To:	Dr. Wang
From:	Ron Alverson
Date:	March 1, 2021
RE:	Response to literature search on 4R nitrogen fertilizer management

Thank you for your response to the American Coalition for Ethanol, South Dakota Corn Growers Association, and the Kansas Corn Growers Association on January 20, 2021 regarding your ongoing work on biofuel GHG modeling.

Due to my 50 years of farming experience, my experience as a board member at a local farmer owned ethanol plant, and my familiarity with your GREET model, I have been asked by the American Coalition for Ethanol, the South Dakota Corn Growers Association, and the Kansas Corn Growers Association to respond to your request for "4R" (**R**ight rate, **R**ight form, **R**ight place, **R**ight time) fertilizer management references.

As you know, nitrogen (N) is an essential nutrient for plant/crop health and vegetative growth. Research agronomists have determined that N fertilization is directly responsible for a 30%-40% increase in grain production from corn, wheat, rice, and other cereal crops. Because of this large impact on productivity, N fertilization is essential for the economical and efficient production of food, fiber and biofuels in the U.S. and the World. Indeed, scientist and author Vaclav Smil has said; *"The range of our planet's dependence on the Haber–Bosch synthesis of ammonia nitrogen is as follows: for about 40% of humanity it now provides the very means of survival; only half as many people as are alive today could be supplied by pre-fertilizer agriculture…," and, "Now nearly 2.5 billion people are here because proteins in their bodies are built of amino acids whose nitrogen came—via plant and animal foods—from the Haber–Bosch synthesis. Virtually all the protein needed for the growth of 2 to 4 billion children to be born during the next two generations will have to come from the same source, from the synthesis of ammonia nitrogen from its elements."*

Because nitrogen fertilizers are a major cost of production for biofuel feedstock producers and have significant environmental effects, there has been considerable research to determine the impacts of 4R management to improve fertilizer utilization efficiency and reduce negative effects on the environment. This document provides comments on these practices, their impacts on the factors that effect N_2O emissions, and links to many peer reviewed studies and reports.

I have been using your GREET model to calculate the carbon intensity (CI) of corn production and ethanol refining for several years and have collected many references on 4R management. Following your invitation to provide information and references, I also reached out to my good friend Dr. Paul Fixen and informed him that you and your team are interested in investigating this subject and incorporating that information into your GREET FD-CIC. Paul is uniquely qualified as an expert on this subject as he is one of the two people that are most often credited with coining the term "4R" a couple decades ago. Paul indicated to me that he is eager to help and sent me several reports/studies he has collected on 4R management impacts on nitrogen fertilizer use efficiency and N_2O emissions. Paul's references and literature can be accessed via this link:
https://www.dropbox.com/sh/b1054z6jg4zd8ur/AAA2pkoi9MS3zA17sjxggnuNa?dl=0

I am also providing you with additional references and reports about 4R impacts on <u>direct</u> N_2O from fertilizer and corn residue nitrogen as well as <u>indirect</u> N_2O emissions from nitrogen losses from soil due to volatilization, runoff and leaching. They can be accessed via this link:

https://www.dropbox.com/sh/w0k53snryr0f5ur/AAAhwvIVJECXYVD5YaJf2jJUa?dl=0

Paul is now retired but spent his entire career working on fertilizer nutrient use utilization efficiency issues, as well as fertilizer nutrient use environmental issues, first as a researcher at South Dakota State University, then as the director of research at the International Plant Nutrition Institute. He finished his career as first Vice President of the IPNI and along the way was President of the Tri-Societies (American Society of Agronomy, Crop Science Society of America, and the Soil Science Society of America). He has a broad knowledge on this subject.

