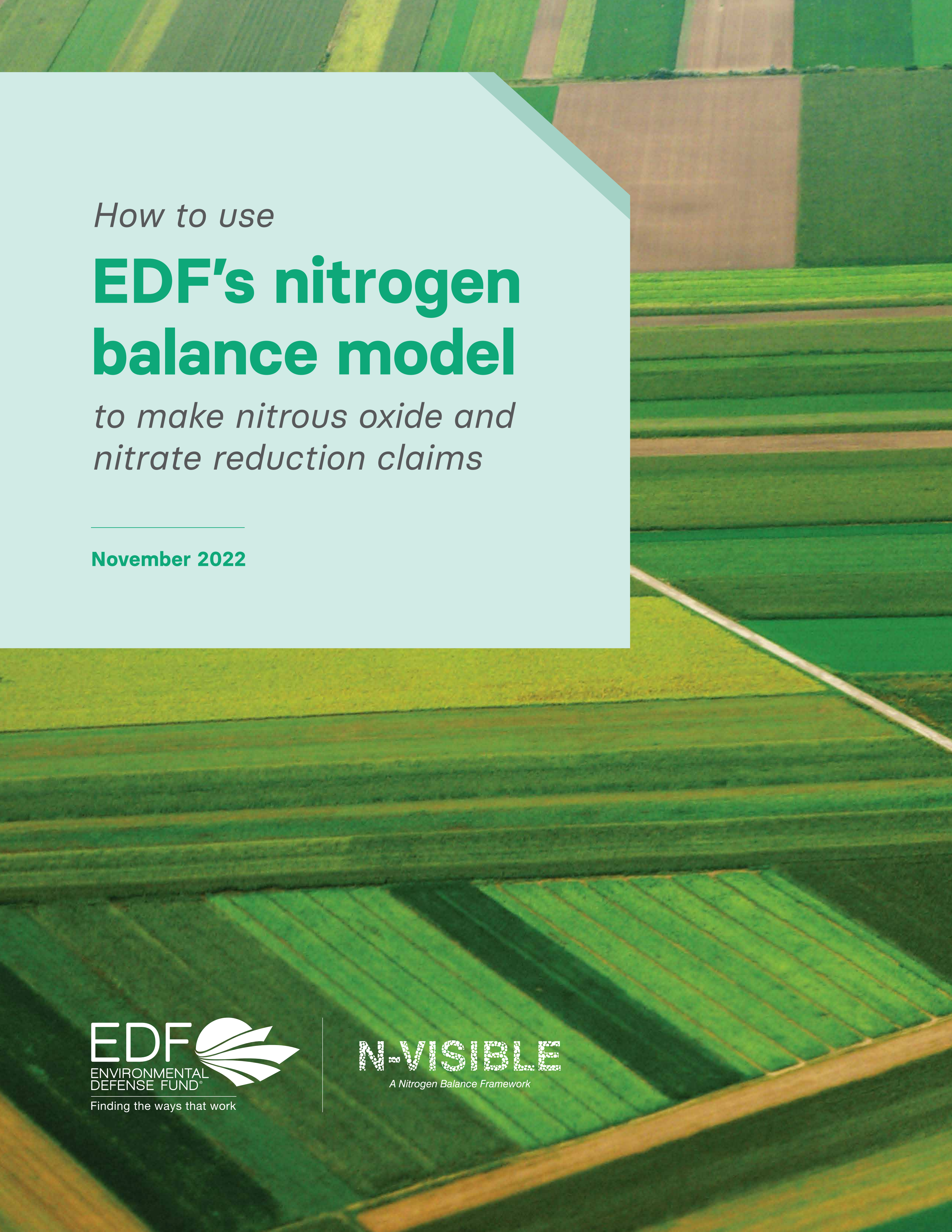


How to use

EDF's nitrogen balance model

to make nitrous oxide and nitrate reduction claims

November 2022

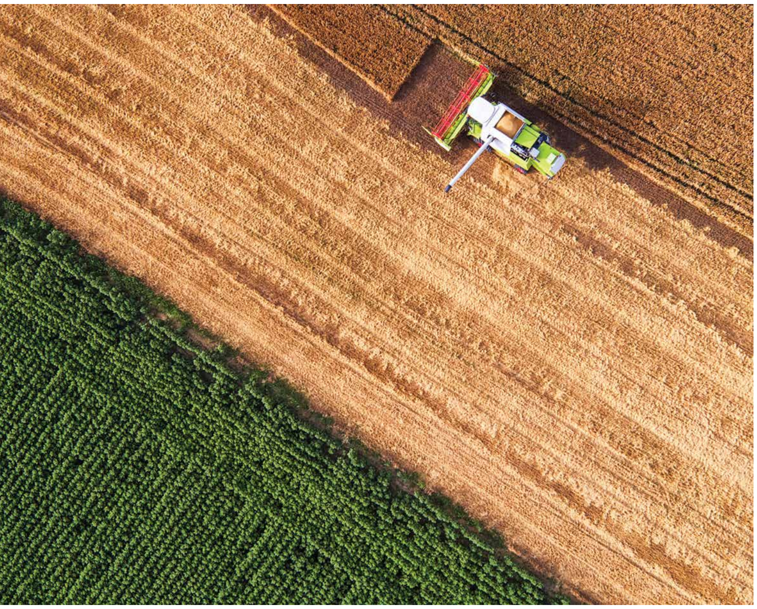
EDF
ENVIRONMENTAL DEFENSE FUND®
Finding the ways that work

N-VISIBLE
A Nitrogen Balance Framework

Contents

Introduction

Nitrogen (N) is essential for life on Earth, but excess N causes pollution — in the form of nitrous oxide (N_2O) and ammonia (NH_3) in the atmosphere and nitrate (NO_3) 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]



Agriculture — which relies on N to support high annual crop yields and feed a growing population — is the largest global source of N pollution. Farmers are motivated to be efficient with their inputs in the face of rising production costs, environmental concerns and societal pressure, but the necessity of maintaining and/or improving yields can create a limited-choice environment for them. Companies in the food supply chain are also increasingly setting ambitious greenhouse gas reduction goals and looking to farmers to help achieve those goals through reduced N losses.

Over the years, EDF 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. These approaches include direct measurement of losses, practices as proxy, and the application of complex "process-based" models.

EDF's N balance framework is a user-friendly, scientifically robust way to assess environmental results. N balance — the difference between N inputs to and N outputs from a field over the course of a year or crop rotation — overcomes the challenges of other approaches. The framework includes two empirical models[3] developed by EDF that enable supply chain companies, policymakers and others to translate aggregated field-level changes in N balance into improvements in environmental outcomes, specifically reductions in nitrous oxide emissions and nitrate leaching.

This EDF guide presents the methodology for quantifying, tracking and making annual claims at supply chain-scale of reduced nitrous oxide emissions and nitrate leaching losses from cropping systems. The approach applies broadly across all crops in temperate climates, regardless of soil type or N source, including synthetic and organic N fertilizer.

N balance overview

N balance indicates the amount of N left over and at risk of being lost to the environment. It is calculated as the difference between N added and N removed, for example fertilizer N applied minus N removed in harvested grain. While variability is expected because of weather, pests or other production issues that affect yield each year, N balance is strongly related to management.[4] This is partly because N application rate (the first number that goes into N balance) is a management decision, but also because other management choices affect yield and N removed in that crop (the second number that goes into N balance).

[1] Sobota, Compton, McCrackin, and Singh, S., 2015.

[2] van Grinsven, Holland, Jacobsen, Klimont, Sutton & Jaap Willems, 2013.

[3] These models were introduced in McLellan et al., 2018 and further refined in Eagle and McLellan et al., 2020 and Tamagno et al., 2022.

