The Nitrogen Balancing Act: Tracking the Environmental Performance of Food Production

EILEEN L. McLELLAN, KENNETH G. CASSMAN, ALISON J. EAGLE, PETER B. WOODBURY, SHAI SELA, CHRISTINA TONITTO, REBECCA D. MARJERISON, AND HAROLD M. van ES

Farmers, food supply-chain entities, and policymakers need a simple but robust indicator to demonstrate progress toward reducing nitrogen pollution associated with food production. We show that nitrogen balance—the difference between nitrogen inputs and nitrogen outputs in an agricultural production system—is a robust measure of nitrogen losses that is simple to calculate, easily understood, and based on readily available farm data. Nitrogen balance provides farmers with a means of demonstrating to an increasingly concerned public that they are succeeding in reducing nitrogen losses while also improving the overall sustainability of their farming operation. Likewise, supply-chain companies and policymakers can use nitrogen balance to track progress toward sustainability goals. We describe the value of nitrogen balance in translating environmental targets into actionable goals for farmers and illustrate the potential roles of science, policy, and agricultural support networks in helping farmers achieve them.

Keywords: nitrogen balance, nitrogen pollution, supply chain, agricultural production, environmental outcomes

Nitrogen fertilizer poses a huge challenge for modern agriculture (figure 1). Although essential for achieving high crop yields, its abundant use makes fertilizer the dominant contributor to global nitrogen pollution, which poses substantial risks to climate, human health, and ecosystems (Erisman et al. 2013). Nitrogen (N) fertilizer is the dominant source of new anthropogenic N in US landscapes, resulting in estimated ecosystem and health damages of US$157 billion per year (Sobota et al. 2015). At a global scale, anthropogenic contributions to N flows have driven us beyond the "safe operating space" for human development (Steffen et al. 2015). As a result, there is growing interest in N-related indicators that can track progress in reducing N losses to the environment while maintaining or increasing food production (Zhang et al. 2015).

In the United States, small profit margins and increasing public concern about the environmental impacts of food production have driven substantial efficiency improvements in agricultural production (Thomson et al. 2017). Despite these efficiency gains, water quality problems related to N loss from agricultural systems continue and may be worsening. For example, in 2017, the Gulf of Mexico hypoxic zone, which is caused in large part by N losses from crop production upstream, reached the greatest extent ever recorded. This is perhaps not surprising given that, despite significant government payments to upstream farmers, agricultural N loads to the Gulf of Mexico have not declined significantly (Scavia et al. 2017). Consequently, some have concluded that current (voluntary) efforts to improve agricultural sustainability have failed (Ribaudo 2015), and there are increasing calls for regulation. Separately, a growing number of international food retailers and manufacturers have committed to improving the sustainability of their food supply chains. Recognizing that N-fertilizer use dominates the nitrogen footprint of food (Goucher et al. 2017), these industry initiatives seek to improve on-farm environmental performance.

Across multiple scales—farm, watershed, and food supply chain—there is a clear need for environmental performance indicators that are scientifically sound, responsive in the near term to changes in farm management, and credible to broader audiences. Here, we show that the *N-balance indicator* (the difference between N inputs to and N outputs from a field or farm, sometimes referred to as *N surplus*) is a robust gauge of potential N losses from agricultural systems, and we describe how it will allow farmers, food supply-chain companies, and policymakers to track and report progress in reducing the environmental footprint of food. In addition, heeding calls for quantitative targets for the sustainable

doi:10.1093/biosci/bix164 Advance Access publication 7 February 2018

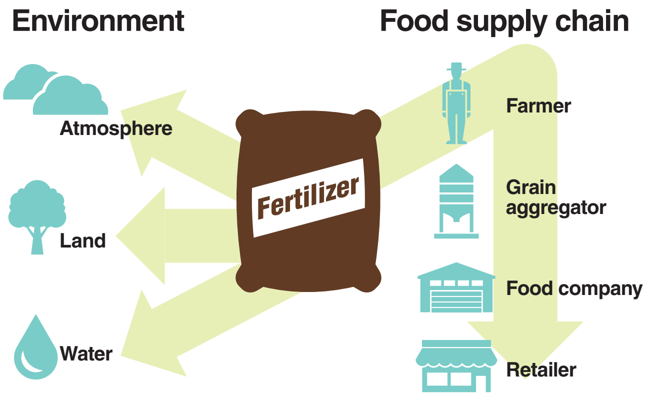

Figure 1. A conceptual diagram illustrating the alternative fates of nitrogen from fertilizer applied to crops. Nitrogen not captured in the food supply chain is likely to be lost to the environment, with impacts on the atmosphere (stratospheric ozone depletion, global warming, and the formation of ground-level ozone, particulate matter, and smog), on land (soil acidification, foliar damage, forest decline, biodiversity loss, and terrestrial eutrophication), and on water (coastal dead zones, freshwater eutrophication, nitrates in drinking water, and biodiversity loss). The most desirable outcome is that as much nitrogen as possible enters the food supply chain and is made available to consumers. The less desirable outcome is that nitrogen is lost to the environment, where it damages human health and ecosystems, and contributes to climate change.

intensification of agriculture (Hunter et al. 2017), we suggest how environmental thresholds can be translated into N-balance targets and propose a framework to help farmers achieve those targets. We focus primarily on N balance in cropping systems, recognizing that farm-scale N balances are already broadly accepted as a sustainability indicator for animal production systems (e.g., de Klein et al. 2017) and that feed (grain) is a major component of the US livestock production footprint.

Current approaches to quantifying environmental progress

Assessing the effectiveness of attempts to reduce N losses from agriculture is challenging for several reasons (Cherry et al. 2008). Most assessments track the adoption of specific practices, such as improved fertilizer management or use of cover crops. Although these practices effectively reduce some types of N losses in research plots under specific agricultural or environmental conditions, performance at this spatial scale does not necessarily translate to the farm or watershed level. This disconnect occurs because larger spatial scales encompass differences in temperature, precipitation, soil texture, soil organic matter, landscape position, and management history, all of which influence soil N pools and N cycling and therefore the impact of a given practice on N losses. Thus, the impact of a specific practice can vary greatly within a watershed, even to the point of having opposite effects on N losses in different places. Furthermore, practices that reduce N losses to the atmosphere may increase N discharges to surface- and groundwater and vice versa (i.e., pollution swapping; Stevens and Quinton 2009). The only practice that will consistently decrease N losses at all locations, by all pathways and for all forms of N, is reduction in N input rates, which risks compromising crop yields.