Even though Paul is now retired, once a scientist/researcher, always a scientist/researcher, and he is eager to help advance the science of the subject he loves. I would encourage you to contact Paul if you think his insights might benefit your work. He can be reached at this email address: paulfixen@gmail.com For further information about Paul, here is a link to a video of Paul talking about his career and the history and evolution of "4R."
https://www.youtube.com/watch?v=Va_l04XnW_k&feature=share

ACE, South Dakota Corn, and Kansas Corn thank and commend you and your team's work in 2019 *(Xu, Cai, and Kwon 2019)* to update the GREET Midwest average direct N-to-N_2O emissions factor for nitrogen fertilizer use in corn. Your thorough work resulted in a very well-supported direct N_2O emissions factor for nitrogen fertilizer. As you know, a significant number, but not all, of the studies/papers your team reviewed and summarized in the meta-analysis included some of the 4R nitrogen management methods and even the use of **E**nhanced **E**fficiency Nitrogen **F**ertilizer (EEFs) products. So, on average, some of the positive N_2O impacts of 4R management are reflected in your Midwest average N fertilizer direct N-to-N_2O emissions factor. However, it is also notable that many of the studies contained experiments that purposely applied abnormally high rates of N to determine "nitrogen overapplication effects" on the N_2O emissions, so your emissions factor may have also been influenced by those experiments.

A few years ago, I sorted/summarized a data set of N_2O emission studies from various sources (including your 2012 analysis-*Wang et al 2012*) to determine the regional (annual precipitation) and EEF impacts on nitrous oxide emissions from Nitrogen applications to corn. I also sorted the data and made a graph that shows the relationship between N_2O emissions and nitrogen application rate (lbs. N/bushel production). That data set along with summary charts can be accessed via this link:
https://www.dropbox.com/s/77vvvs6gbbbbtaq/N2O%20database%20analysis.xlsx?dl=0
This analysis suggested that direct N_2O emissions from N fertilizer are significantly impacted by annual precipitation, Enhanced Efficiency N Fertilizers, and per bushel nitrogen fertilizer application rates.

Corn producers that implement the 4Rs begin the process by determining the **R**ight rate. This is a multi-step process often done in consultation with their agronomist, fertilizer retailer, or university soil and crop scientists. First, a yield goal is determined that is based on historical yields and the nitrogen that will be embedded in the corn grain protein and removed from the field. Many producers also employ GPS yield monitoring/mapping and precision fertilizer application equipment, and this enables them to easily conduct N rate strip trials to determine the economic optimum N rate for each field. Producers also utilize soil sampling/testing to determine nutrient and organic matter levels in their fields. This information is used to calculate an optimum economic N fertilizer application rate.

The calculation often looks like this example: Bu./acre yield goal **X** Lbs. per bu. N rate determined from N rate strip trials, or expert recommendations and then subtraction of any nitrogen credits from nitrates found by soil testing, credits of high organic matter, and credits for N from legumes crops in the rotation. It might result in these numbers: (200 bu./ac. **X** .95 lbs./bu. **–** 15 lbs./ac. NO_3 credit from soil test **–** 20 lbs./ac. O.M. N credit **–** 20 lbs./ac. N credit for soybean rotation **equals** 125 lbs. of N fertilizer needed per ac.). This would be an average rate for the entire field.

Many producers have also adopted and implemented even more precision agriculture technology than has already been described in the preceding paragraph and that has expanded the **R**ight rate determination. For example, many producers not only have digital records of the yield of each field, but also have digital records of the yield and fertilizer application rates from each sub-section of surface area in each field (the size of these rectangles are determined by planter, fertilizer and harvesting operation widths, the speed of the equipment, and the data collection frequency of the software). Ninety square ft., 120 square ft., and 180 square ft. sub-sections are common. In this case, soil testing is then typically done by "zones" (groups of sub-sections that have similar yield histories, soil characteristics, or nutrient/organic matter levels) rather than each sub-section of the field. Producers often refer to this as "farming by the square foot" and the benefits are captured with the use of computer-controlled, on-the-go fertilizer application equipment that can vary the rate of N, P, K application for each zone. Implementation of the **R**ight rate part of 4R fertilizer management has significant cost implications but is generally profitable because fertilizers are expensive and are a large portion of the total cost to produce crops. Obviously, this determination of the **R**ight rate is purely fertilizer cost optimization. A low carbon program that incentivizes GHG reductions at the farm level would introduce environmental services' value into this equation and drive even further fertilizer use optimization.

