NITROGEN AND PHOSPHORUS BALANCES IN IOWA CROPPING SYSTEMS:

SUSTAINING IOWA'S SOIL RESOURCE

Laura Christianson, Michael Castellano, and Matthew Helmers
College of Agriculture and Life Sciences
Iowa State University

in collaboration with
The Iowa Department of Agriculture and Land Stewardship

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Key Points:

- Iowa's exceptional agricultural productivity is dependent upon nutrient-rich soils with high carbon and nitrogen stocks.

- Soil carbon and nitrogen stocks in Iowa corn-soybean rotations are at significant risk of long-term decline.

- Soil carbon and nitrogen stocks are a function of crop residue inputs.

- Nutrient input levels that do not maximize crop yield and residue production are likely to reduce soil carbon and nitrogen stocks.

- If soil carbon and nitrogen stocks decline, water quality improvements become more difficult.

- Soil carbon and nitrogen balances are extremely difficult to measure, but positive balances are essential to the future of Iowa agriculture.

Recommended Actions:

- Accurate measurement of soil carbon and nitrogen balances is exceptionally difficult, but can be accomplished with sufficient investment and long-term planning.

- The ideal approach will include a combination of measurements from farms and experimental networks that manipulate nutrient inputs.

- With proper planning and cooperation, Iowa State University and the Iowa Department of Agriculture and Land Stewardship can address the concerns raised in this report regarding the future of Iowa's soil resource and agricultural productivity.

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Executive summary

The future of Iowa agricultural productivity depends on high soil organic carbon and nutrient stocks. However, there is growing concern among scientists and farmers that soil carbon, nitrogen, and phosphorus stocks in corn-based cropping systems may be declining as a result of nutrient outputs that exceed nutrient inputs. In response, the Iowa legislature authorized and financed the Iowa Department of Agriculture and Land Stewardship in cooperation with the Iowa State University College of Agriculture and Life Sciences to perform an assessment of nitrogen and phosphorus balances in agriculturally managed Iowa soils.

Soil nutrient stocks represent the balance of nutrient inputs and outputs (collectively, fluxes). Accordingly, this report evaluated potential changes in soil nutrient stocks in Iowa's most prevalent cropping systems, continuous corn and corn-soybean rotation, using two methods: (1) measurement of 'stock change over time' and (2) estimation of 'input-output balance'. Iowa soil nitrogen balances were estimated with both these methods. Iowa soil phosphorus balances were estimated with the 'input-output balance' method. The project goals were to determine: 1) the likelihood of long-term soil nutrient stock decline, 2) the potential range in rates of soil nutrient stock change based on scientific uncertainties in measurements of inputs, outputs, and stocks, and 3) gaps in the accurate measurement of nutrient inputs, outputs and stock changes.

Both evaluation methods present significant challenges. Accurate measurement of soil nitrogen stock change over time is challenging because potential annual stock changes represent a small proportion of the total soil nitrogen pool (<1%). Alternatively, development of input-output balances is challenging because not all soil nitrogen fluxes can be measured due to analytical limitations as well as high spatial and temporal variability. Although accurate measurement of phosphorus fluxes also presents challenges, soil phosphorus fluxes are typically measured with greater accuracy than nitrogen due to the lack of a relevant gaseous phase.

Results from this report highlight significant uncertainty in the status of soil nitrogen balances. The inability to estimate large nitrogen fluxes such as biological nitrogen fixation and denitrification limit our ability to unequivocally determine if nitrogen balances in widespread, corn-based cropping systems are positive, negative, or neutral.

Nevertheless, the nitrogen mass balances developed in this report indicate significant risk of long-term soil nitrogen stock reductions in corn-soybean rotations. At three economically-derived nitrogen fertilizer input rates evaluated in this report, two-year nitrogen balances for the full corn-soybean rotation showed net negative balances at all nitrogen fertilizer input rates (Table 1). There is extremely high uncertainty associated with these nitrogen balances because the second largest nitrogen input in corn-soybean rotations, biological nitrogen fixation, is highly variable and difficult to measure. However, measurements of long-term changes in soil nitrogen stocks from corn-soybean rotations on Iowa State University research farms corroborate this finding.

In contrast to the corn-soybean rotation, the soil nitrogen balances developed for continuous corn were consistently positive, indicating potential for increases in soil nitrogen stocks associated with large crop residue inputs to the soil. At three economically-derived nitrogen fertilizer input rates, the estimated uncertainties for continuous corn nitrogen balances were much smaller than the positive net nitrogen balances (Table 1). Measurements of long-term changes in soil nitrogen stocks from continuous corn systems on Iowa State University research farms corroborate this finding.

Net negative soil nitrogen balances represent a significant concern to the long-term sustainability of Iowa's soil resource in a broad context that extends beyond soil nutrient availability. Soil nitrogen stocks are dominated by organic nitrogen (~99%) and, in the Midwestern Corn Belt region, soil organic nitrogen is the largest source of crop nitrogen uptake – regardless of nitrogen fertilizer inputs. Nevertheless, nitrogen fertilizer inputs are required to maintain soil organic nitrogen stocks by promoting high yields and crop residue inputs to the soil. Moreover, soil organic nitrogen is bound to soil organic carbon in soil organic matter compounds. Thus, as soil nitrogen stocks decline, so do soil organic carbon and organic matter stocks. When all other factors (e.g., depth to water table, precipitation, temperature) are equal, crop yield is inextricably linked to soil organic matter due to positive effects on nutrient availability, water holding capacity and other environmental processes. If soil organic matter stocks decline, water quality improvements become more difficult due to reduced soil nutrient availability and water holding capacity.

Crop residues are the source of soil organic matter including organic nitrogen. As nitrogen fertilizer inputs enhance crop yield and residue production, nitrogen fertilizer inputs are positively correlated with soil organic matter and nitrogen stocks. However, this correlation is only valid to the point at which crop production is no longer limited by nitrogen; nitrogen fertilization above this point (i.e., fertilization above the maximum agronomic response) will not increase soil organic matter stocks and has the potential to enhance carbon and nitrogen losses to atmospheric and aquatic environments.

Table 1: Net soil nitrogen balances and uncertainty estimates for three fertilization levels of continuous corn and corn-soybean rotations in Iowa; fertilization levels were based upon the Maximum Return to Nitrogen (MRTN) with Low and High application rates determined to both produce net returns of $1 per acre less than the MRTN. See Sawyer et al. 2006.

Rotation and Fertilization Scenario (Applied Rate to Corn)	Net nitrogen balance	Uncertainty: assumed 50% potential error for estimates of biological nitrogen fixation, denitrification, and atmospheric deposition
	---------- lb N/ac-yr ----------	
Continuous Corn - Low (178 lb N/ac)	60	±6.5
Continuous Corn - MRTN (192 lb N/ac)	69	±6.7
Continuous Corn - High (204 lb N/ac)	76	±6.9
Corn-Soybean - Low (123 lb N/ac)	-22	±49
Corn-Soybean - MRTN (135 lb N/ac)	-19	±49
Corn-Soybean - High (147 lb N/ac)	-15	±49

Results from this report raise fewer concerns for phosphorus balances in Iowa soils. Several Midwestern studies have reported net neutral contemporary phosphorus balances despite high phosphorus inputs and high soil phosphorus test values observed in the latter half of the 20th century. There is now concern of a negative trend over time for these previously high soil total phosphorus stocks. However, phosphorus balances developed for common Iowa cropping rotations in this report showed the optimum soil testing phosphorus scenarios, coupled with phosphorus fertilization that replaces phosphorus removal in grain, resulted in near neutral phosphorus balances. The high soil test phosphorus scenarios resulted in negative balances for both crops, as expected, to allow crop utilization of existing surplus soil phosphorus. Adherence to removal-based phosphorus application methods in conjunction with soil testing and consideration of phosphorus losses as estimated by the Iowa Phosphorus Index should maintain phosphorus nutrient stocks over time. In general, phosphorus balances can be managed with greater accuracy than nitrogen balances.

Project background

The exceptional productivity of Iowa soils is a result of favorable climate and large soil organic matter (SOM) nutrient stocks. However, there is growing concern among scientists and farmers that nutrient stocks in Iowa's agriculturally managed soils may be declining as a result of nutrient outputs that exceed inputs. This project was established to assess nitrogen (N) and phosphorus (P) balances of agriculturally managed Iowa soils.

Legislation

Iowa Senate File 509, Division VII section 17 directed the Watershed Improvement Review Board (WIRB) (established in section 466A.3) to authorize up to fifty thousand dollars to be available in the watershed improvement fund created in section 466A.2, for the fiscal period beginning July 1, 2011, and ending January 1, 2013, to finance a study of soil nutrient mass balance issues. The study financed by the WIRB under this section shall be conducted by the Iowa Department of Agriculture and Land Stewardship (IDALS) in cooperation with Iowa State University (ISU) College of Agriculture. The findings shall be submitted by IDALS to the WIRB, the governor, and the general assembly by 10 January 2013.

Project goals

This project evaluated peer-reviewed scientific literature and Iowa State University Research Farm data to better understand carbon and nutrient balances in Iowa's most common cropping systems**:** continuous corn and corn-soybean rotation**.** Working within the framework of these cropping systems, the project goals were to determine: 1) the likelihood of long-term soil N and P stock reduction, 2) the potential range in rates of soil N and P stock change based on scientific uncertainties in measurements of nutrient inputs, outputs, and stocks, and 3) gaps in the accurate measurement of N and P fluxes and stock changes.

Approach

The team at ISU leading this research included Post-Doctoral Research Associate Laura Christianson, Assistant Professor of Agronomy Michael Castellano, and Associate Professor of Agricultural and Biosystems Engineering Matthew Helmers. As part of this project, a regional group of scientific experts (Appendix A) was convened to advise and focus the project goals. The group met on two occasions to discuss the project and provide input on this report. The meetings were based in Ames, Iowa with the first held in February 2012 and a subsequent meeting in June 2012. The advisory group had the opportunity to comment on a draft of this report before the second meeting.

Soil nutrient stocks represent the balance of nutrient inputs and outputs (collectively, fluxes). Accordingly, changes in soil nutrient stocks can be estimated with two methods. First, the size of soil nutrient stocks can be measured at two points in time; the net change in stock size represents the average rate of change between the two sampling points ('stock change over time' method). Second, nutrient inputs and outputs can be measured during a period of time; the balance between inputs and outputs represents stock change during the measurement period ('input-output balance' method). This report reviewed scientific literature that used both the 'stock change over time' and 'input-output balance' methods to develop nutrient balances in Midwest agricultural soils.

Based on input from the advisory group, this report focused on N and P balances in continuous corn and corn-soybean rotation cropping systems because they are the most widespread systems in Iowa. Nitrogen balances were estimated with 'stock change over time' and 'input-output balance' methods. Phosphorus balances were estimated by the 'input-output balance' method.

Despite the apparent simplicity of these methods, both contain significant uncertainty. Potential annual N stock changes represent an extremely small proportion of the total stock. In common Iowa cropping systems with little erosion, the potential annual change in soil N stocks is less than ±1% of the total stock (e.g., Adviento-Borbe et al., 2007; David et al., 2009a). Measurement of a small change in stock is challenging because analytical measurement error is typically ±5%, and thus measurement uncertainty is greater than the change in stock. Moreover, the potential rate of change is very small when compared to natural spatial variability of soil N stocks (Cambardella et al., 1994). Nevertheless, this method is the only way to measure changes in N stocks with high, quantifiable certainty. In contrast, this method is less useful for P because P mineralization is not well correlated with P stock size. The mineralization of P is more affected by soil pH and mineralogy.

The development of nutrient balances with the input-output balance method is necessarily guided by the conservation of mass so that inputs minus outputs must equal storage (that is, the soil stock) (Legg and Meisinger, 1982). However, similar to measurement of nutrient stocks, accurate measurement of nutrient inputs and outputs presents significant challenges. An international group of agricultural nutrient balance experts noted: "One constraint to our ability to diagnose nutrient-driven problems, and to design their solutions, is the scarcity of detailed, on-farm nutrient budgets that quantify multiple pathways of nutrient input and loss over time" (Vitousek et al., 2009). Scarcity of detailed on-farm nutrient budgets (or nutrient balances, here) is due to a lack of modern scientific methods that permit affordable and accurate measurement of all nutrient inputs and outputs, particularly in regard to N. Methodological challenges include technical skill requirements and analytical limitations that are compounded by high spatial and temporal variability of nutrient fluxes. For example, several N inputs and outputs cannot be accurately measured; most notable are dinitrogen gas outputs, atmospheric deposition inputs, and leguminous biological nitrogen fixation inputs. Reported values of these important N fluxes can vary widely within fields and among nearby fields. Although accurate measurement of P fluxes can also present challenges (e.g., erosional losses), P fluxes are typically measured with greater accuracy than N due to the lack of a significant gaseous phase and biological inputs.

All empirically measured input-output balances for N develop what is most accurately described as a "partial" balance because not all fluxes are included. For example, a nutrient balance created by the National Research Council (1993) did not consider N inputs such as wet and dry deposition, nutrients in planted seeds, non-symbiotic N fixation and foliar absorption of atmospheric N. However, inputs such as wet and dry deposition can account for as much as 16% of total inputs (e.g., Libra et al., 2004). Many N fluxes are typically omitted from N balance estimations including soil erosion, surface runoff losses, gaseous losses from the soil, and gaseous losses from maturing crops. While simplified partial balance approaches can estimate trends in nutrient stock changes over large areas (e.g., Fixen, 2011), they cannot determine when, where, and why nutrient inputs and outputs do not balance.

The uncertainty of each individual input or output plays an important role in the overall uncertainty of the total nutrient balance because the least well understood process generally determines the minimum uncertainty of the final balance (Meisinger and Randall, 1991). If a large and a small flux have the same proportional uncertainty (error), the larger flux must be estimated more accurately as its associated error may be greater than the magnitude of the smaller flux. Meisinger and Randall (1991) recommended the uncertainty of each flux be assessed early in the balance process to avoid overly precise estimation of secondary processes that can be adequately estimated more crudely.

This report used two approaches to assess N and P balances in Iowa soils. First, scientific literature was reviewed and summarized to develop input-output balances. Second, long-term changes in soil N and carbon stocks from experiments at Iowa State University research farms were evaluated. In the first approach, published data on agricultural N and P fluxes from regional continuous corn and corn-soybean rotation cropping systems were summarized. The range of published estimates for all inputs and outputs are reported to indicate variability in flux rates. Based on these published estimates and guidance from the advisory group, a confidence level associated with the ability to measure or model each input and output was assigned. From these nutrient flux data, input-output balances were estimated. In the second approach, preliminary measurements were made of changes in total soil carbon and N concentrations from a unique set of long-term continuous corn and corn-soybean rotation experiments at ISU research farms. The experiments managed corn at multiple N fertilizer rates. Soil was sampled in 1999 or 2000 and again in 2009. The long-term change in soil carbon and N concentrations and stocks was determined from these samples. All nutrients other than N were maintained at agronomic optimum.

Nitrogen

Background

Soil N stocks are dominated by organic N compounds that are embedded in soil organic matter (SOM). The organic N in SOM is covalently bound to soil organic carbon (SOC). Accordingly, SOC and soil organic N stocks (SON) are well correlated in Iowa soils and beyond (Russell et al., 2005). Organic N that is mineralized during the growing season is typically the dominant source of crop N uptake, regardless of fertilizer N inputs (Stevens et al. 2005; Gardner and Drinkwater 2009). Typically, 1-2% of total SON stocks are annually mineralized to inorganic N. Consistent with this observation, the concentration of organic N and C in the soil is positively correlated with mineralization of SON (Booth et al., 2005). This highlights the importance of SOM, and more specifically SON, for maximizing N delivery to crops. This role of SOM complements other positive impacts of SOM on crop production including enhancement of soil water holding capacity and many other environmental processes (e.g., soil aggregation and aggregate stability, soil aeration, infiltration capacity, reduced resistance to root penetration). **At the county scale, Iowa crop yields are positively correlated with SOM contents (Williams et al., 2008a).**

In summary, crop yield is positively associated with SOC and SON stocks which are in turn dependent upon crop residue returns to the soil (Smil, 1999). This relationship is clear from statistical analyses of USDA databases as well as the correlation between yield and thickness of the organic matter-rich soil A horizon (Figure 1) (Cruse and Herndl, 2009; Fenton et al., 2005; Williams et al., 2008a). Because N fertilizer inputs enhance crop yield and residue production, it is no surprise that N fertilizer inputs are positively correlated with SOC and SON concentrations and stocks (Figure 2) (Russell et al., 2005; Russell et al., 2009). Iowa research indicates that N fertilizer inputs increase SOM inputs more than they increase rates of SOM decomposition (Russell et al., 2009). **A global review reported that, in general, the long-term use of synthetic N fertilizer can increase SON and N mineralization through impacts upon crop residue production and composition (Glendining and Powlson, 1995). And Lal (1995) summarized this finding by noting: "…there is a misconception in some quarters that yield and sustainability are fundamentally antagonistic. Yet the data… suggest that yield may be the best indicator of [soil] sustainability".**

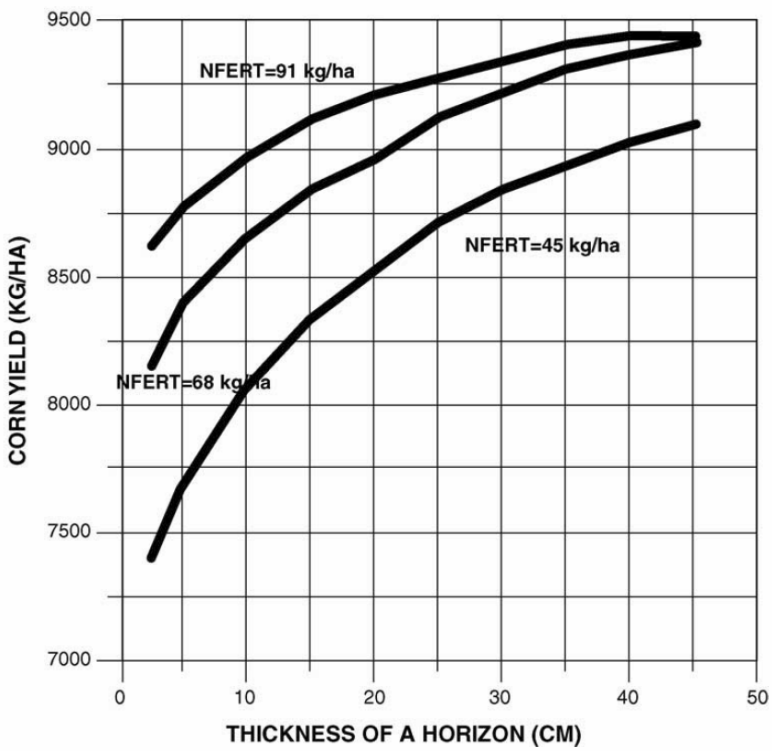

Figure 1: Relationship between the thickness of the soil A horizon (carbon-rich topsoil) and corn yields for loess and till-derived soils in Iowa at three fertilization rates; from Fenton et al. (2005) . 1 kg per hectare = 0.89 pounds per acre.