Given the challenges of a practice-based assessment approach, some have attempted to evaluate environmental progress directly by measuring changes in greenhouse gas emissions or water quality. However, this is difficult and costly because of multiple loss pathways, rapid transformations among different forms of N (e.g., ammonia, NH_3; nitrate, NO_3^-; nitrous oxide, N_2O; and dinitrogen gas, N_2), and high spatial and temporal variability (especially for N_2O emissions). Likewise, inferring progress from water-quality data is complicated by possible impacts of legacy N sources in soil and subsurface water (Van Meter et al. 2016), as well as the potential for climate-change-related impacts—such as increased runoff—to obscure the immediate benefits of practice change (Bosch et al. 2014).

As an alternative to direct measurement, environmental models attempt to determine the fate of agricultural nutrients by using a variety of equations to represent the biophysical system. Models range from relatively simple empirical models based on field measurements to very complex models that attempt to simulate biophysical processes in detail within the soil–crop–air–water system. The comprehensive nature of these process-based models makes them appealing for application to a wide array of crops, geographies, and agricultural management practices. However, they perform poorly when used beyond the applications and conditions for which they are calibrated (Baffaut et al. 2017), and the lack of transparency into model inputs and processes can lead to a credibility challenge for model outputs.

Nitrogen balance as a measure of nitrogen losses to the environment

Although there is value to both modeling and environmental monitoring, we believe a simple field- and farm-level indicator of N loss, responsive to changes in farm management practices, is likely to be both more credible and more useful to an individual farmer. Such an indicator will better help her or him understand the direct impact of farm management changes on environmental outcomes. We propose that *N balance*, which has been widely used in the EU and elsewhere (OECD 2013), is an appropriate indicator for this purpose. Nitrogen balance is defined as the difference between N inputs to, and N removed in products from, an agricultural system. At the spatial scale of a single production field, for example, N balance can be calculated from records of inorganic and organic nutrient applications and crop yield. More sophisticated balances can account for additional N inputs, such as atmospheric deposition and net N inputs from legume fixation, as well

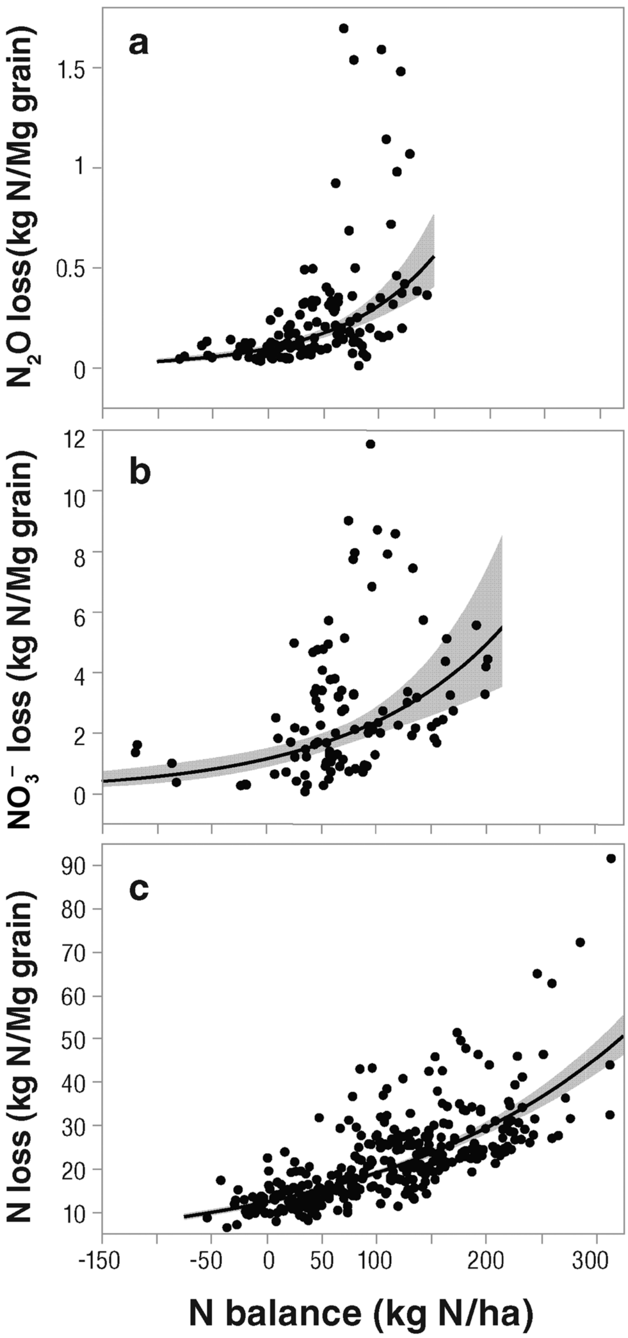

Figure 2. The relationship between nitrogen (N) balance [(N fertilizer)–(N removed in harvested grain)] and (a) yield-scaled N_2O emissions and (b) yield-scaled NO_3^- leaching, derived from published maize cropping system field studies on silt loam and closely related soils in North America. Panel (c) shows the relationship between yield-scaled total N losses and N balance, based on simulations with the Adapt-N model; total losses exceed the sum of N_2O and NO_3^- losses because the total also includes losses in the forms of NO_x, NH_3, and N_2. Note that each panel has a different range of values on the y-axis. Details of the analysis and curve-fitting are provided in the supplemental materials.

as variations in the N content of harvested crop materials and changes in soil organic matter content. At the farm scale, the definition of N balance expands to include inputs and outputs associated with integrated crop–livestock production systems (Soberon et al. 2015). Nitrogen balance can be scaled up to large watersheds (Thorburn and Wilkinson 2013, Cela et al. 2017) and countries (Zhang et al. 2015) and aggregated across industry sectors (Stott and Gourley 2016).

Nitrogen balance for a field, as defined above, is a measure of the extent to which anthropogenic N supply exceeds crop needs. Although modest excess may be required (e.g., to support growth of unharvested plant parts and maintain soil organic matter), a large excess creates a pool of reactive N in soil that is extremely vulnerable to loss and is therefore a potential source of pollution. Assuming steady-state conditions with little or no change in soil organic N stocks, N balance represents a robust estimate of the soil N pool at risk of loss to the environment. To test this hypothesis, we evaluated relationships between N balance and environmental N losses through two complementary approaches, one based on analysis of published field data and the other based on a simulation model (figure 2). We focus primarily on N_2O emissions and NO_3^- leaching, because these have been the subject of supply-chain sustainability initiatives in the United States. To ensure that reductions in N losses are not achieved at the expense of crop yields, we express N loss relationships as yield-scaled N_2O and NO_3^- losses (kilograms N lost per megagram of grain; van Groenigen et al. 2010); the relationship between N balance and area-scaled losses is presented in supplemental figure S2.

