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DEPARTMENT OF ENVIRONMENTAL RESOURCE MANAGEMENT

CYCLES-SIMULATED NITROUS OXIDE EMISSIONS FROM DAIRY SLURRY MANURE FERTILIZER APPLICATIONS TO CORN

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ABSTRACT

This thesis explored modelling nitrous oxide emissions (N_2O) in dairy cropping systems and calculating N_2O emissions from different dairy slurry manure fertilizer management strategies. A portion of animal manure and inorganic urea ammonium nitrate (UAN) fertilizer applied to farmland as fertilizer can emit the greenhouse gas, nitrous oxide, which has a warming potential 298 times greater than carbon dioxide (IPCC, 2006). Potential opportunities to reduce nitrogen losses to the environment are improving the application timing, placement, and rate of fertilizers. In northeastern U.S., livestock manure is typically applied prior to corn planting in spring, making manure nutrients vulnerable to environmental losses. Recent innovations in manure application technology allow for manure application in early stages of corn growth. Research focused on this improved synchronization of manure fertilizer application with crop uptake to reduce N_2O emissions is limited. In this study, we used measured results from a no-till conservation dairy cropping system in Central Pennsylvania to evaluate how well Cycles, an agro-ecosystem computer model, simulates N_2O emissions. We found that Cycles in general accurately simulated emissions from broadcast manure and inorganic liquid urea ammonium nitrate fertilizer applied to corn following soybean. Improvements can be made to fertilizer applied by manure injection and in corn following two years of growing alfalfa and orchard grass. Next, we used Cycles to simulate the N_2O emissions from a continuous corn field managed with different fertilizer application scenarios in the same field in Rock Springs, Pennsylvania. We found that splitting manure into two applications (before corn planting and injected side-dress) and lowering total nitrogen input rate by 56 kg N ha^{-1} reduced average annual total N_2O emissions by 17% to 19%. When more of the total manure was applied as side-dress, the cumulative N_2O emissions were reduced while still achieving similar corn yields. These results can encourage more manure application technological innovations, financial incentives to promote adoption of side-dressing manure, and discourage manure and nitrogen applications that exceed crop N requirements to reduce N_2O emissions and other potential N losses to aquatic ecosystems and to the environment.

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Chapter 1 : Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas with 298 times greater global warming potential than carbon dioxide (CO_2), and agricultural management comprises 74% of all nitrous oxide emissions in the United States (IPCC, 2006; US EPA, 2015). Mitigating greenhouse gases, including non-CO_2 emissions like N_2O, can reduce the dangerous consequences of anthropogenic climate change (Reay et al, 2012). With an increasing global population, a pressing need to feed a growing population, and the threats of the climate crisis, meeting food demands will require high crop yields while reducing nitrogen pollution and greenhouse gas emissions, especially nitrous oxide. Nitrogen (N) is a key nutrient in agronomic field systems; nitrogen deficiency lowers a crop's crude protein and can cause stunting in root systems and plant growth (Cornell University, 2004). Soil processes due to the widespread use of nitrogenous fertilizers and manure on agricultural land contribute to greenhouse gas emissions (Reay et al, 2012).

While it is important to have enough nitrogen to increase crop yields, overapplication of nutrients to farmlands can runoff, leach, and volatilize to the atmosphere and pollute waterways. Much of Pennsylvania is within the Chesapeake Bay watershed, which means that nutrients applied to Pennsylvania farmlands can pollute the Chesapeake Bay. Excessive amounts of nitrogen in the Chesapeake Bay is harmful to water quality and living organisms (Chesapeake Bay Foundation, 2020). Proper nutrient management and conservation agriculture practices can protect the Chesapeake Bay in addition to mitigating climate change.

Nitrogen Cycle and Nitrous Oxide

Nitrous oxide can come directly from agricultural soil emissions. Direct N_2O emissions from agricultural soils are most often biogenic, meaning N_2O is produced by bacteria in fertilized soils. N_2O is produced from the nitrification and denitrification processes of the nitrogen cycle (Fig. 1). The biogenic production of N_2O depends on the amount of inorganic N, which is the form of nitrogen that plants can uptake; nitrification and denitrification rates increase as available inorganic N increases. Therefore, anthropogenic N inputs to soils, such as synthetic fertilizers and animal manures, increase the rates of nitrification and denitrification processes. Consequently, these anthropogenic N inputs are drivers of N_2O emissions from agricultural fields (Mosier et al, 1998).

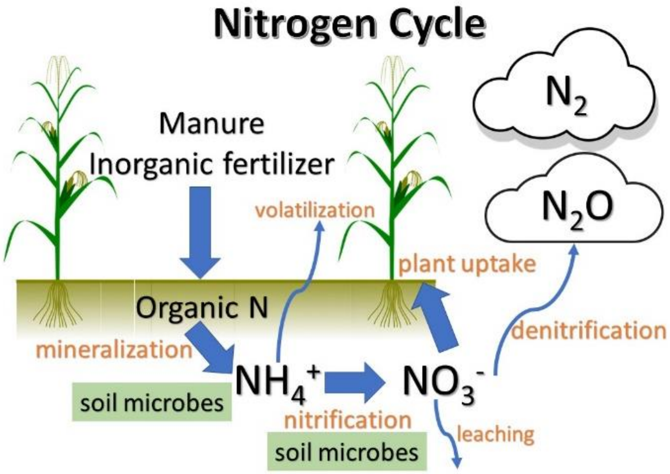

Figure 1: Nitrous oxide is produced through microbial processes under certain conditions in the nitrogen cycle.

Conservation practices, such as no-till and manure injection, nutrient management, and cover crops, can reduce the amount of nitrogen fertilizer runoff. There are four nutrient management practices that may increase or decrease nitrous oxide emissions: right source, right rate, right time, and right place (Nutrient Stewardship, 2017).

Application Rate

The rate that nitrogen is applied to soils affects nitrous oxide emissions. Yield-scaled emissions from corn are small up until an application rate of 187 kg N ha^{-1}, and emissions drastically increase when application rates are greater than 200 kg N ha^{-1} (Van Groenigen et al., 2010). Two meta-analyses quantitatively synthesized that lowering the application rate of nitrogen inputs to agricultural systems reduces nitrous oxide emissions. A meta-analysis by Shcherbak et al. (2014) analyzed the rate of nitrogen application and the exponential growth in N_2O emissions when the rate of nitrogen applied in agroecosystems was increased. From the 78 publications in Shcherbak et al.'s meta-analysis, the main finding was that N_2O increases with increases in nitrogen inputs, which supports the importance of applying the right rate of fertilizer (Shcherbak et al., 2014).

In another meta-analysis by Zhen et al. (2017), several categories of management strategies were analyzed: fertilizer use efficiency (fertilizer, rate, placement, timing, and source), reduced tillage, ecologically-based nutrient management (cover crops and rotation), and comparison of manure to inorganic N fertilizers. This meta-analysis also concluded that the rate of nitrogen added to agricultural land is the main driver of nitrous oxide emissions. The other management practices did not significantly reduce N_2O emissions.