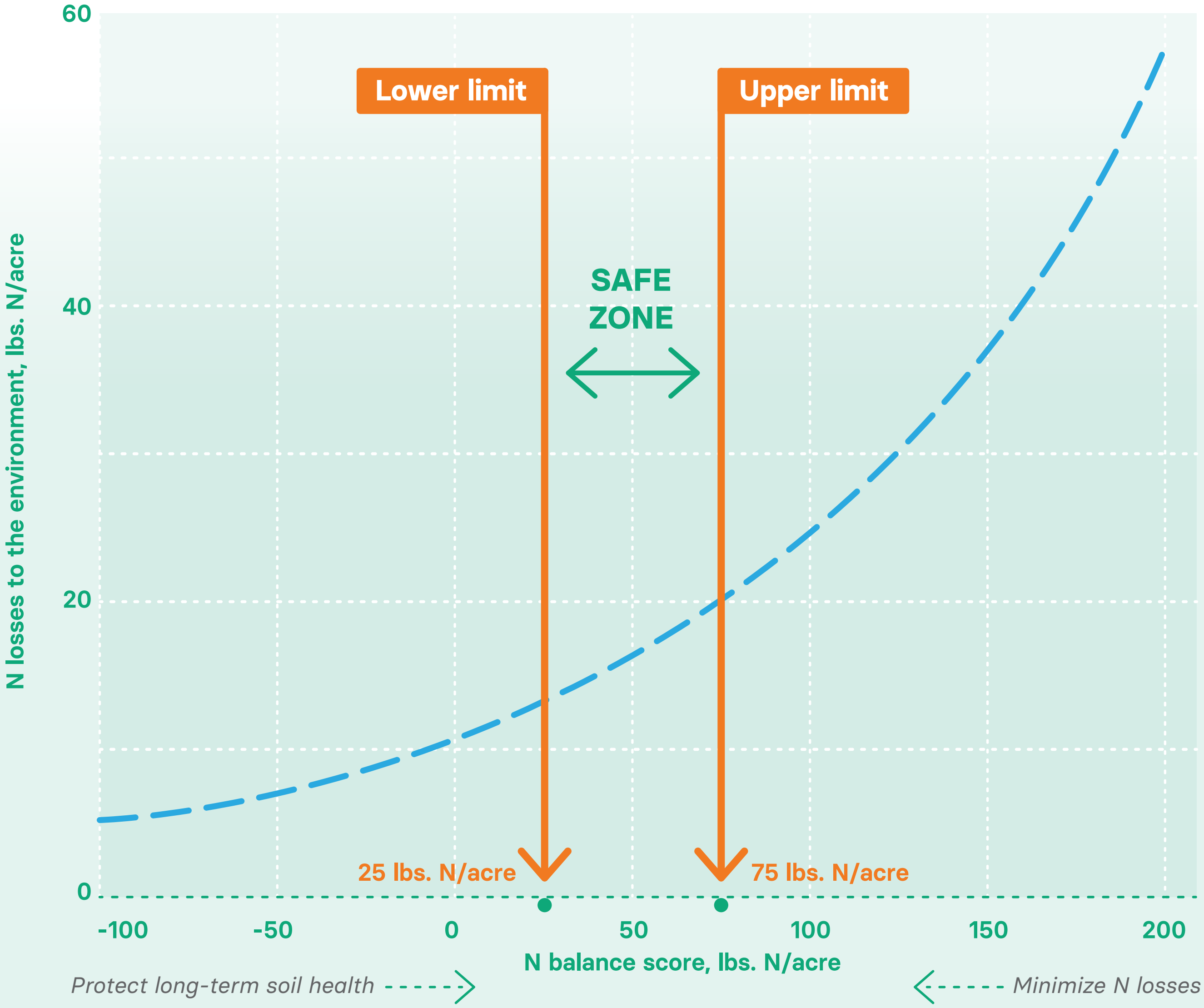
[4] Tenorio et al. 2021(a), Tenorio et al. 2021 (b).

Ideally, N balance scores will fall into a "safe zone"— experts suggest this is generally 25–75 lbs. N/acre for a crop such as maize.[5] Within this N balance safe zone, a farmer is optimizing yields, using N additions efficiently, minimizing N losses to the environment and protecting long-term soil health (see figure 1 below).

As N balance scores rise above 75 lbs. N/acre and leave the safe zone, the risk of N losses to the water as nitrate and to the air as nitrous oxide increases dramatically. Beyond this upper threshold, the crop does not need or use the extra N added.[6] 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 without sacrificing productivity.

Alternatively, when N balance scores fall below 25 lbs. N/acre, the N applied from outside sources may be insufficient to replace N mineralized from the soil during the growing season and used by the crop. If plants rely on N mineralized from soil organic matter that is not replenished, long-term productivity and soil health may suffer.[7]

Figure 1: The N balance safe zone



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[5] See "What the Nitrogen Balance 'Safe Zone' Indicates" in Appendix.

[6] McLellan et al., 2018.

[7] Campbell and Zentner, 1993; van der Pol and Traore, 1993.

Modeling environmental outcomes:

How to quantify nitrous oxide emissions and nitrate losses using N balance

General guidelines

To ensure the highest quality reporting possible, EDF recommends the following best practices related to data management, calculations, and claims:

✓ ***Field-level data is strongly preferred.***

Field-level data results in greater confidence in environmental outcomes and more accurately reflects what is happening in the field. Reliance on book values, county estimates or other data sources in lieu of field-level data creates variability and uncertainty that could negatively impact public-facing claims. Non-field-level data will also make it more challenging to detect change over time, identify opportunities to drive improvement and demonstrate an attributable impact.

✓ ***Fields can be grouped together within the same farm to account for crop rotation.***

If a program is designed to target a specific crop within a rotation, field-level data from that crop can be used even if the field shifts to another crop. The fields just need to be associated with the same farmer and under similar management. For example, a supply chain program focused on corn may include a farmer who uses a corn-soy rotation. The farmer can submit N balance data in the both the first and the second year from active corn fields, even if the actual field(s) and/or acreage have shifted. The farmer may be asked to verify N balance scores by considering how well their prior- and current-year management and yield represent typical results for fields that they manage.

✓ ***Environmental outcomes must be aggregated across at least 300 fields.***

Because many environmental and management factors affect N cycling, the losses from each individual field can be quite variable. These equations estimate average field-level nitrous oxide emissions and nitrate losses, and they improve in accuracy when large numbers of fields are aggregated.

While direct measurements — if they were feasible to collect — 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 size and uniformity of the fields to one another within this aggregated group is irrelevant (i.e., there is no required minimum or maximum field size).

✓ ***Environmental outcome claims must be measured against a three-year average baseline.***

Because of annual variation in growing conditions (e.g., extreme situations such as the U.S. drought of 2012 or the unprecedented rainfall and flooding in the U.S. in 2019, as well as more standard annual variability), EDF is only comfortable with nitrous oxide and nitrate emission trends calculated from changes in N balance scores using a three-year average baseline of participating fields. This means claims must be based on at least four years of data (three years of baseline data and at least one year of program data).

Historical data can be used to establish a three-year average baseline.[8] Preliminary claims can be made with a historical baseline and at least one year of data after a participant has joined the program and worked to improve N balance, but these claims should be considered preliminary until sufficient years of N balance data exist for comparison against the three-year average baseline.

These early trends may be useful to demonstrate progress to internal stakeholders, in tandem with other indicators such as the number of farmers and acreage engaged, progress toward desirable management practice changes and N balance score distribution. Collecting sufficient post-enrollment data to demonstrate real trends reduces the risk for having to retract claims — i.e., the trends are more likely to be real.

The sum of incremental annual improvements in program years beyond the baseline results in a cumulative measure of change in emissions and losses. See the “Making claims” section for more detail.

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[8] Note that EDF does not recommend including any change in emissions and losses within the three baseline years as part of the cumulative total change.

1

Step one: Collect and clean N balance data

Data collection and quality control methodology will vary across programs but incorporating certain best practices will contribute toward more consistent and accurate outcomes. These components maintain the integrity of claims and sharpen the ability to highlight improvements in early program adopters, identify areas where additional program interventions may be beneficial, and help avoid double counting and other accounting issues.

N balance data collection

Data collection processes may vary but should adhere to the minimum required data fields outlined in the N balance implementation modules (see Appendix). Note that data may be generated from various sources, including farm equipment/machinery, receipts and commercial documents, remote sensing and farmers themselves, whether directly entered into a software platform or via attested surveys.

In addition to the minimum required data fields to calculate N balance, EDF recommends that programs collect additional field-level data that provides evidence that N balance change is attributable to specific interventions and associated behavior changes. This will bolster GHG emission reduction and water quality claims.

Suggested broad categories of field-level data to track for N balance attribution include:

- Year of entry to program.
- Program type (e.g., direct payments or agronomic support).
- N fertilizer and manure management practices (i.e., placement, timing, source, rate recommendations and manure nutrient testing).
- Tillage type and timing.
- Tile drainage type.
- Planting date for current crop.
- Pest management.
- Previous cash crop(s) and winter cover crops with planting and harvest dates.

Detailed guidance on the analysis of these data points is not included in this guide, but programs are urged to consider the relationship between management practices and environmental outcomes, especially in those fields with similar geographies and/or climate. Management changes in any number of the above categories are likely to affect N cycling and efficiency, including crop yield. Analysis of trends over time and relationships between these categories, N balance and environmental outcomes can help guide dialogue between program managers and participants, and thus help to identify opportunities for continuous improvement.