The first approach used published field-scale studies of rain-fed maize systems in the north-central United States and southeast Canada from which N balance and yield-adjusted N losses could be calculated, as we detail in the supplemental materials. The resulting empirical relationship between N balance and yield-scaled losses is shown in figure 2a (for N_2O) and 2b (for NO_3^-), together with the 95% confidence interval of the mean response (see the supplemental materials for details). The shape of the best-fit curves in figure 2a and 2b is consistent with biophysical understanding of the fate of N in cropping systems: When N supply exceeds crop uptake requirements, the excess N becomes vulnerable to loss, and N loss rates increase with higher amounts of excess fertilizer. The scatter of individual data points around the best-fit curves reflects variations in weather, soil, and field management that influence N cycling and crop yield in the crop–soil system.

The second approach used a simulation model to estimate the effect of N-fertilizer management practices on N losses at 18 locations in the Corn Belt. We used a research version of Adapt-N, a field-level model that simulates changes in soil N pools, crop N uptake, and losses of N to air and water (Sela et al. 2016; see the supplemental materials for details of model validation). Using this model provides an assessment of the relationship between N balance and environmental

N losses across a wider range of N balance and environmental conditions than can be found in published data from field experiments. In addition, the model simulates all transformation pathways, providing an estimate of total losses to the environment from all forms of N, including gaseous losses (NH_3, N_2, N_2O, and NO_x) and NO_3^- leaching. Inclusion of all major N species, together with the ability to simulate losses over an entire year rather than a growing season, leads to much larger estimates of N loss from model simulations (figure 2c) than from field experiments that only measure one form (figure 2a, 2b). Despite these differences, the results from our model simulations (figure 2c) define a relationship between N balance and yield-scaled total N losses that is both strong and consistent with the analysis of the field-measured N_2O and NO_3^- loss data (figure 2a, 2b).

Together, the analyses of field data and simulation results provide compelling evidence that a robust relationship exists between N balance and environmental N losses. Therefore, N balance is a robust predictor of field-scale N losses when aggregated over multiple sites and years. Relationships of similar form have been noted recently for N_2O and NO_3^- losses separately in North American maize systems, varying slightly depending on soil type, crop rotation, and nutrient management (Zhao et al. 2016, Omonode et al. 2017). Here, the comparable response of both N_2O and NO_3^- to N balance means that management of N balance to mitigate high losses of one form of N is synergistic for the other, thus minimizing the pollution-trade-off risks that exist with some management practices (e.g., drainage water management that reduces NO_3^- losses but could increase N_2O emissions). Relationships similar to those in figure 2 also exist for other crops and regions (e.g., van Groenigen et al. 2010, Cui et al. 2013). Therefore, it is clear that N balance is a robust indicator of potential environmental N losses associated with N inputs applied in crop production.

Entities interested in translating changes in N balance into changes in greenhouse gas emissions and water quality could potentially use empirical relationships such as those shown in figure 2a and 2b. For example, on the basis of figure 2a, a reduction in N balance from 150 kilograms N per ha to 100 kilograms N per ha (at constant yield) would correspond to a decrease in N_2O emissions of 45%. Similar empirical models could be developed for maize grown with manure, for other crops, and for other regions. Likewise, a well-validated empirical model for water quality (similar to figure 2b) could estimate field-scale changes in NO_3^- leaching below the root zone resulting from a specific N balance change. Transport factors such as those included in the SPARROW water quality models (Robertson et al. 2014) could upscale this field-level NO_3^- leaching reduction to NO_3^- load changes in the nearest stream or the outlet of a larger river basin (Woodbury et al. 2017).

Using nitrogen balance to track environmental progress

Given public concern about environmental N losses and the strong relationship between N balance and N losses described above, we anticipate that both individual farmers and the broader agricultural community would be interested in using the N-balance indicator to track N losses from crop production systems as a way of demonstrating a reduced environmental footprint of farming. For example, commodity groups might see value in using aggregated N-balance data to demonstrate industry-wide improvement in mitigating N losses. Supply-chain companies, such as food processors and retailers, might be interested in using N balance to document the impact of their sustainability initiatives. As an example, Unilever has previously reported on total reductions in N pollution along its international supply chain for specialty crops, using aggregated N-balance data obtained from its suppliers under its Sustainable Agriculture Code (Unilever 2010). Likewise, the Stewardship Index for Specialty Crops has adopted a "Nitrogen Use" metric that is related to N balance (SISC 2013) to help track improved N management by its suppliers. Field to Market, a multistakeholder initiative to improve supply-chain sustainability for commodity crops, is in the process of adopting a new metric for cropland N_2O emissions that relies on the relationship between these emissions and N balance. Once adopted, this N-balance-based metric will help track the environmental benefits of various supply-chain sustainability projects.

Policymakers outside the United States have used N balance as an indicator to track progress in reducing the environmental impacts of food production. For example, it has been used across Europe (EEA 2017), where a variety of national policies have been adopted to decrease regional and national N balances. The success of these policies is illustrated by Denmark, which has reduced its country-level N balance by 40% (Dalgaard et al. 2014), with the result that NO_3^- leaching has been reduced by 50% and ammonia emissions have also declined. Other OECD countries also use N balance (OECD 2013) as an indicator of sustainable intensification. In the United States, California (where in some counties over 40% of wells exceed safe drinking-water standards for nitrate) will soon require farmers to track and report nutrient budgets (essentially N balances; Harter 2015).

Setting nitrogen-balance goals: Carrying capacity, thresholds, and safe operating spaces

Hunter and colleagues (2017) noted that the discourse around sustainable intensification has primarily focused on food production goals and that corresponding environmental goals are largely lacking. Nitrogen balance offers an opportunity to set environmental goals that are also connected to farm productivity levels. Zhang and colleagues (2015) translated the "safe" planetary boundary for N (Steffen et al. 2015) into a globally averaged N balance compatible with that boundary of 39–78 kilograms N per ha per year. To mitigate the impacts of N-related air and water pollution at airshed or river-basin scales, however, will require the establishment of safe N boundaries and corresponding N balances at those scales, as well as disaggregation of those N balances across different agricultural systems within those airsheds or watersheds. In Europe, for example, where ammonia-related air pollution is a big concern, regional reductions in N balance have been correlated with reductions in atmospheric N deposition (Dalgaard et al. 2014) but have not yet been related to critical loads for specific ecosystems (e.g., national parks or estuaries). More progress has been made on water quality. For example, in parts of New Zealand, where tourism is threatened by degraded water quality, the N-load carrying capacity of lakes and streams has been quantified and translated into “nitrogen discharge allocations”—based on N balance—at the watershed and farm level (Duhon et al. 2015). In the United States, efforts to restore the Chesapeake Bay have likewise led to identification of ecosystem carrying capacity and the N-load reductions needed to reach it. Cela and colleagues (2017) have described how improvements in N balance on New York State dairies can track progress toward these N-load reduction targets.