Application Method/Right Place

The method of applying fertilizer to plots has an effect on runoff and emissions. Fertilizer can be applied to different places of the soil. It can be applied onto the surface of soil (broadcast) and then incorporated which requires tillage, or fertilizer can be applied subsurface into the soil (injection). Subsurface application has lower nutrient N losses compared to surface application of fertilizer (Kleinman et al, 2016). This reduction in N loss may be from reduced ammonia (NH_3) volatilization, but at the same time, subsurface application in a concentrated injection band may lead to greater N losses from denitrification in the form of dinitrogen gas (N_2) or as N_2O. When manure is injected to soil subsurface, microbial activity rates may increase from the addition of manure carbon material, and as microbial activity decreases oxygen levels, anaerobic conditions are created, making it suitable for denitrification (Dell et al, 2011). Whether fertilizer is broadcast applied at the soil surface or incorporated/injected into the soil subsurface, each method of application has its benefits and disadvantages.

Right time (Synchronization of fertilizer application with plant uptake)

The rate that plants uptake nitrogen varies throughout the crop's development in addition to the availability of N in soil. The rate that plants uptake nitrogen largely depends on the plant's growth rate and nitrogen demand (Gastal and Lemaire, 2002). Applying fertilizers that synchronize with the plant growth rate and nitrogen demand could reduce excess nitrogen that could nitrify or denitrify as N_2O. In a meta-analysis by Van Groenigen et al., 2010, the main conclusion was crop N uptake must be maximized to minimize N_2O emissions. When there was an N surplus (N application minus above-ground N uptake), N_2O was emitted because N application rate exceeded crop N uptake. Excess mineral N was then available to become denitrified or nitrified. Above-ground N uptake and N application rate have a linear relationship, but N_2O emissions are exponential once N application rate exceeds crop N demand (Van Groenigen et al., 2010; Scherback et al., 2014).

Dairy slurry manure fertilizer is commonly applied before planting, but alternatively, it can also be applied as side-dress between corn rows when corn is 15 to 20 centimeters high to improve the timing of plant-available N (Beauchamp, 1983). Side-dressing is commonly practiced by applying more fertilizer to crops several weeks after planting and crop emergence, often sometime between May 1 and early July, to supply more nutrients to crops. Crop yields increase as side-dress dairy manure fertilizer rates increase (Beauchamp, 1983). Equipment to side-dress manure is still being developed for commercial use. Innovations to current technology, such as narrowing wheels and adapting drag hose technology, enable opportunities to side-dress crops with liquid dairy manure (Ohio’s Country Journal, 2014).

From current research, opportunities to reduce N_2O emissions include reducing the amount of nitrogen applied to a field during a growing season and timing the application of nitrogen to best meet crop nitrogen demand. This is based on meta-analyses that have quantitatively synthesized these conclusions from over 70 experiments (Scherbak et al, 2014) and 19 independent studies (Van Groenigen et al, 2010).

Nitrous Oxide Data Collection

Field experiments have been conducted to research opportunities for nitrous oxide emissions reductions in agricultural soils and activities. Automated chamber systems are available to measure nitrous oxide fluxes in field experiments, but the equipment and technology costs are often expensive (Phillips et al, 2013; Rapson and Dacres, 2014). A cheaper method is the chamber-based flux methodology, in which a chamber is manually placed each time a measurement is taken (Parkin and Venterea, 2010). However, this method also is a more labor-intensive method to measure nitrous oxide emissions (Ponce de Leon, 2017).

Computer Models

Labor, technology, cost, and time are all factors that can make it difficult to use the most appropriate data collection method. Computer models can provide a less labor-intensive, cheaper, and faster alternative to conducting field experiments for evaluating nitrous oxide emissions from agriculture. Process-based biogeochemistry models, such as DAYCENT and Denitrification Decomposition model (DNDC), have been used to estimate greenhouse gas emissions (Yue et al, 2019). DAYCENT models carbon and nitrogen cycles between the atmosphere, vegetation, and soil in a daily time step. It simulates crop yield, soil organic matter levels, and trace gas flux, including N_2O emissions (Del Grosso et al, 2002). The DNDC models crop growth, soil temperature, soil carbon dynamics, and trace gases including nitrous oxide (Institute for the Study of Earth). Each model has their advantages, but each also has limitations. DAYCENT and the DNDC model have not always reliably simulated N_2O emissions (Del Grosso, 2002; Jagadeesh Babu et al, 2005). Another challenge can be the user-friendliness of using models to calculate results.

Cycles is another cropping systems model that has been developed to be user-friendly and to simulate daily time steps in cropping systems. Cycles has been tested with experiments under conventional tillage, and evaluations of the model have focused on assessing the simulated soil organic carbon to the measured soil organic carbon (Kemanian and Stöckle, 2010).

Drawdown

Drawdown is an organization that has explored “the most comprehensive plan ever proposed to reverse global warming” within sectors, such as electricity, health and education, transportation, buildings, and food, agriculture, and land use. This paper aims to add research to the food, agriculture, and land use sector. Drawdown has three primary solutions in which nitrous oxide applications should be considered. These include nutrient management, conservation agriculture, and regenerative agriculture. This research is an opportunity to reduce nitrous oxide greenhouse gas from the atmosphere, furthering Drawdown's goal to reach drawdown, the point where greenhouse gas concentration in the atmosphere begins to decline (Project Drawdown, 2020).

Chapter 2 : Evaluating Cycles-simulated nitrous oxide emissions against field measured results

Research Objective

Cycles is a newer cropping systems model, and few studies have compared its simulated results to field measured data, especially in a no-till cropping system. The objective of this study is to use the measured experimental field data of nitrous oxide emissions from a no-till dairy cropping system as a valuation dataset to evaluate how well Cycles projects nitrous oxide emissions in no-till dairy cropping systems. Model validation provides support in the model's outputs and whether the model sufficiently simulates reality (Bayarri et al, 2005).

Materials and Methods

Cycles

Cycles is a process-based agroecosystem simulation model. It models water, carbon, and nitrogen balance of a soil-crop system based on weather conditions, soil properties, and management practices. The model requires the following inputs in order to run: 1) location and daily weather data, 2) the initial soil profile, 3) a description of the crops and rotation sequence, 4) the sequence of tools and tillage operations, and 5) irrigation operations. The model allows for customization with its ability to use daily weather data and soil profiles that reflect local conditions. Users can choose crop types, fertilization rates and timing, irrigation events, tillage events, soil properties, and climatic conditions.

Models in this paper were run with the spin-up feature which runs models to equilibrium. In the spin-up feature, Cycles repeats the weather data and operations until reaching equilibrium, when the change in total soil organic carbon before and after the simulation is less than 1%. The model's outputs are created from the conditions at equilibrium. Cycles predicts grain and forage yield, nutrient and water stresses, and nutrient losses from leaching, volatilization, nitrification, and denitrification. This paper focuses on the evaluation of the following outputs from Cycles: nitrous oxide emissions from denitrification, nitrous oxide emissions from nitrification, grain yield at harvest, daily nitrogen stress value of the crop, and average total nitrous oxide emissions over the duration of the simulation (Kemanian and Stöckle, 2010).

