ton} \times 2 \text{ tons/acre} = 100 \text{ lbs. N/acre} \]

\[ \text{Total N Applied} = \text{Fertilizer N} + \text{Manure N} = 75 \text{ lbs. N/acre} + 100 \text{ lbs. N/acre} = 175 \text{ lbs. N/acre} \]

**N balance** = 175 lbs. N/acre — 134 lbs. N/acre = **41 lbs. N/acre**

**Example 2 (metric units)**
- 0 lbs. N fertilizer per acre (**Fertilizer_N = 0**)
- 3,000 kg (3 t) poultry litter per hectare (**Manure_Applied**), 75 kg N/t “as is” (**Manure_Test_N**)
- 12.5 t/hectare corn grain, at 15.5% moisture (**Crop_Yield**)

\[ N_{\text{Removed}} = 12 \text{ kg N/t corn} \times 12.5 \text{ t/hectare} = 150 \text{ kg N/hectare} \]

\[ \text{Manure N} = 75 \text{ kg N/t} \times 3 \text{ t/hectare} = 225 \text{ kg N/hectare} \]

\[ \text{Total N Applied} = \text{Manure N} = 225 \text{ kg N/hectare} \]

**N balance** = 225 kg N/hectare — 150 kg N/hectare = **75 kg N/hectare**

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\(^6\) Calculations use the IPNI standard Grain_N of 0.67 lbs. N/bu corn (12 kg N/t grain corn).

\(^7\) **Manure_Test_N** (in lbs. N/ton or kg N/Mg) may also be calculated by correcting dry matter N concentrations (e.g., g N/kg dry manure) by the measured moisture content.
**Legume_Fixed_N**

For legumes, it is impractical to measure BNF at a field level, so the N balance calculation instead uses an estimate of the BNF as a standard proportion of legume yield.\(^7\)

**Legume_Fixed_N_Soybean**

For soybeans, the total N fixed is approximately equal to 79% of soybean Grain_N.

The equation for soybeans is thus:

\[
\text{Legume_Fixed}_N\_{\text{Soybean}} = 0.79 \times \text{Grain}_N
\]

\[
\quad \left( \frac{\text{lbs. N}}{\text{acre}} \right) \times \left( \frac{\text{lbs. N}}{\text{acre}} \right)
\]

where Legume_Fixed_N in this case is the total amount of BNF for soybeans.

**Legume_Fixed_N_Cover_Crop**

Winter cover crops that include legumes will also add N to the system. For these crops, use a conservative estimate of 50% of aboveground N coming from N fixation.

If a cover crop is composed of a mixture of legumes and non-legumes, this value is then adjusted by the proportion of legumes in the total biomass (preferred) or the proportion of legumes in the seed mixture (if biomass not available).

The equation for legume cover crops is thus:

\[
\text{Legume_Fixed}_N\_{\text{Cover_Crop}} = 0.50 \times \text{Cover_Crop}_Biomass_N
\]

\[
\quad \left( \frac{\text{lbs. N}}{\text{acre}} \right) \times \left( \frac{\text{lbs. N}}{\text{acre}} \right)
\]

where Cover_Crop_Biomass_N is the total aboveground amount of N in the cover crop.\(^8\)

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**Example calculations with a legume cash crop:**

Data needed: Crop_Yield (required) and Grain_N (optional)

<table>
<thead>
<tr>
<th>Example 1 (imperial units)</th>
<th>Example 2 (metric units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean crop of 40 bu per acre, at 13% moisture (Crop_Yield)(^9)</td>
<td>Soybean crop of 2.5 t/hectare, at 13% moisture (Crop_Yield)</td>
</tr>
<tr>
<td>(N_{\text{Removed}} = 3.3 \text{ lbs. N/bu soybeans} \times 40 \text{ bu/acre} = 132 \text{ lbs. N/acre})</td>
<td>(N_{\text{Removed}} = 55 \text{ kg N/t soybean} \times 2.5 \text{ t/hectare} = 137.5 \text{ kg N/hectare})</td>
</tr>
<tr>
<td>(\text{Legume_Fixed}_N = 0.79 \times 132 \text{ lbs. N/acre} = 104.3 \text{ lbs. N/acre}) ((= \text{Total}_N_\text{Applied} \text{ in this case}))</td>
<td>(\text{Legume_Fixed}_N = 0.79 \times 137.5 \text{ kg N/hectare} = 108.6 \text{ kg N/hectare}) ((= \text{Total}_N_\text{Applied} \text{ in this case}))</td>
</tr>
<tr>
<td>(N \text{ balance} = 104.3 \text{ lbs. N/acre} - 132 \text{ lbs. N/acre} = -27.7 \text{ lbs. N/acre})</td>
<td>(N \text{ balance} = 108.6 \text{ kg N/hectare} - 137.5 \text{ kg N/hectare} = -29 \text{ kg N/hectare})</td>
</tr>
</tbody>
</table>