Using the "**R**ight rate" impacts both direct and indirect N_2O emissions. A recent meta-analysis *(Eagle et al. 2020)* argues that "nitrogen balance" is a good indicator of the potential for the magnitude of both direct and indirect N_2O emissions. Indeed, calculating N balance is exactly how corn producers have graded themselves for how efficiently they have utilized the Nitrogen fertilizer they applied to their crops for decades. Following is a link to Eagle et al. 2020:
https://www.dropbox.com/s/ekh8sr6i162mmnu/Eagle%20et%20al%20N%20balance%20is%20key%20to%20predicting%20N2O.pdf?dl=0

Nitrogen balance is defined as applied nitrogen less the nitrogen removed from the field in the harvested grain and stover. Nitrogen removed from the field in grain is determined simply by multiplying the weight of the grain dry matter by its nitrogen concentration (typically about 16%). Ethanol production plants regularly track the nitrogen content (electronic grain protein testers) of incoming corn because they are required to label/guarantee a specific protein content when distillers grains are marketed. Obviously, if the amount of applied N fertilizer is significantly greater than the N that was removed in the grain, it results in leftover, or surplus soil N that at best, remains in the soil profile until the next crop utilizes it, or at worst is leached by water down through and out of the soil rooting profile before it can be utilized by the following crop. Surplus N can have severe environmental consequences in regions of the corn belt where rainfall is significantly greater than crop water use (evapotranspiration) because most often it leaches away and enters estuaries, lakes, streams, and rivers during the months before the next growing season. **R**ight rate and **R**ight timing are especially crucial in those regions. On the other hand, in areas of the corn belt where corn crop evapotranspiration is roughly equal to, or more than growing season precipitation, the potential for negative consequences from surplus N is greatly reduced.

The USDA maintains a data set of historical fertilizer use by the major crops in the U.S. Using these fertilizer use data, corn yield data, and the assumption that average crude protein content of grain dry matter is 10% and the nitrogen content of corn crude protein 16%, one can calculate annual U.S. corn

production N balance over the past several decades. The USDA data set is at this link:
https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx

Corn producers have significantly improved their N use efficiency over the past few decades, and the data suggests that N balance has improved in part because the price of N fertilizer has increased substantially. At this link are charts that show the historical trends in corn yield, nitrogen fertilizer application rates, N balance and N fertilizer prices:
https://www.dropbox.com/s/9pu32nrof8bnwia/USDA%20Historical%20Fertilizer%20Use%20Database%20with%20N%20use%20efficiency%20charts-Eagle%20et%20al%202020.xls?dl=0

Implementation of other components of 4R management, such as **R**ight form, and **R**ight place, also can have positive impacts on N_2O emissions. As you know, the GREET model assumes that 10% of the nitrogen fertilizer is lost via ammonia (NH_3) volatilization. Choosing the **R**ight form of N fertilizer and then injecting or incorporating the N fertilizer into soil (**R**ight placement) at application time can greatly reduce N losses from ammonia volatilization. In 2002, Dr. A.F. Bouwman and two other scientists quantified the impacts of various N fertilizer forms, application management, soil, and climate factors on ammonia fertilizer volatilization losses. His work resulted in a calculation that is used to inform and guide agronomists and crop producers on the best way to reduce ammonia fertilizer volatilization losses. The calculation is described in their paper in table 3 on page 8. We believe this would be a useful calculator to include in a "4R" section in your GREET Corn FD-CIC. A.F. Bouwman's paper is at this link: https://www.dropbox.com/s/963q5apxqpdninw/A.F.Bouwman%202002.%20%20N%20volitalization%20losses.pdf?dl=0

I have included a simple Excel calculator using A.F. Bauman's volatilization factors to quickly estimate these ammonia losses here:
https://www.dropbox.com/s/o2ig6jb1k373sxq/AF%20Bouwman%20et%20al%202002%20N%20volatilization%20rate%20Calculator.xlsx?dl=0

Biofuel feedstock producers that use this as a guide can potentially reduce N fertilizer volatilization losses down to as low as 1-2%. Interestingly, if this calculator is used to determine the average ammonia volatilization loss from the multiple forms and amounts of N fertilizer GREET modelers have determined to be "Midwest average," it results in an estimated volatilization loss rate of 3.29% if the N fertilizer is incorporated, and 5.96% if the N fertilizer is not incorporated. Both are well below the GREET default volatilization loss rate of 10%.

Right placement of N fertilizer (injecting/incorporating into soil) can also significantly reduce nitrogen fertilizer runoff losses and their associated N_2O emissions.