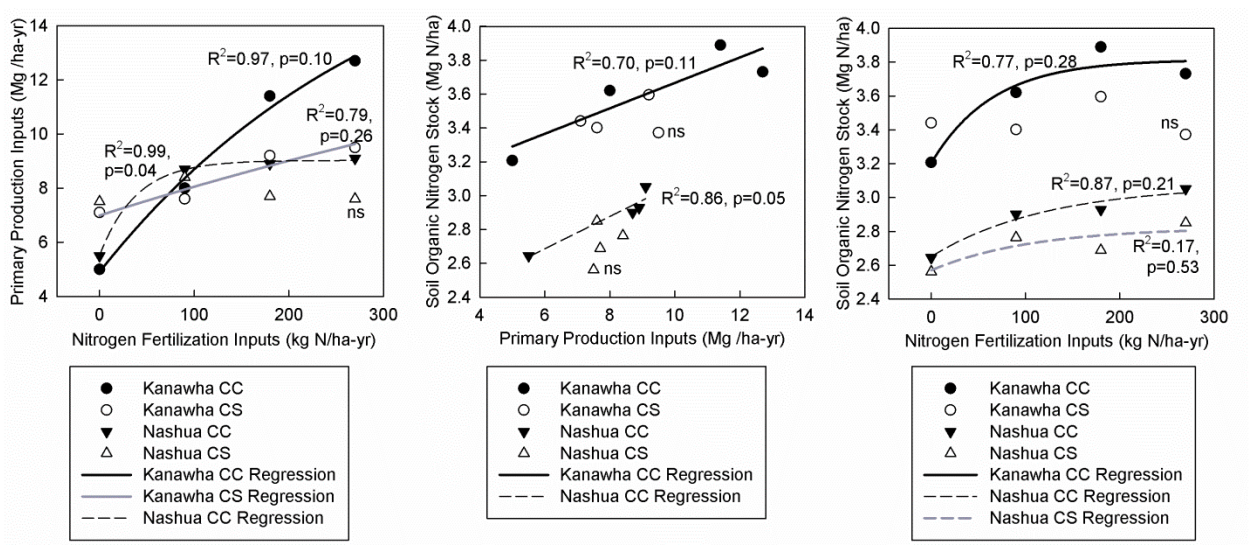

Figure 2: Relationship between primary production, nitrogen fertilization rate, and soil organic nitrogen adapted from Russell et al. (2005) and Russell et al. (2009); data shown for continuous corn (CC) and corn-soybean (CS) rotations from Nashua and Kanawha, Iowa at the 0-15 cm soil depth; "ns" indicates regression was not significant (adjusted R^2 = 0.0). Note, within each site CC has greater soil N storage (stock) than CS. 1 kg per hectare = 0.89 pounds per acre.

At a state-wide scale, Iowa nutrient balances have been evaluated. The most recent nutrient budget developed by the Iowa Department of Natural Resources (Libra et al., 2004) estimated that state-wide N

inputs and outputs are roughly in balance with inputs of 3.89 million tons per year and outputs of 3.98 million tons per year (Figure 3). Another state-wide balance developed by the International Plant Nutrition Institute (IPNI) using the NuGIS model suggested Iowa has maintained positive N balances for the past 20 years (Figure 4)(IPNI, 2012).

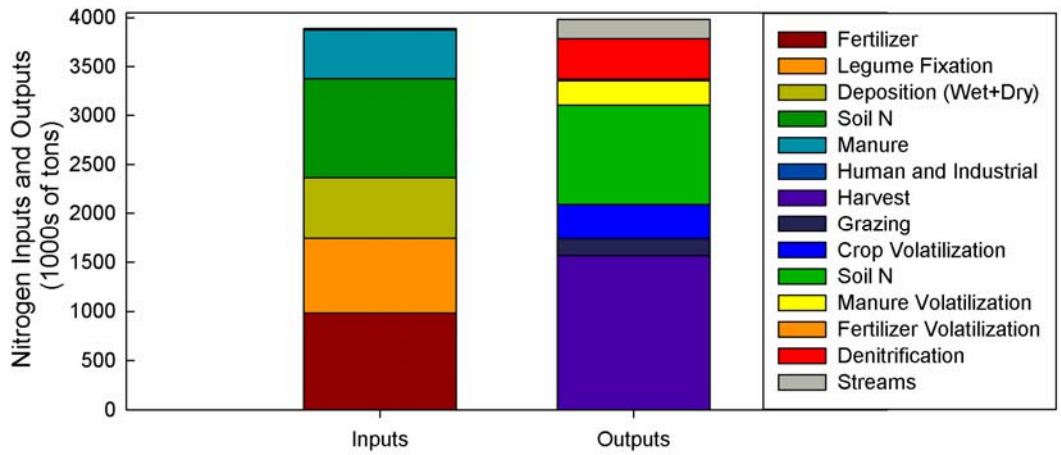

Figure 3: Nitrogen inputs and outputs from an Iowa state-wide nitrogen budget by Libra et al. (2004) representing an average year for the 1997 to 2002 period.

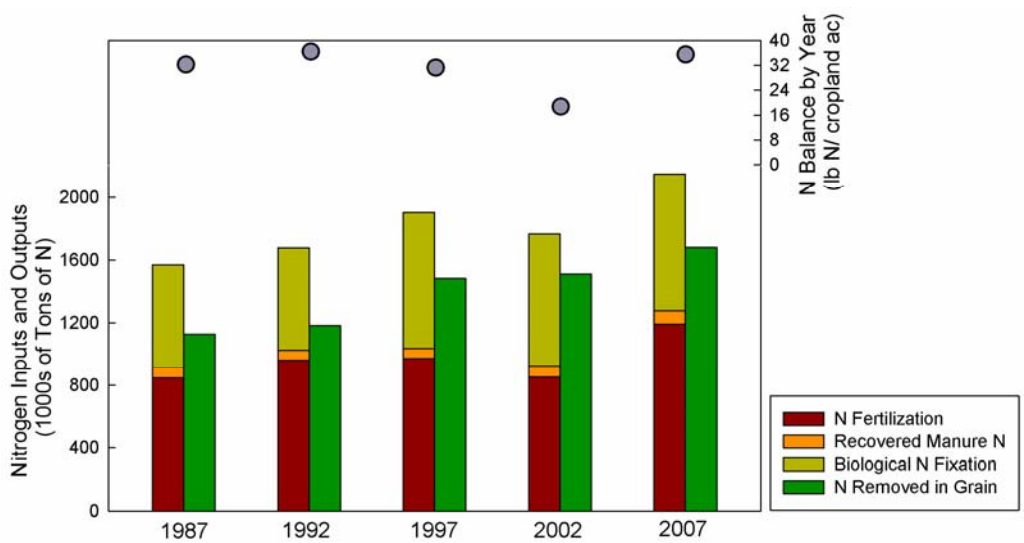

Figure 4: Nitrogen inputs and outputs and partial net balances for the state of Iowa based on the NuGIS model; from IPNI (2012).

Several field-scale nutrient balances have reported that N outputs can exceed inputs in typical Midwestern rotations (Gentry et al., 2009; Jaynes and Karlen, 2008; Jaynes et al., 2001) which led Jaynes and Karlen (2008) to note that environmental studies which do not investigate both water and soil quality are incomplete. For example, Jaynes and Karlen (2008) reported that while drainage water from three levels of fertilization of a corn-soybean rotation exceeded water quality guidelines, only the highest fertilization treatment did not appear to result in a decline in soil N based upon a partial N balance (Figure 5). **Consideration of soil nutrient resources in addition to water quality is vital in development of truly comprehensive environmental sustainability plans for Iowa's most common cropping rotations.**

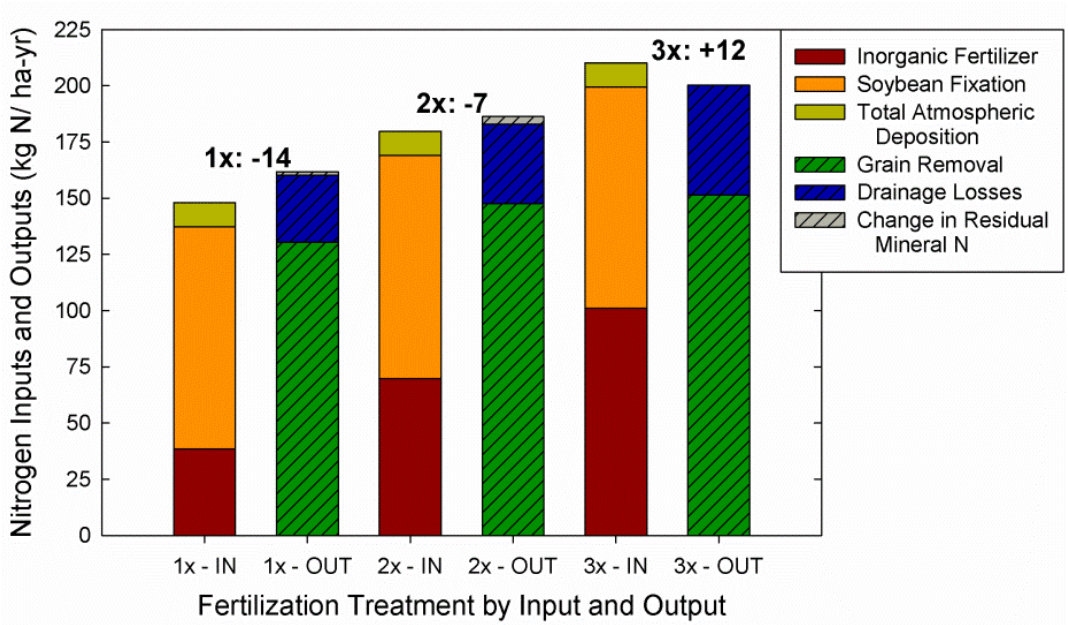

Figure 5: Nitrogen inputs and outputs and partial net balances for four years of a corn-soybean rotation in Iowa at three fertilization rates (1x: approximately 67 kg N/ha, or 60 lb N/ac, with 2x and 3x at two and three times this rate, respectively); from Jaynes and Karlen (2008). 1 kg per hectare = 0.89 pounds per acre.

The necessity to pursue both an input-output balance and soil sampling approaches to determine long-term changes in N at the field scale is highlighted by Drinkwater et al. (1998). In this study, partial input-output balances that omitted several fluxes resulted in positive soil N stock balances. However, measurements of soil N stock over time that integrate all N inputs and outputs revealed significant declines in soil N stocks. This discrepancy was likely due to the inability of the input-output balance method to accurately estimate gaseous N losses and biological N fixation by soybeans (Drinkwater et al., 1998). In a study from Illinois, Gentry et al. (2009) reported a slightly positive N balance in a dry year (+6 kg N/ha or +5.3 lb N/ac, 2001) and very negative balance in a wetter year (-67 kg N/ha or -60 lb N/ac, 2002) due to leaching and denitrification losses. Such year-to-year variability is another significant limitation of input-output balance approaches to long-term nutrient stock evaluation. In contrast, measurement of stock changes over long periods of time integrates variability among years.

Several studies have evaluated SOC and N stock changes in Midwestern cropping systems with the 'stock change over time' approach. In general, these studies show that over time, a corn-soybean rotation experiences decline (or the lowest relative increase) in SOC and/or N, whereas continuous corn experiences an increase in these materials (Adviento-Borbe et al., 2007; Russell et al., 2005). These studies indicate that N fertilizer increases SOC and SON stocks by increasing biomass production and residue inputs (primary production) from the corn crop (Adviento-Borbe et al., 2007; Glendining and Powlson, 1995; Russell et al., 2005). Nevertheless, it is important to note that the positive effect of N fertilizer on SOM declines as N fertilizer inputs increase, particularly beyond the level required to produce maximum crop yield (i.e., no N supply limitation on yield; Figure 2).

The major weakness of measuring changes in SOC and N stocks over time is high in-field variability that leads to low statistical power (ability to measure changes over time). For example, a study over a twelve year period in Iowa, Russell et al. (2005) documented only two of nine treatments (Continuous Corn and Corn-Oat-Alfalfa- Alfalfa systems in Kanawha, IA) experienced statistically significant increases in SOC (i.e., SOC rates of change that were statistically different from zero) (Figure 6). Compared to unfertilized

continuous corn, fertilized continuous corn had a significantly greater rate of SOC change at only one of two Iowa research locations. The corn-soybean treatments had the lowest mean SOC and SON rates of change at both sites leading to the conclusion this rotation will not increase SOC stocks in the Midwest (Russell et al., 2005). Indeed, continuous corn consistently had higher rates of SOC change than corn-soybean rotations. Russell et al. (2009) corroborated the Russell et al. (2005) findings by reporting the two treatments experiencing significantly increased SOC also had OC inputs that exceeded OC decomposition (decay) rates (statistically significant positive C balance). The seven treatments that did not experience a significant change in SOC had crop residue additions that were essentially negated by enhanced SOM decay (Russell et al., 2009).

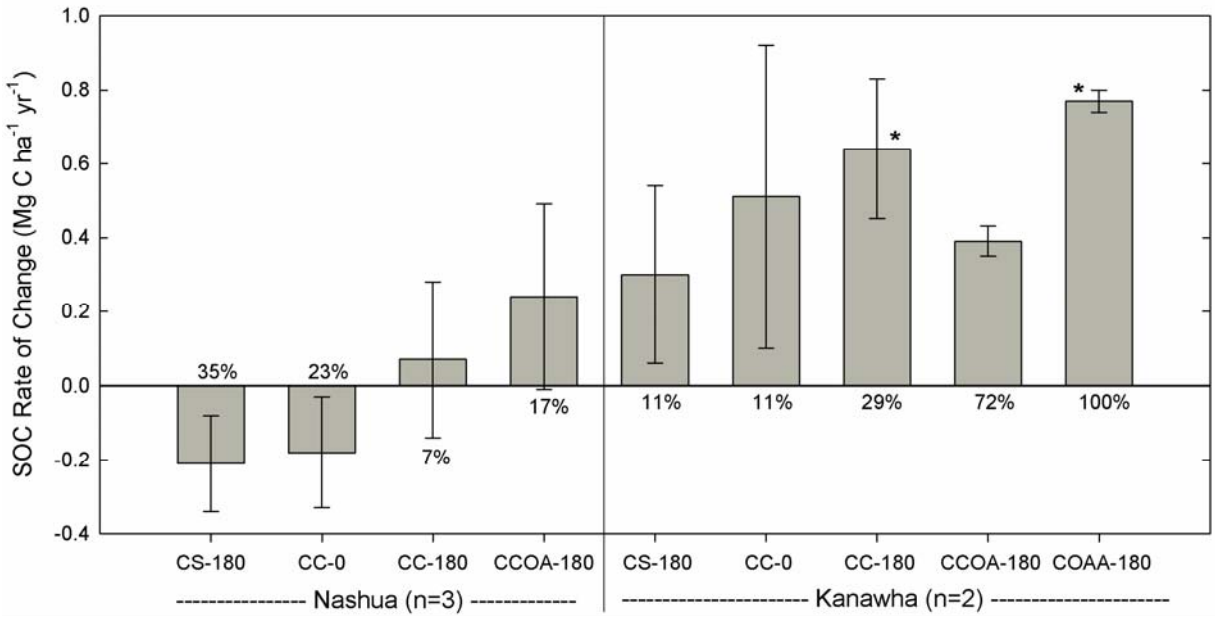

Figure 6: Changes in soil organic carbon at two sites in Iowa over twelve years (1990-2002) under four cropping rotations and two synthetic nitrogen input levels (0 to 15 cm soil depth) from Russell et al. (2005); * indicates treatment was significantly different from zero; C=corn, S=soybeans, O=oat, A=alfalfa followed by fertilization level to the corn phase of the rotation (0 or 180 kg N/ha). Percent values by each bar indicate the statistical power (percent chance of determining a rate of change was significantly different from zero if it was truly significantly different from zero) of the experiments based on three replicates at Nashua (n=3) and two at Kanawha (n=2). 1 kg per hectare = 0.89 pounds per acre.

In a long-term Midwestern study spanning 100 years, David et al. (2009a) reported soil C and N stocks in corn-soybean rotations declined significantly between the early 1900s and 1950s. However, there was no significant difference between stocks in the 1950s and present, indicating these stocks are now at a steady state (David et al., 2009a; McIsaac et al., 2002). It is interesting to note that fertilizer N inputs began in the 1950s. Annual increases in total N in the profile generally ranged from 18 to 49 kg N/ha-yr (16 to 44 lb N/ac-yr). However, similar to the majority of treatments studied by Russell et al. (2005), these rates were not significantly different from zero (David et al., 2009a).

In a study from Nebraska, continuous corn treatments under recommended or intensive management showed gains in both SOC and total soil N over five years (Adviento-Borbe et al., 2007). On a per year basis, the gains for these recommended and intensive treatments of continuous corn were approximately +0.44 and +0.62 Mg C/ha-yr (+393 and +553 lb C/ac-yr) and approximately +0.04 and +0.07 Mg N/ha-yr (approximately +36 and +62 lb N/ac-yr), respectively. The intensively managed corn-soybean treatment (i.e., fertilized with N during both soybean and corn phases) had five-yr cumulative

SOC and soil total N balances very close to net neutral, while the corn-soybean rotation under recommended management experienced losses of SOC and total N (Adviento-Borbe et al., 2007).

Nitrogen Input-Output Balance Scenarios

Development

This report developed partial N balances for continuous corn and corn-soybean cropping systems consisting of inputs and outputs associated with a range of uncertainty levels (Table 2). In general, fluxes involving soil biological or atmospheric processes (e.g., biological fixation, atmospheric deposition, denitrification) are the most difficult to estimate and thus had the highest uncertainties (David and Gentry, 2000; Libra et al., 2004) (Table 2). The "Estimation Uncertainty" in Table 2 gives an indication of the variability associated with measurement of each flux at the field scale; these categorizations were not intended to be rankings of the spatial variability of each flux between fields. For each cropping system, balances were developed with three different N fertilizer input rates to corn. In all corn-soybean scenarios, N fertilizer inputs to soybean were assumed to be in the form of either Mono-ammonium Phosphate (MAP) or Diammonium Phosphate (DAP) and were set equal to the Iowa average application of N to soybeans in 2006 of 14 lb N/ac (most recently available data; USDA NASS, 2012).

Table 2: Nitrogen balance inputs and outputs and an associated estimation of uncertainty along with the source of estimation for each flux.

Fluxes	Magnitude of Contribution	Estimation Uncertainty	Scenario Source
Inputs			
Inorganic fertilizer	Major	Low	N Rate Calculator: Sawyer et al. (2006)
Symbiotic Biological Fixation	Major	High	Review: mean of 24 values and belowground consideration from Rochester et al. (1998)
Atmospheric Deposition	Variable	High	Review: mean of 27 values
Seed Inputs	Minor	Low	Review: mean of 3 values for each crop
Nonsymbiotic Fixation	Minor	Low	Review: median of 8 values
Outputs			
Grain Removal	Major	Low	USDA NASS (2012), Sawyer et al. (2006), Ciampitti and Vyn (2012), and IPNI (2012)
Drainage Leaching	Major	Moderate	Lawlor et al. (2008) and Thorp et al. (2007)
Fertilizer Volatilization	Minor	Moderate	Review: mean of 6 values
Denitrification	Variable	High	Hoben et al. (2010), Gillam et al., (2008), and Schlesinger (2009)

Application of N fertilizer to only corn in corn-soybean rotations is standard practice, but application rates (N mass/area) and corn response (yield) vary among sites and years. To account for this variability, this report evaluated N balances at three N application rates for each cropping system based on the approach of maximum economic return to N fertilizer application, which is the N rate recommendation system used in Iowa and across the Midwest USA (Sawyer et al., 2006). The Maximum Return to Nitrogen (MRTN) is described as the: "N rate where the economic net return to N application is greatest" (Sawyer et al., 2006). This MRTN method is a useful approach for developing N rate

recommendations because it utilizes N response data from a large number of field trials representing all physiographic regions in Iowa to more fully capture the large variation in potential corn N responses (Sawyer et al., 2006). At present, the MRTN is calculated from approximately 1,400 trials across the Midwest and 325 trials in Iowa, with new data regularly incorporated into the database system. It is likely the most widely used N fertilizer application tool for United States corn production.

This MRTN model recommends N fertilizer inputs based upon the probability of achieving a given economic return. Application rates above the MRTN rate reduce profits because the yield gain per N fertilizer input decreases. On the other hand, application rates below the MRTN rate also limit profits because additional N fertilizer inputs would generate yield increases that would generate profits exceeding N fertilizer costs (Figure 7). In addition to yield response, the MRTN also depends on the given fertilizer price to grain price ratio. For example, increased fertilizer N price at a given corn grain price increases this ratio and reduces the net return and the corresponding MRTN rate. The MRTN rate differs for continuous corn and the corn phase of a corn-soybean rotation because higher N fertilizer inputs are required to achieve maximum agronomic and economic yield in continuous corn versus corn-soybean rotation.