---

\(^7\) See Appendix B for the rationale underlying assumptions about BNF portion of Legume_N.

\(^8\) See Appendix B for an alternative method to calculating N Balance when Cover_Crop_N is unknown.

\(^9\) Soybean examples assume no Fertilizer_N and use IPNI standard Grain_N of 55 kg N/t soybean (3.3 lbs. N/bu soybean).
**Example calculations with corn following a legume cover crop:**

Data needed: *Fertilizer_N* (required), *Crop_Yield* (required), *Grain_N* (optional), *Cover_Crop_Dry_Biomass* (required), and *Cover_Crop_N* (optional)\(^\text{11}\)

### Example 1 (imperial units)

Red clover cover crop, 1,600 lbs./acre dry matter (Cover_Crop_Dry_Biomass), 3.5% N (Cover_Crop_N) \(^\text{10}\)

- 150 lbs. N fertilizer per acre (*Fertilizer_N*)
- 200 bu per acre corn grain, at 15.5% moisture (*Crop_Yield*)
- \(N_{\text{Removed}} = 0.67 \text{ lbs. N/bu corn} \times 200 \text{ bu/acre} = 134 \text{ lbs. N/acre}\)
- \(\text{Cover_Crop_Biomass}_N = 1,600 \text{ lbs./acre} \times 3.5\%\ N = 56 \text{ lbs. N/acre}\)
- \(\text{Legume}_{\text{Fixed}}_N = 0.50 (\% \text{ N that is BNF}) \times 56 \text{ lbs. N/acre} = 28 \text{ lbs. N/acre}\)
- \(\text{Total}_N_{\text{Applied}} = \text{Fertilizer}_N + \text{Legume}_{\text{Fixed}}_N = 150 \text{ lbs. N/acre} + 28 \text{ lbs. N/acre} = 178 \text{ lbs. N/acre}\)
- \(N_{\text{balance}} = 178 \text{ lbs. N/acre} — 134 \text{ lbs. N/acre} = 44 \text{ lbs. N/acre}\)

### Example 2 (metric units)

50:50 mix of red clover and rye, 1,600 kg/hectare dry matter (Cover_Crop_Dry_Biomass), 3.5% N (Cover_Crop_N) \(^\text{10}\)

- 160 kg N fertilizer per hectare (*Fertilizer_N*)
- 12.5 t/hectare corn grain, at 15.5% moisture (*Crop_Yield*)
- \(N_{\text{Removed}} = 12 \text{ kg N/t corn} \times 12.5 \text{ t/hectare} = 150 \text{ kg N/hectare}\)
- \(\text{Cover_Crop_Biomass}_N = 1,600 \text{ kg/hectare} \times 3.5\%\ N = 56 \text{ kg/hectare}\)
- \(\text{Legume}_{\text{Fixed}}_N = 0.50 (\% \text{ red clover}) \times 0.50 (\% \text{ N that is BNF}) \times 56 \text{ kg/hectare} = 14 \text{ kg N/hectare}\)
- \(\text{Total}_N_{\text{Applied}} = \text{Fertilizer}_N + \text{Legume}_{\text{Fixed}}_N = 160 \text{ kg N/hectare} + 14 \text{ kg N/hectare} = 174 \text{ kg N/hectare}\)
- \(N_{\text{balance}} = 174 \text{ kg N/ha} — 150 \text{ kg N/ha} = 24 \text{ kg N/hectare}\)

---

\(^{10}\) While non-legume cover crops capture or scavenge N from the soil — preventing losses and keeping those nutrients in the system for following crops — they do not actually add any N to the system. Thus, non-legume cover crops do not appear in the N balance equations.