Experimental Data

The Cycles model was evaluated using experimental data from Ponce de Leon, 2017. In the Ponce de Leon, 2017 experiment, soil N_2O emissions were measured at the Pennsylvania State University Russel E. Larson Agronomy Research Farm, Pennsylvania, USA. Two-year corn-soybean rotations were compared with different fertilizer application methods: broadcast manure (S-BM), shallow disk manure injection at 10 cm depth (S-IM), and inorganic liquid urea ammonium nitrate fertilizer (S-UAN). The crop rotations were no-till managed. Corn for grain was planted between 14 May and 19 May in 2015 and in 2016. Corn was harvested on 5 Nov. 2015 and 28 Oct. 2016. Starter fertilizer was applied in all three treatments at 22 kg ha^{-1} N as 12-40-0. In 2015 prior to corn planting, dairy slurry manure was surface broadcasted (S-BM) and shallow disk injected (S-IM) at 44 Mg ha^{-1} with 168 kg ha^{-1} N, and in 2016, they were applied at 42 Mg ha^{-1} with 167 kg ha^{-1} N. For the S-UAN treatment, no additional fertilizer was applied prior to corn planting besides the starter. S-BM treatment was side-dressed with liquid UAN at 53 kg ha^{-1} N in 2015 and 100 kg ha^{-1} N in 2016. S-UAN treatment was side-dressed with liquid UAN at 129 kg ha^{-1} N in 2015 and 122 kg ha^{-1} N in 2016.

Soil N_2O emissions were also measured from corn grown after 2-year alfalfa and orchard grass forage with broadcast manure (AO-BM) and no-till managed. Alfalfa and orchard grass were planted on 24 Apr. 2013 and 14 Apr. 2014. In 2015, corn was grown for grain, and in 2016, corn was grown for silage. Starter fertilizer was applied at 22 kg ha^{-1} N in 2015 and 2016. Alfalfa and orchard grass were terminated on 8 May 2015 and 27 Apr. 2016. The C:N ratio of the alfalfa and orchard grass aboveground biomass was 11.6 in 2015 and 11.5 in 2016.

N_2O gas samples were collected in 2015 from 15 April to 7 December and in 2016 from 12 April to 9 September. The samples were collected with vented static chambers, and approximately two samples were collected each week. Cumulative N_2O emissions were later calculated by linear extrapolation between sampling dates. Soil temperature and volumetric soil water content were also collected each time N_2O gas samples were collected. The weather data was from NRCS-ARS SCAN site at Rock Springs, Pennsylvania (Ponce de Leon, 2017).

Statistical Analysis

To assess the accuracy of Cycles' model of nitrous oxide emissions, the mean absolute error (MAE), the root mean square error (RMSE), and the index of agreement (IA) were used. The MAE is the averaged difference between the observed and modelled values, and RMSE also calculates the differences between observed and modelled values (Willmott, 2005). The smaller the MAE and RMSE, the more similar the measured and modelled values are. The IA is a unitless measurement of model accuracy and looks at the variation between observed and simulated data. The IA is bounded by 0 and 1, 0 meaning no agreement and 1 meaning a perfect fit (Willmott, 1981).

$$MAE = \frac{1}{n}\sum\nolimits_{i=1}^{n}|M - O|$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(M - O)^2}{n}}$$

$$IA = 1 - \left[\frac{\sum_{i=1}^{n}(O - M)^2}{\sum_{i=1}^{n}(|M - \bar{O}| + |O - \bar{O}|)^2}\right]$$

In the equations, *n* is the number of data observations, *M* is modelled data, and *O* is observed data.

In this study, the MAE and RMSE statistics were calculated using Microsoft Excel, and IA was calculated with an online Agricultural and Meteorological Software calculator (AgriMetSoft, 2019).

Results and Discussion

Results for simulated N_2O emissions from Cycles are shown in a daily time step, and the measured emissions from the field experiment are encircled at each sampling date with linear extrapolation between samplings (Fig. 2 & 3).

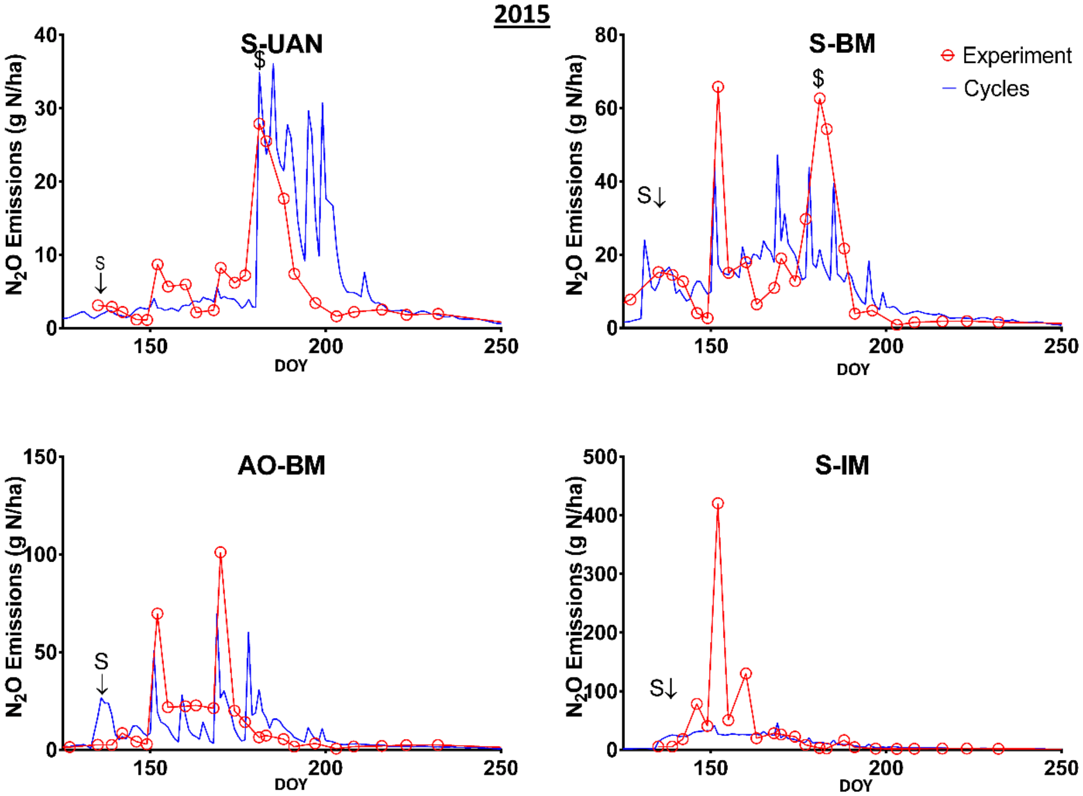

Figure 2: 2015 Cycles simulated N_2O fluxes (blue line) compared to 2015 field measured N_2O fluxes (red circles) from corn planted after the following crops and amendments: soybean with inorganic fertilizer (S-UAN), soybean with broadcast manure (S-BM), alfalfa and orchard grass with broadcast manure (AO-BM), and soybean with injected manure (S-IM). S indicates when manure was applied, ↓ indicates when corn was planted, and $ indicates when side-dress N was applied. Results are shown between day of year (DOY) 125 to DOY 250.