Finally, **R**ight timing of N fertilizer applications can significantly reduce direct N_2O emissions due to nitrification, denitrification, and the indirect N_2O emissions resulting from runoff and leaching losses. As mentioned in the "**R**ight rate" discussion, corn production regions that receive more rainfall than crops can utilize are vulnerable to N leaching losses, so it is important to minimize the time between N applications and crop uptake periods. In 2017, a meta-analysis was done by *Eagle et al* (link below).

https://www.dropbox.com/s/xws7bnajron4gek/Eagle%20et%20al.%202017%20N%20leaching%20losses%20and%20N2O%20Meta%20analysis.pdf?dl=0

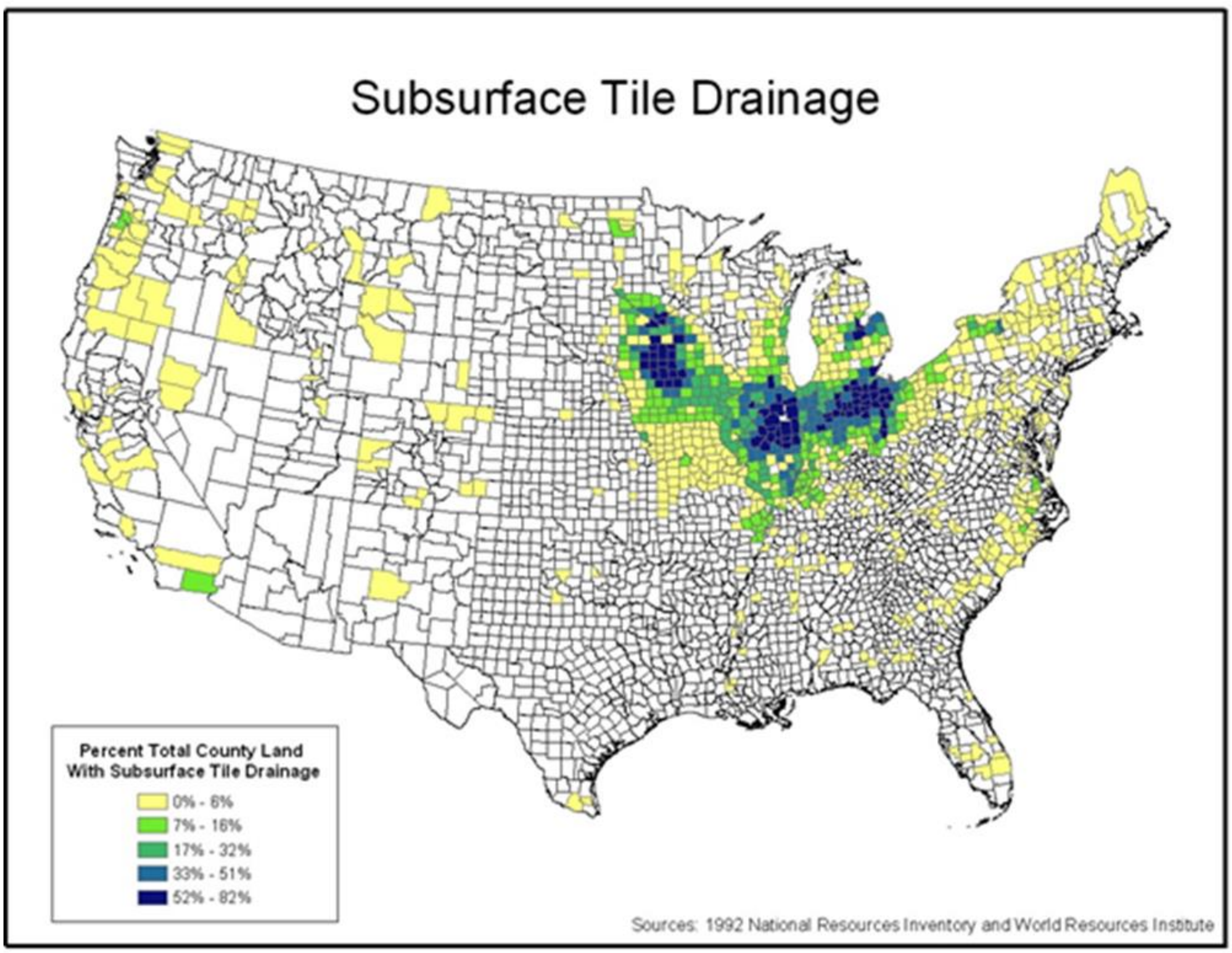
Their meta-analysis determined the effects of nitrogen application timing, as well as the effects of EEFs on N_2O emissions and nitrogen leaching losses. Both **R**ight time and EEFs significantly reduced N_2O.