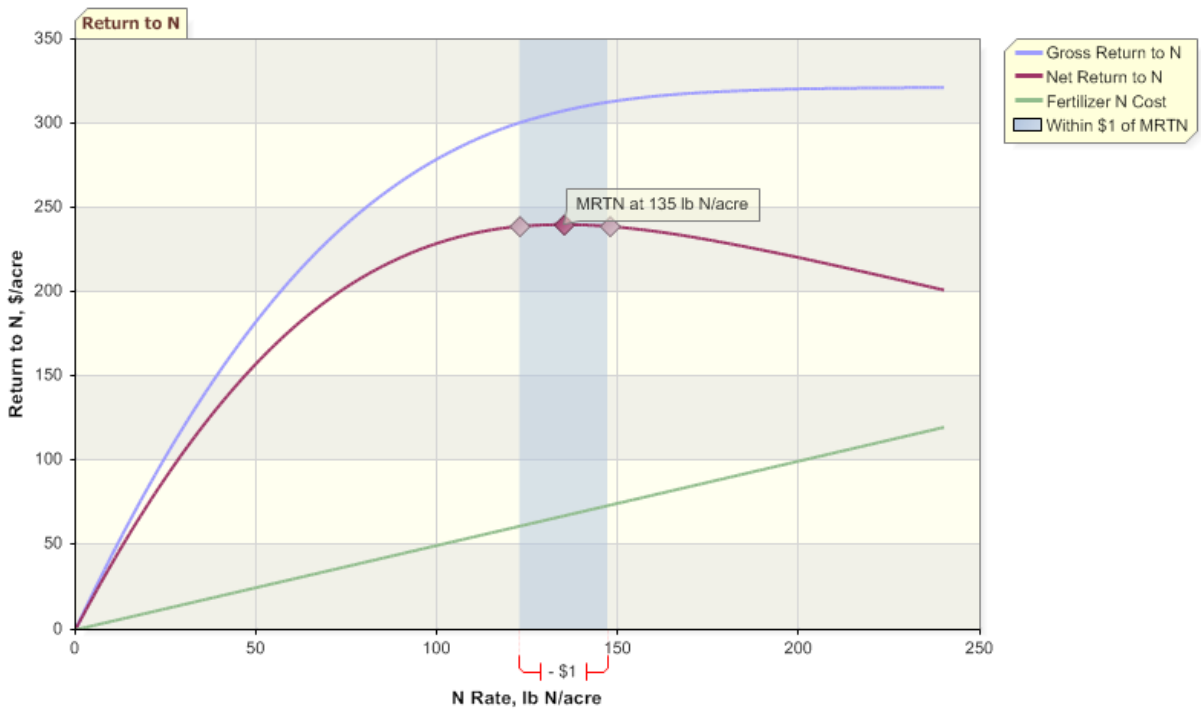

Figure 7: Example Nitrogen Rate Calculator results showing how yield return and fertilizer costs interact to affect net return. Note that Maximum Return to Nitrogen (MRTN) is always slightly below maximum yield; adapted from Sawyer et al., (2006). Data shown for corn-soybean rotation in Iowa at a 0.1 fertilizer: grain ratio ($0.50/lb N and $5.00/bu corn).

Using the Iowa MRTN rate calculator (Sawyer et al., 2006), N input rates at the common fertilizer-to-grain price ratio of 0.1 were selected. The three input rates were (1) the MRTN, (2) a N fertilizer rate higher than the MRTN that generated a net return of $1 per acre less than the MRTN, and (3) a N fertilizer rate lower than the MRTN that generated a net return of $1 per acre less than the MRTN.

Working within the framework of two cropping systems and three N fertilizer input rates, all other N inputs and outputs were estimated from published scientific literature. It is important to note that the

amount of N fertilizer inputs affects the magnitude of several other N inputs and outputs. When scientific literature provided sufficient direction, we considered this effect of N fertilizer inputs on other N inputs and outputs.

Fertilizer N inputs and symbiotic biological N fixation of atmospheric N_2 by soybean are the largest N inputs to the cropping systems considered herein (David et al., 2001; Gentry et al., 2009; Jaynes and Karlen, 2008; NRC, 1993). We estimated biological N fixation based on a mean of 24 values from the literature (Appendix B). Ten of these values were corrected to include N fixed in belowground plant parts while the other 14 values were assumed to be already reported as total plant N. A value of 24% of total plant N was allocated in below ground parts (Rochester et al., 1998); in other words, the ten aboveground fixation values from the literature review were each divided by 76% to calculate the total plant N due to fixation before the total mean (n=24) was developed. However, importantly, estimates of this input are highly variable and the amount of biological N fixation can decrease with increasing soil N availability.

Similar to symbiotic biological N fixation, estimates of atmospheric N deposition are highly variable. This report estimated wet plus dry atmospheric N deposition from the mean of 27 regional values from the literature review (Appendix B). However, atmospheric N deposition varies largely as a result of proximity to emission sources such as livestock operations; redeposition of locally derived ammonia from these livestock hotspots was not included here. Variability in biological N fixation and atmospheric deposition inputs are discussed in more detail in the "Detailed Component Information" section. Additional minor N inputs included crop seed and non-symbiotic biological fixation by soil microbes not directly associated with soybean. Crop seed inputs are easily measured and were estimated here based on the mean of literature review values. Although non-symbiotic biological fixation is extremely difficult to measure, literature indicates this input is small (Meisinger and Randall, 1991; Stevenson 1982). This input value was based on the median of literature reports as the mean value was greater than considered acceptable in several reports.

The largest N output is grain removal and these values were developed from a combination of current USDA yield statistics for Iowa and the N Rate Calculator (Sawyer et al., 2006; USDA NASS, 2012). The three year average (2009-2011) Iowa corn and soybean yields of 173 and 50.8 bu/ac, respectively, were assumed to be the initial maximum yields for each crop (USDA NASS, 2012). Corn yields for continuous corn and corn-soybean rotations were based on this 173 bu/ac using a difference of 8% because the 173 bu/ac represents an average of corn grown in monoculture and corn-soybean rotations; the potential maximum yield for continuous corn yield was 166 bu/ac (173 bu/ac minus 4%) and for corn-soybean was 180 bu/ac (173 bu/ac plus 4%). In order to estimate corn yields pertinent to each fertilization rate, these rotation specific corn yields were multiplied by the "percentage of maximum yield" developed by the N Rate Calculator at each fertilization level (Sawyer et al., 2006). Grain N concentration was set at 1.2% for corn (Ciampitti and Vyn, 2012; J. Sawyer, personal communication, June 2012) and 6.2% for soybean (IPNI, 2012). Corn and soybean yields were assumed to be reported at 15.5% and 13% moisture content, respectively, and these yields were corrected to a dry matter basis (0% H_2O) before calculation of N.

The second largest N output in Iowa is typically nitrate-nitrogen (NO_3-N) leaching in drainage waters, and increased fertilizer application rate typically increases this drainage NO_3-N loss. The total mass of NO_3-N loss was calculated as the product of drainage NO_3-N concentrations and drainage volume. To determine NO_3-N concentrations in drainage at each fertilization rate, we used a model for Iowa corn-based cropping systems developed by Lawlor et al. (2008):

$$Nitrate\ Concentration\ in\ Drainage = 5.72 + 1.33e^{(0.0104 \times N\ Rate)}$$

where *Nitrate Concentration in Drainage* is in mg N/L and the *N rate* is in kg N applied/ha. This simplified approach ignores other factors (soil mineralization, annual precipitation, etc.) known to impact NO_3-N concentrations in drainage. However, when these factors are constant, increasing N fertilizer inputs consistently increase NO_3-N leaching from Iowa soils (Jaynes et al., 2001; Lawlor et al., 2008). A constant drainage depth of 7.7 inches of drainage/yr was assumed for all scenarios; this volume was the mean from ten years of drainage monitoring at a long-term research site in Iowa described by Thorp et al. (2007). This drainage depth compared well with the sixteen year average drainage depth from plots studied by Lawlor et al. (2008) (10.1 inches), and was chosen due to the more realistic drain spacing and more central location in the state of the Thorp et al. (2007) study. In scientific literature, there has been no consistent significant difference between NO_3-N leaching in corn and soybean rotational phases; thus, NO_3-N concentrations and losses in drainage were assumed to be equal in corn and soybean rotation phases (Cambardella et al., 1999; Helmers et al., 2012; Lawlor et al., 2008; Logan et al., 1994). In other words, for the corn-soybean rotation, the same Lawlor et al. (2008) model was used to calculate drainage N concentrations in both the corn year and the soybean year, with both years based upon the fertilizer application rate in the corn year.

Fertilizer volatilization is affected by type of fertilizer N product, application method, soil properties (texture, pH, residue coverage, etc.), and climate (Meisinger and Randall, 1991; Stanley and Smith, 1956). For example, broadcast urea or urea-ammonium nitrate solution (UAN) can result in up to 30% N volatilization losses in extreme loss environments while direct injection of anhydrous ammonia can potentially eliminate these losses. Because anhydrous ammonia and UAN together have previously comprised approximately 80% of N fertilizer consumption in Iowa (Sawyer, 2003), fertilizer volatilization was calculated based upon the mean of values reported for the percentage of anhydrous ammonia and UAN fertilizer lost at a soil pH of less than 7. Volatilization averaged 1.9% of N application which was multiplied by the fertilizer application rate for each scenario (Bouwman et al., 1997; Burkart et al., 2005; Libra et al., 2004; Meisinger and Randall, 1991).

Denitrification was calculated based upon the percentage of inorganic N fertilizer application emitted as nitrous oxide (N_2O) developed from work by Hoben et al. (2010) in conjunction with a mean of N_2O to total N emission ratios from Schlesinger (2009) and Gillam et al. (2008). Regressions between N application rate and N_2O-N flux for each site-year reported by Hoben et al. (2010) were used with the reported Agronomic Optimum N Rates (AONR) to calculate the percentage of this AONR emitted as N_2O. The mean of these percentages (mean: 2.6% of AONR; range: 1.2 to 4.0% of AONR) was used to calculate the N_2O emission based on fertilizer application for each scenario here (including the 14 lb N/ac for soybeans). These values were converted to total N denitrification emissions using a mean N_2O-N:(N_2+ N_2O)-N ratio of 0.54 developed from Schlesinger (2009) and Gillam et al. (2008) who reported ratios of 0.375 and 0.70, respectively. This flux is highly variable (e.g., Table 2) and can be greatly affected by precipitation timing, N fertilizer applications, and residue levels.

Nitrogen balance results

Nitrogen balances for continuous corn at all three N fertilizer input rates were net positive with increasingly positive balances with higher N fertilization input rates (Figure 8; Table 3). The largest inputs and outputs were fertilizer and grain removal, respectively. Although increasing fertilization rates for the three scenarios increased net balances, it is important to note that for these positive N balances to translate into long-term soil N accumulation, the inorganic fertilizer N must be transferred to the soil

organic matter through biological (plant or microbe) processes and subsequently protected in stable organic N compounds.

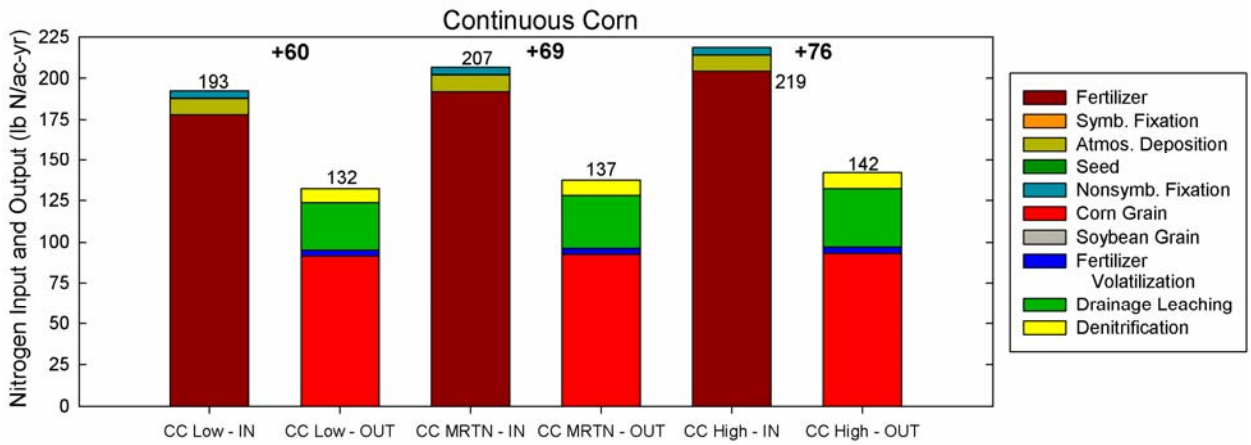

Figure 8: Nitrogen inputs, outputs and net balance (values at top) for continuous corn in Iowa at three fertilization rates (low, MRTN, and high); balances may not sum due to rounding. 1 kg per hectare = 0.89 pounds per acre.

Table 3: Nitrogen input and output values and corresponding net balances for continuous corn (CC) and a corn-soybean (CS) rotations in Iowa at three N fertilization levels. The balance reflects changes in the soil stock.

		Inputs					Outputs									
		N Application *	Symbiotic Biological N Fixation#	Atmospheric Deposition#	Seed#	Nonsymbiotic Fixation#	Corn Yield¶		N Removal with Corn Grain‡	Soybean Yield§	N Removal with Soybean Grain‡	Fertilizer Volatilization#	Drainage Leaching**	Denitrification¶¶	-- N BALANCE --	
		lb N/ac-yr					% of yield	bu/ac-yr	lb N/ac-yr	bu/ac-yr		lb N/ac-yr			(partial)	lb N/ac-yr
CC Low†		178	--	9.8	0.3	4.5	97.3	162	92	--	--	3.4	29	8.6		**60**
CC MRTN		192	--	9.8	0.3	4.5	98.2	163	93	--	--	3.7	32	9.3		**69**
CC High†		204	--	9.8	0.3	4.5	98.9	164	93	--	--	3.9	35	9.9		**76**
CS Low	**Corn†**	123	--	9.8	0.3	4.5	97.8	176	100	--	--	2.4	20	5.9	10	**-22**
	Soybean ††	14	98	9.8	4.0	4.5	--	--	--	51	165	--	20	0.7	-55	
CS MRTN	**Corn**	135	--	9.8	0.3	4.5	98.5	177	101	--	--	2.6	21	6.5	19	**-19**
	Soybean ††	14	98	9.8	4.0	4.5	--	--	--	51	165	--	21	0.7	-56	
CS High	**Corn†**	147	--	9.8	0.3	4.5	99.1	178	101	--	--	2.8	23	7.1	27	**-15**
	Soybean ††	14	98	9.8	4.0	4.5	--	--	--	51	165	--	23	0.7	-58	

*Developed using the Corn N Rate Calculator: Iowa sites at 0.1 price ratio for anhydrous ammonia, non-responsive sites not included (Sawyer et al., 2006).

† Low and high scenarios based on a $1.00 per acre reduction from the MRTN (Sawyer et al., 2006).

†† Average Iowa state-wide N application to soybeans from USDA NASS (2012).

¶ Plus 4% and minus 4% of the three year average (2009-2011) Iowa corn yield (173 bu/ac) was used for corn-soybean and continuous corn yields, respectively (USDA NASS, 2012); percentages of maximum yield developed using the N Rate Calculator (Sawyer et al., 2006).

‡Assumed corn and soybean yields were reported at 15.5% and 13% moisture, respectively, and corrected to dry weight here; corn 1.2% N and soybean 6.2% N (Ciampitti and Vyn, 2012; J. Sawyer, personal communication, June 2012; IPNI, 2012).

§Three year average (2009-2011) Iowa soybean yield: 50.8 bu/ac (USDA NASS, 2012).

#Mean or median from literature review, with the literature review mean for biological N fixation corrected for belowground N (Rochester et al., 1998).

** Based on the relationship developed by Lawlor et al. (2008) for corn fertilization and drainage nitrate-N concentration with drainage volumes from Thorp et al. (2007); leaching during soybean year of CS rotation assumed to be the same as the corn year.

¶¶ Based on percentage of N application emitted as nitrous oxide (Hoben et al., 2010) with mean N_2O-N:(N_2+ N_2O)-N ratio of 0.54 developed from Schlesinger (2009) and Gillam et al. (2008).

In contrast to continuous corn, two-year rotation corn-soybean N balances were all net negative (Figures 9 and 10; Table 3). Higher N fertilizer input rates in the corn phase reduced N deficits, but nevertheless even at the highest rates, corn-soybean N balances remained negative. This result is consistent with previous reports that N removed in soybean grain is greater than the amount fixed by the crop (Barry et al., 1993; Goolsby et al., 1999; NRC, 1993). A global review by Salvagiotti et al. (2008) showed the majority of soybean balances were negative or close to neutral and net negative balances increased with yield. Additionally, Schipanski et al. (2010) highlighted the importance of soybean N fixation by demonstrating that the percentage of soybean N derived from fixation can predict the net direction of corn-soybean rotation N balances.

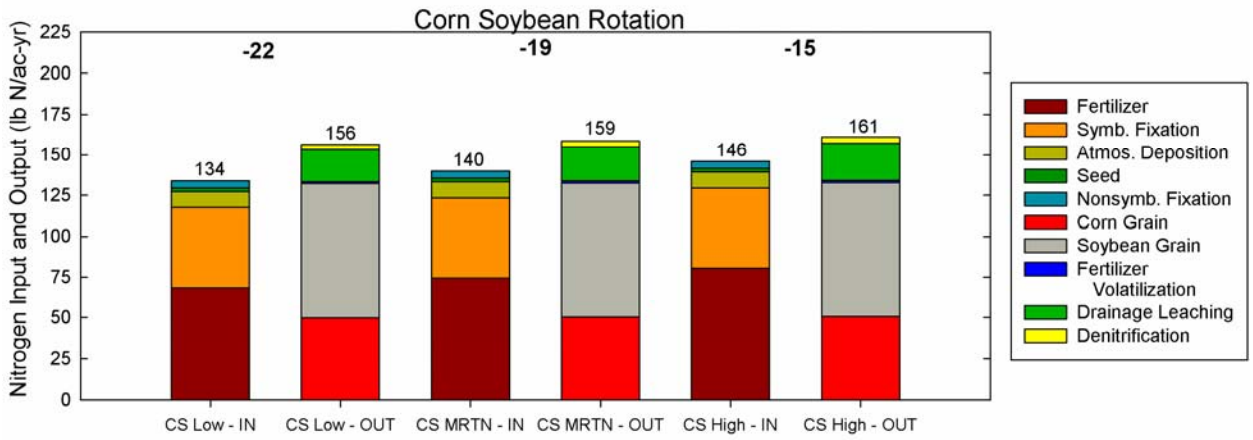

Figure 9: Nitrogen inputs, outputs and net balance (values at top) for a corn-soybean rotation in Iowa at three fertilization rates (low, MRTN, and high); balances may not sum due to rounding. 1 kg per hectare = 0.89 pounds per acre.

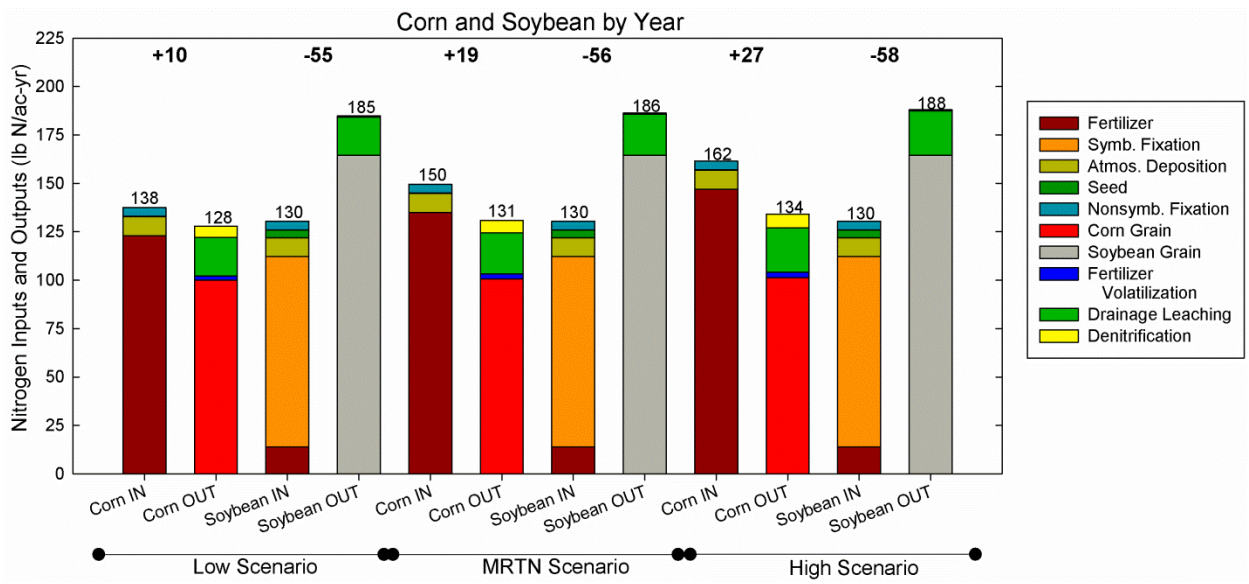

Figure 10: Nitrogen inputs, outputs and net balance (values at top) for a corn-soybean rotation in Iowa at three fertilization scenarios (low, MRTN, and high) shown by individual crop years; balances may not sum due to rounding. 1 kg per hectare = 0.89 pounds per acre.

