Nitrogen, carbon, and phosphorus balances in Iowa cropping systems: Sustaining the soil resource

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Cause for concern

The Corn Belt's exceptional productivity depends on high soil organic carbon and nutrient stocks (that is, the amount of carbon and nutrients stored in the soil). 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 outputs that exceed inputs. The lack of certainty about the status of soil carbon and nutrient stocks is largely due to the extreme difficulty associated with measurement of inputs, outputs, and stocks of soil organic carbon and nutrients.

In response to this concern, the Iowa legislature requested Iowa State University and the Iowa Department of Agriculture and Land Stewardship to examine and report on nutrient balances in Iowa cropping systems. The results of this work were released in October 2012 (Christianson et al. 2012) and summarized herein.

The report concludes that soil organic matter carbon and nitrogen stocks in Iowa corn-soybean rotations are at risk of significant long-term decline regardless of nutrient input levels. In contrast, the report concludes that continuous corn cropping systems can increase soil organic carbon and nitrogen stocks. The report raises fewer concerns for soil phosphorus stocks.

Soil organic carbon and nitrogen stocks are a function of crop residue inputs. Continuous corn cropping systems have the potential to increase soil organic carbon and nitrogen stocks through large amounts of crop residue inputs. Insufficient crop residue inputs are likely a major factor affecting negative soil organic carbon and nitrogen balances in corn-soybean rotations. Soil nutrient inputs are critical to maintain high crop yields that maximize residue inputs to the soil. However, maximum yields in corn-soybean rotations may not produce sufficient crop residue inputs to maintain soil organic carbon and nitrogen stocks despite a lack of nutrient limitation. The effect of low soybean residue inputs on soil organic carbon and nitrogen stocks is likely compounded by two additional factors: Soybean residues decompose more rapidly than corn residues (Russell et al. 2009). And soybeans grown in Iowa soils appear to remove more nitrogen in grain than they biologically fix; as such, Iowa soybeans may be net removers of soil nitrogen despite their ability to biologically fix nitrogen (Christianson et al. 2012).

Maintenance of soil organic carbon and nitrogen stocks is critical to the future of agricultural productivity and environmental quality. If soil carbon and nitrogen stocks decline, crop yields could decline and water quality improvements will become more difficult. Most nitrogen uptake by corn in any given growing season is from mineralization of the indigenous soil nitrogen stock rather than that year's fertilizer inputs (Stevens et al. 2005; Gardner and Drinkwater 2009). Although fertilizer additions are required to maintain soil nitrogen stocks, fertilizer nitrogen inputs must be cycled through biological systems before they can contribute to long-term soil storage. Accordingly, nitrogen fertilizer inputs in excess of crop demand (that is, the nitrogen application required to achieve economic optimum yield) will lead to environmental nitrogen losses rather than increases in soil nitrogen stocks.

Soil organic carbon and nitrogen are the foundation of soil organic matter. Soil organic matter is positively correlated with crop yield amount and stability across Iowa (Williams et al. 2008). Soil organic matter is also positively correlated with plant-available water holding capacity (Hudson 1994) and indigenous production of crop-available nitrogen (that is, nitrogen mineralization; Booth et al. 2005). High water holding capacity can limit nitrate leaching and boost drought resilience. High nitrogen mineralization can provide resilience to nitrogen losses.

Determination of carbon and nutrient balances

Analytical approach

All nutrient and carbon balances reported herein refer to the change in the soil stock. 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 and carbon 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 estimated during a period of time; the balance between inputs and outputs represents stock change during the measurement period ('input-output balance' method). Major inputs include fertilizer, leguminous nitrogen fixation, and atmospheric deposition. Major outputs include grain harvest, dissolved nitrogen losses, and gaseous nitrogen losses. The first method was used to measure changes in soil nitrogen and carbon stocks. The second method was used to estimate potential changes in soil nitrogen and phosphorus stocks.

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 typically less than ±1% of the total stock. 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. Nevertheless, this method is the only way to measure changes in N stocks with high, quantifiable certainty.