Although using EEF N fertilizers is not formally a “4R”, practice, they have proven to have similar N_2O reduction impacts as 4R management. In 2016 *Thapa et al.* also published a meta-analysis of EEF N_2O reduction effects.

https://www.dropbox.com/s/jbmd4r1ymswqaev/Thapa%20et%20al%202016%20EEF%20Meta%20Analysis.pdf?dl=0

There have been many studies conducted in very specific regions of the corn belt to determine the quantity of N leached from fertilized fields. Regions with consistently excessive precipitation and poorly drained soils that have been corrected with extensive subsurface drainage systems are “hot” spots for N fertilizer leaching losses. This environmental concern has meant that almost all the studies conducted to quantify leaching and runoff losses have been conducted in hot spots. The maps below are from a study by Zachary Sugg in 2007 which show these areas of extensive subsurface drainage and large N leaching losses. Sugg estimated that about 38 million acres in the 12 Midwest states have subsurface drainage installed. This is about 20% of the corn, soybean and wheat production acreage of Midwest states.

Figure 4. Final estimated subsurface drainage.



In 2010, David et al., using USGS stream flow N concentration data, subsurface drainage data, and N loss study data predicted N losses from the Mississippi River basin regions of the Corn Belt:

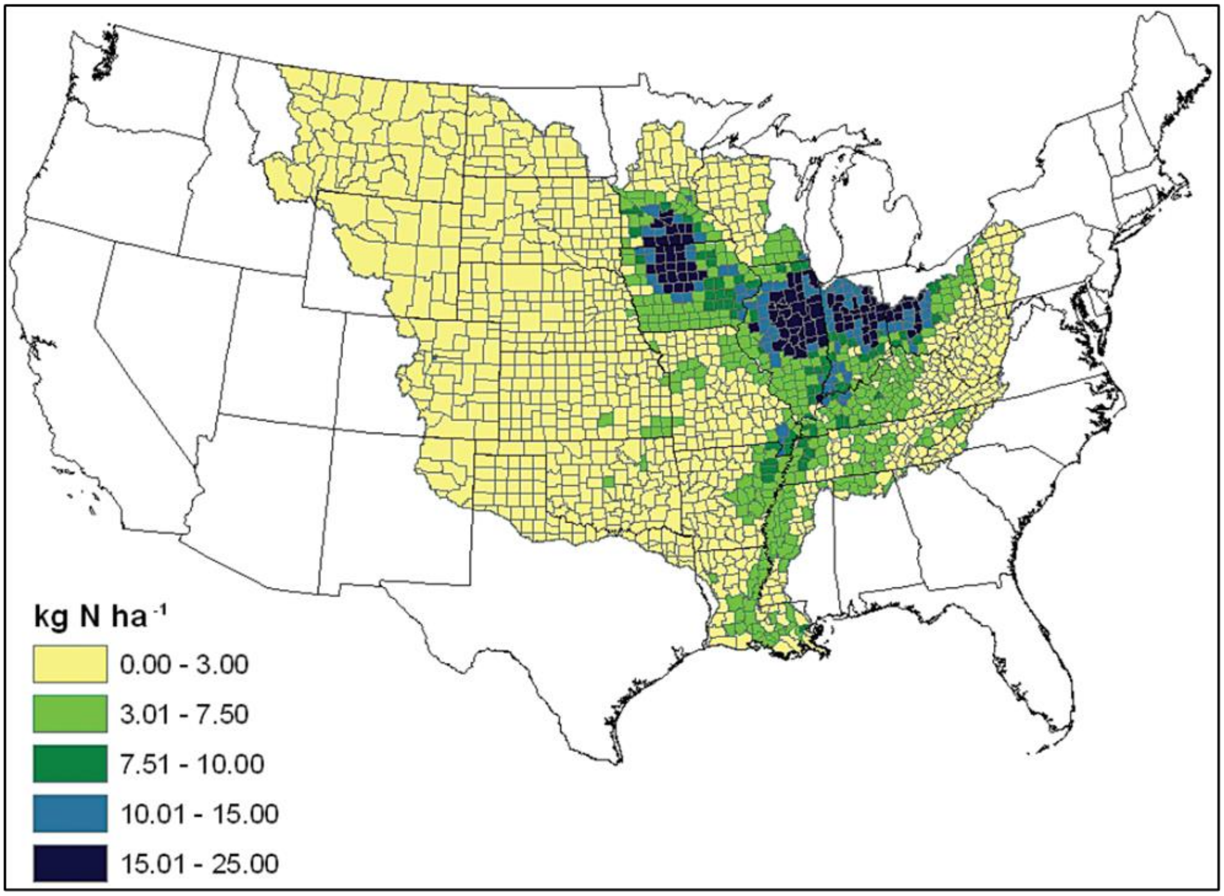


Fig. 8. Predicted average riverine nitrate N yield, January to June, for all counties in the Mississippi River basin for the period 1997 to 2006.
Link to David et al. 2010, Sources of Nitrate Yields in the Mississippi River Basin:
https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2010.0115

One carefully controlled long-term ongoing experiment conducted in a "hot spot" in North Central Iowa has found that over the past 21 years, 23% of the applied N fertilizer has been lost due to leaching and runoff. When the N in crop residues is added to fertilizer N, the average leaching rate of both fertilizer and crop residue N was 17% over the long term. This is about half the GREET runoff and leaching default value of 30%. The average annual precipitation at Gilmore City, Iowa is approximately 30 inches per year, corn crop evapotranspiration is about 22 inches per year, and about 10 inches of rainwater per year percolated down and out the subsurface drainage system installed