Although these balance calculations provide an indication of net direction of the nutrient stock, it is important to keep in mind the variability and associated uncertainty of many of these inputs and outputs. In the continuous corn system, N fluxes with greatest uncertainty were denitrification and

atmospheric deposition (Table 2). Because the magnitudes of these two fluxes were relatively small, the overall uncertainty for the continuous corn rotation was relatively small. For example, atmospheric deposition was estimated at 9.8 lb N/ac with denitrification averaging 9.2 lb N/ac across the three fertilization scenarios. Assuming a liberal variation of 50% for these two fluxes and using the Root Sum of Squares error estimation method resulted in an error term of only 6.7 lb N/ac:

$$Continuous\ Corn\ Root\ Sum\ of\ Square\ Error = 6.7\ \frac{lb\ N}{ac} = \sqrt{\left(9.8\ \frac{lb\ N}{ac} \times 50\%\right)^2 + \left(9.2\ \frac{lb\ N}{ac} \times 50\%\right)^2}$$

This uncertainty value for the continuous corn rotation was much less than the magnitude of the net balance values for all three scenarios (6.7 lb N/ac < 60, 69, and 76 lb N/ac) lending additional validation of the positive balance for this rotation.

In contrast, uncertainty associated with biological N fixation in the corn-soybean rotation greatly increased the estimated error for this rotation. Even assuming a more conservative potential variation of 33% for deposition, denitrification (average of both phases), and biological N fixation in the corn-soybean rotation, the total error term was 33 lb N/ac, a value that was larger in magnitude than the net N balance deficits:

$$Corn - Soybean\ Root\ Sum\ of\ Square\ Error = 33\ \frac{lb\ N}{ac}$$
$$= \sqrt{\left(9.8\ \frac{lb\ N}{ac} \times 33\%\right)^2 + \left(3.6\ \frac{lb\ N}{ac} \times 33\%\right)^2 + \left(98\ \frac{lb\ N}{ac} \times 33\%\right)^2}$$

Using an uncertainty of 50% as for the continuous corn rotation yielded a total error term of 52 lb N/ac which was again much greater than the balance deficits. This highlights the difficulty in obtaining precise estimates of changes in soil nutrient stocks using the balance of inputs and outputs.

Importantly, N drainage losses and denitrification are sizeable outputs for these cropping systems because for a portion of the year there is no live vegetation on the soil to capture the N and reduce the water flux. Simply replacing these N losses through addition of inorganic fertilizer will not enhance cropping system sustainability in the broadest sense that includes air, soil, and water quality (Jaynes and Karlan 2008). In contrast, management strategies such as insertion of cover crops within a rotation or rotating annuals with perennial crops can potentially provide more complete approaches to long-term sustainability of soil nitrogen stocks. Additionally, rather than conclude that increased fertilizer N in the corn-soybean rotation might reduce SON loss, it is important to note that the **fundamental limitation of the corn-soybean rotation is the low amount of plant residue returned to the soil during the soybean phase.** Such low residue return can also be a challenge during the corn phase if this material is harvested for feed or cellulose; here it was assumed no residue removal occurred. Low residue return cannot be ameliorated with additional fertilizer N that does not increase yield and residue production. However, residue inputs can be augmented through implementation of management practices that maintain or add organic matter to the soil. For example, cover crops can increase crop residue inputs and limit nitrate leaching. When this occurs without a negative impact on corn and soybean yields that negates the cover crop residue input, it can benefit soil quality.

Detailed nitrogen component information

While the "N Application" category listed in Table 3 was assumed to be composed primarily of inorganic N inputs in these balances, this category could also feasibly include manure as this flux was considered the "total" N application. However, manure was not explicitly included in this balance as this would

greatly complicate the N cycle through additional complication of the carbon cycle. Moreover, considerations of manure additions are best handled though large scale balances due to very large variability in manure forms, nutrient availabilities and application rates. Likewise, erosion was not considered as part of this N balance due to highly complex effects on soil N stock loss and subsequent accumulation.

Inputs

Fertilizer

Past extension reports from Blackmer et al. (1997) recommended N application rates of 168-224 kg N/ha (150-200 lb N/ac) for corn following corn and 112-168 kg N/ha (100-150 lb N/ac) for corn following soybean in Iowa (no manure; all applied preplant or before crop emergence). More recent reported rates of inorganic fertilizer use encompass a similar range (e.g., David et al. (1997): 197 kg N/ha or 176 lb N/ac; Galloway et al. (2008): 160 kg N/ha or 143 lb N/ac; Gentry et al. (2009): 184 kg N/ha or 164 lb N/ac).

Symbiotic Biological N Fixation (BNF)

Within the United States and the Mississippi River Basin, soybean is the most widely grown legume (De Bruin et al., 2010; Russelle and Birr, 2004). To supply a portion of the N for the soybean grain's relatively high protein content (De Bruin et al., 2010; Keyser and Li, 1992), soybean is capable of utilizing symbiotic bacterial N fixation to convert atmospheric N_2 to plant-available NH_4. The N fixation process provides a portion of soybean N requirement, typically ranging from 36 to 69% of total N uptake (25th and 75th percentile of range from Salvagiotti et al., 2008). While symbiotic bacteria are essential to the fixation process, inoculation of such bacteria into fields with a history of soybean production neither enhances soybean yield nor increases economic returns (De Bruin et al., 2010), because these bacteria (*Bradyrhizobium japonicum*) are naturalized in our soils.

Russelle and Birr (2004) noted that biological N fixation (BNF) varies widely among years and within soybean fields due to factors affecting both the N demand of the crop and the N supply in the soil. The amount of N fixed by a given soybean crop depends upon factors including soybean cultivar, strain of bacterial symbiont, root nodule position, available soil N, crop management, soil water, soil chemical environment, and temperature (Keyser and Li, 1992; Meisinger and Randall, 1991). Perhaps the most important factor affecting BNF is the available N content of the soil (Harper, 1976) with N fixation generally decreasing as soil N availability increases (George et al., 1988; Patterson and LaRue, 1983a). Efforts to model BNF have assumed maximum fixation rates occurred at soil mineral N contents of less than 100 kg N/ha per m root zone (89 lb N/ac per 3.3 ft root zone), while no fixation has been assumed to occur at soil mineral N contents greater than 300 kg N/ha per m root zone (268 lb N/ac per 3.3 ft root zone) (Bouniols et al., 1991; Williams et al., 2008b). An integral component of soil available N content in intensively managed agricultural systems is the type, rate, and method of inorganic N fertilizer applied (Keyser and Li, 1992; Salvagiotti et al., 2009). It is well documented that N fertilization of soybeans can decrease BNF (Johnson et al., 1975; Patterson and LaRue, 1983b; Salvagiotti et al., 2009); Salvagiotti et al. (2008) showed the mass of N_2 fixed declines exponentially with increasing fertilizer rate for fertilizers applied within the upper 20 cm of soil.

With this large number and wide variety of factors influencing BNF, it is no surprise there is great uncertainty associated with the estimation of the contribution of soybean fixation to a field-scale N balance. Smil (1999) stated, "Although many estimates have been published …, we are still unable to offer reliable, representative values of average annual fixation rates even for the most important

leguminous cultivars." **Because BNF associated with soybean is one of the largest sources of uncertainty in Midwestern N balances, improved ability to quantify this input would significantly reduce overall uncertainty in balance development (Jaynes and Karlen, 2008).** Herridge et al. (2008) reviewed analytical methods to measure fixation, but unfortunately, measurement of this input is analytically challenging and costly (Unkovich et al., 2010).

Although there is significant uncertainty surrounding estimation of BNF inputs, it is widely recognized that soybean crops often require more N (or export more N in grain) than they fix (Barry et al., 1993; Goolsby et al., 1999; Jaynes and Karlen, 2008; NRC, 1993; Salvagiotti et al., 2008; Schepers and Mosier, 1991). This often results in a net negative N balance following the soybean year of a corn-soybean rotation. However, negative N balances with soybean crops are not exclusively the case as Schipanski et al. (2010) found that N balances for one soybean variety grown at thirteen sites (some fertilized) ranged from −10 to +91 kg N/ha (-9 to +81 lb N/ac), and that a positive N balance resulted when the percentage of N from fixation was greater than 60%.

In previous state- or regional-scale N balance studies, BNF rates of 75 to 78 kg N/ha-yr (67 to 70 lb N/ac) have been used (Burkart and James, 1999; Goolsby et al., 1999; Jordan and Weller, 1996; Puckett et al., 1999). In other N balance studies, the metric of 0.91 kg N/bu soybean (2.0 lb N/bu) has been used to calculate the total fixation input from yield information (Libra et al., 2004; McIsaac et al., 2002). Reported ranges of annual fixation by soybean in the Midwest region generally span from 57 to 114 kg N/ha (51 to 102 lb N/ac) (Rennie, 1985; Schepers and Mosier, 1991) and Russelle and Birr (2004) reported soybean in the Mississippi River Basin fixed an average of 84 kg N/ha (range: 0 to 185 kg N fixed/ha; mean: 75 lb N/ac, range: 0 to 165 lb N/ac). For reference, N removal in soybean grain harvest in this region is generally 100 to 200 kg N/ha (mean: 147 kg N/ha or 131 lb N/ac removed in 1997; Russelle and Birr, 2004). Considering the variability of this flux, Smil (1999) used a range of fixation values (60, 80, and 100 kg N/ha; 54, 71, and 89 lb N/ac) in balance development. Similarly, early reports put average fixation at 80 to 100 kg N/ha (71 to 89 lb N/ac) in North America and Europe (Harper, 1976; Rennie, 1985).

Several reports of higher fixation values are also worth noting. Gentry et al. (2009) estimated soybean fixation was 163 and 150 kg N/ha-yr (145 and 134 lb N/ac) in an Illinois watershed. Even greater fixation estimates (187-208 kg N/ha; 167-186 lb N/ac) were developed by Jaynes et al. (2001) using a soybean grain yield/ fixation relationship developed by Barry et al. (1993):

$$N\ fixed\ in\ \frac{kg\ N}{ha} = 81.1 \times soybean\ grain\ yield\ in\ \frac{t}{ha} - 98.5$$

In a review of scientific literature, Salvagiotti et al. (2008) reported a global average fixation rate for soybean of 111 kg N/ha (or 125 kg N/ha for datasets without fertilizer application; 99 and 112 lb N/ac, respectively) with a maximum of 337 kg/ha (301 lb N/ac). Another review Peoples et al. (2009) reported a mean fixation rate for North America of 144 kg N/ha (129 lb N/ac).

In terms of percentage of plant N derived from the atmosphere (%Ndfa), fixation values used are commonly 50% for Midwestern soybean (David and Gentry, 2000; Harper, 1976; Johnson et al., 1975; Peoples et al., 2009; Rennie, 1985) (Figure 11). Because Harper (1976) reported a typical %Ndfa range of 25 to 50%, it was concluded soil N was the main N source and fixation was the secondary N source for soybean. However, some studies indicate that fixation is the main source of soybean N with reported percentages of N from the atmosphere at greater than 50% (Gentry et al., 2009; George et al., 1988; Russelle and Birr, 2004). Using a meta-analysis of over 600 international soybean datasets, Salvagiotti et

al. (2008) calculated a mean %Ndfa of 52% (58% for unfertilized datasets) which was lower than the 68% global soybean %Ndfa value reported in a review by Peoples et al. (2009).

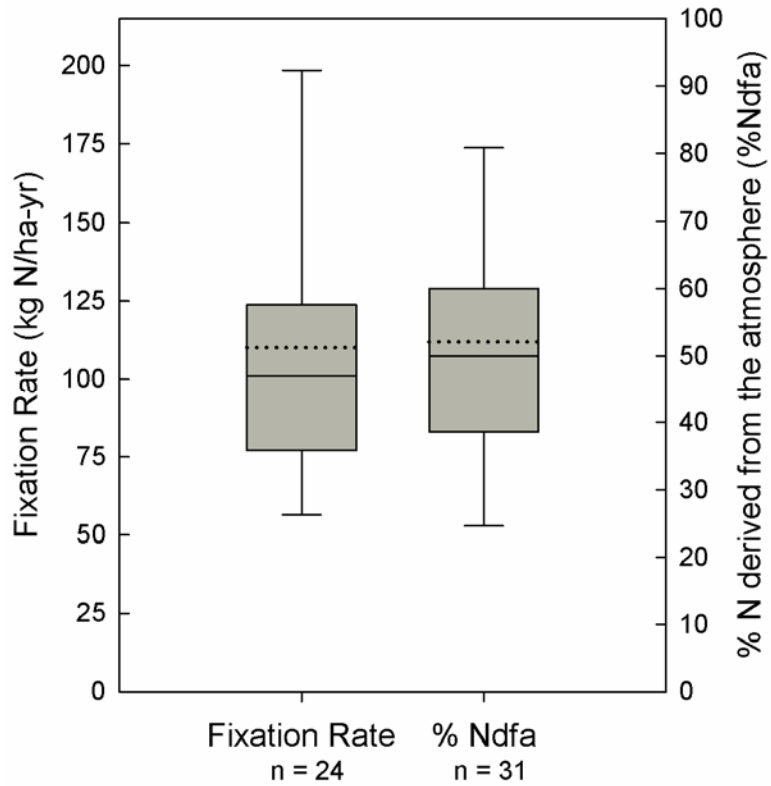

Figure 11: Review of soybean biological fixation rates and percentage of nitrogen derived from the atmosphere (%Ndfa); the box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dotted line represents the mean, and the whiskers show the 10th and 90th percentiles; see Appendix B for references. 1 kg per hectare = 0.89 pounds per acre.

In addition to the large uncertainty associated with this flux, literature-based legume fixation values may underestimate actual fixation as these values often do not include belowground N (e.g., N in "non-recovered roots, detached nodules, and products of root necrosis") (Herridge et al., 2008; Salvagiotti et al., 2008). Rochester et al., (1998) reported this belowground fraction was 24% of total soybean N at maturity (39% at podfill). Herridge et al. (2008) reported the below ground percentage of total soybean plant N ranged from 22-68% and values of 24%, 33%, and 38% have been used by Salvagiotti et al. (2008), Herridge et al. (2008), and Unkovich et al. (2010), respectively.

Deposition

Atmospheric deposition of N is comprised of wet processes (i.e., N deposited with precipitation) and dry processes (i.e., deposition of N particles and vapor generally in the absence of precipitation; Goolsby et al., 1999). This distinction may be slightly misleading, however, as Ferm (1998) reported that dry deposition could occur even during wet deposition. In the atmosphere, NH_3 is the principal form of N (Ferm, 1998; NADP, 2011), and much of this N is often dry deposited very near the emission source (Ferm, 1998; Goolsby et al., 1999). However, because NH_3 is also highly reactive in the atmosphere, the resulting particles and NH_4^+ can be transported over long distances (Asman and van Jaarsveld, 1992; Ferm, 1998; Loubet et al., 2006). The most common reported forms of dry deposited N include NH_3,

NH_4^+ (or NH_x, when reported together), NO_3, and HNO_3 (Anderson and Downing, 2006; Goolsby et al., 1999) whereas wet deposition commonly includes NH_4^+, NO_2^-, NO_3^- and organic N (Stevenson 1982).

Measurement of wet deposition is typically more straightforward than dry deposition, and is often calculated as the product of precipitation volume and N concentration (Jaynes et al., 2001; Meisinger and Randall, 1991). Nitrate concentrations in precipitation used to calculate wet N deposition in the Midwestern region range from 0 to 1.7 mg NO_3-N/L (Hatfield et al., 1996; Hoeft et al., 1972; Jaynes et al., 2001; Thorp et al., 2007). Total N concentrations in precipitation are typically 2 to 3 mg N/L (Libra et al., 2004; Meisinger and Randall, 1991) although precipitation near a livestock operation may contain twice this concentration (Meisinger and Randall, 1991). More accurate point estimates of deposition, not just precipitation N concentration, can be obtained with the use of bulk samplers (i.e. automated sampling buckets) (Anderson and Downing, 2006; Goolsby et al., 1999).

Due to a lack of monitoring stations and general scarcity of dry N deposition data, many reports have attempted to estimate dry deposition from measured or estimated wet deposition values. Sisterson (1990) recommended a ratio of 0.3 to 0.7 for dry: total deposition and gave specific examples of ratios of 0.57 for Argonne, IL and 0.52 for Bondville, IL. Hanson and Lindberg (1991) reported a similar dry: total deposition ratio range of 0.2 to 0.7 for N deposition to plant surfaces. Many authors have used a similar value of 0.70 for the ratio of dry: wet deposition (David and Gentry, 2000; Goolsby et al., 1999; Jaynes and Karlen, 2008; Libra et al., 2004; McIsaac et al., 2002), while others have most simply assumed dry N deposition was equal to wet (Jordan and Weller, 1996; Meisinger and Randall, 1991; Schepers and Mosier, 1991). Considering that deposition inputs are relatively minor compared to N fertilizer and BNF, such approximations may be suitable (David and Gentry, 2000).

Previous reports of total (wet+dry) deposition in the Midwest span 5 to 15 kg N/ha with this review documenting a mean of 11.0 kg N/ha or 9.8 lb N/ac (Figure 12; 25th and 75th percentiles are 7.0 and 10.8 kg N/ha, respectively). The most recent measurements from within Iowa document total annual deposition of 7.7 kg N/ha (6.9 lb N/ac) (Anderson and Downing, 2006). For Illinois and Ohio, Goolsby et al. (1999) reported total deposition was approximately 8 to 11 kg/ha (7.1 to 9.8 lb N/ac). Specifically in terms of wet deposition, Tabatabai et al. (1981) generalized this input at 5 to 20 kg N/ha (4.5 to 17.8 lb N/ac) per year for the Midwestern region. At six sites in Iowa in the 1970s, annual wet deposition ranged from 4.8 to 7.2 kg NO_3-N/ha (4.3 to 6.4 lb NO_3-N /ac) and 5.0 to 7.2 kg NH_4-N/ha (4.5 to 6.4 lb NH_4-N /ac), respectively (Tabatabai et al., 1981). A decade later, modeled wet deposition in the state of Iowa was on the order of 7.8 to 14.8 kg NO_3-N/ha (7.0 to 13.2 lb NO_3-N/ac) and 2.5 to 3.8 kg NH_4-N/ha (2.2 to 3.4 lb NH_4-N/ac), respectively, for the period of 1985-1987 (Sisterson, 1990). Only considering NO_3 deposition in precipitation, Jaynes et al. (2001) reported annual wet deposition values ranging from 11 to 15 kg N/ha (9.8 to 13.4 lb N/ac). More recently, Jaynes and Karlen (2008) reported slightly lower values of 3.7 to 7.0 kg N/ha-yr (NO_3+NH_4) (3.3 to 6.2 lb N/ac) for total annual wet deposition. Several geographic-based reports approximate wet deposition at 4.5 to 7 kg N/ha (4.0 to 6.2 lb N/ac) for Iowa (Burkart and James, 1999; Schepers and Mosier, 1991). There are far fewer reported values for annual dry deposition rates; Goolsby et al. (1999) reported dry NO_3-N deposition at sites in Iowa was generally 1.8 to 2 kg NO_3-N/ha-yr (1.6 to 1.8 lb NO_3-N/ac) and Schepers and Mosier (1991) reported total dry deposition ranged from 2 to 15 kg N/ha-yr (1.8 to 13.4 lb N/ac).