Data quality assurance protocols

Data quality protocols should consider the following:

- Assign each field and crop year a unique identifier. When available, this unique field ID should be tied to the following geospatial information to generate more accurate and actionable insights for a program:
  - Field boundary definition.
  - Field acreage.
  - Field boundaries overlap detection (using unique field IDs and overlap detection to prevent duplication of fields reported and inaccurate emissions and losses reductions).
- Confirm input data are field-level and that repetitive values have not been entered for all participating farmer's fields. For example, N application rates and yield are highly unlikely to be identical across an entire operation.
- Note inputs with high uncertainty[9] (e.g., using book values for manure N content vs. actual measurements) to compare outcomes later and identify potential issues with assumptions.
- Note yield values with high uncertainty (e.g., when the value is likely the county average yield instead of the actual yield).

2

Step two: Calculate and analyze field-level N balance scores

Calculate annual field-level N balance scores for each field. Detailed instructions can be found in Appendix B: How to calculate nitrogen balance.[10]

Suggested initial N balance data analysis

Review the distribution of N balance scores. N balance scores across a farmer's fields should be variable — identical values may represent data input errors.

Utilize cross tabulations and simple plots to summarize data. Try grouping yield and N balance by year, geographic region, etc. This can help identify outliers and odd data groupings, which can be corrected if caused by data entry error or removed, if deemed appropriate.

For programs interested in using N balance to promote continuous improvement among participants, consider the following analyses as a starting point:[11]

1. Conduct statistical analysis to address research questions about what factors affect N balance.
   - **a.** Multivariate regression analysis with the entire data set.
     - **i.** Set N balance as dependent variable.
     - **ii.** Control for weather and soil variables (categorical or continuous variables).
     - **iii.** Test year as a fixed effect to control for other variables.
     - **iv.** Run models to both include and exclude N rate as an independent variable to help identify the impact of other practices on N balance and to test interactions.
   - **b.** What practices improve N management and reduce high N balances to a "safe zone" level?
     - **i.** Repeat multivariate analysis without the data points below 25 lbs. N/ac.
   - **c.** What practices increase low N balances to a safe zone level?
     - **i.** Repeat multivariate analysis without the data points above 75 lbs. N/ac.
2. Plot some of the results to visualize trends. This can help ensure that relationships identified in regressions or other statistical models are real, unbiased and make practical sense.

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[9] Programs should establish expected variability ranges around data inputs where book values or other secondary data sources are used. For example, if book values are used for manure N content (rather than measured N content), N balance should be calculated with the lower and upper book values to understand the variability range. If the outcomes are outside of an acceptable percentage or lbs. N/acre value, the data may need to be re-evaluated and/or any statements must acknowledge the variability and its source(s).

[10] Also available at edf.org/n-balance.

[11] Note that this document provides analysis guidance but does not represent endorsement or verification of any specific N balance claims or outputs. Programs are encouraged to enlist a third-party for verification, if desired.

3

Step three: Apply the environmental models

Apply the published nitrous oxide and nitrate models to the annual N balance score for each field to calculate nitrous oxide emissions and nitrate losses.

Calculation example: *Nitrous oxide emissions*

Calculate nitrous oxide emissions for each unique field ID using the following equation:[12]

$$N_2O = 1.25e^{0.0053NBal}$$

where N_2O denotes emissions in units of lbs. N_2O-N/acre/year, and NBal is N balance in lbs. N/acre/year.

Example:

Fields with N balances 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_2O-N/acre/year, respectively.

Calculation example: *Nitrate leaching losses*

Calculate nitrate leaching losses for each unique field ID using the following equation:

$$NO_3 = 15.1e^{0.00404NBal}$$

where NO_3 is leaching losses in units of lbs. NO_3-N/acre/year,[13] and NBal is N balance in lbs. N/acre/year.

Example:

Fields with N balances of 25, 75 and 125 lbs. N/acre/year would have average NO_3 leaching losses of 17, 21 and 25 lbs. NO_3-N/acre/year, respectively.

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[12] This equation can also be expressed as $N_2O = \exp(0.224 + 0.0053 \times \text{N balance})$.

[13] This equation can also be expressed as $NO_3 = \exp(2.72 + 0.00404 \times \text{N balance})$.

Aggregate and calculate total losses

For each year of available data, multiply each field's nitrous oxide emissions value by its acreage, where the result is total lbs. N_2O-N emissions/field/year. If desired, one can aggregate field-level nitrous oxide emissions by adding to the highest spatial scale of interest (e.g., total lbs. N_2O-emissions/farm, county, watershed, state or region per year). Repeat for nitrate leaching losses (i.e., for each year of available data, multiply each field's nitrate leaching losses value by its acreage), where the result is total lbs. NO_3-N leaching losses/field/year. Total field-level nitrate leaching losses can also be aggregated to the highest spatial scale of interest. The sum of total lbs. N_2O-N emissions and total lbs. NO_3-N leaching losses per acre per year is the total annual nitrous oxide emissions and nitrate losses.

Companies may choose to convert the total direct nitrous oxide emissions value — i.e., those that come directly off a field, as opposed to those that indirectly become nitrous oxide when nitrate in the water denitrifies into nitrous oxide— to its carbon dioxide equivalent (CO_2e), the standard unit of measure for GHG/carbon footprint reporting.

Nitrous oxide to carbon dioxide equivalent conversion

Step A: Divide total lbs. N_2O-N emissions by 2.205 to convert to kg N_2O-N, divide by 1,000 to convert to metric tonnes (t N_2O-N).[14]

Step B: Multiply t N_2O-N by 1.5711 to convert to t N_2O/year (1 t N_2O-N = 1.5711 t N_2O).

Step C: Multiply t N_2O/year by 265 to convert to t CO2e/year.[15] The result is total t CO_2e/year.

4

Step four: Quantify program impacts

The previous steps should be completed for each year of collected N balance data.

Establish the baseline

Many programs begin in a pilot phase and then scale up to meet a target acreage or farmer engagement goal. As such, a multi-year program may have several program baselines (comprised of participating grower baselines) if the participating population dramatically shifts. This approach is designed to provide efficiency and flexibility to programs while scaling up, and to create a clear pathway to making claims.

For example, a program may begin with 50,000 acres and expand to 100,000 and then 200,000 or more in subsequent years. It is not recommended that historical data be used for the first year of measured progress as it would be nearly impossible to attribute that change to a specific program intervention. Historical data may be used for the baseline but should not be used to measure change from the baseline. Acres that join in subsequent program years will be reflected in a unique baseline that reflects three years of historical data prior to the farmer's year of program entry.

Both of the following scenarios are acceptable when utilizing historical data for the three-year average baseline:

- **The farmer has high-quality records of crop inputs and yields for three or more years prior to joining the program.** This data can be accepted as the three-year average baseline. If there are additional years of data available, this can also be added to strengthen the baseline or understand longer-term trends.
- **The farmer has low-quality or incomplete records of crop inputs and yield for three or more years prior to joining the program.** If the farmer has confidence in the prior year's N input and yield data but is unsure about the two preceding years, one-on-one conversations with participating farmers are strongly recommended to provide context to historical data. For example, the program should understand: Does the data represent typical N rate and yields for that field? If not, is the N rate or yield generally higher or lower? By how much? Historical data can then be extrapolated and admitted with notation that it is uncertain or is likely an over/under-estimate of N balance, as appropriate.

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[14] 1 tonne = 1000 kg = 1 Mg (megagram) = 1 x 10^6 g.

[15] 100-year GWPs ~ CO_2:CH_4:N_2O = 1:28:265 (IPCC, 2014).