The shape of the N-balance to N-loss relationships in figure 2 suggests a possible alternative approach to setting N-balance goals. Figure 2 illustrates dramatically increasing environmental losses above a threshold value of N balance. If further work verifies the N-balance-threshold concept, threshold values of N balance will represent useful targets for environmental performance, and the greatest reductions in N pollution could be achieved by incentivizing producers to reduce their N-balance values to the threshold level. Obviously, different cropping systems, climates, and soils would need appropriately adapted thresholds to account for other major factors governing N losses.

Nitrogen-balance targets must also be supportive of other sustainability goals, especially those related to maintaining soil organic N stocks, a critical factor in long-term soil fertility. Likewise, it will be important to relate N balance to other aspects of farm-level sustainability, such as overall productivity (yield) and profitability. The European Union Nitrogen Expert Panel (EU-NEP), a science advisory group convened by the European fertilizer industry, has introduced the concept of a safe operating space for crop production (EU-NEP 2015; see figure 3). The *safe operating space* is defined by a minimum acceptable level of productivity (to meet food needs), a maximum acceptable level of N balance (to minimize N pollution), and an acceptable range of nitrogen use efficiency (NUE; the ratio of N inputs to outputs). Excessively high NUE risks mining soil organic matter, whereas excessively low NUE wastes fertilizer and other resources.

Modeled after this safe operating space for fertilizer-based European agriculture, similar limits could be defined for other agricultural systems. Such guidelines could also incorporate broader approaches to nutrient management, such as using manure and legumes for N sources, extending crop rotations with winter cover crops, or other options (figure 3). These management practices can promote N retention in long-term soil N pools and enhance internal N cycling, thereby offering significant opportunities to reduce N balances (Gardner and Drinkwater 2009, Zhou et al. 2016). In addition, they recouple carbon and N cycling, mitigating the risk of achieving a small N balance simply by mining soil organic matter. Brentrup and Lammel (2016) showed how coupling extended rotations with improved fertilizer management moved wheat systems into the safe operating space, whereas de Klein and colleagues (2017) attempted to map safe operating spaces for dairy systems. These sustainability targets must be developed for specific agroecological regions and farming systems; one size does not fit all (Gourley et al. 2007, de Klein et al. 2017).

Nitrogen balance: The view from the farm

Our analyses above establish a robust relationship between N balance and N losses. From the perspective of a farmer seeking to reduce N losses, the challenge is identifying what changes can be made to their operation to reduce N balance while maintaining productivity and profitability.

In general, N-balance reductions can be achieved by better matching N inputs and N outputs in time and space while maintaining or increasing yields (Cassman et al. 2002, Snyder et al. 2014). This relationship creates a win–win opportunity for farmers to achieve high productivity levels while reducing environmental impact. For example, Adapt-N simulations (detailed in the supplemental materials) suggest that delaying most fertilizer N application to the maize growing season leads to smaller N balances, with less total N loss, while maintaining crop yields (figure 4). Because delaying fertilizer application usually enables lower N application rates, such improvements in fertilizer management can reduce costs and increase overall profitability (Sela et al. 2016). More broadly, Soberon and colleagues (2015) and Buckley and colleagues (2016) have shown that improved environmental performance (reduced N balance) can go hand in hand with improved production and increased profitability.

For any crop field, the size of the N balance is a function of the local biophysical setting (including factors influencing N losses, such as climate and soil type, that are not controllable by the farmer), the cropping system, and farmer management practices that affect the fate of applied N and determine actual crop yield. This suggests that across a cohort of farms with similar climate, soil type, and cropping system, and with comparable yield levels, N balance is a measure of the effectiveness of farm management practices in tightening the N cycle. As such, comparison of N balance values across cohort farms can be used to identify those farm management practices that best reduce N balance (Dalgaard et al. 2012, Blesh and Drinkwater 2013) and therefore N losses to the environment. Such benchmarking approaches have identified opportunities to improve water and N use efficiency for irrigated maize in Nebraska (Grassini and Cassman 2012) and to improve dairy-farm nutrient management in Australia and New York State (Gourley et al. 2007, Cela et al. 2014).

As an example of how such an approach could help farmers improve N balance, we show data on N balance, fertilizer