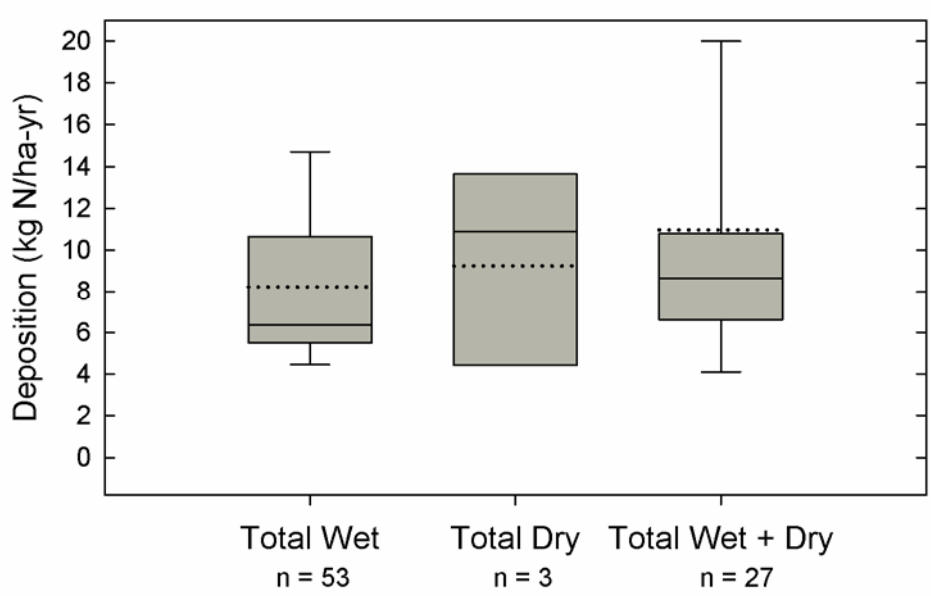

Figure 12: Review of Midwestern regional wet, dry, and total nitrogen atmospheric deposition rates; the box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dotted line represents the mean, and the whiskers show the 10th and 90th percentiles when the sample size was sufficient; see Appendix B for references. 1 kg per hectare = 0.89 pounds per acre.

In the United States, monitoring networks established for wet and dry N deposition include the National Trends Network (NTN), the Ammonia Monitoring Network (AMoN), and the U.S. Environmental Protection Agency's Clean Air Status and Trends Network (CASTnet) (NADP, 2011; NADP, 2012; USEPA, 2012). However, the number of monitoring sites for wet deposition is far greater than for dry which leads to larger uncertainty in quantification of dry deposited N (Goolsby et al., 1999). There have been multiple calls for improved deposition research and monitoring networks (Goolsby et al., 1999; Russelle and Birr, 2004). This is especially relevant for this study as there are only two monitoring stations in Iowa, both of which are far from concentrated animal feeding areas of the state (NADP, 2012).

Deposition of locally derived ammonia (NH_3)

Deposition of locally derived NH_3 is particularly variable. Because agriculture is the source of 85% of atmospheric NH_3 in the United States (NADP, 2011), NH_3 emission and deposition near agricultural housing and waste facilities is high (Loubet et al., 2006). Accordingly, these facilities are often referred to as "hot spot" sources of NH_3. Although emissions of NH_3 from these hotspots can be very high, they are usually spatially small or isolated and may be of short duration (e.g., during and for days after manure applications) (Cellier et al., 2009; Loubet et al., 2006).

Transport from the NH_3 source depends upon factors including source height, atmospheric stability, wind speed, structure of the surrounding canopies, leaf area index, surface roughness, resistance, and wetness, NH_3 compensation point, and reactions with other molecules (Ferm, 1998; Loubet et al., 2006). Atmospheric modeling in European agricultural systems by Asman and van Jaarsveld (1992) showed that approximately 50% of NH_x emissions from a point source are deposited within 50 km downwind. After this approximate distance, the NH_x can be transported over longer distances with Ferm (1998) stating that "far from the source", deposition is halved every 400 km. By comparison, NO_x deposition is more linear in regards to distance from the source with deposition generally constant for the first 800 km and then halved every additional 600 km (Ferm, 1998). While transfer of these European results to the Midwest region of the United States should be interpreted with caution

(Russelle and Birr, 2004), Midwestern estimates of local NH_3 deposition show the same trend of decreasing deposition rate with increased distance from a source (Stevens and Tilman, 2010).

Local emission or deposition of NH_3 also depends upon the NH_3 concentration gradient between the air and the deposition surface. For example, there will be very little or no dry deposition to fields recently having undergone manure spreading (Asman and van Jaarsveld, 1992). Moreover, individual plants can serve as either sources or sinks of NH_3 depending upon their N nutrition status and the NH_3 dynamics in the surrounding air (Loubet et al., 2006). This balance has been termed "compensation point" (Asman and van Jaarsveld, 1992; Farquhar et al., 1980). When atmospheric NH_3 concentrations are below the compensation point, plant leaves are an NH_3 source; when they are above the compensation point, plant leaves are an NH_3 sink (Farquhar et al., 1980). However, this concept has limited practical utility because the compensation point is difficult to measure and can be highly variable over short periods of time and space (i.e., on different leaves of the same plant; Francis et al., 1997). Although absorption of atmospheric NH_3 by fertilized crops is typically not expected to represent a significant plant N uptake source, it could be significant near an NH_3 emission hot spot due to high atmospheric NH_3 concentrations (Schepers and Mosier, 1991).

Emission and deposition of NH_3 within a crop canopy may be considered a fairly rapid process of recirculation. This has led many authors to consider locally derived NH_x an internal cycle and to discount it from N balances (David and Gentry, 2000; David et al., 2001; Goolsby et al., 1999; Jordan and Weller, 1996). Indeed, Puckett et al. (1999) reported that counting NH_3 absorption by crop leaves as a unique N input in addition to manure could cause double counting especially if manure N volatilization losses were not considered. Nevertheless, in one regional balance and one western Iowa watershed balance deposition of locally derived NH_3 was considered large with a range of 23 to 40 kg N/ha (21 to 36 lb N/ac) (Burkart and James, 1999; Burkart et al., 2005).

N content of crop seed

Nitrogen inputs via crop seed are minor, but easy to determine (Smil, 1999). Corn seed N inputs are approximately 0.2 to 0.3 kg N/ha (0.2 to 0.3 lb N/ac), while N inputs from soybean seed have been reported at 2.5 to 5 kg N/ha (2.2 to 4.5 lb N/ac) due to the greater N concentration of the latter (Barry et al., 1993; Legg and Meisinger, 1982; Meisinger and Randall, 1991).

Nonsymbiotic N_2 fixation

Nonsymbiotic N_2 fixation, the transformation of atmospheric N_2 to NH_3 by free-living soil algae and bacteria not associated with legumes, is a minor N input and is ignored in most N balances. This process is typically performed by blue green algae and free-living bacteria, most specifically *Azotobacter* and *Clostridium* (Meisinger and Randall, 1991; Stevenson 1982; Troeh and Thompson, 1993). In agriculturally managed soils receiving large synthetic N inputs, nonsymbiotic N fixation ranges from 3 to 7 kg N/ha (2.7 to 6.2 lb N/ac) (Meisinger and Randall, 1991; Stevenson 1982) with 5 kg N/ha (4.5 lb N/ac) a commonly reported value (Barry et al., 1993; Drinkwater et al., 1998; Jordan and Weller, 1996; Puckett et al., 1999; Smil, 1999).

Outputs

Grain N Removal

The largest N output from corn and soybean agricultural systems is N removal in harvested grain. On an aerial basis, grain N removal rates are higher for soybean than corn. For example, average soybean N grain removal in the Mississippi River Basin was 147 kg N/ha (131 lb N/ac) in 1997 (Russelle and Birr,

2004), while harvested corn grain N removals are on the order of 50 to 150 kg N/ha (45 to 134 lb N/ac). For an average Iowa corn grain yield of 173 bu/ac, grain N removal is approximately 100 lb N/ac (assuming 15.5% moisture and 1.2% N content). Increased fertilization rates increase corn grain N removal through increased yield and increased grain N concentration (Asghari and Hanson, 1984; Halvorson and Reule, 2006; Johnson et al., 1975).

Grain N removal is typically calculated as the product of grain yield at 0% moisture and grain N concentration with grain N concentration often estimated as a percent of measured crude protein concentration. The crude protein content to N ratio is usually reported at 6.25:1 for both corn and soybean (David and Gentry, 2000; David et al., 1997; Gentry et al., 2009; Jaynes and Karlen, 2008; Russelle and Birr, 2004). Average protein concentrations have been reported at 9-10% for corn and 40% for soybeans (David and Gentry, 2000; David et al., 1997; Gentry et al., 2009). Corn grain N concentrations appear to be declining (Table 4) (Ciampitti and Vyn, 2012).

Table 4: Corn and soybean grain nitrogen content on a percentage basis reported in literature (at dry weight, 0% moisture).

	---------- % N ----------	
Reference	Corn	Soybean
Legg and Meisinger (1982)	1.5	6.06
Meisinger and Randall (1991)	1.5 (range: 1.35-1.75)	6.5 (range: 6.1-6.9)
NRC (1993)	1.5	6.3
Troeh and Thompson (1993)	1.4	6.0
David et al. (1997)	1.6	6.4
David and Gentry (2000)	1.6	6.4
Salvagiotti et al. (2008)	---	6.3 (range: 3.8-8.1)
Gentry et al. (2009)	1.44	6.4
Ciampitti and Vyn (2012)	1.2 (range: 0.3-2.7)	---

Mean corn and soybean N concentrations in grain on a percentage basis range from 1.2 to 1.6% N for corn and from 6.0 to 6.5% N for soybeans (Table 4). Because estimates of total N grain removal also depend upon yield estimates, the accuracy of the yield estimate is important; modern yield monitors typically have high accuracy (e.g., 4% under normal operating conditions, Burks et al., 2004). Grain yields must be converted to a dry weight basis for N removal calculations. Moisture contents of 15.5% and 13% for corn and soybean, respectively, were used here (Adviento-Borbe et al., 2007).

N leaching in drainage

Leaching of N in drainage, predominantly in the nitrate form, can be a major output from the soil system in Midwestern cropping systems. Typical loads range from 20 to 35 kg N/ha (18 to 31 lb N/ac) (David et al., 1997; Gentry et al., 2000; Jaynes et al., 2001; Kalita et al., 2006), although losses can be greater than 80 kg N/ha (71 lb N/ac) (Kaspar et al., 2007; Lawlor et al., 2008). There are many “controllable” and “uncontrollable” factors effecting drainage N loss including tile depth and spacing, cropping rotation, N management, soil type, and N mineralization (Randall and Goss, 2001). Precipitation (e.g., amount, timing, and extreme events) is one of the most important uncontrollable factors influencing these losses (Randall and Goss, 2001).

In addition to drainage nitrate-N losses, it also bears to mention that leaching of dissolved organic N can be an important loss pathway from agricultural systems (van Kessel et al., 2009). However, this flux was not included here due to the lack of information available on this output from row cropped, tile drained systems. Similarly, the loss of nitrous oxide gas emitted from drainage waters was not included because of the scarcity of information on this output.

Denitrification

Denitrification, the microbial transformation of nitrate to gaseous nitric oxide, nitrous oxide and dinitrogen gas (NO, N_2O and N_2), is typically the predominant N loss pathway from the soil to the atmosphere. In nature, the vast majority of these gaseous denitrification emissions are in the form of N_2O and N_2 rather than NO (Chapin et al., 2002). Recent advances in the use of stable isotopes in denitrification research led Schlesinger (2009) to note this pathway is "more widespread and of greater significance than we realized just a few years ago".

In agricultural systems with high nitrate concentrations, denitrification is typically controlled by soil water content (oxygen availability) and dissolved organic carbon availability. Thus, SOM and drainage class can provide an estimate of potential denitrification (Meisinger and Randall, 1991; Table 5). However, this process is highly temporally variable due to its dependence upon soil moisture and precipitation variability, which is not reflected in Table 5. Although the reported percentages in Table 5 have an associated accuracy of ±20-50% (Meisinger and Randall, 1991), this information has been used fairly widely (Burkart et al., 2005; Burkart and James, 1999; Goolsby et al., 1999). Based on an assumed organic matter content of 3.5% for Iowa soils, Goolsby et al. (1999) estimated denitrification losses were 20% of available N inputs. For an Iowa state-wide N budget, Libra et al. (2004) assumed 15% of available N was lost to denitrification. For an Illinois N budget, David and Gentry (2000) assumed 10% of the fertilizer application was lost. Figure 13 presents a review of these values.

Table 5: Percentage of inorganic soil nitrogen lost to denitrification as influenced by soil organic matter content (%) and drainage class; from Meisinger and Randall (1991)

Percent soil organic matter content	---------- Percent of soil inorganic N lost to denitrification (%) ----------				
	---------- Drainage Class ----------				
	Excessively well	Well	Moderately well	Somewhat poorly	Poorly
<2	2-4	3-9	4-14	6-20	10-30
2-5	3-9	4-16	6-20	10-25	15-45
>5	4-12	6-20	10-25	15-35	25-55

*See adjustment factors associated with the original table for the practice of no-till, use of manure, and the installation of tile drainage (Meisinger and Randall, 1991).

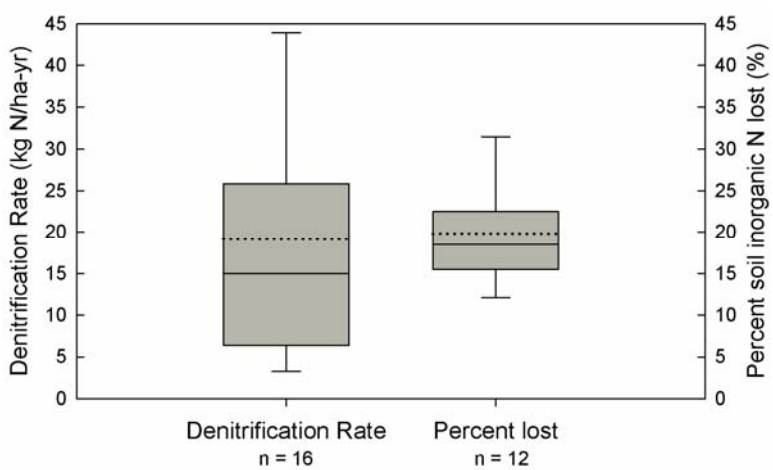

Figure 13: Review of Midwestern regional denitrification rates and percentages of soil inorganic N lost through denitrification; the box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dotted line represents the mean, and the whiskers show the 10th and 90th percentiles; see Appendix B for references. 1 kg per hectare = 0.89 pounds per acre.

Modeled estimates of denitrification losses range from 6 to 30 kg N/ha (5.4 to 27 lb N/ac) for the Midwestern region (Burkart and James, 1999; Goolsby et al., 1999; Seitzinger et al., 2006). Slightly above this range, Hofstra and Bouwman (2005) developed an N balance where at N fertilization rates of 75-225 kg N/ha (67-201 lb N/ac), denitrification was estimated to be 40-46 kg N/ha-yr (36-41 lb N/ac-yr) for poorly drained soils and 25-29 kgN/ha-yr (22-26 lb N/ac-yr) for well drained. In a comparison of five denitrification simulation models, David et al. (2009b) reported annual denitrification rates ranged from 3.2 to 34 kg N/ha-yr (2.9 to 30 lb N/ac-yr) with corn and soybean denitrification loss rates averaging 14.5 kg N/ha-yr (12.9 lb N/ac-yr) and 9.4 kg N/ha-yr (8.4 lb N/ac-yr), respectively, for an Illinois watershed. Other modeling work by Thorp et al. (2007) estimated denitrification at 1.3 to 18 kg N/ha-yr (1.2 to 16.1 lb N/ac-yr, mean: 6.8±5.2 kg N/ha-yr or 6.1±4.6 lb N/ac-yr), though the ability of this model (RZWQM) to simulate denitrification may be limited. Some N balances simply do not include denitrification (Barry et al., 1993; Bremer et al., 2011; Jaynes and Karlen, 2008), and though this flux can be sizeable given optimum conditions, the inability to measure denitrification at the field scale limits the certainty associated with this N output (Groffman et al., 2006).

Beyond modeling, Parkin and Kaspar (2006) measured N_2O loss rates from a corn and soybean rotation in Iowa and reported ranges of 7.6 to 15.4 kg N_2O-N/ha (6.8 to 13.7 lb N_2O-N/ac) and 2.2 to 8.2 kg N_2O-N/ha (2.0 to 7.3 lb N_2O-N/ac) for the corn and soybean phases, respectively (note measurement periods were just shy of one year). However, these rates must be converted to total N loss rates before being considered total denitrification loss. The relative proportion of N_2O versus N_2 emitted from denitrification is variable due to a number of factors including relative availability of nitrate and dissolved organic carbon (Weier et al., 1993). The consistency of this ratio is important when trying to estimate total gaseous N denitrification losses because only N_2O can be measured at the field scale (Weier et al., 1993). Weier et al. (1993) did not recommend using an average N_2:N_2O ratio to calculate total N losses because this ratio is highly variable. Nevertheless, Schlesinger (2009) reported the average N_2O-N:(N_2+ N_2O)-N ratio for agricultural soils was 0.375±0.035 (SE) and Gillam et al. (2008) reported mean N_2O-N:(N_2+ N_2O)-N ratios of 0.5 to 0.8 with values frequently greater than 0.70.

Fertilizer volatilization

Volatilized ammonia loss from fertilizer is related to the type of N fertilizer, application method, soil pH, and timing of rainfall after application (Meisinger and Randall, 1991). The amount and type of surface residue can also impact volatilization from surface applied urea/urea-based products, products which, in general, can be subject to large volatilization losses. Soil type can influence such losses with coarse textured soils losing a greater percentage of applied anhydrous ammonia N than fine textured soils (Stanley and Smith, 1956). Losses can be minimal with use of ammonia-based fertilizers if placement is at least 15 cm in depth and if application occurs when soil moisture conditions are optimal (Stanley and Smith, 1956). However, such application under “optimal soil conditions” can be challenging due to the precipitation event-driven nature of this flux.

Generally, the reported range of percent of fertilizer lost through volatilization in the Midwest is 0 to 15% (Burkart et al., 2005; Burkart and James, 1999; Jordan and Weller, 1996; Puckett et al., 1999; Stanley and Smith, 1956). More specifically, volatilization losses from anhydrous ammonia and N solutions/UAN have been listed at 1 to 4% and 2.5%, respectively, of the soil inorganic N content (Bouwman et al., 1997; Libra et al., 2004). Burkart and James (1999) and Goolsby et al. (1999) decribed this output as ranging from 2 to 6 kg N/ha (1.8 to 5.4 lb N/ac) in Iowa. Jaynes and Karlen (2008) did not include fertilizer volatilization in their partial N balance for Iowa corn-soybean rotation systems because they considered this output negligible by assuming correct application methods. Properly injected anhydrous ammonia typically makes volatilization losses negligible unless soil moisture conditions are

not optimal (Bouwman et al., 1997). Similar to other gaseous N outputs from the soil, fertilizer volatilization is difficult to quantify, highly variable, and is associated with high uncertainty.

Plant senescence

Plants are capable of serving as sources or sinks of NH_3 depending upon the NH_3 compensation point and the plant growth stage and nutrition level (Francis et al., 1997). After flowering, plants emit NH_3 through their leaves due to internal translocation of N during senescence (Francis et al., 1993; Smil, 1999). These senescent losses may be greater in soils with higher levels of N or from plants that have higher N contents (Francis et al., 1993; Francis et al., 1997).

Modeled estimates of plant senescent losses for Iowa range from 9 to 40 kg N/ha-yr (8 to 36 lb N/ac-yr) (Burkart and James, 1999; Goolsby et al., 1999) with Schepers and Mosier (1991) reporting a wider range of 10-50 kg N/ha-yr (8.9 to 45 lb N/ac-yr). Goolsby et al. (1999) assumed 45 and 60 kg N/ha (40 and 54 lb N/ac) is lost through this pathway for soybean and corn, respectively, in their balance, although McIsaac et al. (2002) reported these values were an order of magnitude too large. Senescent losses for corn were initially reported as high as 45 to 81 kg N/ha (40 to 72 lb N/ac) (Francis et al., 1993), but these isotopic dilution measurements may have been overestimated due to un-quantified additional N input processes in the field (Francis et al., 1997). Senescent losses from soybean have been reported at as high as 45 kg N/ha (40 lb N/ac) (Stutte et al., 1979); however, McIsaac et al. (2002) noted these high values may have been incorrect due to faulty measurement method. Regardless if these previously reported values are too high, Smil (1999) wrote such losses from plant canopies could nevertheless be sizeable and assumed a minimum and maximum of approximately 3 and 10 kg N/ha-yr (approximately 5 and 15 Tg/yr; 2.7 and 8.9 lb N/ac-yr) for such losses from global croplands. Schepers and Mosier (1991) recommended moderate values as a replacement factor to compensate for the amount of N lost by senescing plants (22 kg N/ac; 20 lb N/ac) and Meisinger and Randall (1991) estimated that 2 to 8% of the total aboveground plant N could be lost in this way (approximately 4 to 18 kg N/ha or 3.6 to 16 lb N/ac).