The Christianson et al. (2012) report developed input-output nitrogen balances for continuous corn and corn-soybean rotation systems at three economically derived nitrogen fertilizer rates identified using the Corn Nitrogen Rate Calculator at a fertilizer-to-grain price ration of 0.1 (Sawyer et al. 2006): http://extension.agron.iastate.edu/soilfertility/nrate.aspx. The three selected nitrogen (N) rates were: (1) the 'Maximum return to nitrogen' (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 the three N fertilizer input rates in continuous corn and corn-soybean rotation systems, 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. Similar input-output estimates were used to develop phosphorus balances.

The report also used measures of 'change over time' to determine long-term trends in soil organic carbon and nitrogen stocks. Soil fertility experiments from four Iowa State University research farms were used including: Ames, Chariton, Crawfordsville, and Sutherland. All experiments included corn-soybean and continuous corn cropping systems with 5 or 7 nitrogen fertilizer rates. All other nutrient levels were maintained at agronomic optimum. Soil samples from 0-15 cm were collected in 1999 or 2000 and again in 2009. The change in soil organic carbon and nitrogen concentrations was reported. Importantly, these experiments and soil sampling strategies were not designed to measure stock changes in soil C and N; accordingly, statistical power was low.

Results

Nitrogen input-output balance

Nitrogen (N) 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 1; Table 1). 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.

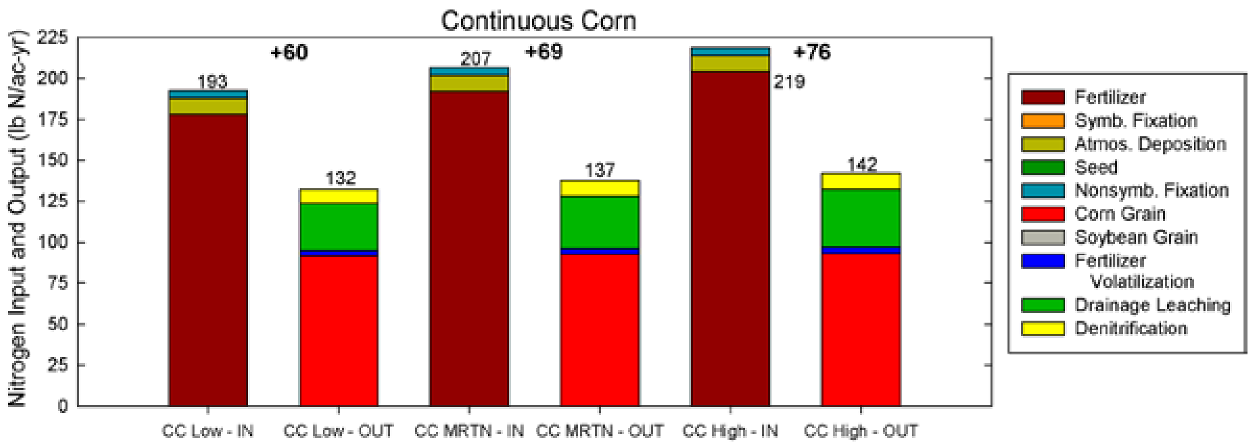

Figure 1. Nitrogen inputs, outputs and net balance (values at top) for continuous corn in Iowa at three fertilization rates (low, MRTN, and high); balances may not sum due to rounding. 1 kg per hectare = 0.89 pounds per acre.