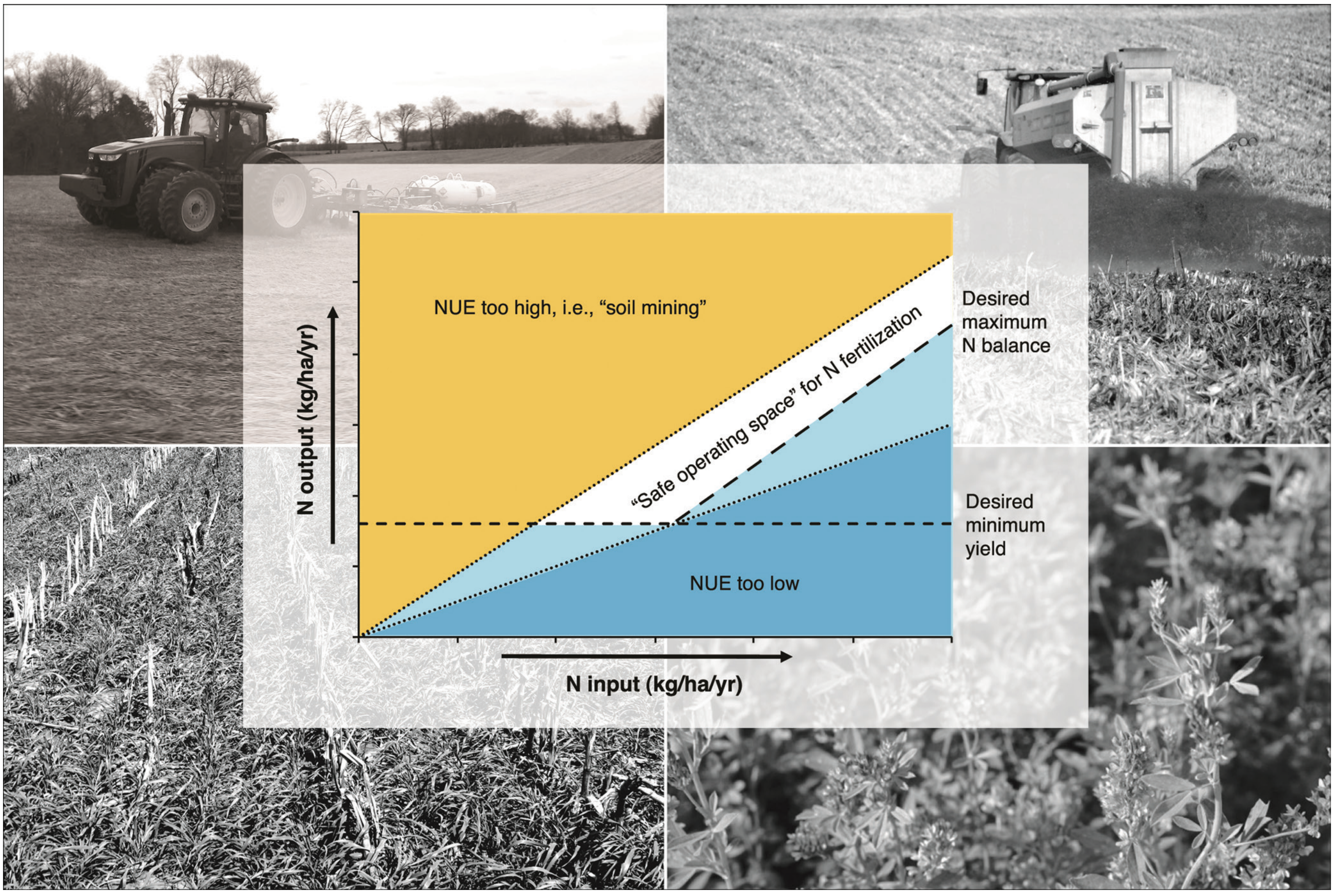

Figure 3. An illustration of the safe operating space concept (inner diagram) in the broad context of nutrient management (outer diagram). The inner diagram (modified from EU-NEP 2015) shows the relationship between total nitrogen (N) input (from fertilizer, manure, and biological N fixation), N outputs (N removed in harvested grain), N use efficiency (NUE), and N balance. A safe operating space requires that NUE is sustained within an accepted range; values that are too low (blue shaded area) are inadequate to meet food production goals and are inefficient for resource use, whereas values that are too high (gold shaded area) risk mining soil organic matter. Likewise, we assume that there is some minimum productivity (yield) goal, shown here by the horizontal dashed line, and some acceptable maximum level of N balance, shown here by the diagonal dashed line. Expert judgment is needed to define appropriate values of N balance, NUE, and yield for a given cropping system and ecoregion. The intersection of these criteria (the white space in the inner diagram) represents the safe operating space for that cropping system and ecoregion. The outer diagram shows the broad suite of approaches to nutrient management (from top left: improved fertilizer management; substitution of manure for synthetic fertilizer; use of legumes as an alternative nitrogen source; use of cover crops to tighten internal nutrient cycling), which can help move a cropping system into the safe operating space.

N rate, and yield for maize production on 66 farms in the Corn Belt (figure 5; details in the supplemental materials). The farms are typical of the region in terms of cropping system (corn–soybean) and the types of crop and soil management practices used. Highlighted in figure 5 is a subset of farms that are in close geographic proximity and share similar soil and climate characteristics, such that variations in N balance most likely reflect different farm management practices. Even within this subset of similar farms, the range in yield and N balance approximates that at the other 49 sites. So for the sake of illustrating the benchmarking process, we assume that N-balance variations among all farms reflect the influence of farm management practices.

Figure 5 shows that for any given fertilizer-N rate or yield, there is a range of N-balance values indicating that farms with a large N balance (in orange) could improve environmental performance by following the practices of small-N-balance farms (in blue). A cooperative data-sharing approach, using anonymized and aggregated N-balance data, could help farmers and their advisors benchmark their N management performance and learn about the best practices of others (Wood et al. 2014). Sewell and colleagues (2017) described the factors that are crucial to the success of such efforts, including the collaborative learning among farmers and advisors that builds the trust essential to data sharing.

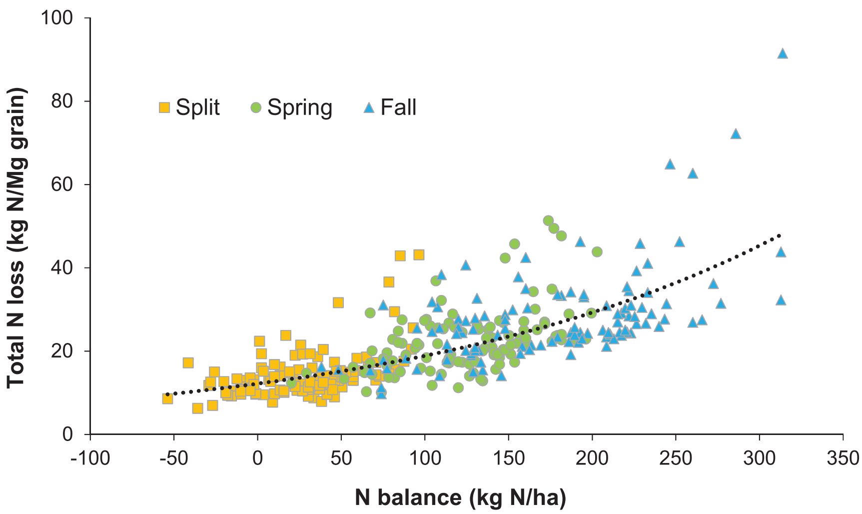

Figure 4. The relationship between nitrogen (N) balance and total yield-scaled total N losses (NH_3, N_2, N_2O, NO_x, and NO_3^-) in Adapt-N simulations of rain-fed maize systems on silt loam soils in the US Corn Belt. Simulations were split into three groups based on the timing of primary N fertilizer application (fall, spring, or split), with side-dress application rates during the growing season adjusted on the basis of Adapt-N predictions of plant N needs.

Polices based on N-balance outcomes could create incentives for farmers to adopt measures that move them toward or into the appropriate safe operating space for their farming system and ecoregion or reward them for meeting other environmental performance targets. Likewise, the shape of the curves in figure 2 suggests that focusing public and private stewardship efforts on regions (or specific farms) with large N balances will increase the efficiency (in terms of pollution reduced per dollar spent) and effectiveness of those efforts. The mapping of N balance at a regional scale can serve to identify “hotspots” of large N balance, which are opportunities for such high-impact focus.