\(^{11}\) See Appendix B for guidance on cover crop biomass calculations.
Appendix A: Crop-specific nutrient removal estimates ("book" values)

IPNI provides nutrient removal estimates\textsuperscript{12} (i.e., the amount of N in each ton or bushel of harvested crop) that may be used as \textit{Grain}\textsubscript{N} in the \textit{N balance} calculation. Note that N removal is different from N uptake per unit, the latter of which is total N accumulated in the aboveground plant parts — including straw, stover and residue, in addition to grain.

\textbf{IPNI estimates for the amount of N removal by select crops, imperial units (metric units in parentheses)}

<table>
<thead>
<tr>
<th>Crop,</th>
<th>Grain\textsubscript{N}</th>
<th>Silage\textsubscript{N}</th>
<th>Stover\textsubscript{N}</th>
<th>Fall\textsubscript{N}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn, grain (standard marketing convention, 15.5% moisture)</td>
<td>0.67 lbs./bu (12 kg/t)</td>
<td>9.7 lbs./ton* (4.9 kg/t)</td>
<td>0.33 lbs./bu (8.0 kg/t)**</td>
<td>3.3 lbs./bu (55 kg/t)</td>
</tr>
<tr>
<td>Corn, silage (67% water)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn, stover</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean, grain (standard marketing convention, 13% moisture)</td>
<td>3.3 lbs./bu (55 kg/t)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat, spring (standard marketing convention, 13.5% moisture)</td>
<td>1.5 lbs./bu (25 kg/t)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat, winter (standard marketing convention, 13.5% moisture)</td>
<td>1.2 lbs./bu (19 kg/t)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\* Note that here, “t” is the imperial ton, which is equal to 2,000 lbs.

\** This is the IPNI value for total nutrient uptake for corn with the subtracted IPNI corn grain value (1.0 lbs. N/bu – 0.67 lbs. N/bu = 0.33 lbs. N/bu).

If measured values for \textit{Grain\textsubscript{N}} are not available, IPNI nutrient removal estimates provide a useful book value because:

- The IPNI nutrient removal estimates are well-known values that are used by or familiar to many crop consultants, farmers and researchers.

- Recent data on grain corn N from the Corn Belt\textsuperscript{13} suggests that the IPNI value of 1.4\% N is a good estimate of the mean corn grain N (dry). The IPNI value of 12 kg N/t grain at 15.5\% moisture is equivalent to 14.2 kg N/t grain (1.42\% N) in the grain on a dry matter basis. With some variability around the mean, it may be possible to fine-tune this value further, but any resulting differences are likely to be within ±20 kg N/hectare, which would not change N balance enough to be significant.

- Using data about corn grain yield and fertilizer N application from on-farm trials,\textsuperscript{14} EDF calculated N balance using both the IPNI estimate and an empirical equation we derived from peer-reviewed published data. The N balance produced by the two methods differed somewhat, but 95\% of the N balance values calculated using the IPNI estimate were within 30 kg N/hectare of the value from the empirical equation. The IPNI estimate is preferable because it is less complex than the empirical equation.

- IPNI has a commitment to update these values with current data on a regular basis (when deemed necessary).

\textsuperscript{12} Nutrient removal estimates for N, phosphorus and potassium are available at http://www.ipni.net/article/IPNI-3296.

\textsuperscript{13} Tenorio et al., 2019, which used more than 10,000 observations from 1999 through 2016.

\textsuperscript{14} Field data from 2015 included 66 observations of farmers’ normal fertilizer practices for a corn crop that followed a soybean crop.
Appendix B: Legume nitrogen fixation

The N in legume crops, including winter cover crops, comes both from the soil and from N fixed by rhizobium bacteria on the legume roots. For a field with little soil N supply, nearly all the N in the crop is added to the system by BNF, i.e., from the $N_2$ in the air.

When soil N supply is unknown, use standard assumptions to estimate N added by legume fixation. While the rate of N fixation (% N from BNF) varies — between species, from year to year and by location — total legume biomass production, in general, has a stronger impact on total mass of N fixed than does % legume N from fixation. This provides support for using standard values of % N from fixation, in the absence of better information.

Soybeans

The soybean BNF value comes from the work of several researchers whose published estimates are based on experiments that measured soybean N fixation in the U.S. Corn Belt.