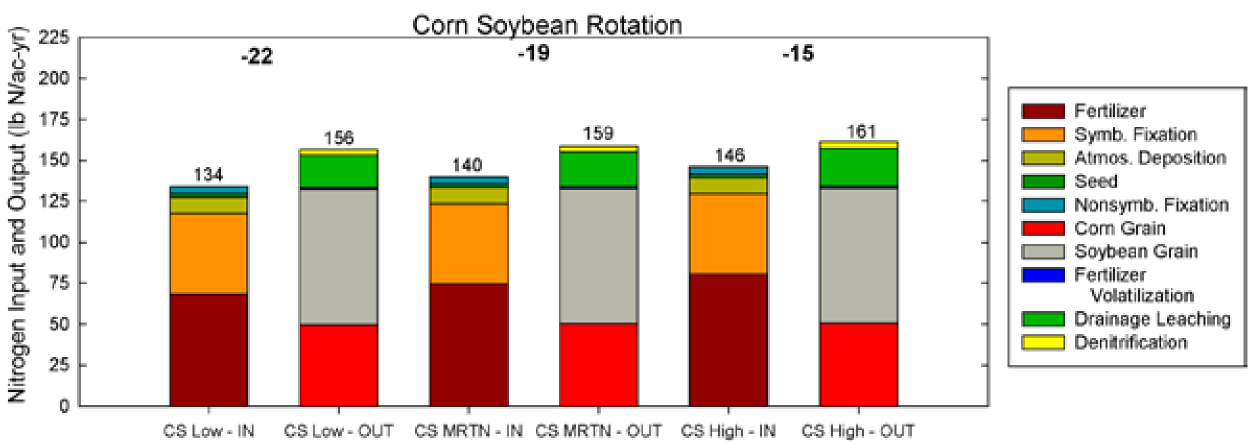

Figure 2. Nitrogen inputs, outputs and net balance (values at top) for a corn-soybean rotation in Iowa at three fertilization rates (low, MRTN, and high); balances may not sum due to rounding. 1 kg per hectare = 0.89 pounds per acre.

In contrast to continuous corn, two-year rotation corn-soybean N balances were all net negative (Figures 2 and 3; Table 1). 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.

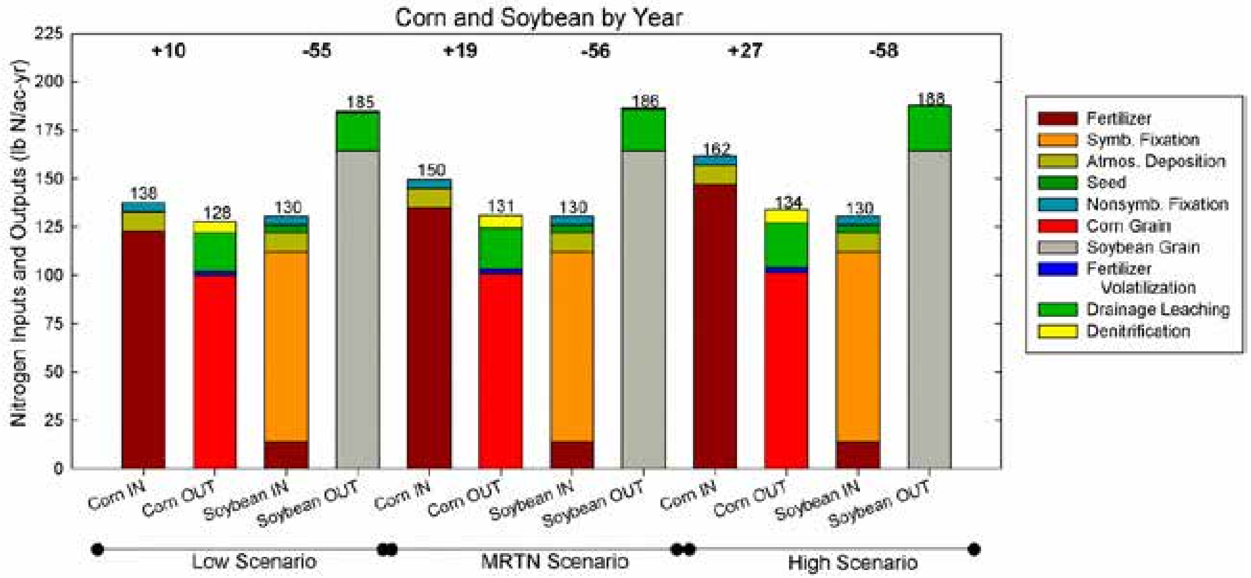

Figure 3. Nitrogen inputs, outputs and net balance (values at top) for a corn-soybean rotation in Iowa at three fertilization scenarios (low, MRTN, and high) shown by individual crop years; balances may not sum due to rounding. 1 kg per hectare = 0.89 pounds per acre.

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 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 (Christianson et al. 2012). 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 (Christianson et al. 2012). 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.

Table 1. 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. 1 kg per hectare = 0.89 pounds per acre.

		Inputs					Outputs									N BALANCE	
		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¶¶			
		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).

Soil carbon and nitrogen 'stock change over time'

Average carbon (C) and nitrogen (N) balances were negative at profitable N fertilizer rates in corn-soybean rotation systems, but they were positive at profitable fertilizer N inputs in continuous corn systems (Figure 4). 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. 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 sites, C and N balances were negative (Figure 5). 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 1), this result was expected because the stock change measurements in Figures 4 and 5 only account for changes in the top 15 cm of soil while the input-output balances account for changes in the total soil profile.