Outcome-oriented policies need not be regulatory to be successful; voluntary efforts to improve N balance offer an opportunity for leadership by the US agricultural community. For inspiration on how to structure such efforts, they might look to New Zealand, which is experimenting with a community-based, collaborative “audited self-management” approach to mitigate N pollution at the watershed scale (Holley 2015). Groups of farmers and other local stakeholders collaboratively manage watershed-level N carrying capacity, determining together how to achieve a specified environmental goal, with auditing by governmental agencies or independent third parties to verify that the goal is met. This approach combines meaningful goal setting and accountability for progress with local self-determination and flexibility in meeting the goal, including the development of highly innovative and verifiable farm-to-farm trading schemes based on N balance. In the United States, Nebraska’s Natural Resource Districts already use an audited self-management approach to groundwater allocation (Stephenson 1996), which could be expanded to address broader water-quality goals and replicated elsewhere.

To support such efforts, a cohesive and coordinated research initiative will be needed to refine potential threshold values of N balance, such as those illustrated in figure 2, or other targets for environmental performance. Science must also inform any efforts to identify safe operating spaces for various cropping systems and ecoregions. Science-based recommendations on region- and cropping-system-specific management practices for achieving those targets are also needed. A useful starting point for such efforts is the work of Snyder (2016) in identifying suites of best practices for fertilizer management in specific crops and regions, which could be expanded to consider broader (including landscape-scale) approaches to mitigating nutrient losses such as cover crops, drainage water management, restored or constructed wetlands, or re-integration of livestock into crop production

A nitrogen-balance framework for sustainable intensification

An N-balance approach to agricultural N management can help society meet the twin challenges of increasing food production while reducing N pollution. For such an approach to be successful, policymakers, scientists, private industry, public agency staff, extension agents, crop consultants, and—most importantly—farmers will need to collaborate in developing an implementation framework that both establishes N-balance goals and provides the political, economic, and social support to help farmers achieve those goals.

Historically, policies to manage N-related pollution from agriculture have focused on incentivizing or mandating reduced fertilizer inputs, an approach that is often incompatible with food production goals and that ignores the risks and uncertainties that motivate farmers to apply excess N (van Es et al. 2007). Likewise, promoting particular practices overlooks the highly variable impacts such practices may have on N-loss reductions (including the risk that under some circumstances, a practice may even increase some forms of N loss), as well as potential economic and practical barriers to on-farm implementation. We believe that policies focused on improving N-balance outcomes will be more effective than such approaches. Focusing on outcomes ensures that environmental benefits are achieved while stimulating innovation by individual farmers to develop approaches that work in the context of their farming operation. In addition, because N-balance improvements correspond to improvements in other sustainability indicators that can potentially increase farmer profits, farmers may be motivated to make operational changes that benefit their self-interest.

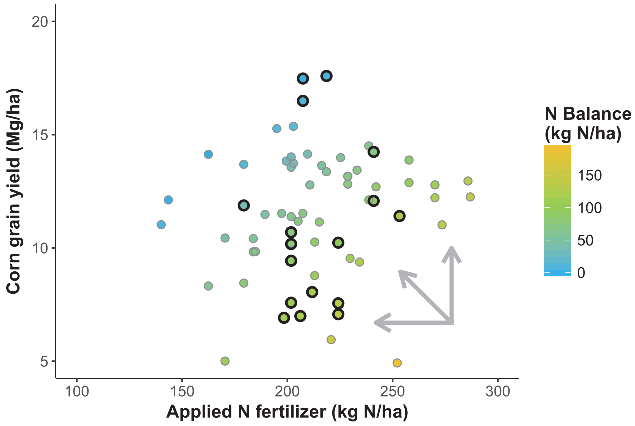

Figure 5. The relationship of nitrogen (N) fertilizer application rate, maize crop yield, and N balance from maize fields on 66 farms in five US midwestern states in 2015. The subset of highlighted farms shown in darker outline is in close geographic proximity, and these farms are assumed to share a similar production environment in terms of soils and climate. The farms are typical of the region in terms of cropping system (corn–soybean) and the types of crop and soil management practices used, although the specific practices differ from farm to farm leading to differences in N balance. Note that at any given fertilizer rate (or yield), there is a range of values of N balance, suggesting that producers could improve both agronomic and environmental outcomes by improving yield (or lowering fertilizer rate), as is shown by the vertical (and horizontal) arrows. More generally, lower-performing producers (those with large N balances) could improve N management and environmental outcomes by adopting some of the practices used by higher-performing producers (with small N balances), as is shown by the diagonal arrow.

systems (Billen et al. 2013, McLellan et al. 2015). Research will also be needed to reduce the uncertainty of N-balance calculations at the field and farm scale by better quantifying N inputs (and losses) from manure and biological N fixation, improving estimates of the N content of harvested crops, and estimating changes in soil organic N stocks.

Private industry investment in innovations and services (e.g., new fertilizer formulations, precision fertilizer application equipment, and sophisticated decision-support tools) can help farmers achieve the needed improvements in N balance. Increased technical assistance will be needed to help farmers incorporate these technologies into their operations. As was noted by Ketterings (2014), outcome-based approaches to farm management are most effective in an adaptive management setting that combines on-farm research, extension, and collaboration with farmers to help them achieve their goals. The US Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) has introduced a practice standard for nutrient management that incentivizes farmers to use an adaptive management approach. One possible model for doing this effectively is Sweden's "Focus on Nutrients" program (Olofsson 2017), which pairs farmers with advisors who meet regularly to help them calculate, manage, track, and understand their farm nutrient balance and how it relates to farm productivity and profitability. USDA-NRCS staff, extension agents, crop consultants, and others will be crucial in helping farmers achieve their and society's sustainability goals.

Success will depend on the willing engagement of farmers. Although we believe that farmers' innate desire to improve their operations and be good stewards of the land will help motivate improvements in N balance, incentives will be important for recognizing progress and encouraging continuous improvement. Such incentives could be provided through public or private funding and acknowledgment. We believe that the value of such incentives—avoiding the cost of N-pollution damage—will far exceed their cost now and in the future.

Conclusions

Given the legacy effects of N use in crop production on water quality and the intensification of N pollution anticipated to result from future climate change (Suddick et al. 2013), we foresee increasing public demand for evidence that agriculture is reducing N losses. Reconciling further intensification of agricultural production with protection and restoration of the planet is possible with an N-balance framework. Data currently collected by producers on N applications and crop yields, suitably aggregated and anonymized, could be used to begin benchmarking efforts, to develop a baseline of current N-balance status, and to identify regional N-balance hotspots that might receive increased attention and funding from the USDA or other public- or private-sector funders. Proactive development of an N-balance framework—led by farmers and supply-chain entities and in partnership with scientists, private industry, and extension agents—can begin now, drawing on lessons learned elsewhere and laying the groundwork for policy innovations that reward synergistic outcomes of improved food production and environmental performance.