David et al. showed a linear increase in soybean N fixation from 50% in 1985 to 60% in 2006 of aboveground N (with an 80% N harvest index). Other researchers then used variations on this method for numerous calculations of N balance. Blesh and Drinkwater, for example, “assumed that 57% of aboveground soybean N was from fixation.” McIsaac et al. extended the increasing BNF rate in soybean beyond that of David et al., reaching 63% of total aboveground N from BNF as of 2014.

An aboveground N uptake of 63% with an N harvest index of 80% is equal to 78.75% of $Grain_N$ (0.63/0.8 = 0.7875). This is rounded up to 79%. Following past research, and with little precedent to do otherwise, estimates do not at this time account for root N that originated from BNF. For example, if N removal is 55 kg N/ton and N harvest index is 80%, then total N uptake (grain plus residue) would be 69 kg N/ton. Sixty-three percent of this is 43 kg N/ton of grain, or 78.75% of $Grain_N$.

In comparison, IPNI nutrient removal estimates assume that BNF is equal to N removal by soybeans, as well as for peanuts and alfalfa. Using the IPNI assumptions — 100% of the 55 kg N/ton removed is BNF and the soybean harvest N index is 67% — the resulting BNF for soybeans is thus 100% × 67%, or 67% of total aboveground N. Since this value is close to the 63% of aboveground N from McIsaac et al., use the conservative estimate of McIsaac et al. — 79% of $Grain_N$.

Fertilization — and by extension, differences in soil N supply — has a big effect on the proportion of total plant N coming from BNF. Gelfand and Robertson compared non-nodulating soybeans against nodulating lines and found that the “average whole-plant BNF contribution decreased from ~84% in unfertilized plots to a plateau of ~34% at fertilization rates greater than 84 kg/hectare.” They wrote:

“Based on an average US soybean production between 2002 and 2012 (FAOSTAT 2014; 2.8 ± 0.1 Mg hectare$^1$), which was very similar to soybean yield at our site for 2012 (2.6 ± 0.1 Mg hectare$^1$), and our estimate of [reactive N, or Nr] from the conventionally managed plots, we can calculate the total Nr delivered to the environment due to soybean cultivation. Nr production from the conventionally tilled plots in 2012 was 69 kg Nr ha$^1$ in grain, 7 kg Nr hectare$^1$ in aboveground vegetative biomass and 4 kg Nr hectare$^1$ in roots. Total Nr production due to soybean BNF therefore sums to 80 ± 11 kg Nr hectare$^1$ (excluding fertilization; Table 2). This translates to 43 ± 6 g Nr kg$^{-1}$ grain (Table 2).”

Compare this to the IPNI estimate of N removal in soybean grain (55 g N/kg grain) and the IPNI assumption that BNF is equal to N removal. 43 g N/kg grain of Nr would seem lower than the IPNI value, but in fact, BNF is 80 kg/hectare and grain N removed was 73 kg N/hectare — so the total BNF was more than the grain N content (110%).

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19 IPNI, 2012.
Legume winter cover crops

This section provides guidance on calculating N inputs from leguminous winter cover crops via BNF. Understanding this N addition results in a more accurate N balance score and subsequent recommendations. The three methods of estimating N inputs from this source are based on a review of scientific literature and land-grant university extension guidance. The methods are presented in order of decreasing precision and confidence in calculated outcomes.

For legume cover crops, the closest applicable IPNI standard values would be those for alfalfa, which assume 100% of aboveground N derives from BNF.

Experiments demonstrate BNF ranging from 24% to 96% of aboveground N for various legume cover crops, with these rates affected by species mix, soil texture and cover crop termination timing. Poffenbarger et al. used 15 N methods to measure the proportion of N from biological fixation in hairy vetch using different mixtures of hairy vetch and cereal rye. They found “that hairy vetch fixed between 64% and 96% of its N for three of the four site-years.”

In Ontario, Coombs et al. measured soil mineral N and fall biomass N for three different cover crops and compared this with soil mineral N in a non-cover treatment. Based on this experiment (assuming that the reduced soil mineral N in cover crop treatments was instead in the cover crop biomass), the estimated cover crop fixed N was between 45% and 68% of the N in aboveground biomass in the fall.

In the same study, spring assessments of soil mineral N and cover crop biomass N generate BNF estimates between 24% and 52% of aboveground N. Given such a large range in possible values, and without species- or region-specific alternatives, we use a conservative estimate of 50% of cover crop aboveground N originating from BNF.