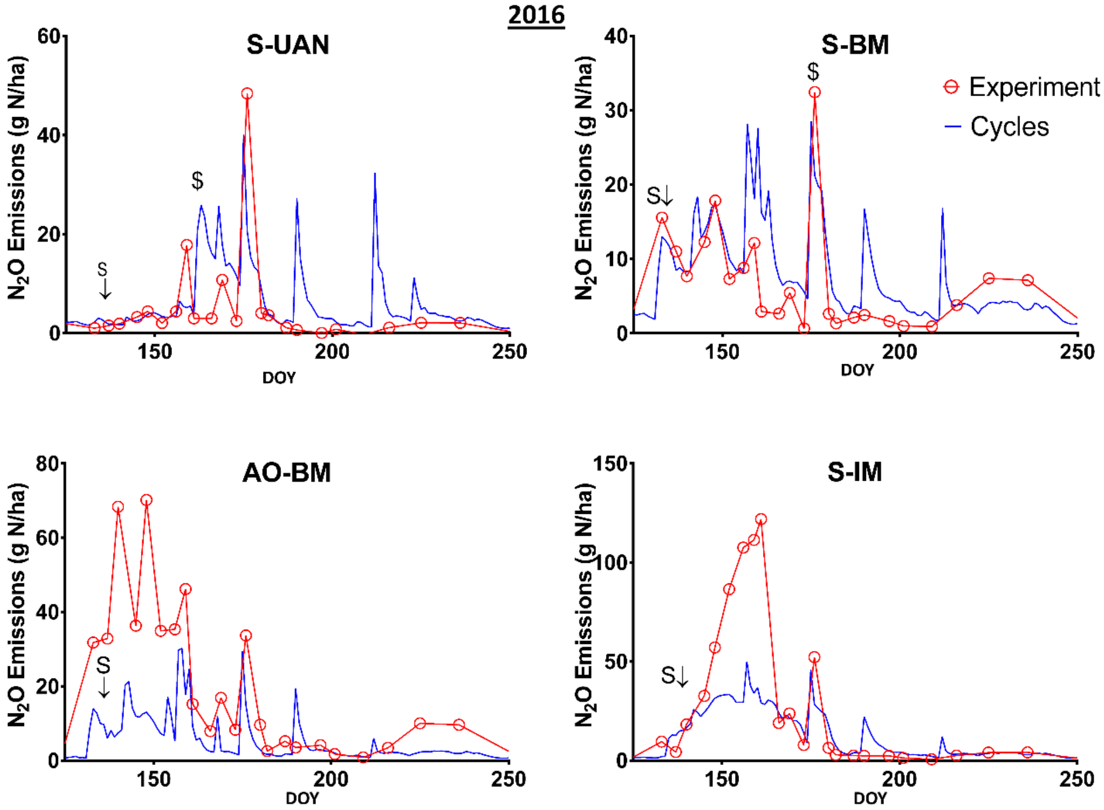

Figure 3: 2016 Cycles simulated N_2O fluxes (blue line) compared to 2016 field measured N_2O fluxes (red circles) from corn planted after the following crops and amendments: soybean with inorganic fertilizer (S-UAN), soybean with broadcast manure (S-BM), alfalfa and orchard grass with broadcast manure (AO-BM), and soybean with injected manure (S-IM). S indicates when manure was applied, ↓ indicates when corn was planted, and $ indicates when side-dress N was applied. Results are shown between day of year (DOY) 125 to DOY 250.

Nitrous oxide fluxes from corn following soybean with injected manure (S-IM)

In S-IM, the N_2O emissions measured from the experiment largely increased after manure was applied via injection in 2015 and in 2016 (Ponce de Leon, 2017). These peaks in emissions were not simulated by Cycles (Fig. 2 & 3). Cycles predicted smaller nitrous oxide emissions compared to the emissions from the experiment. The small emissions simulated by Cycles could be because in the field, manure injections were concentrated in between the rows of corn. Cycles did not simulate the manure being concentrated in those areas; the manure was probably simulated to be more evenly spread out across the field. As a result, the simulated cumulative N_2O emissions during the corn growing season in S-IM were less than the cumulative field measured fluxes by 52.8% in 2015 and by 38.2% in 2016 (Table 1). The RMSE and MAE were small in 2016 compared to in 2015, and the IA value in 2016 was also closer to 1 than in 2015, indicating better results in 2016 (Table 2). The differences between measured and simulated N_2O fluxes were larger in 2015 possibly because of larger precipitation events and wetter conditions in 2015. These conditions were favorable for denitrification (Griffis et al., 2017), causing an N_2O elevation of 421 g N ha^{-1} on 1 June 2015, day of year (DOY) 152, whereas the largest measured emission in 2016 only reached 122 g N ha^{-1}. The high N_2O elevation in 2015 created a large difference between observed and modelled values.

Nitrous oxide fluxes from corn following soybean with inorganic fertilizer (S-UAN)

In the S-UAN field experiment, the measured N_2O emissions increased as much as four to six-fold four days after manure was applied via injection in 2015 and three to five-fold after application in 2016 (Ponce de Leon, 2017). These elevated emissions were closely simulated by Cycles (Fig. 2 & 3). DAYCENT could not simulate these elevated emissions in Ponce de Leon, 2017, but Cycles could. However, Cycles continued to simulate elevated emissions after about 20 days, when the measured emissions from the experiment dropped after the peak in emissions from side-dressing UAN. This difference may be because Cycles was more sensitive to precipitation events (Fig. 4), or because the experimental data had to extrapolate data in between field measurements and missed these fluxes in between field measurements. As a result, the simulated cumulative N_2O emissions during the corn growing season in S-UAN were greater than the cumulative measured fluxes by 66% in 2015 and by 121% in 2016 (Table 1).

Nitrous oxide fluxes from corn following soybean with broadcast manure (S-BM)

In S-BM, the simulated cumulative N_2O emissions during the corn growing season were smaller than the cumulative field measured fluxes by 10.5% in 2015 and greater than the cumulative measured fluxes by 27.9% in 2016 (Table 1). The results from the IA, MAE, and RMSE favor the model in 2016 over the model in 2015 (Table 2).