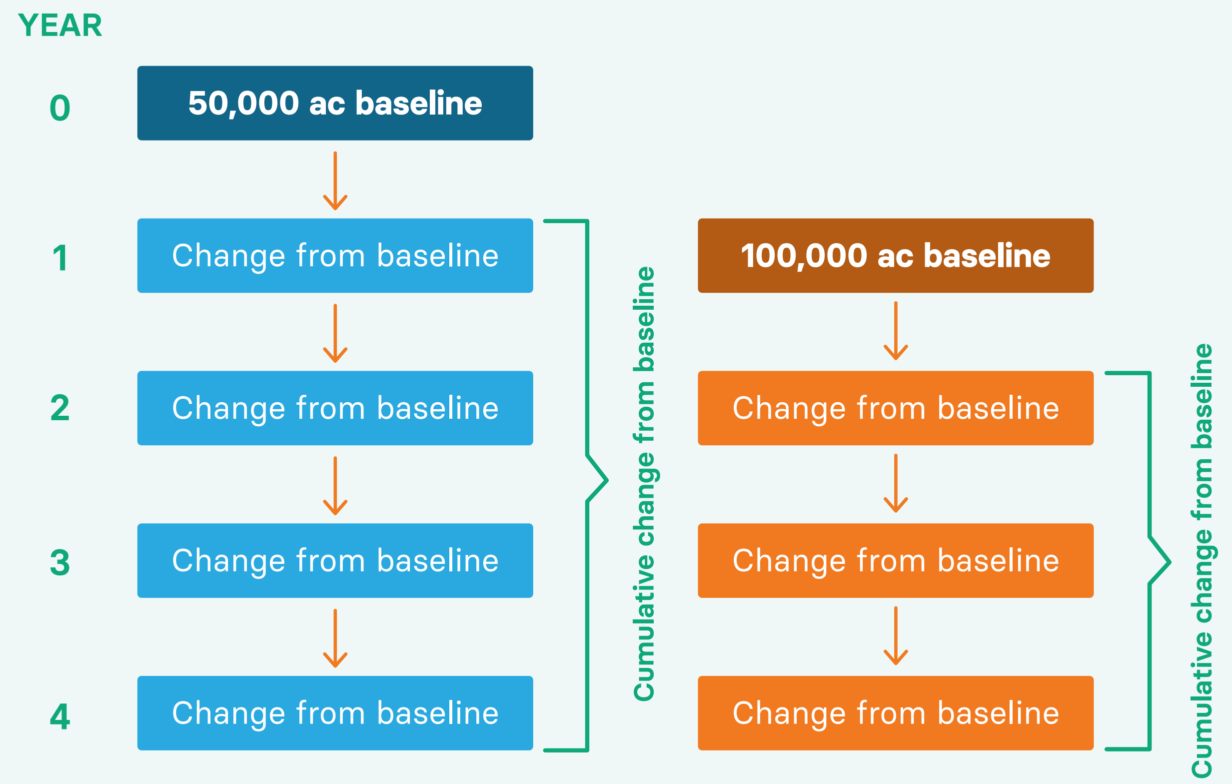
The three-year average baseline should represent all active acres within their respective years, even if the total acreage or participating farmer population shifts. The optimum approach would be to maintain participants and fields, but it is understandable that acres may shift in response to program strategy, weather or other factors. It is the burden of the program to demonstrate a good faith effort that the reported data accurately reflects the target sourcing region, and that participation and reporting is not intentionally shifted to create the illusion of more positive environmental outcomes.

Measure year-over-year progress

With the three-year average baseline, subsequent years of data collected through the program can be used to measure progress toward improved environmental outcomes.

The figure below provides a simplified example of how progress can be measured for acres that enter the program in different years. In this scenario, 50,000 acres enter with three years of historical baseline data and the change from that baseline can be calculated with data from year one of the program. The aggregated environmental outcomes from each subsequent year are compared to the baseline, with each quantification of change eventually added together for the cumulative impact of those 50,000 acres over a four-year program. An additional 100,000 acres join the program in year one, also with three-years of historical baseline data. The first measurement of progress against the baseline is feasible in year two, with each subsequent year of data compared to that group's baseline.

Outcomes from multiple baselines can be added together in a single year. For example, this program could report the overall change to date in year two by adding the impacts associated with the 50,000 acres in year one and two to the impacts of the 100,000 acres in year two.



Making claims: Best practices

N balance provides a scientifically robust framework for measuring and reporting progress toward nitrous oxide GHG emission and nitrate leaching reduction goals related to crop production. Every effort has been made to create an efficient, yet credible, pathway to making environmental outcome claims.

Caution should be used in publicly reporting improvements based on four years or less of N balance data. Just as the baseline is intended to provide a realistic look at trends and help smooth out impacts of external factors, additional program year data does the same. The first year of a program may very well lead to improvements, but there are factors beyond control such as weather or pests that could cause emissions or leaching increases in the second year and damper the cumulative improvement.

There are three types of claims an N balance program can support:

1. ***Participation claims***
   "We are working with growers in this watershed to do X."
2. ***Measurement claims***
   This year we observed Y GHGs emitted." (i.e., a single metric, not necessarily an improvement).
3. ***Environmental Impact claims***
   "We have achieved Z improvement in GHGs over 5 years."

Participation claims can be made at the initiation of a program and updated each year. These can be helpful storytelling data points, and can include:

- Number of growers and/or acres engaged (i.e., received recommendations or services toward improved practices via participation in a given program).
- Number of growers and/or acres currently using conservation practices and/or adopting new practices as a result of program participation.

Measurement claims require at least one year of N balance data and can help begin to show progress over time:

- Percentage of acres where N balance scores are below, within and above the N balance safe zone.
- Management/conservation practice and N balance trends across spatial and temporal scales.
- Observed relationship between N balance improvements and practice adoption.
- Annual tonnes nitrous oxide or carbon dioxide-equivalent emissions.
- Annual tonnes nitrate leaching losses.

Environmental impact claims require at least four years of N balance data (three-year average baseline and one year of post-intervention data), with additional years strongly recommended:

- Quantification of change (+/-) in nitrous oxide emissions and nitrate losses compared to the three-year average baseline values for a single year.
- Cumulative change (+/-) in nitrous oxide emissions and nitrate losses compared to the three-year average baseline values over the course of multiple years.

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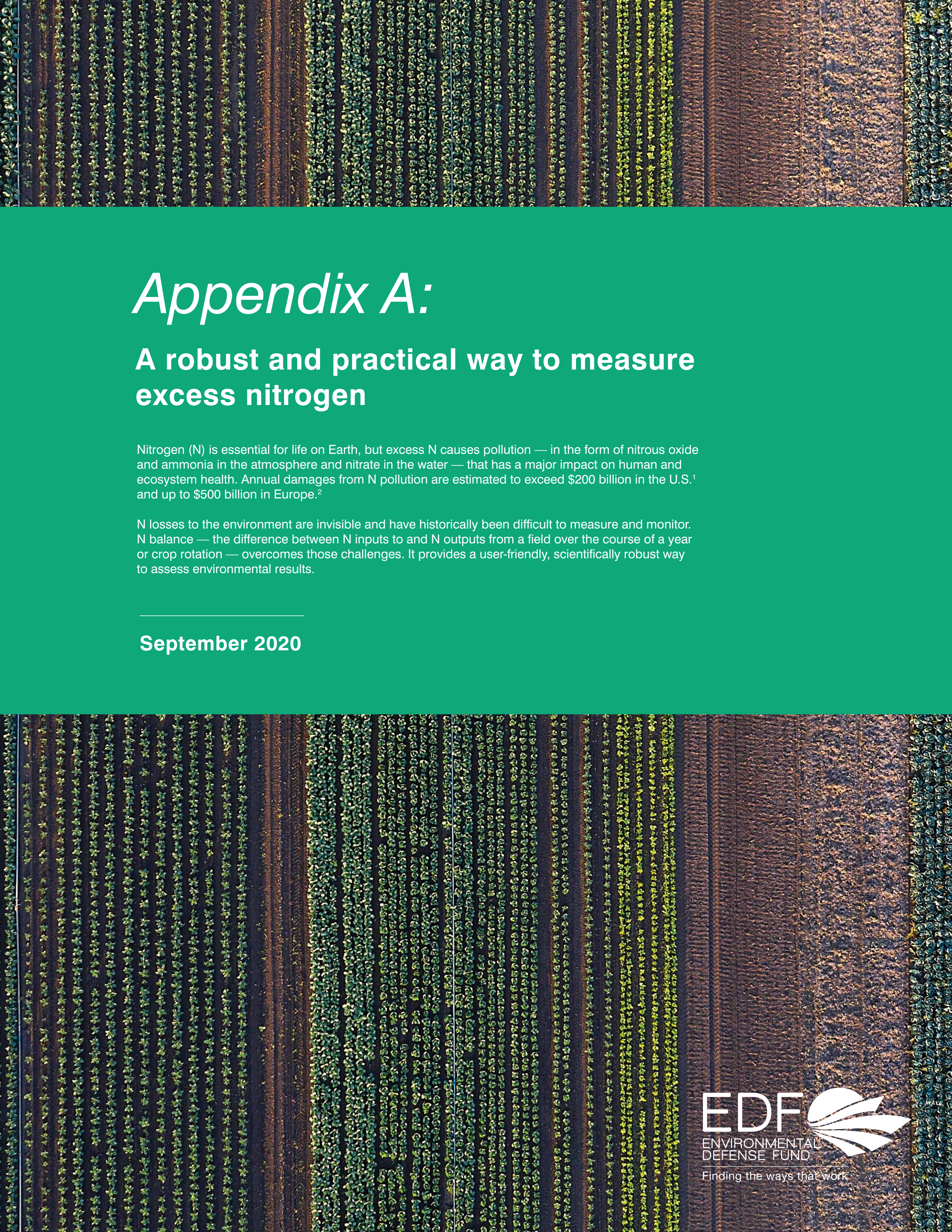

Appendix A:

A robust and practical way to measure excess nitrogen

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.