at the site. This high annual rainfall area, along with the extensive subsurface drainage system designed to catch and measure 100% of the water leached through the soil, represents a near worst case scenario for nitrogen leaching losses in the corn belt. Based on this long-term experiment in Iowa, the GREET default runoff and leaching rate is significantly higher than reality even in this near worst case situation. In the drier corn production regions of Kansas, Nebraska, and South and North Dakota, runoff and leaching losses are a much smaller

percentage of nitrogen fertilizer and nitrogen in crop residues. The description of this long- term experiment and results can be viewed by following this link:
https://www.dropbox.com/s/6s9cc27c1n19dkq/Gilmore%20City%20ISU%20Nitrogen%20leached%20study.pdf?dl=0

Twelve more peer reviewed nitrogen runoff and leaching loss studies are available via the link below. These studies were mostly conducted in areas that have extensive subsurface drainage systems and annual precipitation that consistently exceeds corn crop evapotranspiration. The average N loss from these studies was 18% of fertilizer N and crop residue N. I have included an Excel "summary" spreadsheet with these references.
https://www.dropbox.com/sh/69s9y50fkxwgb4v/AADBW6oenbGLxaCbS-GSvhzza?dl=0

Although 4R N management has little or no impact on N_2O emissions from the nitrogen in crop residues, many believe this emission factor needs to be updated by the IPCC. As you obviously know, GREET assumes that the nitrogen in corn crop residue has the same direct N-to-N_2O emissions factor as well as the same runoff leaching loss factor as fertilizer nitrogen. Over the past couple of decades soil and environmental scientists have looked at this issue in greater detail. Following is a link to a file folder with sixteen "crop residue nitrogen impacts on N_2O" peer reviewed papers and an Excel worksheet that provides a summary of each of those sixteen studies. These studies indicate that N_2O emissions from corn crop residue N are significantly less than the N_2O emissions from fertilizer N. Crop residue nitrogen N_2O emissions are greatly influenced by the ratio of their carbon and nitrogen content. Crop residues with high C:N ratios produce significantly less N_2O than crop residues with low C:N ratios.
https://www.dropbox.com/sh/f9u1t8o9qb4sksm/AABk23MW_2zCoJU233RHmfxOa?dl=0