Managing nitrogen losses

Importantly, nitrogen (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 N and reduce water flux. Replacing these N losses through addition of inorganic fertilizer may not be possible due to the lack of biological storage mechanisms and will not enhance cropping system sustainability with regard to air, soil, and water quality measures (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 such as some types of manure and cover crops. 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.

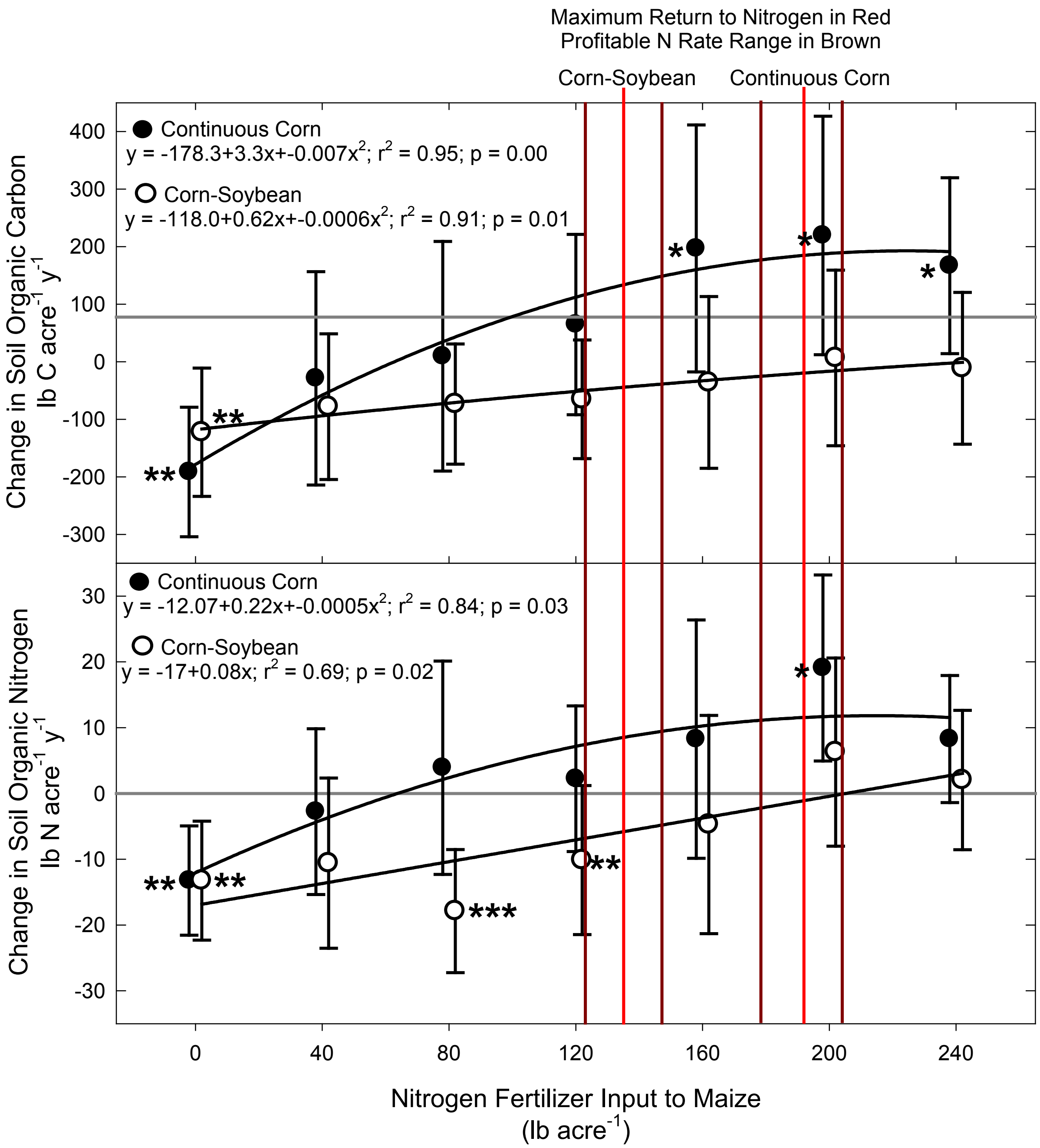

Figure 4. Average annual rates of change in soil organic carbon and nitrogen stocks in the top 7.87" (15 cm) of soil as a function of nitrogen fertilizer inputs to the corn phase of continuous corn and corn-soybean crop rotation systems. Data represent averages of four sites at 0, 120, and 240 lb N/acre (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. Probability of type II error is reported in Christianson et al. 2012. 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.