As with other gaseous N fluxes, senescent losses are often not included in N balances as this output may be deemed an "internal redistribution" of N (Smil, 1999) and is neither well understood nor well quantified (Jaynes and Karlen, 2008; Meisinger and Randall, 1991). This potential for "internal redistribution" is why this flux was not included here. Considering that senescent loss estimates vary over an order of magnitude, improved monitoring techniques are needed to enhance field-scale measurements of this output (Jaynes and Karlen, 2008). However, Smil (1999) strongly noted, "Given the magnitude of [losses from tops of plants], it is imperative that all N balance studies should consider this neglected variable before attributing any unaccounted losses to unknown factors or to higher rates of denitrification or leaching."

Phosphorus

Background

Like N, balances for P in Midwestern areas have been developed. However, these P balances are less complex than N balances because P lacks a significant gaseous phase, P is less mobile than N, and P fluxes are dominated by physical rather than biological processes. Phosphorus inputs and outputs are dominated by agricultural fertilizer and crop harvest (Figure 14). The Iowa state-wide budget developed by Libra et al. (2004) showed a small net negative P balance (11%) which was interpreted to mean P stocks in the state were "roughly in balance". Libra et al. (2004) noted this was different from the historical trend as evidenced by previously high soil testing P values common across the state. Work

from the Lake Mendota watershed in Wisconsin corroborated high historical soil P levels in the region through use of budgeting and investigation of long-term (1974-1994) soil P concentration data (Bennett et al., 1999). Also within the region, David and Gentry (2000) showed Illinois had a net neutral P balance in the late 1990s, though large P inputs during the 1960s and 1970s resulted in large soil surpluses. Although the majority of soils in Iowa tested above the "medium soil test P level" at the beginning of this century (Fixen, 2002), Fixen et al. (2011) reported many Corn Belt soils now show a negative P balance with consistent declines in the median soil testing P levels in this region between 2005 and 2010 (IPNI, 2010).

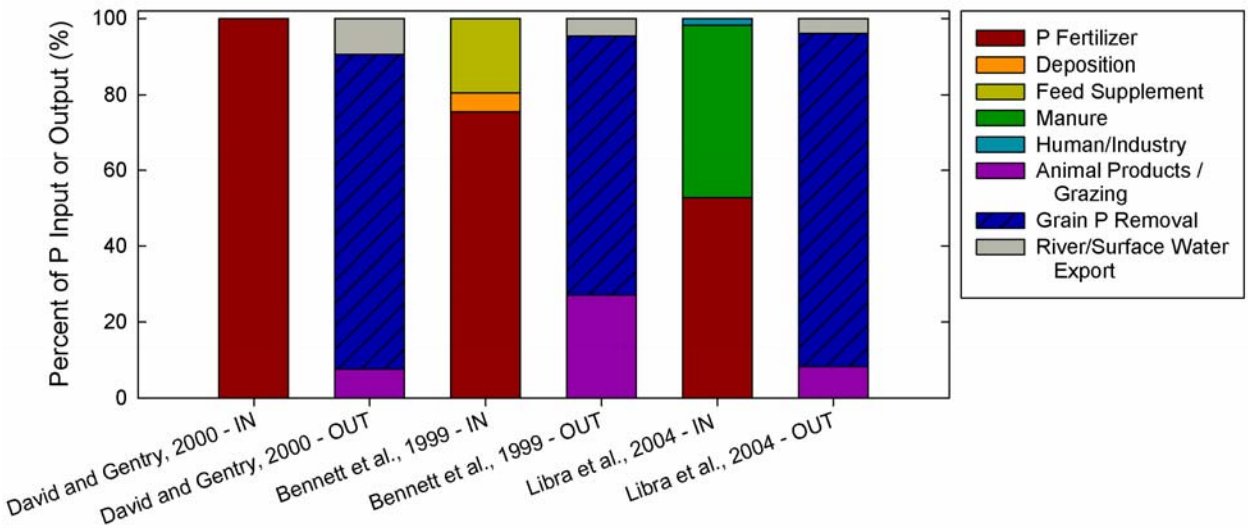

Figure 14: Percentage of phosphorus inputs or outputs for three previous Midwestern phosphorus balances: David and Gentry (2000) state-wide Illinois balance, Bennett et al. (1999) budget for Lake Mendota watershed in Wisconsin, and Libra et al. (2004) state-wide Iowa budget.

Phosphorus Input-Output Balance Scenarios

Development

Like previous P balances, the major inputs and outputs here were inorganic fertilizer and grain P removal, respectively; smaller fluxes included atmospheric P deposition and losses to surface waters through surface transport or drainage (Table 6). This balance implicitly assumed that potential soil test P changes in the topsoil would correlate with total soil P. Moreover, this work did not consider subsoil (below 6 inches, 15 cm) P depletion by crop removal or buildup by excess P application. Such subsoil considerations could be very important for long-term changes in total soil P. However, few data are available on long-term changes in subsoil P. General indications show there is little change in soil test P below 12 inches (30 cm) at high P fertilizer application rates (Haq et al., 2011).

Table 6: Phosphorus balance inputs and outputs and an associated estimation of uncertainty along with the source of estimation for each flux.

Fluxes	Magnitude of Contribution	Estimation Uncertainty	Scenario Source
Inputs			
Inorganic fertilizer	Major	Low	Mallarino (2008)
Atmospheric Deposition	Minor	High	Anderson and Downing (2006)
Outputs			
Grain Removal	Major	Low	USDA NASS (2012) and Mallarino et al. (2011)
Erosion / Runoff / Drainage	Variable	High	Iowa P Index: Iowa NRCS (2004)

Fertilizer

Soil P fertilizer recommendations in Iowa endorse response-based and removal-based P application for soils with low or optimum soil test P levels, respectively (Mallarino et al., 2011). In order to perform this management at optimum soil P levels, it is necessary to have reliable estimates of P removal in harvested grain. Mallarino (2008) and Sawyer et al. (2002) provided general P application rate recommendations based upon this concept for corn of 55 to 100 lb P_2O_5/ac (24 to 44 lb P_2O_5-P/ac) and for soybeans of 40 to 80 lb P_2O_5/ac (17 to 35 lb P_2O_5-P/ac) depending upon the soil test P level and desired yield (Table 7). In this report, P balances were developed with three P fertilization levels for each corn and soybean. These rates were based upon the "Very Low" and "High" soil test P levels to achieve the maximum yield of both crops in Table 7, while the "Optimum" soil test fertilization rate was set at grain P removal for those corn and soybean scenarios.

Table 7: Recommended P application rates in lb P_2O_5/ac based upon soil test level and desired corn or soybean yield (Mallarino, 2008)

Soil Test P Category	Bray-1 Soil Test Level	---------- P_2O_5 Application rate (lb P_2O_5/ac) ---------			
		-------- Corn Yield --------		--- Soybean Yield ---	
		150 bu/ac	200 bu/ac	50 bu/ac	60 bu/ac
Very low	0-8	100	100*	80	80*
Low	9-15	75	75	60	60
Optimum	16-20	55	75	40	48
High	21-30	0	0*	0	0*

*used in P balance

Deposition

Low magnitude and limited data availability for atmospheric P deposition means this input is sometimes disregarded in P balances (David and Gentry, 2000). The majority of P deposited from the atmosphere occurs as dry deposition rather than wet (Anderson and Downing, 2006; Bennett et al., 1999), and reported total (wet + dry) annual P deposition for Iowa is 0.3 kg P/ha-yr (no standard error reported; 0.3 lb P/ac-yr) (Anderson and Downing, 2006). Based on this, atmospheric deposition of P generally represents no more than 2% of P in grain removal. David and Gentry (2000) presented unpublished data for another site in the region (Bondville, IL) where wet P deposition averaged only 0.02 kg P/ha-yr (0.02 lb P/ac-yr) for 1995 through 1998; because most deposition of P occurs as dry, this value may underestimate the total P contribution.

Grain P Removal

Grain removal is the largest P output and is calculated as the product of grain P concentration and yield. Based on a summary of statewide data, Mallarino et al. (2011) observed that there was no correlation

between grain P concentration and grain yield for either corn or soybeans, and that because grain P concentrations varied less than yield, average P concentrations could be used to estimate grain P removal. However, due to potentially high spatial variability in yield, Mallarino et al. (2011) indicated that a fairly precise estimate of yield is required to accurately calculate P removal in this way.

Values of the P_2O_5 content of corn and soybean grain range from 0.31 to 0.38 lb P_2O_5/bu (0.14 to 0.16 lb P_2O_5-P/bu) and 0.76 to 0.82 lb P_2O_5/bu (0.33 to 0.36 lb P_2O_5-P/bu), respectively (Table 8). To calculate grain P removal in this balance, the latest values reported by Iowa State University Extension (i.e., 0.31 and 0.76 lb P_2O_5/bu or 0.14 and 0.33 lb P_2O_5-P/bu; Mallarino et al., 2011) were used in combination with the USDA NASS three year average (2009-2011) Iowa corn and soybean yields (173 and 50.8 bu/ac, respectively; USDA NASS 2012). Like with the N balance, these yields were corrected to dry weight from 15.5% and 13% moisture content for corn and soybean, respectively.

Table 8: Corn and soybean P contents (lb P_2O_5/bu) reported in literature.

Reference	Corn	Soybean
	----- lb P_2O_5/bu -----	
Kellogg et al. (2000)	0.34	0.82
Libra et al. (2004)	0.38	0.80
Sawyer et al. (2002)	0.38	0.80
Mallarino et al. (2011)	0.31	0.76

P Outputs: Erosion/Runoff/Drainage

Another potentially considerable output of P from soil is loss to surface water bodies. Phosphorus can be transported attached to sediment, dissolved in surface runoff, and leached through the soil profile (Lemunyon and Daniel, 2002). Factors influencing this type of P loss have been grouped into transport (e.g., erosion, surface runoff, subsurface flow, soil texture, irrigation runoff, connectivity to streams, channel effects, proximity of P sensitive water, sensitivity to P input) and source/site management categories (e.g., soil P, applied P, application method, application timing) (Sharpley et al., 2001; Sharpley et al., 2003). The greatest erosion or runoff P loads primarily occur in small, “hydrologically active” areas of a watershed typically during a few storm events (Sharpley et al., 2001; Sharpley et al., 2003). These hydrologically active, “critical source areas” lie at the intersection of high transport and source factors (Sharpley et al., 2003).

The three approaches for agro-environmental P planning and water quality risk management are: (1) soil P test recommendations, (2) environmental P thresholds, and (3) a P index (Sharpley et al., 2003). The use of soil P test levels alone provides an incomplete picture of water quality risk because transport and management factors are not considered (Sharpley et al., 2001; Sharpley et al., 2003). The most complete approach, use of a P Index, is the most widely used method in the United States (Sharpley et al., 2003). While there has been little evaluation of P Indices against observed P loss, existing studies indicate the P index can explain a large amount of variation in P loss (Sharpley et al., 2003; Harmel et al., 2005).

The Iowa P Index considers the three soil P loss mechanisms (erosion, runoff, and tile drainage losses) to provide a comprehensive management decision tool to reduce P transported to surface waters (Iowa NRCS, 2004). In this model, a multiplicative rather than additive approach is used to combine P transport and source factors including soil test and total P, P application rate, method, and timing, erosion and sediment delivery, location relative to water bodies, conservation practices, precipitation, and runoff and drainage flows (Iowa NRCS, 2004; Mallarino et al., 2002). After initial P transport risk values for each of the three transport mechanisms are summed (in units of lb P/ac-yr), this value is

placed into one of five risk categories ranging from “Very Low” (0 to 1 P Index) to “Very High” (greater than 15 P Index) (Iowa NRCS, 2004). Although the Iowa P index is not intended to provide quantitative predictions of P delivery to water bodies (Iowa NRCS, 2004), this intermediate step of the summation of the erosion, runoff and drainage components was used to estimate the magnitude of these losses for this P balance. While P Indices developed in many other states do not generate values in terms of lb P/ac-yr, the ability of the Iowa P Index to generate such values lends great utility to this evaluation. However, the use of the P Index quantitative results was done here only with the greatest of caution as it is well noted P indices are only intended to provide semi-quantitative (as in the Iowa P Index) or qualitative approaches to P loss risk assessment (Sharpley et al., 2001; Mallarino et al., 2002; Sharpley et al., 2003).

For this P balance, the Iowa P Index was used to calculate the lb P/ac-yr lost based on the three P fertilizer scenarios for both corn and soybean. To use the P Index, a location had to be assumed (Story County, Des Moines Lobe, Clarion soil type with 5 to 9% slope, moderately eroded) and 5 tons erosion per acre was used as a P Index input (5 tons/ac as sheet erosion, no ephemeral or gully erosion). Other assumptions for the scenarios were that there were no sediment trap practices, the distance from the center of the field to the stream was 500 ft, there was no sediment filter (0-19 ft selected), the enrichment factor was based upon tillage, the land use was row crop (straight row with good crop residue for corn and poor crop residue for soybeans), and tile drainage was present. The soil test P input factor varied for each scenario based upon Table 7 (Bray-1; Very low: 5; Optimum: 18; High: 30) with fertilizer inputs (assumed fertilizer incorporation within one week) from the balance.

Phosphorus balance results

High soil test P scenarios resulted in negative balances for both crops as expected to allow utilization of existing surplus soil P that was at greater levels (soil test) than needed for crop production (Figures 16 and 17; Table 9). The optimum soil test scenarios resulted in balances very close to neutral, whereas the very low soil test scenarios showed accumulation of P in the soil (Figures 16 and 17; Table 9). Under the very low soil test scenarios, if P were applied only at the replacement rate and below the recommended rate, these soils would continue to have low soil P crop availability (soil test P). These results verify P recommendation efforts in that high soil test sites provide higher relative risk of P export offsite, and reduction of soil P at these sites due to a net negative P balance may precipitate improved water quality. Likewise, the near neutral balances for the optimum soil test scenarios resulted from P application recommendations based upon grain removal. In terms of water quality, export of P calculated based on the Iowa P Index resulted in four of the scenarios in a “Very Low” risk category (0-1 P index) and two scenarios in the “Low” risk category (>1-2 P Index) (Table 9) (Mallarino et al., 2002; Iowa NRCS, 2004).

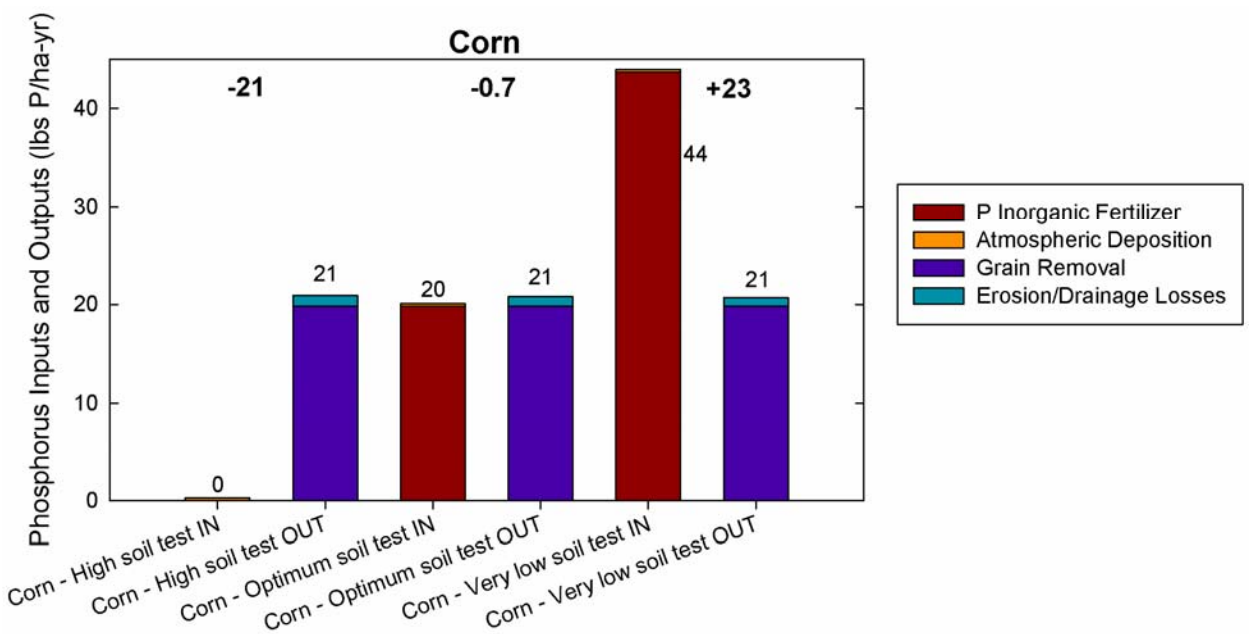

Figure 15: Phosphorus inputs, outputs and net balance (values at top) for corn production in Iowa at three P fertilization rates based upon soil test level.

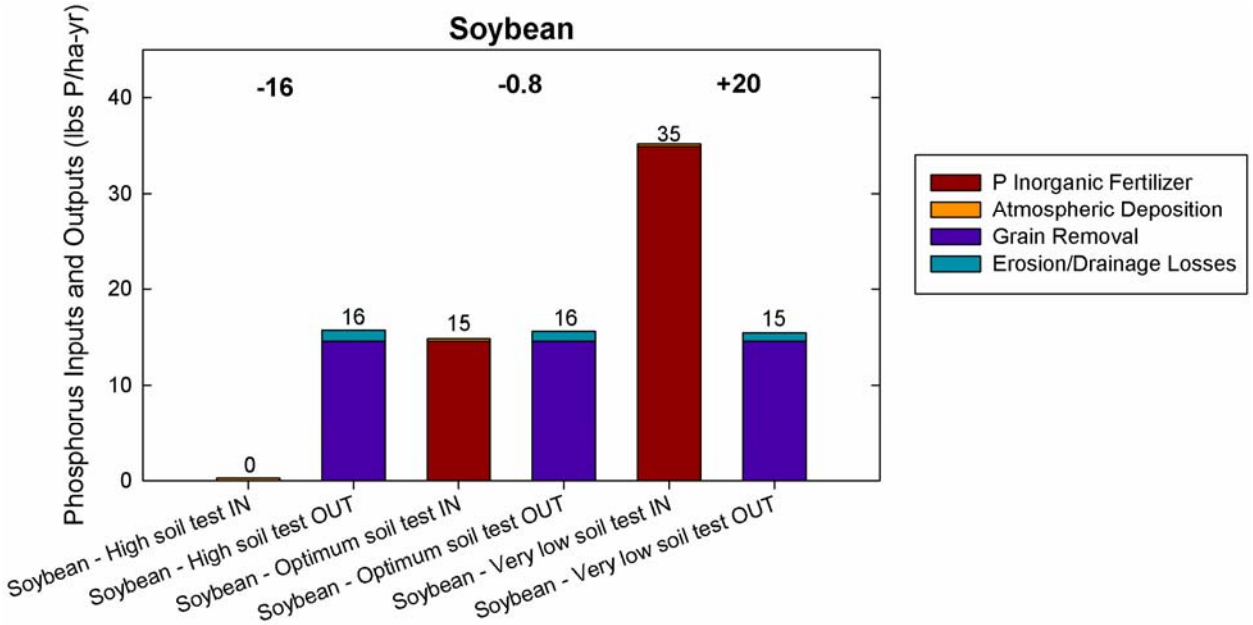

Figure 16: Phosphorus inputs, outputs and net balance (values at top) for soybean production in Iowa at three P fertilization rates based upon soil test level.

Table 9: Phosphorus input and output values and corresponding net balance for corn and soybeans in Iowa at three P fertilization levels based upon soil test level.

	Fertilizer*	Deposition	Crop Harvest Grain Removal†	Export to Water	**P BALANCE**
	---------- lb P/ac-yr ----------				
Corn - High soil test	0	0.27	19.8	1.1	**-21**
Corn - Optimum soil test	19.8	0.27	19.8	0.99	**-0.7**
Corn - Very low soil test	43.7	0.27	19.8	0.88	**23**
Soybean - High soil test	0	0.27	14.7	1.2	**-16**
Soybean - Optimum soil test	14.7	0.27	14.7	1.0	**-0.8**
Soybean - Very low soil test	34.9	0.27	14.7	0.91	**20**

*From Mallarino (2008) for "Very Low " and "High" and grain removal-based for "Optimum"
† from USDA NASS (2012): Iowa average (2009-2011) 173 bu/ac corn and 50.8 bu/ac soybean; assumed corn and soybean yields reported at 15.5% and 13% moisture and corrected to dry weight here; corn: 0.31 lb P_2O_5/bu and soybeans: 0.76 lb P_2O_5/bu (Mallarino et al., 2011)

These P balances were corroborated by long-term soil test P data at several research farm sites in Iowa (Figure 18). Research investigating P applications to corn and soybean cropping systems showed that in plots receiving no P fertilizer, soil tests levels decline approximately 1 ppm (Bray-1) per year (Mallarino and Prater, 2007). Conversely, plots receiving P fertilization experienced increased soil P tests levels over time (Mallarino and Prater, 2007).