For all methods, if the legume cover crop species was grown along with non-legume cover crop species, the total BNF should be adjusted to account for the percent of biomass that was leguminous. For example, if a cover crop was 40% red clover (legume) and 60% ryegrass (non-legume), multiply the result by 0.4.

High precision method

Use this method if both cover crop biomass and N content of that biomass is known (e.g., lbs. dry weight per acre) or can be measured (e.g., % N in dry biomass via plant samples).

If cover crop biomass is known

Multiply dry biomass by N content to get total above ground N in the cover crop biomass. Multiply that result by 50% to get the portion of the cover crop N from BNF (assuming an average of 50% of the N in the legume comes from BNF and remainder from the soil).

If cover crop biomass is unknown

Make a rectangular frame of PVC pipe or other material. (Four square feet is the recommended size). Throw the frame onto four to six random areas of the field. For each area, cut the cover crop vegetation to the soil surface and put it into a paper bag. Dry it after sampling is complete, and open bags as soon as possible to avoid mold growth on wet samples. The typical drying time is 48 hours at 104 degrees F. Weigh the dried biomass and calculate the mass per area (lbs./acre or kg/hectare). For example:

\[
(Dry \ sample \ weight - weight \ of \ bag)/frame \ area = \text{ounces/sq. ft.}
\]

16 ounces = 1 pound = 453.6 g

1 acre = 43,560 sq. ft.

Submit at least one well-mixed sample to a laboratory for analysis of N content. Multiply dry biomass (the average of the four to six areas sampled) by N content to get total aboveground N in the cover crop biomass. Then multiply that result by 50% to get portion of the cover crop N coming from BNF.

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21 Non-leguminous cover crops do not affect the N input portion of the N balance calculation.
24 These are our own calculations, based on data from Figure 1 in Coombs et al., 2017.
25 While the presence of non-legume plants competing for soil N will tend to increase the % of N in a legume that originates from BNF, “as long as there are effective rhizobia in the soil, the N supply from BNF will largely be governed by total legume biomass production rather than by the % of legume N from fixation (Crews et al., 2016; Schipanski & Drinkwater, 2011).” — quote from Blesh, 2018.
**Moderate precision method**

Use this method if cover crop biomass (e.g., lbs. dry weight per acre) is known or can be measured, N content of biomass is unknown, and the cover crop species was winter pea, chickling vetch, crimson clover or red clover. The BNF of other legume species can be estimated but with lower confidence.

Use the regression equation below to estimate BNF from legume cover crop.

**Regression equations relating aboveground N from BNF to winter cover crop biomass**

In these equations, \( y \) = aboveground N from BNF (lbs. N/acre or kg N/hectare) and \( x \) = aboveground dry biomass (lbs./acre or kg/hectare).

<table>
<thead>
<tr>
<th>Species</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter pea (n=64)</td>
<td>( y = 0.028x - 7.46 )</td>
</tr>
<tr>
<td>Chickling vetch (n=26)</td>
<td>( y = 0.017x + 0.70 )</td>
</tr>
<tr>
<td>Crimson clover (n=64)</td>
<td>( y = 0.018x - 6.50 )</td>
</tr>
<tr>
<td>Red clover (n=64)</td>
<td>( y = 0.022x - 0.84 )</td>
</tr>
<tr>
<td>Other species (avg. of above)</td>
<td>( y = 0.021x - 3.53 )</td>
</tr>
</tbody>
</table>

**Low precision method**

Use if both cover crop biomass and N content of that biomass is unknown, an estimate of cover crop growth (< 6” growth or > 6” growth) can be made, and the cover crop species was alfalfa, red clover, sweet clover or vetch. The BNF of other legume species can be estimated but with lower confidence.

Use this table to estimate BNF from legume cover crops.

**Green manure nitrogen credits**

<table>
<thead>
<tr>
<th>Crop</th>
<th>&lt;6” Growth</th>
<th>&gt;6” Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>lbs. N/acre to credit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>40</td>
<td>60-100(^a)</td>
</tr>
<tr>
<td>Red Clover</td>
<td>40</td>
<td>50-80(^a)</td>
</tr>
<tr>
<td>Sweet Clover</td>
<td>40</td>
<td>80-120(^a)</td>
</tr>
<tr>
<td>Vetch</td>
<td>40</td>
<td>40-90(^{a,b})</td>
</tr>
</tbody>
</table>

\(^a\) Use the upper end of the range for spring seeded green manures that are plowed under the following spring. Use the lower end of the range for fall seedings.