Nitrous oxide fluxes from corn following alfalfa and orchard grass with broadcast manure (AO-BM)

In both years for AO-BM, simulated cumulative N_2O emissions were smaller than the measured N_2O emissions by 16.6% in 2015 and 65.6% in 2016 (Table 1). The MAE, RMSE, and IA were all favorable for the model in 2015 compared to the model in 2016 (Table 2). In the field experiment, there were measured elevated emissions in May of 2016 with peaks on May 19 (DOY 140) and May 27 (DOY 148). The elevated emissions were explained by Ponce de Leon, 2017 to be due to large precipitation events, mineralized N from the recently terminated alfalfa legume, and manure application. All of these created conditions favorable for denitrification and the release of N_2O. While Cycles simulated elevated emissions in May of 2016, the simulated emissions were significantly smaller than the field measured emissions (Fig. 3). The simulated N_2O emissions may be less than the field measured emissions because of nitrogen stress in Cycles. Cycles provided outputs on the daily nitrogen stress value of orchard grass and alfalfa during their season before corn was planted. Orchard grass exhibited nitrogen stress throughout both years of its growth in each model while alfalfa did not experience any nitrogen stress in the models. The cropping system had low nitrogen, resulting in nitrogen stress over the duration of crop growth for the orchard grass. Before orchard grass was terminated, the orchard grass had a cumulative nitrogen stress of 69.6%, and the following corn had a cumulative nitrogen stress of 12.7% in 2015. In 2016, orchard grass had a cumulative nitrogen stress of 49.7%, and the following silage corn had a cumulative nitrogen stress of 20.7%. The other experiments (S-IM, S-UAN, and S-BM) showed cumulative nitrogen stresses of less than 1%. Consequently, the clipping yields for alfalfa and orchard grass were low, and the corn grain yield was reduced in the following season in 2015 relative to the other treatments. Due to limited nitrogen mineralization of the orchard grass, Cycles predicted a smaller corn yield in 2015 compared to the field experiment's corn yield (Table 1) while the other experiments (S-IM, S-UAN, and S-BM) had similar grain yields (≤1.1 Mg ha^{-1} difference) between Cycles and the field experiment.

Smaller N_2O emissions in both years and reduced corn grain yield in 2015 may be in part due to the high carbon to nitrogen ratio (C:N) in orchard grass, and Cycles may have simulated slow microbial mineralization of nitrogen for orchard grass. Cycles may not have properly simulated the decomposition of alfalfa and orchard grass residues because in this no-till system, the residues were not incorporated into the soil, and so less nitrogen was mineralized. To account for the low available nitrogen in the system, new models were run with larger amounts of nitrogen in the orchard grass. This resulted in a small increase of N_2O emissions that better matched the field experiment's emissions. After increasing nitrogen in the system, at termination orchard grass had no cumulative nitrogen stress in both years, and cumulative nitrogen stress of corn was reduced by 3.4% in 2015 and 8.1% in 2016. This reduction in nitrogen stress may indicate that orchard grass was limiting the N availability in the model, and the N inputs from orchard grass residues may need refinement. However, there can still be other possibilities, and this area requires further exploration.

Table 1: Cumulative N_2O emissions during the corn growing season and grain yield for the four cropping systems in the study.

Year	Treatment	Corn growing season N_2O emissions (g N ha^{-1})		Grain Yield (Mg ha^{-1})	
		Measured	Simulated	Measured	Simulated
2015	S-UAN	436	725	11.4	10.5
	S-BM	1420	1271	8.9	9.8
	AO-BM	1262	1053	10.2	8.1
	S-IM	3050	1440	8.9	8.6
2016	S-UAN	370	817	11.1	10.6
	S-BM	742	949	11.1	10.0
	AO-BM	1915	657	NA	NA
	S-IM	2460	1520	10	10.0

From the Cycles results, there were N_2O peaks around DOY 190 to DOY 225 (July 9 to August 13) in most of the models. These peaks may not have been measured in Ponce de Leon's experiment because they only measured N_2O emissions two times a week for 60 days after cover crop termination and manure application, and after the 60 days, N_2O was sampled every 7 to 31 days. Another possible explanation is that Cycles was more sensitive to precipitation events when predicting N_2O denitrification because Cycles consistently predicted peaks in nitrous oxide emissions after rainfall events (Fig. 4). Precipitation creates wet conditions favorable for denitrification, and therefore, fluxes in water content from precipitation can increase N_2O emissions (Lazcano, 2016). In Ponce de Leon, 2017, soil moisture content was identified as a major influence on denitrification and N_2O emissions. Cycles does not provide an output on soil moisture content, and that information could be helpful in understanding simulated N_2O elevations, especially for the results in 2016 when fewer field measurements were taken in 2016 summer season due to drier conditions. If available, comparing field and simulated soil moisture data could corroborate if the simulated soil moisture content was a factor causing spikes in emissions.

Table 2: Model performance measures comparing simulated against measured N_2O emissions for the four cropping systems in the study.

	2015				2016			
N_2O loss (g N ha^{-1})	S-UAN	S-BM	AO-BM	S-IM	S-UAN	S-BM	AO-BM	S-IM
Index of Agreement (IA)	0.93	0.58	0.52	0.19	0.54	0.81	0.37	0.60
Mean Absolute Error (MAE)	2.72	8.42	10.21	25.97	5.28	3.58	13.84	16.24
Root Mean Square Error (RMSE)	3.56	15.55	19.51	80.81	8.51	5.18	21.25	30.78