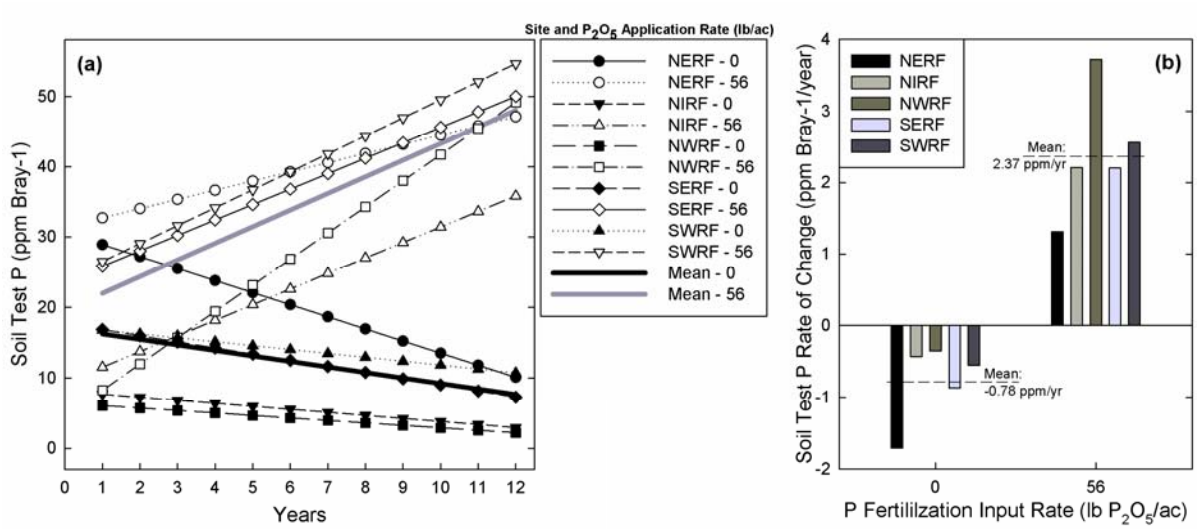

Figure 17: Linear regressions of long-term soil test P levels (a) and rates of soil test P change (b) at five research farm sites in Iowa over twelve years at two phosphorus fertilization rates (0 and 56 lb P_2O_5/ac); NERF: Northeast Research Farm, NWRF: Northwest Research Farm, NIRF: North Central Research Farm, SERF: Southeast Research Farm, and SWRF: Southwest Research Farm; From Mallarino and Prater, 2007.

Long-term changes in nitrogen stocks based on soil sampling

Accurate long-term changes in soil nitrogen stocks can only be achieved with measurement of the 'stock change over time'. An unequivocal understanding of change in soil N stocks is particularly desirable because total N stocks are positively correlated with N mineralization, yield level, and yield stability (Booth et al., 2005; Williams et al., 2008a). Agricultural soils in the Midwestern Corn Belt region have

SOM composed of approximately 55% carbon (C) and 5% N resulting in a carbon to nitrogen ratio (C:N) of approximately 10:1; this ratio can range from 10-14:1 for topsoil to 7-10:1 for subsoil (Espinoza et al., 2012; Russell et al., 2005). Because SON is covalently bound to SOC, as SOM changes, so does soil N.

There are a number of challenges to historical scientific studies of soil N stocks including: lack of replication or randomization, lack of true control treatments, modifications to the experiment over time, incomplete description of experiment and sampling protocol, and potential movement of soil between plots (Glendining and Powlson, 1995). However, the largest challenge to measurement of a N 'stock change over' is the lack of ability to detect statistically significant changes because changes in soil N stocks are typically very small while the total N pool is very large and variable in space (Glendining and Powlson, 1995; Jaynes and Karlen, 2008). For example, the maximum annual SOC rates of change in the surface soils from work by Russell et al. (2005) (Figure 6) were only 1.4% of the total SOC stock. Another complication of long-term studies is the spatial variability of soil C and N (Cambardella et al., 1994). Over five years, Adviento-Borbe et al. (2007) noted the standard errors of cumulative SOC changes (0.6 to 1.3 Mg C/ha; 540 to 1,160 lb C/ac) were large due to spatial variability; on an annual basis, these standard errors could be large enough to obscure the actual magnitude of a change in SOC.

For many measurements of soil N and C stock changes over time, there is a significant possibility that a reported lack of change is spurious and the result of poor statistical design or insufficient sampling intensity. In other words, the soil stocks may be changing, but experimental methods were not capable of measuring the change. In statistics, this type of false negative conclusion (lack of change) is termed Type II error in which two treatment means are declared to not be different from each other when they actually do differ. A statistical method called a power analysis helps to minimize Type II errors during experiment design and planning or identify Type II errors after experiments have been conducted by determining if a lack of statistical significance is due to the absence of meaningful differences or due to lack of replication (sample number). Using a power analysis for a dataset from Michigan, Kravchenko and Robertson (2011) found that 14 samples would have to be taken from each of six replicated plots to detect a 10% change in total C in the surface soil with a 90% probability that this difference between treatments was "real" (i.e., a power of 90%). This sample number was considerably larger than the five samples per plot actually collected in the study, which resulted in only a 52% chance (power) of detecting a 10% difference in means between management treatments.

Importantly, statistical power is a function of the number of samples, variation among samples and effect size that is desired to be measured (for example, a 10% change in N stocks over 10 years). Accordingly, measurement of changes in soil C and N stocks often increases with soil depth because variation in C and N stocks increases with depth. An important unanswered question in this area of soil C and N stock-change research is whether changes in surface soil C and N stocks are proportional to changes in subsoil C and N stocks within a given management system over time. In other words, can relatively easy-to-measure changes in surface soil C and N stocks serve as a proxy for similar proportional changes in subsoils?

In this report, soil samples at four Iowa State University Research Farms in Iowa were collected either in 1999 or 2000, and again in 2009. These four sites (Ames, Crawfordsville, Chariton, and Sutherland, Iowa) represented a wide geographic cross-section of the state from the southeast to northwest corners. Plots at these sites were in continuous corn and corn-soybean rotation cropping systems; inorganic N fertilizer was applied during the corn years at one of several application rates. Soil samples were analyzed for total N and total C in the Iowa State University Plant and Soils Testing Laboratory with dry combustion elemental analysis. The N fertilization rate treatment in each cropping system was

replicated four times. Thus, there were four replicate continuous corn plots at each N fertilizer rate at each site. However, because each phase of the corn-soybean rotation was represented every year, there were 8 replicate plots for corn-soybean rotations at each site. For initial samples at the Ames and Sutherland sites (1999 and 2000), only composited samples were collected from each block. Homogeneous soil properties were assumed over these blocks, allowing these block values to be compared with corresponding individual plot samples from 2009. Bulk density, measured in 2009 by replicate and rotation, was assumed to be the same over time. Data were analyzed using general linear models, t-tests, and power analyses. **Importantly, these experiments and soil sampling strategies were not designed to measure stock changes in soil C and N; accordingly, statistical power was low.**

The mean annual rate of C and N change among the four sites was positively correlated with N fertilizer application rates for both continuous corn and corn-soybean cropping systems. **Average C and N balances were *negative* at profitable fertilizer N rates in corn-soybean rotation systems, but they were *positive* at profitable fertilizer N inputs in continuous corn systems (Figure 18; Sawyer et al. 2006).** It is important to note that in continuous corn, gains in soil organic C and N with fertilizer inputs cease beyond the profitable N fertilizer input rate. At profitable N fertilizer rates, continuous corn had significantly higher C and N stocks than corn-soybean rotations at all research sites. Corn-soybean rotations had positive C and N balances at only one of four research sites; at the other three, C and N balances were negative (Figure 19). Although the empirical data indicate rates of change in N stocks that are less than those estimated by input-output balance in the previous sections of this report (Table 3), this result was expected because the stock change measurements in Figures 18 and 19 only account for changes in the top 20 cm of soil while the input-output balances account for changes in the total soil profile.

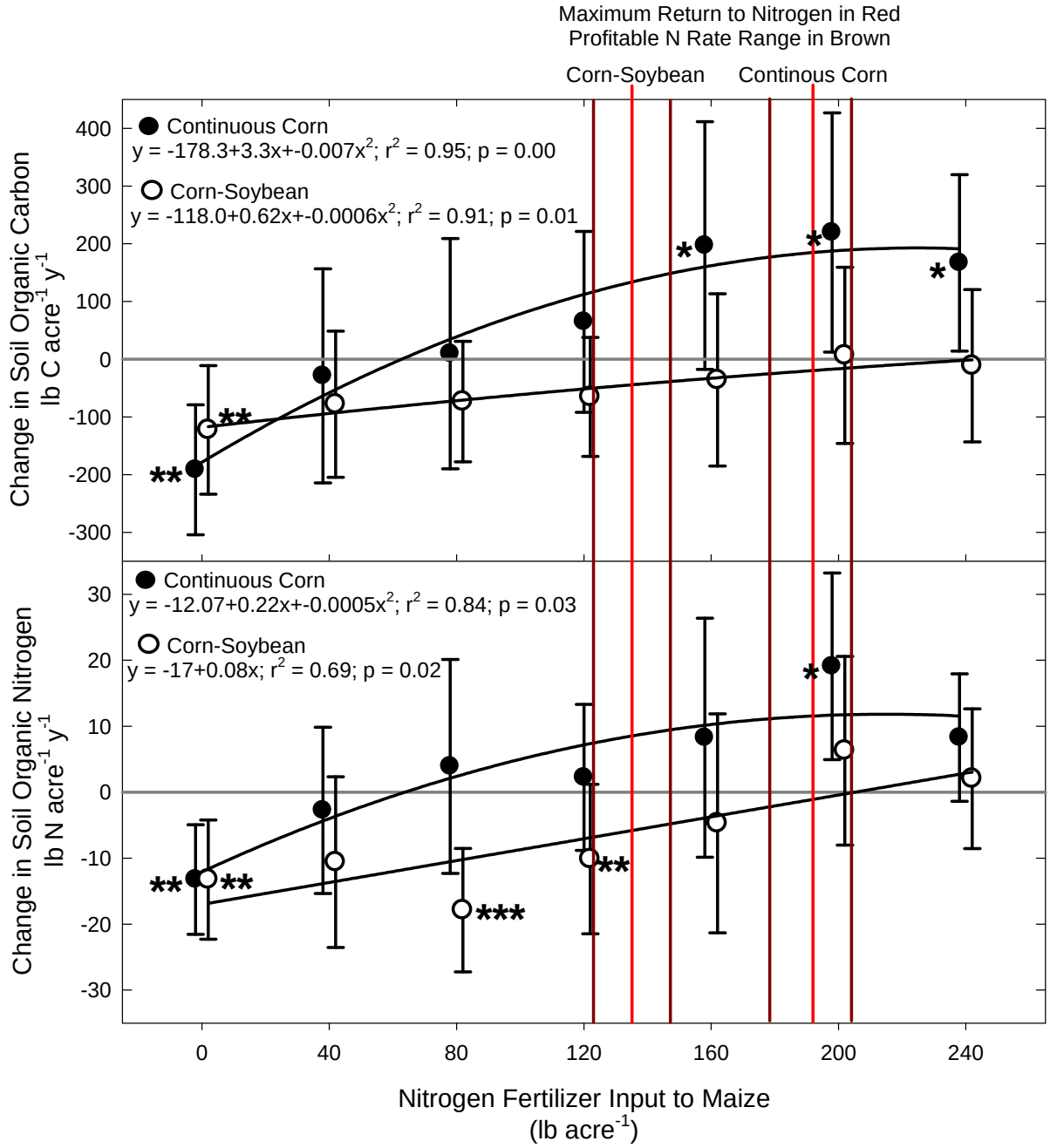

Figure 18. Average annual rates of change in soil organic carbon and nitrogen stocks in the top 7.87" (15 cm) of soil as a function of nitrogen fertilizer inputs to the corn phase of continuous corn and corn-soybean crop rotation systems. Data represent averages of four sites at 0, 120, and 240 lb N/acre (Ames, Chariton, Crawfordsville, Sutherland) and averages of 3 sites at 40, 80, 160, and 200 lb N/acre (Chariton, Crawfordsville, Sutherland). Asterisks indicate the corresponding rate change is different than zero with probability of type I error at: * = 0.1>P>0.05; ** = 0.05>P>0.01; * = 0.01>P>0.001. Vertical red lines indicate the Maximum Return to Nitrogen rate for Iowa according to the Nitrogen Rate Calculator (http://extension.agron.iastate.edu/soilfertility/nrate.aspx) at a nitrogen-to-corn grain price ratio of 0.1. Vertical brown lines indicate the N rates above and below the maximum return to nitrogen that are profitable within $1/acre of the maximum return to nitrogen. 1 kg per hectare = 0.89 pounds per acre. Symbols are offset for visual clarity.**

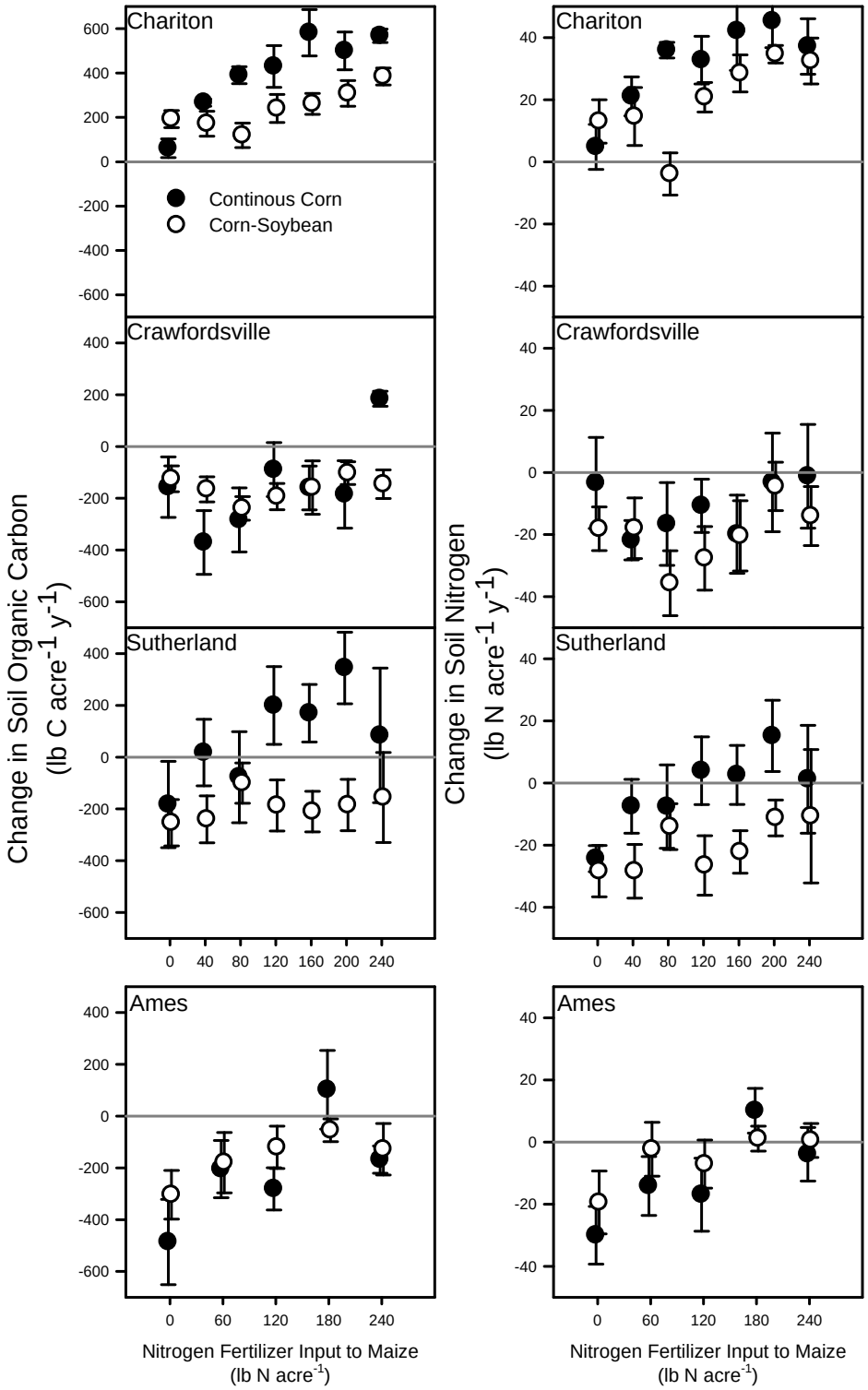

Figure 19. Average annual rate of change of soil organic carbon and total soil nitrogen stocks in the top 7.87" (15 cm) of soil over 10 years at Ames, Chariton, and Carwafordsville and over 9 years at Sutherland. Error bars represent standard error. N = 4 replicated plots for continuous corn, N = 8 replicated plots for corn-soybean. 1 kg per hectare = 0.89 pounds per acre. Open circles are corn-soybean rotation, closed circles are continuous corn. Symbols are offset for visual clarity.

Table 10: Chariton, Iowa soil carbon and nitrogen stock change magnitude and rate of change between two sampling dates (1999 and 2009) for continuous corn and corn-soybean rotations; mean (standard error below in parentheses); 0-15 cm depth. 1 kg per hectare = 0.89 pounds per acre.

	---------- Continuous Corn (n=4) ----------							---------- Corn Soybean (n=8) ----------						
	---------- N Fertilization Rate (kg N/ha) ----------							---------- N Fertilization Rate (kg N/ha) ----------						
	0	45	90	134	179	224	269	0	45	90	134	179	224	269
Carbon Stock Rate of Change (kg C/ha-yr)	68.3 (47.1)	298.7* (18.6)	437.3* (42.8)	481.3* (105.7)	651.5* (117.3)	559.5* (95.4)	636.4* (34.4)	216.0* (43.1)	191.9* (62.7)	133.5* (61.8)	269.1* (70.6)	292.6* (52.8)	345.1* (65.4)	430.4* (42.8)
Power (%)	17.8	99.9	99.9	84.5	94.4	96.1	99.9	98.9	74.7	19.2	90.3	99.7	99.4	99.9
Samples required for power of 80% (No.)	18	3	3	4	4	4	3	5	9	16	7	5	5	3
Nitrogen Stock Rate of Change (kg N/ha-yr)	5.37 (8.11)	23.6* (7.01)	40.3* (2.83)	36.7* (8.59)	47.2* (14.23)	50.8* (9.58)	41.56* (10.02)	14.6* (7.85)	16.33 (10.46)	-4.40 (7.61)	23.3* (5.33)	31.9* (6.72)	38.8* (3.16)	36.3* (8.28)
Power (%)	7.7	62	99.9	80.2	61	92.6	78.2	36	27.2	6	96.1	98.1	99.9	96.2
Samples required for power of 80% (No.)	74	6	3	4	6	4	5	21	28	190	6	6	3	6

* Rate significantly different from zero at alpha < 0.10

Table 11: Crawfordsville, Iowa soil carbon and nitrogen stock change magnitude and rate of change between two sampling dates (1999 and 2009) for continuous corn and corn-soybean rotations; mean (standard error below in parentheses); 0-15 cm depth. 1 kg per hectare = 0.89 pounds per acre.