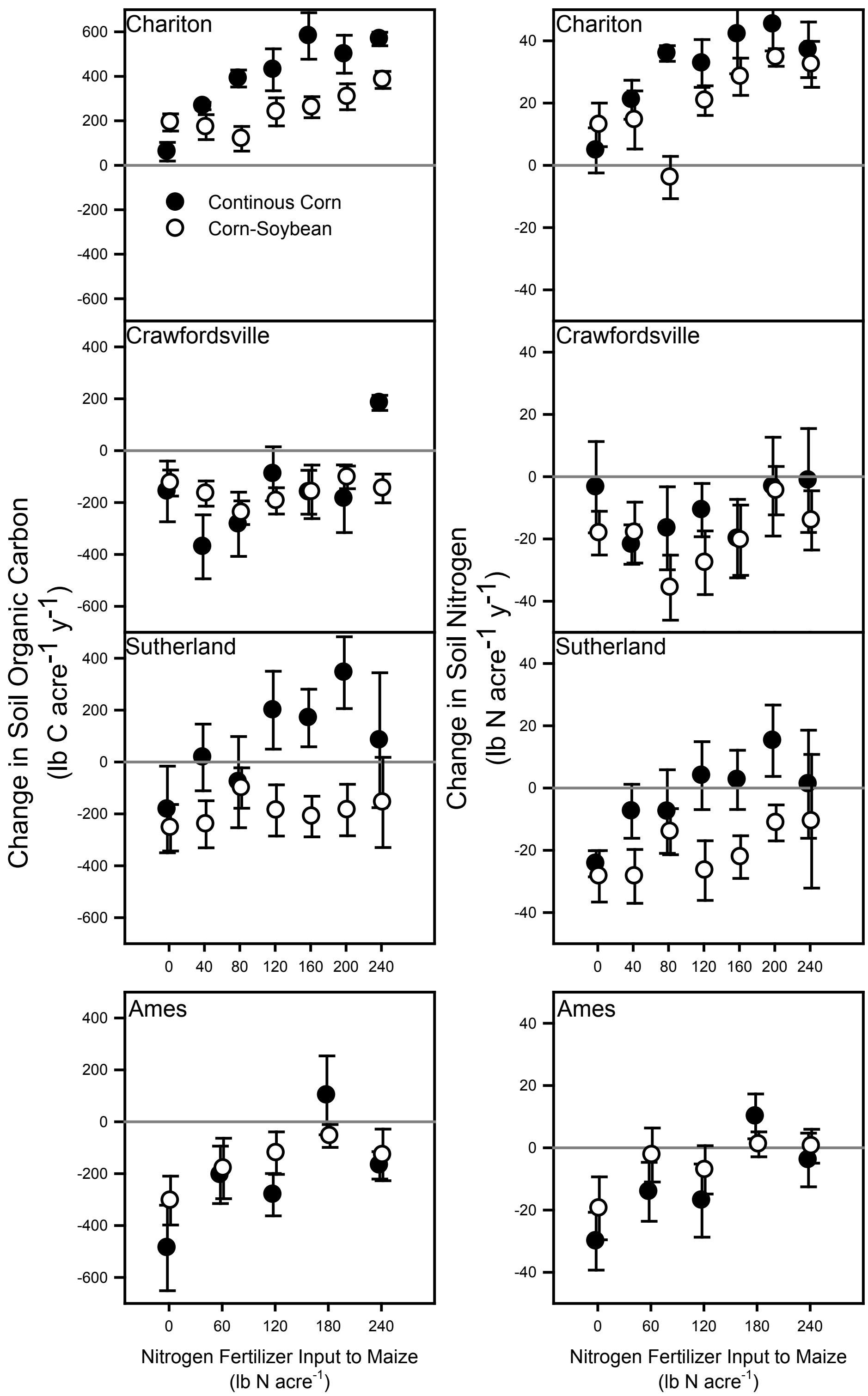

Figure 5. Average annual rate of change of soil organic carbon and total soil nitrogen stocks in the top 7.87" (15 cm) of soil over 10 years at Ames, Chariton, and Carwafordsville and over 9 years at Sutherland. Error bars represent standard error. N = 4 replicated plots for continuous corn, N = 8 replicated 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.