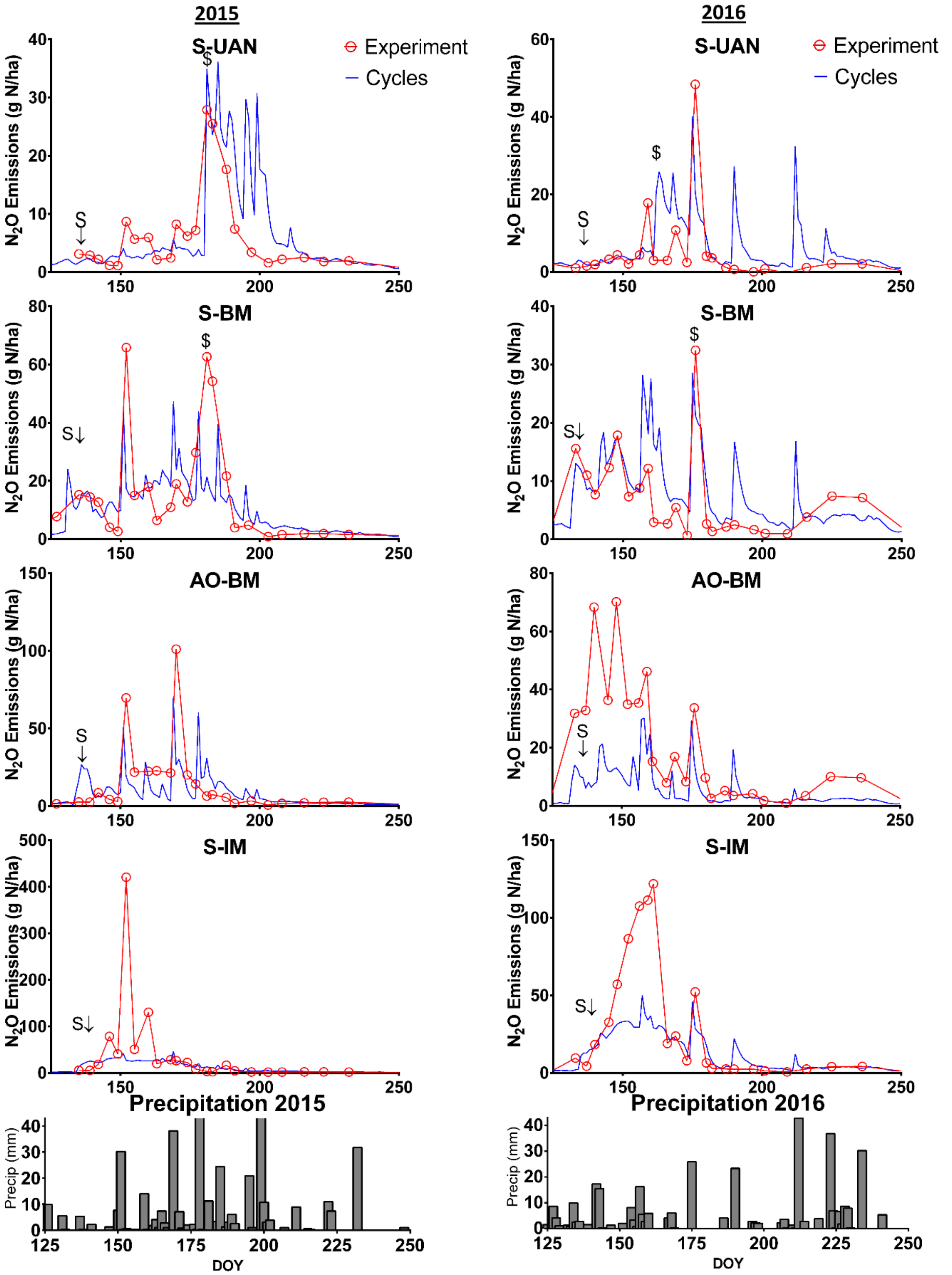

Figure 4: N_2O emissions from corn following soybean with inorganic fertilizer (S-UAN), soybean with broadcast manure (S-BM), alfalfa and orchard grass with broadcast

manure (AO-BM), and soybean with injected manure (S-IM) and precipitation during the seasons in 2015 (left) and in 2016 (right). S indicates when manure was applied, ↓ indicates when corn was planted, and $ indicates when side-dress N was applied.

Conclusion

Using Cycles to model no-till cropping systems with different treatments, we observed that Cycles is capable of simulating N_2O fluxes in response to nitrogen inputs and precipitation similarly to the field measured data depending on the agronomic management. Compared to field measured N_2O fluxes in Ponce de Leon's two-year field study, Cycles modelled nitrous oxide emissions well from no-till cropping system with dairy slurry manure fertilizer for corn-soybean with broadcast manure (S-BM) with the Mean Absolute Errors between measured and simulated corn growing season N_2O emissions ranging from 3 to 8. The corn-soybean rotation with inorganic fertilizer (S-UAN) was also simulated well by Cycles; the measured and simulated corn growing season N_2O emissions had Mean Absolute Errors ranging from 2 to 5. For S-BM and S-UAN, the Mean Absolute Error values were all less than 8.5, and the Index of Agreement values were all greater than 0.50. The other treatments, S-IM and AO-BM, were not modelled as well with higher Mean Absolute Error values ranging 10 to 26 and lower Index of Agreement values ranging from 0.2 to 0.6. Cycles underestimated emissions for corn-soybean with injected manure (S-IM) and corn-alfalfa and orchard grass with broadcast manure (AO-BM). Cycles was not as accurate for estimating the nitrogen in the injected manure bands between corn rows and for estimating how orchard grass and alfalfa mixture influence the rate of nitrogen availability and mineralization. Model refinement is recommended for simulating injected manure bands between corn rows and for alfalfa and orchard grass residues. In addition, further exploration of the simulated N_2O fluxes is needed to understand if Cycles overestimates denitrification from precipitation events or from other factors. These improvements to Cycles will make the model a useful tool for testing scenarios in no-till dairy cropping systems.

Chapter 3 : Reducing nitrous oxide emissions by improving dairy slurry manure application timing, placement, and rate

Current Research Gaps

Overall, N_2O emissions have wide ranges of variability based on weather, crop type, soil type, and fertilizer type, even after controlling the N application rates. Research has shown that side-dressing dairy manure has benefits, including higher crop yields (Beauchamp, 1983), but few studies have researched the effects of side-dressing dairy manure fertilizer on nitrous oxide emissions. Research has also shown that injection of manure reduces nutrient runoff, but at the same time, nitrous oxide emissions from greater denitrification may result (Dell et al, 2011). More research is needed to understand how nitrogen is balanced between N rate application, N application placement, N application timing, plant N uptake, and N_2O emissions.

Side-dressing organic manure, such as dairy slurry manure, is a fairly new practice with recent innovations in technology. It is not commonly practiced in the United States since equipment is expensive, and the technology is still being geographically distributed. In addition, the technology is also being improved to be able to inject manure while not damaging emerged crops. Since technology is still expensive and not widely available for commercial use yet, computer models provide a cheaper and more accessible tool to test different practices and greenhouse gas mitigation scenarios. In Chapter 2, we tested how well Cycles estimates nitrous oxide emissions in no-till corn cropping systems, and although Cycles did not as accurately simulate N_2O fluxes from corn with injected manure, we found that Cycles was generally able to model daily N_2O fluxes from broadcast manure and UAN treatments. Therefore, in this chapter we use Cycles to investigate N_2O mitigation strategies by simulating new technology and equipment that can side-dress dairy slurry manure.

Research Objective

This study focuses on dairy slurry manure and inorganic urea ammonium nitrate (UAN) fertilizers as the sources of nitrogen to corn cropping systems in Central Pennsylvania. Using Cycles, two experiments were conducted to test the impacts of better timing of fertilizer application and better rates of N application on nitrous oxide emissions. In the first experiment (time experiment), we hypothesized that if the application of animal manure fertilizer is applied at a time when corn uptake of N is greater, then N_2O emissions will be reduced without impacting grain yields. This experiment tests for better timing of nutrient management and evaluates the synchronization of fertilizer application with plant uptake.

For the second experiment (rate and placement experiment), we hypothesized that if the total amount of nitrogen applied to crops is reduced and side-dress dairy slurry manure is placed via injection, then total nitrous oxide emissions can be reduced without impacting grain yields. This experiment explores a better rate of nitrogen application and additionally, tests for better application methods, investigating if injection of dairy slurry manure at side-dress is a better place for the fertilizer compared to surface broadcasted placement.

Materials and Methods

Cycles

Cycles is an agroecosystems simulation model that simulates the biophysical processes and management practices occurring within cropping systems and other land uses. It generates results (outputs) that vary based on the model's inputs. Historical weather data from Rock Springs, Pennsylvania from 1986 to 2016 and Hagerstown soil were used in the model. The spin-up feature was used in this study.

Experiment 1: Testing Application Time

Using the Cycles model, a total of five scenarios were tested for nitrous oxide emissions in continuous corn rotation cropping systems in Central Pennsylvania (Table 3). All corn in these scenarios were no-till planted following no cover crop and harvested corn for grain. All five agronomic management scenarios in this experiment applied the same total rate of 255 kg N ha^{-1}, but that total rate was achieved with either a combination of dairy slurry manure with inorganic liquid UAN or just dairy slurry manure. The total amount of nitrogen in the manure was calculated using manure analysis results from Penn State’s Agricultural Analytical Services Laboratory.