Acknowledgments

We acknowledge funding support from the Walton Family Foundation, the David R. and Patricia D. Atkinson Foundation, and the Atkinson Center for a Sustainable Future, Cornell University. We thank Rodney Venterea of the US Department of Agriculture's Agricultural Research Service for sharing unpublished data on N_2O emissions and N balance and all those whose contributions to Environmental Defense Fund (EDF)–funded workshops on N balance in 2015, 2016, and 2017 helped us to refine the ideas presented here. We appreciate initial analyses by EDF interns Trevor Anderson and Katherine Costas. Comments by Doria Gordon and Josette Lewis of the EDF and by three anonymous reviewers greatly improved the manuscript.

Supplemental material

Supplementary data are available at *BIOSCI* online.

References cited

Baffaut C, et al. 2017. Multisite evaluation of APEX for water quality: I. Best professional judgment parameterization. Journal of Environmental Quality 46: 1323–1331.

Billen G, Garnier J, Lassaletta L. 2013. The nitrogen cascade from agricultural soils to the sea: Modelling nitrogen transfers at regional watershed and global scales. Philosophical Transactions of the Royal Society B 368 (art. 20130123).

Blesh J, Drinkwater LE. 2013. The impact of nitrogen source and crop rotation on nitrogen mass balances in the Mississippi River Basin. Ecological Applications 23: 1017–1035.

Bosch NS, Evans MA, Scavia D, Allan JD. 2014. Interacting effects of climate change and agricultural BMPs on nutrient runoff entering Lake Erie. Journal of Great Lakes Research 40: 581–589.

Brentrup F, Lammel J. 2016. Nitrogen use efficiency, nitrogen balance, and nitrogen productivity—A combined indicator system to evaluate nitrogen use in crop production systems. Paper presented at the 2016 International Nitrogen Initiative Conference: Solutions to Improve Nitrogen Use Efficiency for the World; 4–8 December 2016, Melbourne, Australia.

Buckley C, Wall DP, Moran B, O'Neill S, Murphy PNC. 2016. Farm gate level nitrogen balance and use efficiency changes post implementation of the EU Nitrates Directive. Nutrient Cycling in Agroecosystems 104: 1–13.

Cassman KG, Dobermann A, Walters DT. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31: 132–140.

Cela S, Ketterings QM, Czymmek KJ, Soberon MA, Rasmussen CN. 2014. Characterization of nitrogen, phosphorus, and potassium mass balances of dairy farms in New York State. Journal of Dairy Science 97: 7614–7632.

Cela S, Ketterings QM, Soberon MA, Rasmussen CN, Czymmek KJ. 2017. Upper Susquehanna watershed and New York State improvements in nitrogen and phosphorus mass balances of dairy farms. Journal of Soil and Water Conservation 72: 1–11.

Cherry KA, Shepherd M, Withers PJA, Mooney SJ. 2008. Assessing the effectiveness of actions to mitigate nutrient loss from agriculture: A review of methods. Science of the Total Environment 406: 1–23.

Cui Z, Yue S, Wang G, Zhang F, Chen X. 2013. In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. Environmental Science and Technology 47: 6015–6022.

Dalgaard T, et al. 2012. Farm nitrogen balances in six European landscapes as an indicator for nitrogen losses and basis for improved management. Biogeosciences 9: 5303–5321.

Dalgaard T, et al. 2014. Policies for agricultural nitrogen management: Trends, challenges and prospects for improved efficiency in Denmark. Environmental Research Letters 9 (art. 115002).

De Klein CAM, Monaghan RM, Alfaro M, Gourley CJP, Oenema O, Powell JM. 2017. Nitrogen performance indicators for dairy production systems. Soil Research 55: 479–488.

Duhon M, McDonald H, Kerr S. 2015. Nitrogen Trading in Lake Taupo: An Analysis and Evaluation of an Innovative Water Management Policy. Motu Economic and Public Policy Research. Working Paper 15-07. (3 January 2018; *http://motu-www.motu.org.nz/wpapers/15_07.pdf*)

Erisman JW, Galloway JN, Seitzinger S, Bleeker A, Dise NB, Petrescu AMR, Leach AM, de Vries W. 2013. Consequences of human modification of the global nitrogen cycle. Philosophical Transactions of the Royal Society B 368 (art. 20130116).

[EU-NEP] European Union Nitrogen Expert Panel. 2015. Nitrogen Use Efficiency (NUE): An Indicator for the Utilization of Nitrogen in Agriculture and Food Systems. Wageningen University, Alterra. (3 January 2018; *www.eunep.com/reports*)

[EEA] European Environment Agency. 2017. Environmental Indicator Report 2017—Agricultural Land: Nitrogen Balance. EEA. (3 January 2018; *https://www.eea.europa.eu/airs/2017/natural-capital/agricultural-land-nitrogen-balance*)

Gardner JB, Drinkwater LE. 2009. The fate of nitrogen in grain cropping systems: A meta-analysis of ^{15}N field experiments. Ecological Applications 19: 2167–2184.

Goucher L, Bruce R, Cameron DD, Lenny Koh SC, Horton P. 2017. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. Nature Plants 3 (art. 17012).

Gourley CJP, Powell JM, Dougherty WJ, Weaver DM. 2007. Nutrient budgeting as an approach to improving nutrient management on Australian dairy farms. Australian Journal of Experimental Agriculture 47: 1064–1074.

Grassini P, Cassman KG. 2012. High-yield maize with large net energy yield and small global warming intensity. Proceedings of the National Academy of Sciences 109: 1074–1079.

Harter T. 2015. California's agricultural regions gear up to actively manage groundwater use and protection. California Agriculture 69: 193–201.

Holley C. 2015. Crafting Collaborative Governance: Water Resources, California's Delta Plan, and Audited Self-Management in New Zealand. Social Science Research Network. Environmental Law Reporter, vol. 45, no. 4. UNSW Law Research Paper no. 2015-15.

Hunter MC, Smith RG, Schipanski ME, Atwood LW, Mortensen DA. 2017. Agriculture in 2050: Recalibrating targets for sustainable intensification. BioScience 67: 386–391.

Ketterings QM. 2014. Extension and knowledge transfer: Adaptive management approaches for timely impact. Journal of Agricultural Science 152: 57–64.

McLellan E, Robertson D, Schilling K, Tomer M, Kostel J, Smith D, King K. 2015. Reducing nitrogen export from the Corn Belt to the Gulf of Mexico: Agricultural strategies for remediating hypoxia. Journal of the American Water Resources Association 51: 263–289.