September 2020

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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”[3] 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[4] 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.[5] 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.[6]

[1] Sobota et al., 2015.

[2] Van Grinsven et al., 2013.

[3] McClain et al., 2003.

[4] Puckett et al., 2011.

[5] Eagle et al., 2017; Venterea and Coulter, 2015.

[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[7] 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:

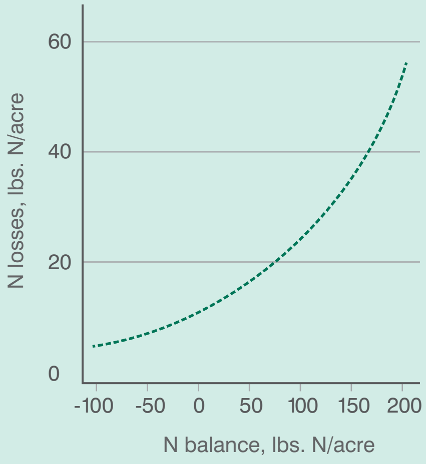
1. Scientifically robust (i.e., linked strongly to N losses to the environment).
2. Easy to implement in the supply chain context (i.e., capable of being aggregated at a large scale, across multiple soil types, climates and cropping systems and using very limited input data).
3. Meaningful to farmers (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.[8] 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.[9]

Figure 1: N balance is a robust and consistent measure of N losses to the environment



This relationship applies to all rainfed cropping systems in temperate regions. It doesn't necessarily apply to irrigated systems or tropical regions.

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, Plantierra, 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[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.[11]

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

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[9] Hansen et al., 2017; Windolf et al., 2012.

[10] Our models are statistically robust when data are aggregated across hundreds of fields, for example across a grain company's sourcing region.

[11] McLellan et al., 2018.

[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.

[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

[14] Eagle and McLellan, et al. 2020

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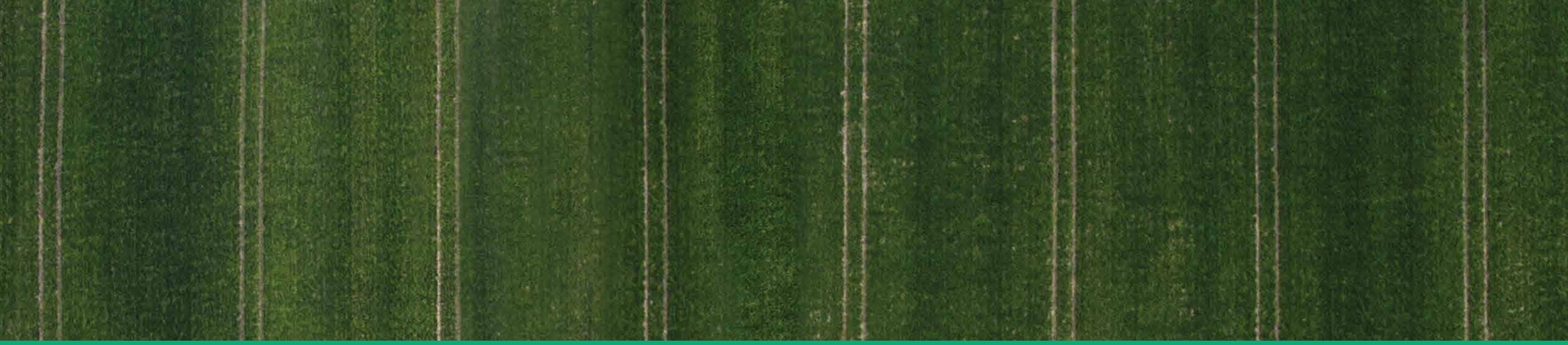

Appendix B:

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.

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The **N balance** equation

N balance is calculated by:

$$\textbf{N}\ \text{balance}\left(\frac{\text{lbs. N}}{\text{acre}}\right) = \text{Total\_}\textbf{N}\text{\_Applied}\left(\frac{\text{lbs. N}}{\text{acre}}\right) - \textbf{N}\text{\_Removed}\left(\frac{\text{lbs. N}}{\text{acre}}\right)$$

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:

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

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:

$$\text{Total\_}\textbf{N}\text{\_Applied}\left(\frac{\text{lbs. N}}{\text{acre}}\right) = \text{Fertilizer\_}\textbf{N}\left(\frac{\text{lbs. N}}{\text{acre}}\right) + \text{Manure\_}\textbf{N}\left(\frac{\text{lbs. N}}{\text{acre}}\right) + \text{Legume\_Fixed\_}\textbf{N}\left(\frac{\text{lbs. N}}{\text{acre}}\right)$$

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.

Fertilizer_N

If synthetic fertilizer is the only added source of nitrogen, then ***Total_N_Applied*** is equal to ***Fertilizer_N***, and **N balance** is equal to the amount of ***Fertilizer_N*** minus ***N_Removed***.

The following examples focus on a single year of a grain crop receiving all N additions from synthetic fertilizer. This method works for a field of any size or a group of fields that are all managed in a similar manner with similar outcomes.

Example calculations *with synthetic fertilizer:*

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

Example 1 (imperial units)	*Example 2 (metric units)*
195 lbs. N fertilizer per acre (*Total_N_Applied* = *Fertilizer_N*)	200 kg N fertilizer per hectare (*Total_N_Applied* = *Fertilizer_N*)
200 bu per acre corn grain, at 15.5% moisture (*Crop_Yield*)	12.5 t/hectare corn grain, at 15.5% moisture (*Crop_Yield*)
50% stover removed from field at harvest	*N_Removed* = 12 kg N/t corn × 12.5 t/hectare = 150 kg N/hectare
N_Removed = *N_Removed* in grain plus *N_Removed* in stover = [0.67 lbs. N/bu corn[5] × 200 bu/acre] + [0.5 x 0.67 lbs. N/bu corn x 200 bu/acre x 50%] = 168 lbs. N/acre	*N balance* = 200 kg N/hectare — 150 kg N/hectare = ***50 kg N/hectare***
N balance = 195 lbs. N/acre — 168 lbs. N/acre = ***27 lbs. N/acre***	

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]

$$\underset{\left(\frac{\text{lbs. N}}{\text{acre}}\right)}{\text{Manure\_}\mathbf{N}} = \underset{\left(\frac{\text{lbs. N}}{\text{ton manure}}\right)}{\text{Manure\_Test\_}\mathbf{N}} \times \underset{\left(\frac{\text{ton manure}}{\text{acres}}\right)}{\text{Manure\_Applied}}$$

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)	*Example 2 (metric units)*
75 lbs. N fertilizer per acre (*Fertilizer_N*)	0 lbs. N fertilizer per acre (*Fertilizer_N* = 0)
4,000 lbs. (2 tons) poultry litter per acre (*Manure_Applied*), 50 lbs. N/ton “as is” (*Manure_Test_N*)	3,000 kg (3 t) poultry litter per hectacre (*Manure_Applied*), 75 kg N/t “as is” (*Manure_Test_N*)
200 bu per acre corn grain, at 15.5% moisture (*Crop_Yield*)	12.5 t/hectare corn grain, at 15.5% moisture (*Crop_Yield*)
N_Removed = 0.67 lbs. N/bu corn × 200 bu/acre = 134 lbs. N/acre	*N_Removed* = 12 kg N/t corn × 12.5 t/hectare = 150 kg N/hectare
Manure_N = 50 lbs. N/ton × 2 tons/acre = 100 lbs. N/acre	*Manure_N* = 75 kg N/t × 3 t/hectare = 225 kg N/hectare
Total_N_Applied = *Fertilizer_N* + *Manure_N* = 75 lbs. N/acre + 100 lbs. N/acre = 175 lbs. N/acre	*Total_N_Applied* = 225 kg N/hectare
N balance = 175 lbs. N/acre — 134 lbs. N/acre = ***41 lbs. N/acre***	*N balance* = 225 kg N/hectare — 150 kg N/hectare = ***75 kg N/hectare***

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[5] Calculations use the IPNI standard *Grain_N* of 0.67 lbs. N/bu corn (12 kg N/t grain corn).