	---------- Continuous Corn (n=4) ----------							---------- Corn Soybean (n=8) ----------						
	---------- N Fertilization Rate (kg N/ha) ----------							---------- N Fertilization Rate (kg N/ha) ----------						
	0	45	90	134	179	224	269	0	45	90	134	179	224	269
Carbon Stock Rate of Change (kg C/ha-yr)	-176.2 (131.1)	-415.3* (138.1)	-318.1* (138.6)	-100.3 (116.9)	-179.6 (94.9)	-207.7 (145.9)	206.5 (32.8)	-140.0* (56.3)	-185.5* (54.5)	-268.1* (51.1)	-217.1* (56.8)	-177.9 (115.6)	-115.3* (49.2)	-163.1* (62.1)
Power (%)	16	53.4	35.7	9.5	26.5	17.4	97.7	57.2	83	69.7	90.4	26.6	52.3	61.7
Samples required for power of 80% (No.)	20	6	9	45	11	18	4	13	8	5	7	29	14	12
Nitrogen Stock Rate of Change (kg N/ha-yr)	-3.8 (16.44)	-24.5* (7.09)	-18.6 (14.95)	-12.0 (9.60)	-22.3 (14.11)	-3.6 (17.78)	-1.4 (18.72)	-20.3 (7.87)	-20.2* (10.96)	-40.0* (11.70)	-31.0* (11.45)	-22.9 (12.67)	-5.1 (8.71)	-15.8 (10.66)
Power (%)	5.3	64.1	14.5	14.6	20.2	5.3	5	60.3	35.6	38.7	64.4	34.6	8	24.9
Samples required for power of 80% (No.)	592	5	23	22	15	761	5670	12	21	8	11	22	188	31

* Rate significantly different from zero at alpha < 0.10

Table 12: Sutherland, Iowa soil carbon and nitrogen stock change magnitude and rate of change between two sampling dates (2000 and 2009) for continuous corn and corn-soybean rotations; mean (standard error below in parentheses); 0-15 cm depth; sampled by block only (not by plot) in 2000. 1 kg per hectare = 0.89 pounds per acre.

	---------- Continuous Corn (n=4) ----------							---------- Corn Soybean (n=8) ----------						
	---------- N Fertilization Rate (kg N/ha) ----------							---------- N Fertilization Rate (kg N/ha) ----------						
	0	45	90	134	179	224	269	0	45	90	134	179	224	269
Carbon Stock Rate of Change (kg C/ha-yr)	-204.9	19.8	-86.9	223.8	190.1	385.9	93.9*	-283.8*	-268.8*	-112.4	-209.3*	-235.5*	-207.4*	-174.5
	(187.0)	(144.0)	(196.8)	(168.1)	(124.2)	(155.0)	(291.4)	(100.5)	(101.6)	(87.4)	(110.7)	(87.8)	(111.2)	(195.0)
Power (%)	12.4	5.1	6.2	15.8	19.3	40.5	5.6	67.9	62.4	10.1	37.2	63.5	36.4	12.2
Samples required for power of 80% (No.)	29	1660	163	20	16	8	305	10	12	40	20	11	21	81
Nitrogen Stock Rate of Change (kg N/ha-yr)	-27.3*	-8.4	-8.5	4.4	2.9	17.0	1.4	-31.8*	-31.8*	-15.8	-29.7*	-24.9*	-12.6*	-12.0
	(4.69)	(9.72)	(15.04)	(12.22)	(10.65)	(12.87)	(19.46)	(9.28)	(9.69)	(8.29)	(10.74)	(7.68)	(6.47)	(24.08)
Power (%)	95.9	9.6	70	5.8	5.5	15.7	5	83.5	80.3	16	66.2	79.3	39	7.2
Samples required for power of 80% (No.)	4	45	101	242	426	20	6468	8	8	20	11	9	19	256

* Rate significantly different from zero at alpha < 0.10

Table 13: Ames, Iowa soil carbon and nitrogen stock change magnitude and rate of change between two sampling dates (1999 and 2009) for continuous corn and corn-soybean rotations; mean (standard error below in parentheses); 0-15 cm depth; sampled by block only (not by plot) in 1999 1 kg per hectare = 0.89 pounds per acre.

	---------- Continuous Corn (n=4) ----------					---------- Corn Soybean (n=8) ----------				
	---------- N Fertilization Rate (kg N/ha) --------					---------- N Fertilization Rate (kg N/ha) --------				
	0	67	134	202	269	0	67	134	202	269
Carbon Stock Change (Mg C/ha)	-3.8* (2.7)	-0.6 (1.7)	-1.5* (1.2)	2.8 (2.4)	-0.2* (1.1)	-5.1* (1.6)	-3.7 (1.7)	-3.0 (1.5)	-2.3 (1.1)	-3.1 (1.5)
Carbon Stock Rate of Change (Mg C/ha-yr)	-0.4 (0.3)	-0.1 (0.2)	-0.2 (0.1)	0.3 (0.2)	0.0 (0.1)	-0.5* (0.2)	-0.4* (0.2)	-0.3* (0.1)	-0.2* (0.1)	-0.3* (0.2)
Power (%)	18	59	14	13	5	76	19	42	41	18
Samples required for power of 80% (No.)	18	218	23	25	697	9	16	18	18	18
Nitrogen Stock Change (Mg N/ha)	-0.26* (0.23)	-0.09 (0.16)	-0.12 (0.13)	0.19 (0.17)	0.03 (0.11)	-0.36* (0.16)	-0.17 (0.14)	-0.22 (0.13)	-0.13 (0.07)	-0.14 (0.13)
Nitrogen Stock Rate of Change (kg N/ha-yr)	-26 (23)	-9 (16)	-12 (13)	19 (17)	3 (11)	-36† (16)	-17 (14)	-22 (13)	-13† (7)	-13 (13)
Power (%)	13	7	10	12	5	47	9	31	37	9
Samples required for power of 80% (No.)	26	113	41	29	429	16	47	24	20	57

* Rate significantly different from zero at alpha < 0.10

Conclusions

Consideration of soil quality *and* water quality is necessary to achieve long-term productivity and environmental quality goals. This report highlights significant uncertainty in the status of soil nutrient balances, particularly with regard to N. The ability to determine whether N balances in continuous corn and corn-soybean cropping systems are positive, negative, or neutral is limited by the inability to measure or accurately predict several large N fluxes and the lack of long-term soil N stock measurements from cropping systems experiments.

Nevertheless, N mass balances developed in this report indicate that long-term N stock reductions are certainly possible, particularly in corn-soybean rotations. At the three N fertilizer input rates evaluated in this report (Table 3), two-year N balances for the full corn-soybean rotation showed net negative balances of -22, -19, and -15 lb N/ac-yr. However, there is extremely high uncertainty associated with the second largest N input in the corn-soybean rotation, biological N fixation; this resulted in overall uncertainty estimates for this rotation (approximately 50 lb N/ac-yr) that exceeded the net balance values. Previous measurements of long-term changes in soil N stocks in Iowa corn-soybean rotations were limited to two locations and these data were inconclusive due to statistical sampling challenges (Russell et al., 2005). However, negative input-output balances were consistent with negative N stock-change analyses. **This report determines that there is significant risk that corn-soybean rotation systems have net negative N balances.**

In contrast to the corn-soybean rotation, the N balances developed for continuous corn systems consistently showed positive N balances. At the three N fertilizer input rates evaluated in this report, continuous corn showed increasingly positive N balances for increasing N fertilization input rates (balances of +60, +69, and +76 lb N/ac-yr). The estimated uncertainty values for continuous corn (≈7 lb N/ac) were smaller than the associated positive net balances, providing additional validation of the positive balance. At one of two Iowa locations where long-term measurements of total N stock-changes have been published, continuous corn systems receiving 180 kg N/ha-yr (161 lb N/ac-yr) showed a statistically significant positive N balance. At the second Iowa location, N stock changes were positive although not significantly different from zero (no change) due to low statistical power (Russell et al., 2005). Nevertheless, data from these sites are completely consistent with the input-output analysis and 'stock-change over time' data reported herein.

One clear pattern in this report was statistically significant positive correlations among N fertilizer inputs, yield, and SOC and N stocks (Figures 2 and 18). These data highlight the importance of N fertilizer inputs to maintain SOM and N stocks in the absence of manure or other significant C and N additions. Declines in SOM decrease yield potential. Accordingly, long-term declines in SOM associated N could lead to lower N fertilizer use efficiency and SOM stocks, increasing the challenge of water quality improvements.

Although accurate measurement of P fluxes can also present challenges, P fluxes are measured with greater accuracy than N due to the lack of a gaseous phase and biological inputs. The optimum soil testing P scenarios had nearly neutral P balances. The high soil P test scenarios resulted in negative balances for both crops as expected to allow utilization of existing crop available soil P. Soil P nutrient stocks can be maintained over time through adherence to removal-based P application rates in conjunction with soil testing and consideration of P losses as estimated by the Iowa P Index.

Appendix A

Project Advisory Group

Participant	Organization
Paul Fixen	International Plant Nutrition Institute (IPNI)
Dan Jaynes	USDA-ARS National Laboratory for Agriculture and the Environment (Iowa)
Sasha Kravchenko	Michigan State University, Department of Crop and Soil Sciences
Dean Lemke	Iowa Department of Agriculture and Land Stewardship (IDALS)
Matt Liebman	Iowa State University, Department of Agronomy
John Lory	University of Missouri, Division of Plant Sciences
Antonio Mallarino	Iowa State University, Department of Agronomy
Jerry Neppel	Iowa Department of Agriculture and Land Stewardship (IDALS)
Michael Russelle	USDA-ARS Plant Science Research Unit (Minnesota)
John Sawyer	Iowa State University, Department of Agronomy
Jeff Strock	University of Minnesota, Department of Soil, Water and Climate

Appendix B

Soybean Biological Nitrogen Fixation (kg N/ha); n=44

Citation	Minimum	Mean	Maximum	Notes
Salvagiotti et al. (2008)	111		125	Global review, with and without N fertilization (means)
**Goolsby et al. (1999), Jordan and Weller (1996), and Puckett et al. (1999)		78		Estimate used for soybean fixation
**Burkart and James (1999)		75		Midwestern soybean fixation value
**Schepers and Mosier (1991)	57		94	Soybean under Midwestern conditions
Thorp et al. (2007)	178	232	276	RZWQM modeling paper, ten years of simulations (range and mean)
*Barry et al. (1993)		102		Estimate used in N budget for soybeans in southwestern Ontario (subtracted nonsymbiotic fixation)
*Barry et al. (1993)		98		Based on regression of: N fixed =81.1*soybean grain yield -98.5; using Ontario average yield
*Unpublished		177		Used Barry et al. (1993) regression with average Iowa soybean yield (50.5 bu/ac)
*Jaynes et al. (2001)	187		208	Used Barry et al. (1993) regression for central IA field
Herridge et al. (2008)		115		Crop legume rhizobia fixation
Herridge et al. (2008)		176		Soybean global crop fixation
Harper et al. (1989)	92		130	Soybeans under two tillage treatments in Georgia
Smil (1999)	60	80	100	Range of means used for global N balances
Russelle and Birr (2004)		84		Mississippi River Basin mean
**M. Russelle (personal communication)		88		Iowa mean
NRC (1993)	175	200	220	Total N fixed by soybeans under low, medium, and high scenarios
Peoples et al. (2009)		144		North America mean
*Rennie (1985)	67	108	114	Review of *Glycine max* grown in US
Rennie (1985)		100		General value for North America and Europe
**Troeh and Thompson (1993)		60		Well nodulated soybeans
**Stevenson (1982)	57		94	Soybean fixation addition to soil
Schipanski et al. (2010)	40		224	Range from 13 sites in New York with various soil N levels
*Harper (1976)	80		100	Range of average estimates
**Gentry et al. (2009)	150		163	Fixation for two years in Illinois watershed
*Dashti et al. (1998)	42		128	Control treatment (no addition of plant growth promoting bacteria), difference method
*Dashti et al. (1998)	58		81	Control treatment (no addition of plant growth promoting bacteria), ^{15}N method

***Used to calculate total plant fixed N mean for N balance (excluding global values), n=14, mean=111 kg N/ha**
**** Used to calculate mean for N balance but reported aboveground fixation value was corrected by 0.24 (Rochester et al., 1998) to account for belowground fixed N before inclusion, n=10, aboveground mean = 92 kg N/ha**

Soybean Biological Nitrogen Fixation (% Nitrogen derived from the atmosphere), n=31

Citation	Minimum	Mean	Maximum	Notes
Salvagiotti et al. (2008)		52	58	Global review, with and without N fertilization (means)
Schipanski et al. (2010)	36	60	82	Range from 13 sites in New York with various soil N levels (range and mean)
David et al. (1997) and David and Gentry (2000)		50		Used for N balance in Illinois watershed
Harper (1976)	25		50	Under normal field conditions, non-nitrogen deficient soils
Herridge et al. (2008)	40	60	80	US soybeans (general range and mean)
Johnson et al. (1975)		48		Unfertilized soybeans
Russelle and Birr (2004)		57		Mississippi River Basin mean
M. Russelle (personal communication)		46		Iowa mean
Peoples et al. (2009)	13	50	80	North America mean and range
Rennie (1985)	37	38	60	Review of *Glycine max* grown in US
Rennie (1985)		50		General value for North America and Europe
Gentry et al. (2009)	60		77	Fixation for two years in Illinois watershed
Dashti et al. (1998)	19		43	Control treatment (no addition of plant growth promoting bacteria), difference method
Dashti et al. (1998)	24		28	Control treatment (no addition of plant growth promoting bacteria), ^{15}N method
Patterson and LaRue (1983a)	50		83	New York; non-nodulating control method, low soil N
Patterson and LaRue (1983a)	74		84	New York; ^{15}N method, low soil N

Atmospheric Deposition (total wet + dry) (kg N/ha), n=27

Citation	Value	Notes
Anderson and Downing (2006)	7.7-10.5	Annual estimates of TN deposition for Ames, IA for January 28, 2003, to January 5, 2004.
Puckett et al. (1999)	4.5	Mean of four site-years (see below)
Puckett et al. (1999)	6.3	Site MN23, 1992 (Minnesota)
Puckett et al. (1999)	5.6	Site MN23, 1993 (Minnesota)
Puckett et al. (1999)	2.3	Site ND11, 1992 (North Dakota)
Puckett et al. (1999)	3.8	Site ND11, 1993 (North Dakota)
Goolsby et al. (1999)	7.9	Cedar River at Cedar Falls, IA; summation of wet NO_3^-, wet NH_4^+, and dry NO_3^-
Goolsby et al. (1999)	8.1	Iowa River at Wapello, IA; “”
Goolsby et al. (1999)	8.1	Skunk River at Augusta, IA ; “”
Goolsby et al. (1999)	7.8	Raccoon River at Van Meter, IA ; “”
Goolsby et al. (1999)	7.8	Des Moines at St. Francisville, MO; “”
Goolsby et al. (1999)	8.6	Bondville, IL
Goolsby et al. (1999)	10.6	Oxford, OH
Schepers and Mosier (1991)	4.5-29	Summed minimum and maximum precipitation (wet deposition) and dry deposition values
Bremer et al. (2011)	4-16	N balance for Northern Great Plains
Galloway et al. (2008)	10-20	Estimated nitrogen deposition for Iowa from deposition map of the World
Barry et al. (1993)	18.4	Estimate for N balance in southwestern Ontario
Barry et al. (1993)	10.8-33	Range for N balance in southwestern Ontario
Jaynes and Karlen (2008)	10.2-10.8	Annual wet + dry deposition for N balance examples
Dentener et al. (2006)	10-20	Estimated reactive nitrogen deposition for Iowa from deposition map of the World

Wet deposition (kg N/ha), NO_3^- and NH_4^+ values summed for n=53 in Figure 12

Citation	NO_3^-	NH_4^+	Total	Notes
Puckett et al. (1999)	1.8	3.0		Site MN23, 1992 (Minnesota)
Puckett et al. (1999)	1.9	2.2		Site MN23, 1993 (Minnesota)
Puckett et al. (1999)	0.7	1.3		Site ND11, 1992 (North Dakota)
Puckett et al. (1999)	1.2	2.0		Site ND11, 1993 (North Dakota)
Goolsby et al. (1999)	2.7	3.4		Cedar River at Cedar Falls, IA
Goolsby et al. (1999)	2.8	3.3		Iowa River at Wapello, IA
Goolsby et al. (1999)	2.8	3.3		Skunk River at Augusta, IA
Goolsby et al. (1999)	2.6	3.4		Raccoon River at Van Meter, IA
Goolsby et al. (1999)	2.6	3.4		Des Moines at St. Francisville, MO
Goolsby et al. (1999)	3.7	3.1		Bondville, IL
Goolsby et al. (1999)	3.3	2.2		Oxford, OH
Tabatabai et al. (1981)	6.0	6.0		Ames, Iowa
Tabatabai et al. (1981)	7.2	6.0		Boone, Iowa
Tabatabai et al. (1981)	6.0	7.2		Charles City, Iowa
Tabatabai et al. (1981)	6.0	6.7		Creston, Iowa
Tabatabai et al. (1981)	4.8	5.0		Eldora, Iowa
Tabatabai et al. (1981)	7.2	7.1		Guthrie Center, Iowa
Thorp et al. (2007)	5.2-9.4			N in precipitation for annual nitrogen mass balance for continuous ten-year simulations in high N rate plots; Assumed 1 ppm nitrate in precipitation (mean: 6.78 kg N/ha)
Sisterson (1990)	7.8-14.8	2.5-3.8		1985-1987; Estimated for Iowa from deposition maps of Midwest
Hoeft et al. (1972)	2.7-3.5	2.9-12.2	13-30	Rural sites (adjacent and removed from barnyard) in Wisconsin; Total wet includes organic N
NADP (2012)			5.0-6.6	Inorganic N wet deposition, two sites in Iowa, 2000
NADP (2012)			6.7-6.8	Inorganic N wet deposition, two sites in Iowa, 2001
NADP (2012)			5.9-6.0	Inorganic N wet deposition, two sites in Iowa, 2002
NADP (2012)			4.9-5.5	Inorganic N wet deposition, two sites in Iowa, 2003
NADP (2012)			5.6-7.3	Inorganic N wet deposition, two sites in Iowa, 2004
NADP (2012)			4.6-6.1	Inorganic N wet deposition, two sites in Iowa, 2005
NADP (2012)			5.4-6.3	Inorganic N wet deposition, two sites in Iowa, 2006
NADP (2012)			6.9-7.5	Inorganic N wet deposition, two sites in Iowa, 2007
NADP (2012)			6.4	Inorganic N wet deposition, one site in Iowa, 2008
NADP (2012)			6.0-6.4	Inorganic N wet deposition, two sites in Iowa, 2009
Burkart and James (1999)			6.0-7.0	Estimated for Iowa from deposition maps of Midwest (not including local redeposition)
Schepers and Mosier (1991)			2.2-14.6	Additions of N in precipitation
Schepers and Mosier (1991)			5.0-6.9	Estimated for Iowa from deposition maps of US
Jaynes et al. (2001)			11-15	Total N in precipitation from nitrate concentration in precipitation
Tabatabai et al. (1981)			5.0-20	N deposition from precipitation in North Central region

Crop Seed (kg N/ha)

Citation	Mean ------ Corn ------	Mean --- Soybean ---	Notes
Meisinger and Randall (1991)	0.34	4.5	
Barry et al. (1993)	0.3	5	Ontario
Legg and Meisinger (1982)	<0.2	2.5	

Denitrification (kg N/ha), n=16

Citation	Minimum	Mean	Maximum	Notes
Goolsby et al. (1999)		>15		Estimated for Iowa from denitrification map of the Midwest
Burkart and James (1999)	6		30	Estimated for Iowa from denitrification map of the Midwest
Thorp et al. (2007)	1.3	6.8	18.4	RZWQM modeling paper, ten years of simulations (range and mean)
Barry et al. (1993)	45		62	A review of denitrification rates for fertilized continuous corn in Ontario
Seitzinger et al. (2006)	15		20	Estimated for Iowa from soil denitrification map of the World
David et al. (2009b)	3.8	14.5	34.1	Range and mean for six model simulations; corn year
David et al. (2009b)	3.2	9.4	21.7	Range and mean for six model simulations; soybean year

Denitrification (% inorganic soil N lost), n=12

Citation	Minimum	Mean	Maximum	Notes
Goolsby et al. (1999)		20		Based on 3.5% organic matter for Iowa soils
Libra et al. (2004)		15		For state-wide Iowa budget
Burkart et al. (2005)	13	17	30	Moderately well to very poorly drained soil with 2-5% organic matter
Burkart and James (1999)	17	20	35	Humid states; moderately well to very poorly drained soil with 2-5% organic matter
Meisinger and Randall (1991)	16	20	25	Soil organic matter of 2-5%; moderately well to poorly drained; upper end of ranges for humid climate; adjusted one drainage class better for tile drainage
David and Gentry (2000)		10		Percent of fertilizer application lost

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