\(^b\) If top growth is more than 12 inches before tillage, credit 110-160 lbs. N/acre.

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\(^{26}\) Equations are adapted from Blesh, 2018.

\(^{27}\) University of Wisconsin Extension, 2012.
Appendix C: References


What the Nitrogen Balance “Safe Zone” Indicates

The “safe zone” provides valuable context for understanding nitrogen balance, or N balance, scores. Scores that fall within the safe zone range indicate that a farmer is optimizing yields, using N additions efficiently, minimizing N losses to the environment and protecting long-term soil health.
How EDF scientists determined the safe zone range

The safe zone includes N balance scores\(^1\) of 25-75 lbs. N/acre (Figure 1).

When N balance scores exceed 75 lbs. N/acre, N losses to the water as nitrate (NO\(_3^-\)) and to the air as nitrous oxide (N\(_2\)O) increase dramatically. Beyond this upper threshold, the crop does not need or use the extra N added.\(^2\) Therefore, staying below the upper limit keeps N losses to the environment as low as possible, while making the most efficient use of N added to the system.

Alternatively, when N balance scores fall below 25 lbs. N/acre, the N provided from outside sources is insufficient to replace N mineralized from the soil during the growing season and used by the crop. If plants must rely on N mineralized from organic matter in the soil that is not replenished, long-term productivity and soil health may suffer.\(^3\)

EDF defined this range with the best available peer-reviewed science. We may continue to refine the safe zone bounds as additional data advances our understanding of the relationship between N balance and specific agro-ecological regions and production systems.

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\(^1\) See How to Calculate Nitrogen Balance on edf.org/n-balance for more information.

\(^2\) McClellan et al., 2018.

\(^3\) Campbell and Zentner, 1993; van der Pol and Traore, 1993.
Additional research on the safe zone

Non-EDF scientists researching the safe zone concept at both global and farm scales have identified some variations on the upper and lower bounds, but their published ranges remain comparable to that used in EDF’s N balance framework.

**U.S. land-grant universities**

A team of researchers connected with Princeton University and the University of Maryland translated the “safe” planetary boundary for N into a comparable global average N balance of 35-70 lbs. N/acre of harvested cropland per year.⁴ They propose that these targets will allow global agriculture to meet 2050 food demand and also meet United Nations Sustainable Development goals.

Researchers from Cornell University established the concept of a whole-farm safe zone of N balance for dairy operations.⁵ The “optimal operational zone” was designed to “allow dairy farms to be economically profitable and environmentally sustainable while promoting flexibility in management practices.” The high end of the zone was determined to be 105 lbs. N/acre, the point below which 75% of studied dairies were operating. Dairies operating within this zone are given some regulatory relief under New York state nutrient management rules. This high-end value is slightly higher than EDF’s recommended upper threshold of 75 lbs. N/acre, but most dairies must account for additional nutrient imports and exports compared to standard row crop operations.

**European Union**

The European Union Nitrogen Expert Panel also applied the safe zone concept to N balance along with N output — productivity from crop yield and other N removal sources.

The panel recommends a target maximum N balance of 68 kg N/hectare/year,⁷ which is comparable to 75 lbs. N/acre, the upper threshold of EDF’s N balance safe zone.

They advise that farmers operate in the safe zone, noting that this can be achieved through intensification or efficiency gains, depending on the situation. The panel also proposes a whole-farm approach with a standardized set of input and output data to ensure uniformity for benchmarking and peer-to-peer comparisons.

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⁴ Bodirsky et al., 2014; de Vries et al., 2013; Steffen et al., 2015.
⁵ Zhang et al., 2015.
⁶ Cela et al., 2014.
⁷ Quemada et al., 2020.
References


How to Use Nitrogen Balance to Estimate Nitrous Oxide and Nitrate Losses

Environmental Defense Fund scientists developed two environmental models¹ that calculate nitrous oxide emissions and nitrate leaching using aggregated nitrogen balance, or N balance, scores.² These breakthrough models provide a practical and cost-effective way to measure environmental outcomes from agriculture across watersheds and sourcing regions.