The first test (BM+UAN) was a conventional or standard management scenario in which all dairy slurry manure is conventionally applied prior to corn planting at 169 kg N ha^{-1} (42,600 kg ha^{-1} manure) with 30 kg N ha^{-1} starter UAN and side-dressed only with UAN at 56 kg N ha^{-1}. The dairy manure was placed on the soil surface by broadcast.

Next, three scenarios (75% SD-BM, 50% SD-BM, and 25% SD-BM) were tested for nitrous oxide emissions by changing the time at which a total nitrogen rate of 255 kg N ha^{-1} was applied to corn for grain. The three rates of 25%, 50%, or 75% of 42,600 kg ha^{-1} manure (169 kg N ha^{-1}) were applied prior to corn planting with 30 kg N ha^{-1} starter UAN. The remaining 75%, 50%, or 25% of the 42,600 kg ha^{-1} manure (169 kg N ha^{-1}) was broadcast applied as side-dress when corn was at V3 stage around day of year (DOY) 163. Side-dress inorganic UAN at rate 56 kg N ha^{-1} was applied on DOY 180. These scenarios test for better timing because when some of the manure is applied at side-dress, the roots of the corn plant are more established and available to uptake nitrogen, making it a better time for application.

The fifth scenario (BM) represented a farm with a high concentration of dairy cattle to farmland. The only source of fertilizer for the farm was dairy slurry manure, and all of the manure was applied prior to corn planting at a greater rate of 64,195 kg N ha^{-1} to supply a total nitrogen rate of 255 kg N ha^{-1}. No inorganic liquid UAN was applied throughout the season. This is a scenario where the manure fertilizer is not applied at the right time (all prior to corn planting), not applied at the right place (surface broadcasted), and not applied at the right rate (too high of a rate).

Table 3: Schedule of events in Cycles for Experiment 1 for the following agronomic managements at total nitrogen input 255 kg N ha^{-1}: standard (BM+UAN), side-dress broadcasted manure at 25%, 50%, and 75% of total dairy slurry manure, and only dairy slurry manure broadcasted (BM).

DOY	Standard (BM+UAN)	3 side-dress manure scenarios (%SD-BM)	Only dairy slurry manure (BM)
112	Fertilization of 42,600 kg ha^{-1} manure broadcasted. (**169 kg N ha^{-1}**)	Fertilization of manure at **75%, 50%, or 25% of 42,600 kg ha^{-1}** manure broadcasted	Fertilization of 64,195 kg ha^{-1} manure (**255 kg N ha^{-1}**)
113	Tandem disk harrow to incorporate manure into the soil	Tandem disk harrow to incorporate manure into the soil	Tandem disk harrow to incorporate manure into the soil
114	Cultivator	Cultivator	Cultivator
115	Planting of corn	Planting of corn	Planting of corn
115	Starter fertilization with liquid UAN (**30 kg ha^{-1}**)	Starter fertilization with liquid UAN (**30 kg ha^{-1}**)	None
163	None	Side-dressing of manure at **25%, 50%, or 75% of 42,600 kg ha^{-1}** manure broadcasted	None
180	Side-dressing of UAN (**56 kg ha^{-1}**)	Side-dressing of UAN (**56 kg ha^{-1}**)	None
279	Harvesting of corn	Harvesting of corn	Harvesting of corn

Experiment 2: Testing Application Rate and Placement

To test for better rates of application coupled with side-dressing the manure via injection, the three side-dress manure scenarios from Experiment 1 were simulated at a reduced total nitrogen application rate (RR) of 199 kg N ha^{-1} (RR 75% SD-IM, RR 50% SD-IM, and RR 25% SD-IM) rather than 255 kg N ha^{-1}. The same agronomic managements for the three SD-BM scenarios from Experiment 1 were practiced, including a starter fertilization with liquid UAN at 30 kg ha^{-1} and 42,600 kg ha^{-1} dairy slurry manure applied in two portions. However, UAN was not side-dressed on DOY 180. The reduced application rate of 199 kg N ha^{-1} was possible by eliminating the side-dressing of UAN. Another change from Experiment 1 was the side-dressing of manure on DOY 163 was injected 10 centimeters into the soil (IM) rather than surface broadcasted. Injection of the side-dress manure more properly represents the new technology that is currently being used to side-dress manure. Therefore, Experiment 2 also tests for improving the placement because the manure at side-dress is injected. Injection of the manure lowers the chances of N volatilization and runoff.

The three reduced rate side-dress injected manure scenarios (RR 75% SD-IM, RR 50% SD-IM, and RR 25% SD-IM) were compared to the same BM+UAN scenario from Experiment 1, which had a total N rate 255 kg N ha^{-1} and conventionally applied dairy slurry manure prior to corn planting at 169 kg N ha^{-1} (42,600 kg ha^{-1} manure) with 30 kg N ha^{-1} starter UAN and side-dressed only with UAN at 56 kg N ha^{-1}.

Results and Discussion

Experiment 1: Testing Application Time

Comparing the different times of applying nitrogen to corn, the results showed that the more nitrogen applied as side-dress, the smaller the amount of cumulative nitrous oxide was emitted (Table 4 and Fig. 5). Grain yields were similar across all simulations, averaging at 12.54 Mg ha^{-1}. These results are consistent with what was expected because when nitrogen is added to a cropping system after corn has emerged, the corn plant is larger and more capable of taking up nutrients, and thus, a lower amount of nitrogen is available for denitrification, nitrification, volatilization, or leaching.

The BM scenario had an average annual total N_2O emissions 47% greater than BM+UAN. The greater amount of manure applied in BM scenario before corn planting put more nitrogen at a time and place susceptible to volatilization into the atmosphere. More N_2O emissions were lost early in the season because there were no corn plants to take up the nitrogen, resulting in a larger amount of nitrogen lost to the atmosphere. When 75% of the total N was side-dress broadcasted manure, the cumulative N_2O emissions were 178.4 kg N ha^{-1} less than the cumulative N_2O emissions of BM scenario. By not applying all 255 kg N ha^{-1} (64,195 kg ha^{-1}) manure fertilizer before corn planting and instead, managing with 75% SD-BM, an average 10.3 kg N ha^{-1} N_2O emissions could be reduced each year. These results show that mid-June could be a better application time for dairy slurry manure to reduce nitrous oxide emissions.

Table 4: Cumulative N_2O emissions from 1986 to 2016, average yearly total N_2O emissions, and percent change in emissions compared to the standard (BM+UAN) from a total nitrogen input rate of 255 kg N ha^{-1} with the following agronomic managements for corn: broadcast manure and UAN applied prior to planting (BM+UAN), only dairy slurry manure (BM), and manure broadcasted at side-dress with rates 25%, 50%, and 75% of 255 kg N ha^{-1} (25%, 50%, & 75% SD-BM). All scenarios except for BM had 30 kg ha^{-1} starter UAN applied at planting and 56 kg ha^{-1} UAN applied at side-dress.