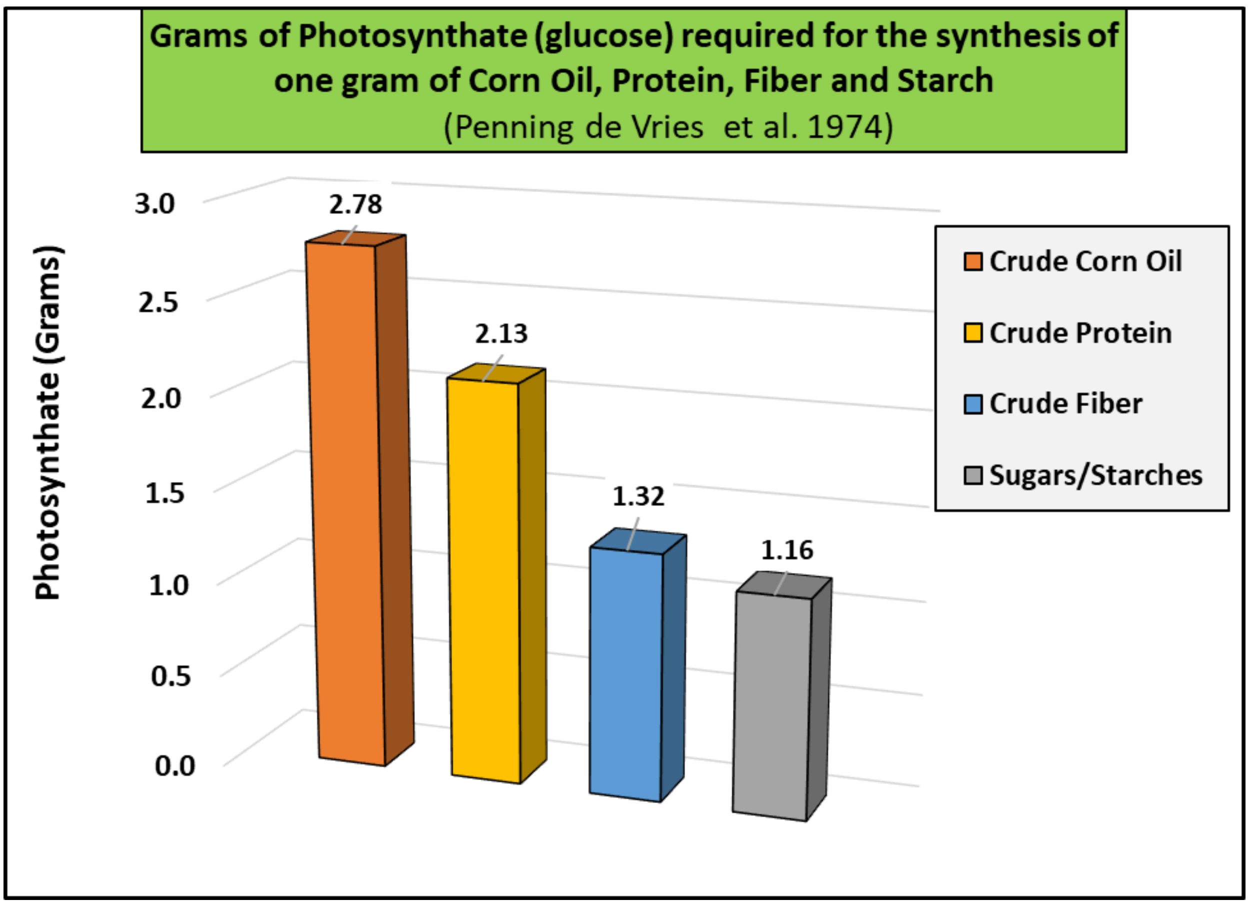
Maize and other cereal crops' residues have high C:N ratios (40 to 80:1 typically) and soil microbes, like humans, require a balanced diet of Carbohydrates and Protein (nitrogen). Soil microbiologists have found that the ideal residue C:N ratio for soil microbes is 24:1. When soil microbes consume and decompose crop residues with higher C:N ratios, there is not enough protein (nitrogen) in those residues for optimal decomposition, so the microbes scavenge any available soil N to supplement the N in the crop residue. When soil microbes consume this N, it is immobilized temporarily. This "immobilization" of N due to high C:N ratio crop residues is a common problem that crop producers routinely need to consider in their N fertilizer management program. If the N content of the residues is insufficient, soil microbes always "beat the growing crop to the dinner table" for this available soil nitrogen (protein) and when that happens, there is little or no soil N for the growing crop. This is detrimental to the growing crop unless producers carefully manage this issue (precision timing and placement of nitrogen near crop roots). But immobilization of this available N has environmental benefits because there is little of no available soil N during this time that can be nitrified, denitrified, or leached through the soil. However, as time goes by, the nitrogen that has been immobilized by the soil microbes in this process is slowly released back into the soil after the soil microbes finish their work and die. Because this soil microbial die off is slow and gradual and occurs in late spring/early summer when crop nutrient needs are high, the nitrogen released back to the soil solution tends to be almost immediately utilized by the crop in the ammonia form, and there is little time and opportunity for this N to be nitrified, denitrified, or leached from soil. Following is a link to a USDA NRCS report that describes this soil and residue carbon and nitrogen cycling issue:
https://www.dropbox.com/s/oqet195a3c5nwpq/C_N_ratios_cropping_systems.pdf?dl=0