¹ McLellan et. al (2018); Eagle et. al (2020).
² N balance measures how much N is not used by crops in a growing season and thus is vulnerable to being lost to the environment as nitrous oxide and nitrate. Visit edf.org/n-balance for additional information about how to calculate N balance.
Applying the environmental models

This guide explains how to use these models to determine N losses to the environment and measure progress over time. We provide both imperial and metric versions of equations. Be sure to double-check all units and unit conversions.

As with most models, having more observations (in this case, N balance scores) provides more precise and accurate results. To have statistical confidence that a program or project has led to real environmental improvement — reduced nitrous oxide emissions and nitrate leaching — EDF recommends aggregating N balance scores from a minimum of 300 fields together and having three years of baseline data from the same 300 fields. Emissions and leaching from subsequent years can then be compared to the three-year baseline to measure change.

The relationship between N balance and nitrous oxide emissions, expressed in the nitrous oxide model, applies to aggregated groups of fields with most common soil types and annual, non-legume crops that are rainfed and receive commercial fertilizer and manure applications.

The relationship between N balance and nitrate leaching, expressed in the nitrate model, applies to rainfed, annual, non-legume crops receiving commercial fertilizer and grown in tile-drained fields.

How to determine nitrous oxide emissions

Calculate the amount of nitrous oxide lost to the environment for each unique field using the following area-based equation.

\[
N_2O = 1.25e^{0.0053 N \text{ balance}}
\]

where \(N_2O\) denotes emissions in units of lbs. \(N\)-N/acre/year, and \(N \text{ balance}\) is N balance in units of lbs. N/acre/year. Using this equation, fields with N balance scores of 25, 75 and 125 lbs. N/acre/year would have average \(N_2O\) emissions equal to 1.4, 1.9 and 2.4 lbs. \(N\)-N/acre/year, respectively.

How to determine nitrous oxide emissions

Calculate the amount of nitrous oxide lost to the environment for each unique field using the following area-based equation.

\[
N_2O = 1.40e^{0.0047 N \text{ balance}}
\]

where \(N_2O\) denotes emissions in units of lbs. \(N\)-N/acre/year, and \(N \text{ balance}\) is N balance in units of kg N/hectare/year. Using this equation, fields with N balance scores of 25, 75 and 125 kg N/hectare/year would have average \(N_2O\) emissions equal to 1.6, 2.0 and 2.5 kg \(N\)-N/hectare/year, respectively.

1. In all cases, we recommend looking at N balance data in their context. For example, compare results from an individual year to see if they are consistent with previous years or if other factors like disease or weather caused an anomaly. In many cases, this consideration can be achieved by using a three-year moving average of N balance scores.

2. McLellan et al. (2018) established the relationship between N balance and both nitrous oxide emissions and nitrate leaching losses from corn on silt loam soils in the Corn Belt. Eagle et al. (2020) found that nitrous oxide emissions from corn on silt loam soils relate to N balance in much the same way as corn grown on other soils, and the same is true for other rainfed, non-legume crops receiving fertilizer and/or manure N and produced on most common soil types.

3. The nitrous oxide model may not be suitable for very high clay soils and organic/peat/histosol soils.

4. Models for estimating nitrous oxide emissions and nitrate leaching from soybean crops, which will allow for estimates of single-crop years and full corn-soybean rotations, are under development in collaboration with Iowa State University and are expected to be complete in late 2021.

5. Research into extending the nitrate leaching losses model to include other cropping systems, including Manure_N and non-tile drained fields, is in progress with partners at the University of California — Davis.

6. The nitrate equation has been adjusted from that presented in McLellan et al. (2018) to be area scaled and in imperial units (i.e., lbs. N/acre). The published version was in yield-scaled metric units (i.e., kg N per Mg grain).

7. This equation can also be expressed in imperial units (lbs. N/acre) as \(N_2O = \exp(0.224 + 0.0053 \times N \text{ balance})\).

8. This equation can also be expressed in metric units (kg N/hectare) as \(N_2O = \exp(0.339 + 0.0047 \times N \text{ balance})\).
How to determine nitrate leaching

Calculate the amount of nitrate lost to the environment for each unique field using the following area-based equation.

\[
\text{NO}_3 = 10.43e^{0.0068 \times \text{N balance}}
\]

where \(\text{NO}_3\) denotes leaching losses in units of lbs. \(\text{NO}_3\)-N/acre/year, and \(\text{N balance}\) is N balance in lbs. N/acre/year. Using this equation, fields with N balance scores of 25, 75 and 125 lbs. N/acre/year would have average \(\text{NO}_3\) leaching losses of 12, 17 and 24 lbs. \(\text{NO}_3\)-N/acre/year, respectively.