Phosphorus input-output balance

Like previous phosphorus balances, the major inputs were inorganic fertilizer and the major outputs were grain P removal; smaller fluxes included atmospheric P deposition and losses to surface waters through surface transport or drainage. Balances developed by Christianson et al. (2012) implicitly assumed that potential soil test phosphorus changes in the topsoil would correlate with total soil phosphorus. Moreover, this work did not consider subsoil (below 6 inches, 15 cm) phosphorus depletion by crop removal or buildup by excess phosphorus application. Such subsoil considerations could be very important for long-term changes in total soil phosphorus. However, few data are available on long-term changes in subsoil phosphorus. General indications show there is little change in soil test phosphorus below 12 inches (30 cm) at high phosphorus fertilizer application rates.

High soil test phosphorus scenarios resulted in net negative balances for both crops as appropriate to allow utilization of existing surplus soil phosphorus that was at greater levels (soil test) than needed for crop production (Figures 6 and 7; Table 2). The optimum soil test scenarios resulted in balances very close to neutral, whereas the very low soil test scenarios showed accumulation of phosphorus in the soil (Figures 6 and 7; Table 2). Under the very low soil test scenarios, if phosphorus were applied only at the replacement rate and below the recommended rate, these soils would continue to have low soil phosphorus crop availability (soil test phosphorus). These results verify phosphorus recommendation efforts in that high soil test sites provide higher relative risk of phosphorus export offsite, and reduction of soil phosphorus at these sites due to a net negative phosphorus balance may precipitate improved water quality. Likewise, the near neutral balances for the optimum soil test scenarios resulted from phosphorus application recommendations based upon grain removal. In terms of water quality, export of phosphorus calculated based on the Iowa phosphorus 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 2) (Mallarino et al., 2002; Iowa NRCS, 2004).

These phosphorus balances were corroborated by long-term soil test phosphorus data at several research farm sites in Iowa (Mallarino et al. 2011). Research investigating phosphorus applications to corn and soybean cropping systems showed that in plots receiving no phosphorus 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).