Below is a link to a report on the preferable and efficient use of the ammonia form of nitrogen by corn:
https://www.dropbox.com/s/1vvrchk5e3yilx8/Ammonia%20N%20vs%20Nitrate%20N.pdf?dl=0

In summary, this memo describes the positive impacts 4R N fertilizer management can have on nitrogen induced N_2O emissions. The scientific data are strong that this precision fertilizer management can significantly reduce both direct N_2O emissions and indirect N_2O emissions resulting from N fertilizer losses from fields due to volatilization, runoff and leaching. If 4R management is fully implemented and Enhanced Efficiency N Fertilizers are used, N_2O emissions could be reduced by up to 50% relative to currently modeled estimates.

Finally, I would like to discuss very briefly the allocation of corn fertilizer emissions in the GREET and other GHG emissions modeling. About 5 years ago I was explaining how the GREET model accounts for corn production GHG emissions to Dr. Greg Carlson, an agronomist, researcher, and teacher in the Plant Science Department at South Dakota State University. As I was describing the allocation of fertilizer GHGs to corn ethanol he interrupted, *"Wait a minute, there is not a gram of fertilizer nutrients in ethanol....the corn kernel nutrients such as protein (nitrogen), phosphorus, potassium, vitamins and other minerals in corn grain are not impacted by the ethanol manufacturing process and all end up in the distillers grains that are used for livestock nutrition/feed to produce meat. Given the minor role these fertilizer nutrients play in the starch portion of corn grain, these fertilizer GHGs should be proportionally allocated to the carbon footprint of food. Furthermore, have you seen the science on photosynthate (glucose) requirements/allocation to the components of corn grain? It takes a lot more photosynthesis derived energy to produce protein than it does starch!"*

He then showed me a chart of the photosynthate requirements to produce the various components of corn grain, protein, oil, starch, and fiber. Here is a chart of the information Dr. Carlson was referring to:



Link to Penning de Vries et al. 1974 information:
https://books.google.com/books?id=bJbzCAAAQBAJ&pg=PA161&lpg=PA161&dq=photosynthate+requirements+for+starch+vs+oil+vs+protein&source=bl&ots=5FQqEmkJVF&sig=hMeUfQvDAaZrHSoOmL4LYAd_VEY&hl=en&sa=X&ved=2ahUKEwiFyaPM2JPdAhUj3YMKHdPWCMYQ6AEwCXoECAAQAQ#v=onepage&q=photosynthate%20requirements%20for%20starch%20vs%20oil%20vs%20protein&f=false

Having said this, the grain starch production of corn most certainly would not be as high without the addition of these fertilizer nutrients, but a strong case can be made that more of the fertilizer-related GHG emissions should be allocated to the distillers grains co-products than is currently. Perhaps this is a debate for another day in the evolution of biofuel lifecycle GHG emissions accounting and allocation.

I sincerely hope you and your team find this information useful. Please do not hesitate to contact any of us if you have questions about any of the information we have provided.

Best Regards,

Ron Alverson,

For the American Coalition for Ethanol, the South Dakota Corn Growers Association
and the Kansas Corn Growers Association.

Brian Jennings – American Coalition for Ethanol
Lisa Richardson – South Dakota Corn Growers Association
Greg Krissek – Kansas Corn Growers Association