[6] *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:

$$\mathit{Legume\_Fixed\_}\boldsymbol{N}\mathit{\_Soybean}\left(\frac{\text{lbs. N}}{\text{acre}}\right) = 0.79 \times \mathit{Grain\_}\boldsymbol{N}\left(\frac{\text{lbs. N}}{\text{acre}}\right)$$

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:

$$\mathit{Legume\_Fixed\_}\boldsymbol{N}\mathit{\_Cover\_Crop}\left(\frac{\text{lbs. N}}{\text{acre}}\right) = 0.50 \times \mathit{Cover\_Crop\_Biomass\_}\boldsymbol{N}\left(\frac{\text{lbs. N}}{\text{acre}}\right)$$

where ***Cover_Crop_Biomass_N*** is the total aboveground amount of N in the cover crop.[8]

Example calculations *with a legume cash crop:*

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

Example 1 (imperial units)	*Example 2 (metric units)*
Soybean crop of 40 bu per acre, at 13% moisture (*Crop_Yield*)[9]	Soybean crop of 2.5 t/hectare, at 13% moisture (*Crop_Yield*)
N_Removed = 3.3 lbs. N/bu soybeans × 40 bu/acre = 132 lbs. N/acre	*N_Removed* = 55 kg N/t soybean × 2.5 t/hectare = 137.5 kg N/hectare
Legume_Fixed_N = 0.79 × 132 lbs. N/acre = 104.3 lbs. N/acre (=*Total_N_Applied* in this case)	*Legume_Fixed_N* = 0.79 × 137.5 kg N/hectare = 108.6 kg N/hectare (=*Total_N_Applied* in this case)
N balance = 104.3 lbs. N/acre — 132 lbs. N/acre = ***−27.7 lbs. N/acre***	*N balance* = 108.6 kg N/hectare — 137.5 kg N/hectare = ***−29 kg N/hectare***

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[7] See Appendix B for the rationale underlying assumptions about BNF portion of *Legume_N*.

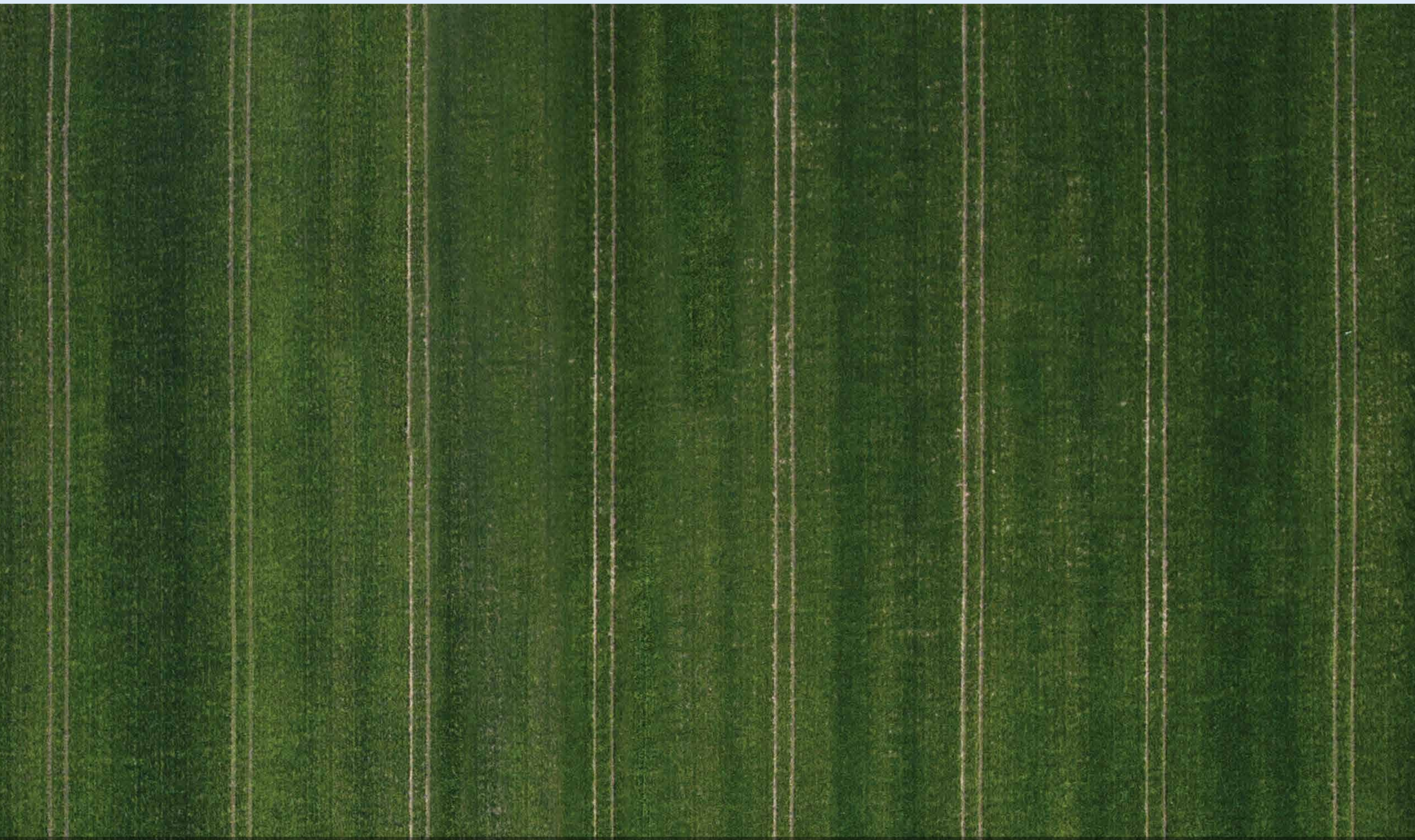
[8] See Appendix B for an alternative method to calculating *N Balance* when *Cover_Crop_N* is unknown.

[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:*[10]

Data needed: ***Fertilizer_N*** (required), ***Crop_Yield*** (required), ***Grain_N*** (optional), ***Cover_Crop_Dry_Biomass*** (required), and ***Cover_Crop_N*** (optional)[11]

Example 1 (imperial units)	*Example 2 (metric units)*
Red clover cover crop, 1,600 lbs./acre dry matter (*Cover_Crop_Dry_Biomass*), 3.5% N (*Cover_Crop_N*)	50:50 mix of red clover and rye, 1,600 kg/hectare dry matter (*Cover_Crop_Dry_Biomass*), 3.5% N (*Cover_Crop_N*)
150 lbs. N fertilizer per acre (*Fertilizer_N*)	160 kg N fertilizer per hectare (*Fertilizer_N*)
200 bu per acre corn grain, at 15.5% moisture (*Crop_Yield*)	12.5 t/hectare corn grain, at 15.5% moisture (*Crop_Yield*)
N_Removed = 0.67 lbs. N/bu corn × 200 bu/acre = 134 lbs. N/acre	*N_Removed* = 12 kg N/t corn × 12.5 t/hectare = 150 kg N/hectare
Cover_Crop_Biomass_N = 1,600 lbs./acre × 3.5% N = 56 lbs. N/acre	*Cover_Crop_Biomass_N* = 1,600 kg/hectare × 3.5% N = 56 kg/hectare
Legume_Fixed_N = 0.50 (% N that is BNF) × 56 lbs. N/acre = 28 lbs. N/acre	*Legume_Fixed_N* = 0.50 (% red clover) × 0.50 (% N that is BNF) × 56 kg/hectare = 14 kg N/hectare
Total_N_Applied = *Fertilizer_N* + *Legume_Fixed_N* = 150 lbs. N/acre + 28 lbs. N/acre = 178 lbs. N/acre	*Total_N_Applied* = *Fertilizer_N* + *Legume_Fixed_N* = 160 kg N/hectare + 14 kg N/hectare = 174 kg N/hectare
N balance = 178 lbs. N/acre — 134 lbs. N/acre = ***44 lbs. N/acre***	*N balance* = 174 kg N/ha — 150 kg N/ha = ***24 kg N/hectare***



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[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[12] (i.e., the amount of N in each ton or bushel of harvested crop) that may be used as ***Grain_N*** in the **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.

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

Corn, grain (standard marketing convention, 15.5% moisture)	**0.67 lbs./bu (12 kg/t)**
Corn, silage (67% water)	**9.7 lbs./ton* (4.9 kg/t)**
Corn, stover	**0.33 lbs./bu (8.0 kg/t)****
Soybean, grain (standard marketing convention, 13% moisture)	**3.3 lbs./bu (55 kg/t)**
Wheat, spring (standard marketing convention, 13.5% moisture)	**1.5 lbs./bu (25 kg/t)**
Wheat, winter (standard marketing convention, 13.5% moisture)	**1.2 lbs./bu (19 kg/t)**

* 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 *Grain_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[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,[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).

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

[13] Tenorio et al., 2019, which used more than 10,000 observations from 1999 through 2016.

[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.[15] 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).[16] 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."[17] 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.[18]

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.[19] Using the IPNI assumptions — 100% of the 55 kg N/t 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^{-1}."[20] 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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[15] Blesh, 2018.