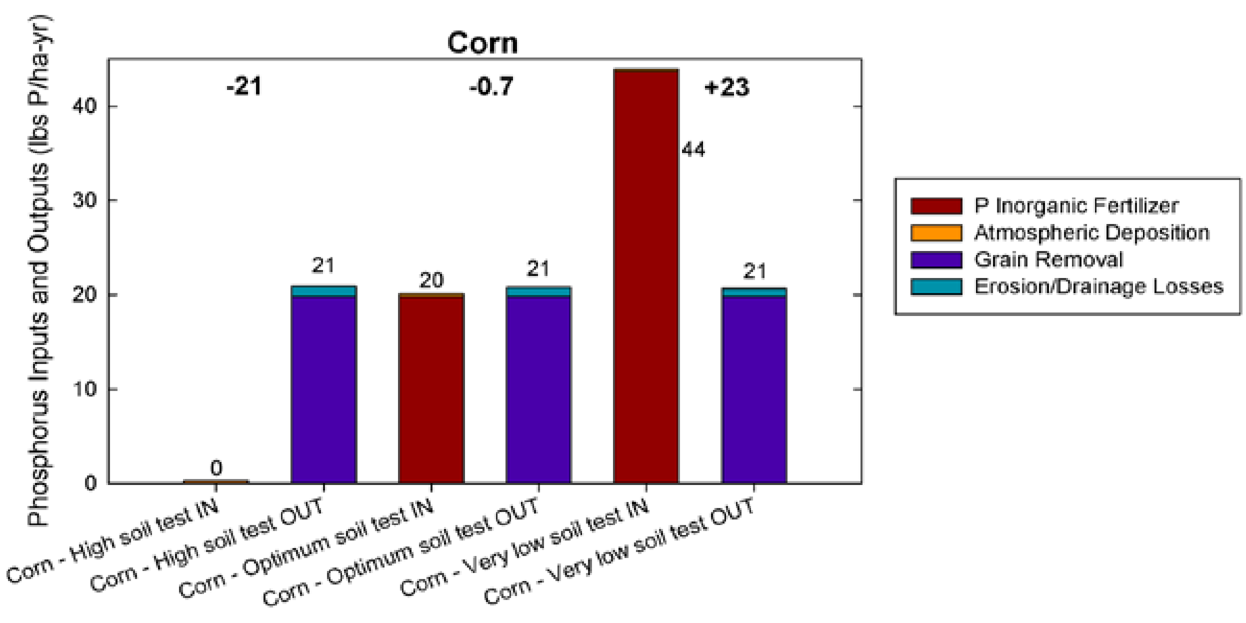

Figure 6. Phosphorus inputs, outputs and net balance (values at top) for corn production in Iowa at three P fertilization rates based upon soil test level.

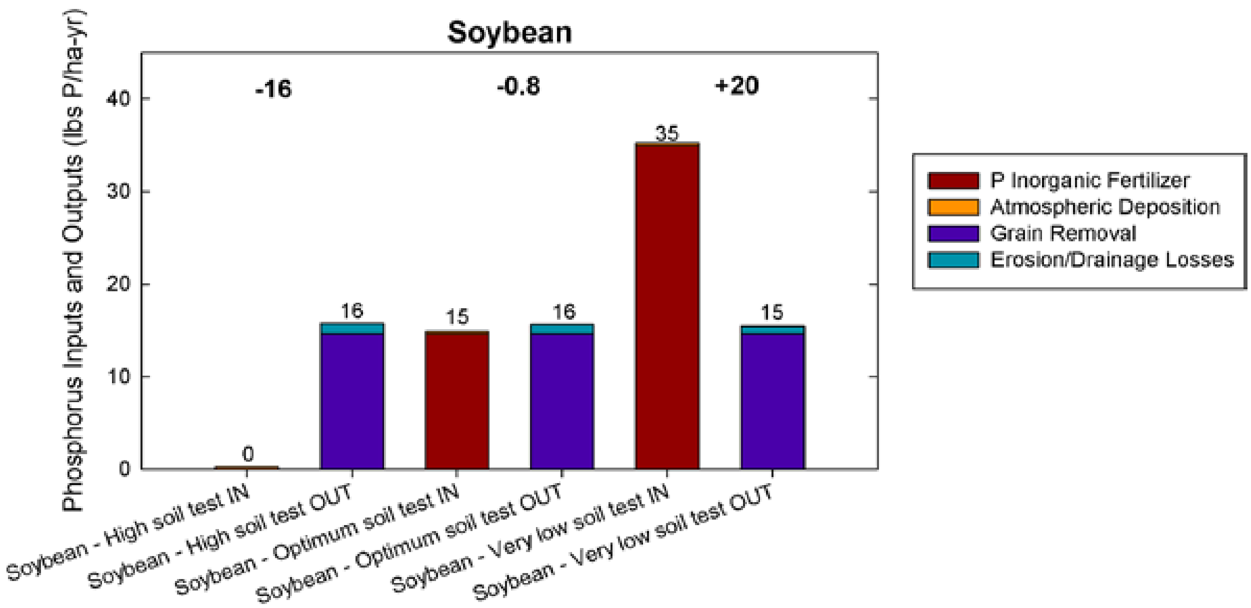

Figure 7. Phosphorus inputs, outputs and net balance (values at top) for soybean production in Iowa at three P fertilization rates based upon soil test level.

Table 2. 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)

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 nitrogen (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, soil N mass balances developed in this report indicate that long-term soil N stock reductions are certainly possible, particularly in corn-soybean rotations. At the three N fertilizer input rates evaluated in this report

(Table 1), 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 soil organic carbon and N stocks (Figure 4). These data highlight the importance of N fertilizer inputs to maintain soil organic matter and N stocks in the absence of manure or other significant carbon and N additions. Declines in soil organic matter decrease yield potential. Accordingly, long-term declines in soil organic matter associated N could lead to lower N fertilizer use efficiency and soil organic matter stocks, increasing the challenge of water quality improvements.

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

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