[OECD] Organisation for Economic Co-operation and Development. 2013. Compendium of Agri-Environmental Indicators. OECD. doi:10.1787/9789264181151-en

Olofsson S. 2017. Focus on Nutrients, a voluntary initiative for environment and economy. Paper presented at the International Interdisciplinary Conference on Land Use and Water Quality Effect of Agriculture on the Environment; 29 May–1 June 2017, The Hague, The Netherlands.

Omonode RA, Halvorson AD, Gagnon B, Vyn TJ. 2017. Achieving lower nitrogen balance and higher nitrogen recovery efficiency reduces nitrous oxide emissions in North America's maize cropping systems. Frontiers in Plant Science 8 (art. 1080). doi:10.3389/fpls.2017.01080

Ribaudo M. 2015. The limits of voluntary conservation programs. Choices 30: 1–5.

Robertson DM, Saad DA, Schwarz GE. 2014. Spatial variability in nutrient transport by HUC8, state, and subbasin based on Mississippi/Atchafalaya River Basin SPARROW models. Journal of the American Water Resources Association 50: 988–1009.

Scavia D, Bertani I, Obenour DR, Turner RE, Forrest DR, Katin A. 2017. Ensemble modeling informs hypoxia management in the northern Gulf of Mexico. Proceedings of the National Academy of Sciences 114: 8823–8828.

Sela S, van Es HM, Moebius-Clune BN, Marjerison R, Melkonian J, Moebius-Clune D, Schindelbeck R, Gomes S. 2016. Adapt-N outperforms grower-selected nitrogen rates in northeast and midwestern United States strip trials. Agronomy Journal 108: 1726–1734.

Sewell AM, Hartnett MK, Gray DI, Blair HT, Kemp PD, Kenyon PR, Morris ST, Wood BA. 2017. Using educational theory and research to refine agricultural extension: Affordances and barriers for farmers' learning and practice change. Journal of Agricultural Education and Extension 23: 313–333.

Snyder CS. 2016. Suites of 4R nitrogen management practices for sustainable crop production and environmental protection. International Plant Nutrition Institute. (3 January 2018; *www.ipni.net/IssueReview*)

Snyder CS, Davidson EA, Smith P, Venterea RT. 2014. Agriculture: Sustainable crop and animal production to help mitigate nitrous oxide emissions. Current Opinion in Environmental Sustainability 9: 46–54.

Soberon MA, Cela S, Ketterings QM, Rasmussen CN, Czymmek KJ. 2015. Changes in nutrient mass balances over time and related drivers for 54 New York State dairy farms. Journal of Dairy Science 98: 5313–5329.

Sobota DJ, Compton JE, McCrackin ML, Singh S. 2015. Cost of reactive nitrogen release from human activities to the environment in the United States. Environmental Research Letters 10 (art. 025006).

Steffen W, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347 (art. 1259855).

Stephenson K. 1996. Groundwater management in Nebraska: Governing the commons through local resource districts. Natural Resources Journal 36: 761–778.

Stevens CJ, Quinton JN. 2009. Policy implications of pollution swapping. Physics and Chemistry of the Earth, Parts A/B/C 34: 589–594.

[SISC] Stewardship Index for Specialty Crops. 2013. Nitrogen Use, Working Metric Version 1.0. SISC. (3 January 2018; *www.stewardshipindex.org/amass/documents/document/12/SISC_Metric_NitrogenUse_2013-07.pdf*)

Stott KJ, Gourley CJP. 2016. Intensification, nitrogen use and recovery in grazing-based dairy systems. Agricultural Systems 144: 101–112.

Suddick EC, Whitney P, Townsend AR, Davidson EA. 2013. The role of nitrogen in climate change and the impacts of nitrogen–climate interactions in the United States: Foreword to thematic issue. Biogeochemistry 114: 1–10.

Thomson AM, et al. 2017. Science in the supply chain: Collaboration opportunities for advancing sustainable agriculture in the United States. Agricultural and Environmental Letters 2 (art. 170015).

Thorburn PJ, Wilkinson SN. 2013. Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. Agriculture, Ecosystems and Environment 180: 192–209.

Unilever. 2010. Unilever Sustainable Agriculture Code, Version 1. Unilever. (3 January 2018; *www.unilever.com/Images/ul-sac-v1-march-2010-spread_tcm244-464943_en.pdf*)

Van Es HM, Kay BD, Melkonian JJ, Sogbedji JM. 2007. Nitrogen management for maize in humid regions: Case for a dynamic modeling approach. Pages 6–13 in Bruulsema TW, ed. Managing Crop Nitrogen for Weather. International Plant Nutrition Institute.

Van Groenigen JW, Velthof GL, Oenema O, van Groenigen KJ, van Kessel C. 2010. Towards an agronomic assessment of N_2O emissions: A case study for arable crops. European Journal of Soil Science 61: 903–913.

Van Meter KJ, Basu NB, Veenstra JJ, Burras CL. 2016. The nitrogen legacy: Emerging evidence of nitrogen accumulation in anthropogenic landscapes. Environmental Research Letters 11 (art. 035014).

Wood BA, Blair HT, Gray DI, Kemp PD, Kenyon PR, Morris ST, Sewell AM. 2014. Agricultural science in the wild: A social network analysis of farmer knowledge exchange. PLOS ONE 9 (art. e105203).

Woodbury PB, Kemanian AR, Jacobson M, Langholtz M. 2017. Improving water quality in the Chesapeake Bay using payments for ecosystem services for perennial biomass for bioenergy and biofuel production. Biomass and Bioenergy. doi:10.1016/j.biombioe.2017.01.024

Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y. 2015. Managing nitrogen for sustainable development. Nature 528: 51–59.

Zhao X, Christianson LE, Harmel D, Pittelkow CM. 2016. Assessment of drainage nitrogen losses on a yield-scaled basis. Field Crops Research 199: 156–166.

Zhou M, Zhu B, Brüggemann N, Dannenmann M, Wang Y, Butterbach-Bahl K. 2016. Sustaining crop productivity while reducing environmental nitrogen losses in subtropical wheat–maize cropping systems: A comprehensive case study of nitrogen cycling and balance. Agriculture, Ecosystems and Environment 231: 1–14.

Eileen L. McLellan and Alison J. Eagle are affiliated with Environmental Defense Fund, in Washington, DC. Kenneth G. Cassman is emeritus with the Department of Agronomy and Horticulture at the University of Nebraska, in Lincoln. Peter B. Woodbury, Shai Sela, and Harold M. van Es are affiliated with the Soil and Crop Sciences Section of the College of Agriculture and Life Sciences at Cornell University, in Ithaca, New York. Christina Tonitto is with the Cornell International Institute for Food, Agriculture, and Development, in Ithaca, New York. Rebecca D. Marjerison is affiliated with the Agronomic Technology Corporation, a Yara International Company.