[16] David, M.B., L.E. Drinkwater and G.F. McIsaac, 2010.

[17] Blesh, J. and L.E. Drinkwater, 2013.

[18] McIsaac, G.F., M.B. David and G.Z. Gertner, 2016.

[19] IPNI, 2012.

[20] Gelfand, I. and G. Philip Robertson, 2015.

Legume winter cover crops

This section provides guidance on calculating N inputs from leguminous winter cover crops[21] 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."[22]

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.[23] 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.[24]

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.[25] 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 = 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.

[22] Poffenbarger, H.J., S.B. Mirsky, R.R. Weil, J.E. Maul, M. Kramer, J.T. Spargo and M.A. Cavigelli, 2015.

[23] Coombs, C., J.D. Lauzon, B. Deen and L.L. Van Eerd, 2017.

[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[26]

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).

Species	Equation
Winter pea (n=64)	$y = 0.028x - 7.46$
Chickling vetch (n=26)	$y = 0.017x + 0.70$
Crimson clover (n=64)	$y = 0.018x - 6.50$
Red clover (n=64)	$y = 0.022x - 0.84$
Other species (avg. of above)	$y = 0.021x - 3.53$

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[27]

Crop	<6" Growth	>6" Growth
	lbs. N/acre to credit	
Alfalfa	40	60-100[a]
Red Clover	40	50-80[a]
Sweet Clover	40	80-120[a]
Vetch	40	40-90[a,b]

[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.

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Appendix C:

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.

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How EDF scientists determined the safe zone range

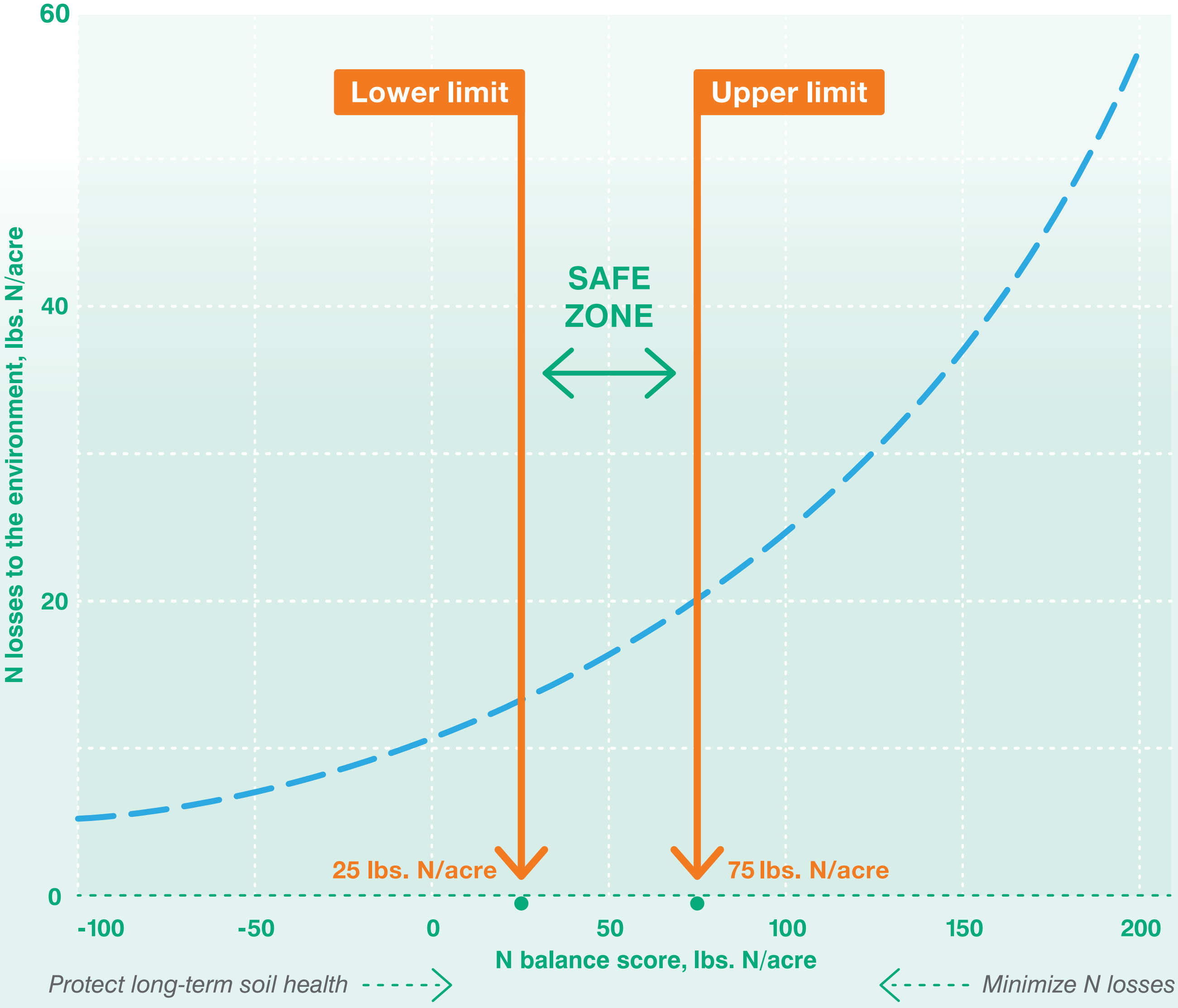
The safe zone includes N balance scores[1] of 25-75 lbs. N/acre (Figure 1).

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_2O) 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.

Figure 1: The N balance safe zone



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[1] See How to Calculate Nitrogen Balance on edf.org/n-balance for more information.

[2] McLellan 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[4] for N into a comparable global average N balance of 35-70 lbs. N/acre of harvested cropland per year.[5] They propose that these targets will allow global agriculture to meet 2050 food demand and also meet United Nations Sustainable Development goals.

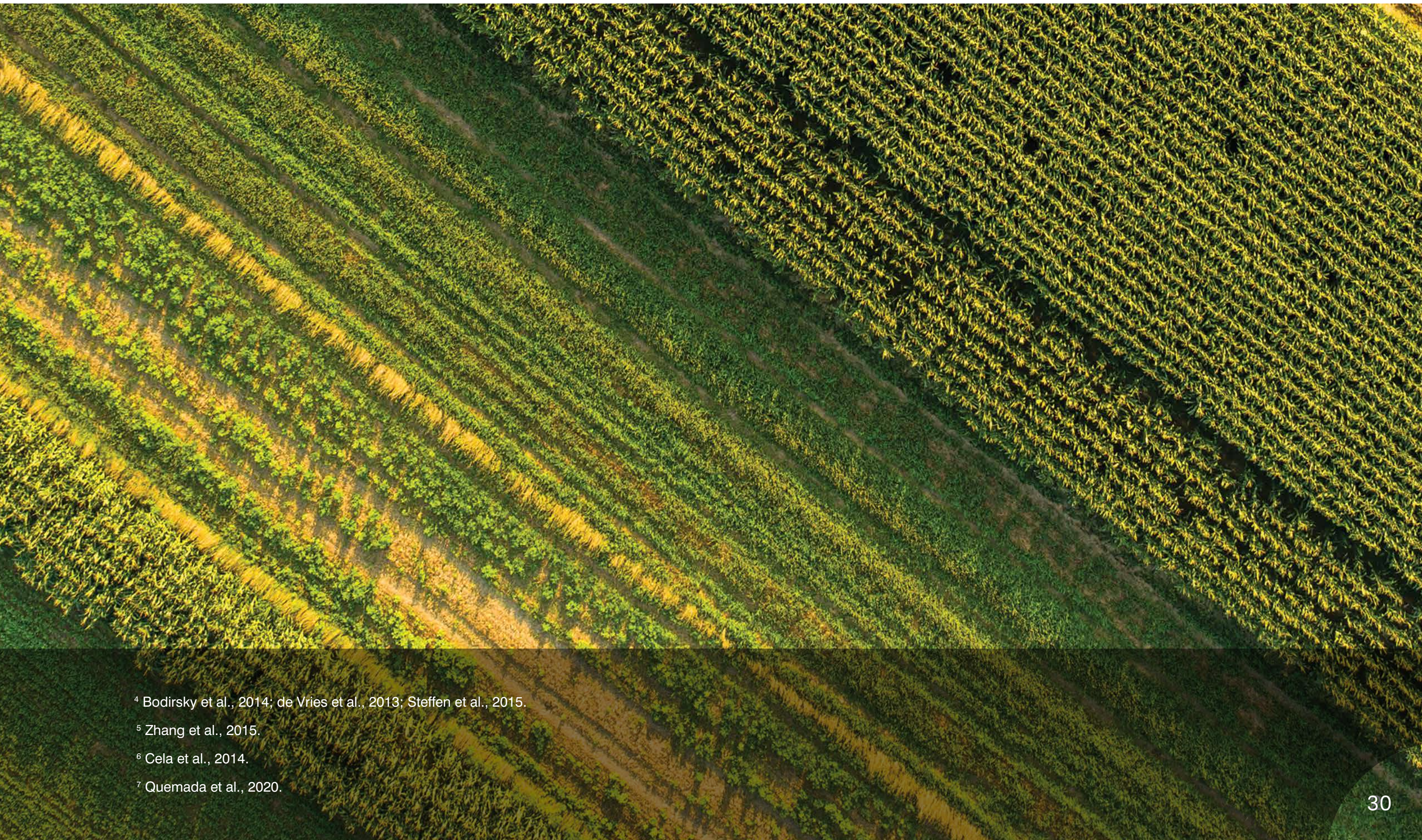
Researchers from Cornell University established the concept of a whole-farm safe zone of N balance for dairy operations.[6] The "optimal operational zone" was designed to "allow dairy farms to be economically profitable and environmentally sustainable while promoting flexibility in management practices." 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.