How to determine nitrate leaching

Calculate the amount of nitrate lost to the environment for each unique field using the following area-based equation.

\[
\text{NO}_3 = 11.69e^{0.0061 \times \text{N balance}}
\]

where \(\text{NO}_3\) is leaching losses in units of kg \(\text{NO}_3\)-N/hectare/year, and \(\text{N balance}\) is N balance in kg N/hectare/year. Using this equation, fields with N balance scores of 25, 75 and 125 kg N/hectare/year would have average \(\text{NO}_3\) leaching losses of 14, 18 and 25 kg \(\text{NO}_3\)-N/hectare/year, respectively.

How to determine — and report on — environmental impacts at scale

The equations above estimate average nitrous oxide emissions and nitrate leaching for a field, and they improve in accuracy when large numbers of fields are aggregated. Because many environmental and management factors affect N cycling, the losses from each individual field can be quite variable. While direct measurements, if feasible, would find exact losses from an individual field to be higher or lower than the average, the high values balance out the low ones, and vice versa, when looking at the group as a whole.

Therefore, individual field-level nitrous oxide and nitrate values must be aggregated over at least 300 farm fields to ensure claims can be made with statistical confidence.

The relationship between N balance and nitrate leaching, expressed in the nitrate model, applies to rainfed, annual, non-legume crops receiving commercial fertilizer and grown in tile-drained fields.

Aggregate total annual N losses to the environment

For every year of available data, multiply each field’s nitrous oxide emissions value by its acreage, where the result is expressed in total lbs. \(\text{N}_2\text{O}-\text{N}\) emissions/field/year. Total field-level nitrous oxide emissions can also be aggregated to the highest spatial scale of interest. For example, it is possible to calculate total nitrous oxide emissions for a whole farm (multiple fields), a group of supplying farms, or for an entire watershed, region, or other spatial scale of interest by adding together the total emissions (lbs. \(\text{N}_2\text{O}-\text{N}/\text{year}\)) for all participating fields.

Repeat this for nitrate leaching. For every year of available data, multiply each field’s nitrate leaching losses value by its acreage, where the result is expressed in total lbs. \(\text{NO}_3\)-N leaching losses/field/year. Total field-level nitrate leaching losses can also be aggregated to the highest spatial scale of interest by adding total lbs. \(\text{NO}_3\)-N leaching losses/year for each participating field.
Establish a baseline and evaluate improvements

Take the three-year average of calculated nitrous oxide emissions and nitrate leaching to establish a three-year baseline for each type of N losses. In subsequent years, measure improvement by subtracting total losses of nitrous oxide and nitrate from the respective baseline.

Report total annual changes in N losses and/or carbon dioxide equivalents

Companies can report annual sums for both nitrous oxide emissions and nitrate leaching without being duplicative because these values measure different ways that N is lost to the environment. Losses can be reported in either area-or yield-scaled units, but area-scaled is preferable as it more accurately reflects overall losses to the environment, which can be masked by improvements in yield efficiency if reporting yield-scaled values.

Many companies use carbon dioxide equivalent (CO₂e) as a standard unit of measure for greenhouse gas/carbon footprint reporting. Follow the steps below to calculate the carbon dioxide equivalent of direct nitrous oxide emissions — emissions that come directly off a field rather than indirect emissions that occur when nitrate leaches into waterbodies and denitrifies to become nitrous oxide.

1. Multiply total lbs. N₂O-N emissions by 2.205 to convert to kg N₂O-N, then divide by 1,000 to convert to metric tons (t N₂O-N).

2. Multiply t N₂O-N by 1.5711 to convert to t N₂O/year (1 t N₂O-N = 1.5711 t N₂O).

3. Multiply t N₂O/year by 265 to convert to t CO₂e/year. The result is total t CO₂e/year.

References


11 This equation can also be expressed in imperial units (lbs. N/acre) as NO₃ = exp(2.34 + 0.0069 × N balance).
12 This equation can also be expressed in metric units (kg N/hectare) as NO₃ = exp(2.459 + 0.0061 × N balance).
13 1 metric ton = 1000 kg = 1 Mg (megagram) = 1 x 10⁶ g.