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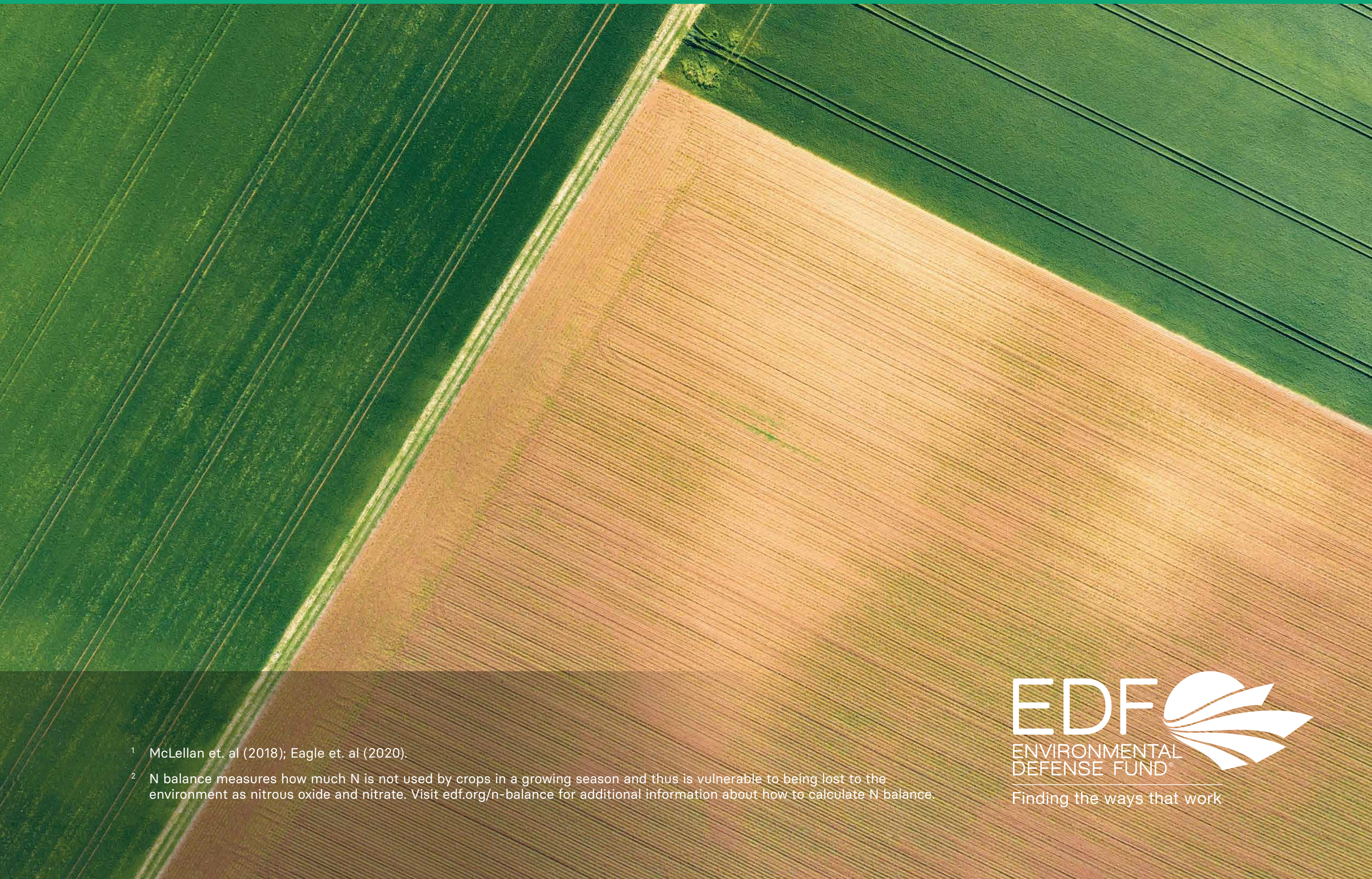
Appendix D:

How to use nitrogen balance to estimate nitrous oxide and nitrate losses

Environmental Defense Fund scientists developed two environmental models[1] 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.

February 2021



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[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 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.

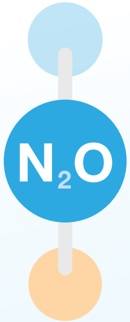
As with most models, having more observations (in this case, N balance scores) provides more precise and accurate results. To have statistical confidence that a program or project has led to real environmental improvement — reduced nitrous oxide emissions and nitrate leaching — EDF recommends aggregating N balance scores from a minimum of 300 fields together and having three years of baseline data from the same 300 fields.[3] Emissions and leaching from subsequent years can then be compared to the three-year baseline to measure change.

The relationship[4] between N balance and nitrous oxide emissions, expressed in the nitrous oxide model, applies to aggregated groups of fields with most common soil types[5] and annual, non-legume[6] 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.

imperial units[7]

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.

$$N_2O = 1.25e^{0.0053NBal}$$

where ***N_2O*** denotes emissions in units of lbs. N_2O-N/acre/year, and ***N 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_2O-N/acre/year, respectively.

metric units[8]

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.

$$N_2O = 1.40e^{0.0047NBal}$$

where ***N_2O*** denotes emissions in units of lbs. N_2O-N/acre/year, and ***N 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_2O-N/hectare/year, respectively.

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[3] 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.

[4] 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. These models were further refined to include other soil types and crops in Eagle et al., 2020 (for N_2O) and Tamagno et al., 2022 (for NO_3).

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

[6] 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.

[7] This equation can also be expressed as $N_2O = \exp(0.224 + 0.0053 \times \text{N balance})$.

[8] This equation can also be expressed as $N_2O = \exp(0.339 + 0.0047 \times \text{N balance})$.

imperial units[9]

How to determine **nitrate leaching**

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

$$NO_3 = 15.1e^{0.00404NBal}$$

where **NO_3** denotes leaching losses in units of lbs. NO_3-N/acre/year, and **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 NO_3 leaching losses of 17, 21 and 25 lbs. NO_3-N/acre/year, respectively.

metric units[10]

How to determine **nitrate leaching**

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

$$NO_3 = 17.0e^{0.0036NBal}$$

where **NO_3** is leaching losses in units of kg NO_3-N/hectare/year, and **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 NO_3 leaching losses of 19, 22 and 27 kg 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. N_2O-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. N_2O-N/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. 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. NO_3-N leaching losses/year for each participating field.

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[9] This equation can also be expressed in imperial units (lbs. N/acre) as $NO_3 = \exp(2.72 + 0.00404 \times \text{N balance})$.

[10] This equation can also be expressed in metric units (kg N/hectare) as $NO_3 = \exp(2.832 + 0.0036 \times \text{N balance})$.

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 (CO_2e) 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. Divide total lbs. **N_20-N emissions** by 2.205 to convert to kg **N_20-N**, then divide by 1,000 to convert to metric tons (t N_20-N).[11]

2. Multiply t **N_2O-N** by 1.5711 to convert to t **N_20**/year (1 t **N_20-N** = 1.5711 t **N_20**).

3. Multiply t **N_2O**/year by 265 to convert to t **CO_2**e/year.[12] The result is total t **CO_2**e/year.

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[11] 1 metric ton = 1000 kg = 1 Mg (megagram) = 1 x 10^6 g.

[12] 100-yr GWPs ~ $C0_2$:CH_4:N_20 = 1:28:265. (IPCC, 2014).