Management Scenario	**Manure/UAN N application rate (kg N ha^{-1})**		**Cumulative N_2O emissions 1980-2016 (kg N ha^{-1})**	**Avg yearly total N_2O emissions (kg N ha^{-1})**	**% change in average yearly total emissions compared to BM+UAN**
	Prior to plant	Side-dress			
BM+UAN	169/30	0/56	614.8	16.6	NA
BM	255	0/0	703.6	24.5	+47.20
25% SD-BM	127/30	42/56	584.7	15.8	-4.82
50% SD-BM	84.5/30	84.5/56	554.7	15.0	-9.64
75% SD-BM	42/30	127/56	525.2	14.2	-14.5

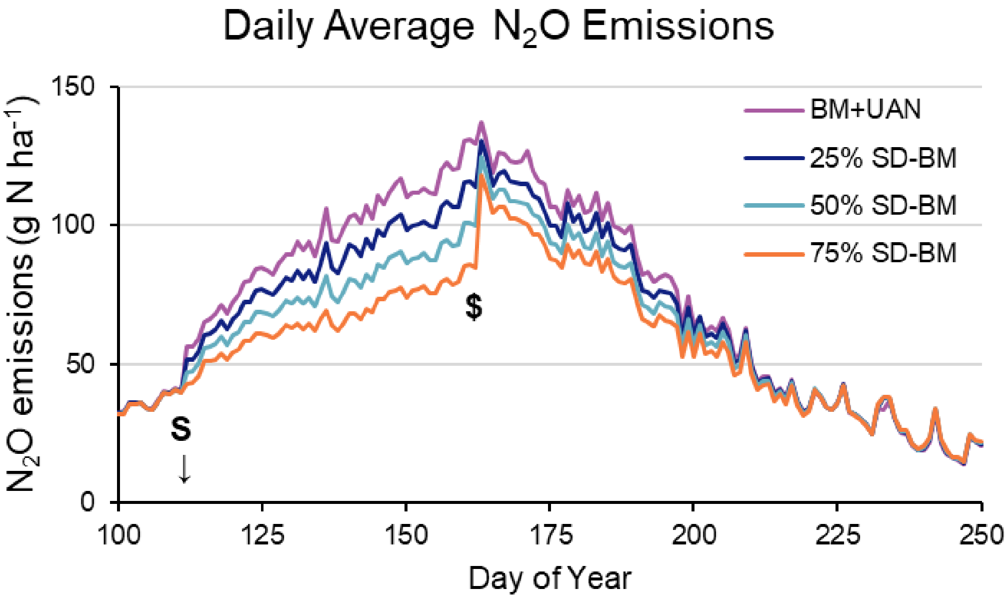

Figure 5: Daily average N_2O emissions (1980-2016) between DOY 100 and DOY 250 from the following agronomic managements with total N input of 255 kg N ha^{-1}: only dairy slurry manure applied (BM), standard management (BM+UAN), and manure broadcasted at side-dress with rates 25%, 50%, and 75% of 255 kg N ha^{-1}. ↓ indicates when corn was planted, S indicates when manure was applied, and $ indicates when side-dress manure was applied on DOY 163.

Experiment 2: Testing Application Rate and Placement

Since the results from Experiment 1 suggested that improving the timing of manure application by side-dressing can reduce N_2O emissions, we experimented with reducing the nitrogen rate and placement of the side-dress manure via injection. In Experiment 1, at a total nitrogen input rate of 255 kg N ha^{-1}, the percent reduction in emissions from the standard (BM+UAN) when manure was side-dressed ranged from 4% to 14% (Table 4). At a lower nitrogen input rate of 199 kg N ha^{-1} in Experiment 2, the percent reduction in emissions from BM+UAN was greater, ranging from 17% to 19% reduction when manure was side-dressed and injected (Table 5).

Removing the side-dress UAN on DOY 180 was possible due to timing the manure N application when the corn could take up more of the manure N rather than before any corn had been planted and growing. In addition, by injecting the manure at side-dress, the manure was applied at a place where nitrogen was less likely to volatilize, and so there was more plant-available N. In comparison, when manure was broadcast applied before corn planting, the nitrogen in the manure could volatilize, and more nitrogen in the form of manure needed to be applied to compensate for lost nutrients. In Cycles, the average annual ammonia volatilization was reduced by 16 to 35 kg N year^{-1} after reducing the total nitrogen rate and injecting side-dress manure. More of the nitrogen may have become available for plants rather than volatilizing. Therefore, with the improvements from application timing and placement, we did not need to apply as much nitrogen from UAN, and we could reduce the total application rate to 199 kg N ha^{-1} by removing the 56 kg ha^{-1} side-dress UAN on DOY 180.

In the continuous corn rotation cropping system, to achieve the best corn yields, the fertilizer rates were already precautionarily set at a higher rate under the assumption that some N would be lost and unavailable for plant uptake. Even when the total N input was reduced by 56 kg ha^{-1}, the corn yields were maintained at an average of 12.54 Mg ha^{-1} because nitrogen was added when the corn actually needed it at the time of side-dressing. In general, the continuous corn rotation cropping system already had enough nitrogen for corn to properly grow, but we found that even if we reduced the total nitrogen input into the system, we could reduce N_2O emissions while maintaining corn grain yields because the time of application was improved by side-dressing manure and because manure injection improved the N placement (Table 5 and Fig. 6). These results are consistent with most literature and meta-analyses on nitrous oxide: reducing nitrogen inputs is a main nutrient management strategy to reduce nitrous oxide emissions from agriculture (Van Groenigen et al., 2010; Scherback et al., 2014).

Literature has shown that injection of dairy slurry manure increases N_2O emissions due to wetter and microbial subsoil conditions conducive for denitrification (Dell et al., 2011). While injected dairy slurry manure tends to increase N_2O emissions compared to broadcasted, the emissions overall were still reduced because manure was applied at side-dress and the total N rate was reduced. In Experiment 1, the side-dress manure was broadcasted, and even though injected manure can increase N_2O emissions, the emissions were still further reduced in Experiment 2 with injected manure side-dress because of the reduced total N rate.

Table 5: Cumulative N_2O emissions from 1980 to 2016, average yearly total N_2O emissions, and percent change in emissions compared to the standard (BM+UAN) with the following agronomic managements for corn: standard with broadcast manure and UAN applied prior to planting (BM+UAN) and manure injected at side-dress with reduced rates 25%, 50%, and 75% of 199 kg N ha^{-1} (RR 25%, 50%, & 75% SD-IM).

Management Scenario	**Manure/UAN N application rate (kg N ha^{-1})**		**Cumulative N_2O emissions 1980-2016 (kg N ha^{-1})**	**Avg yearly total N_2O emissions (kg N ha^{-1})**	**% change in average yearly total emissions by side-dressing**
	Prior to plant	Side-dress			
BM+UAN	169/30	0/56	614.8	16.6	NA
RR 25% SD-IM	127/30	42/0	505.8	13.7	-17.5
RR 50% SD-IM	84.5/30	84.5/0	502.2	13.6	-18.0
RR 75% SD-IM	42/30	127/0	496.4	13.4	-19.3

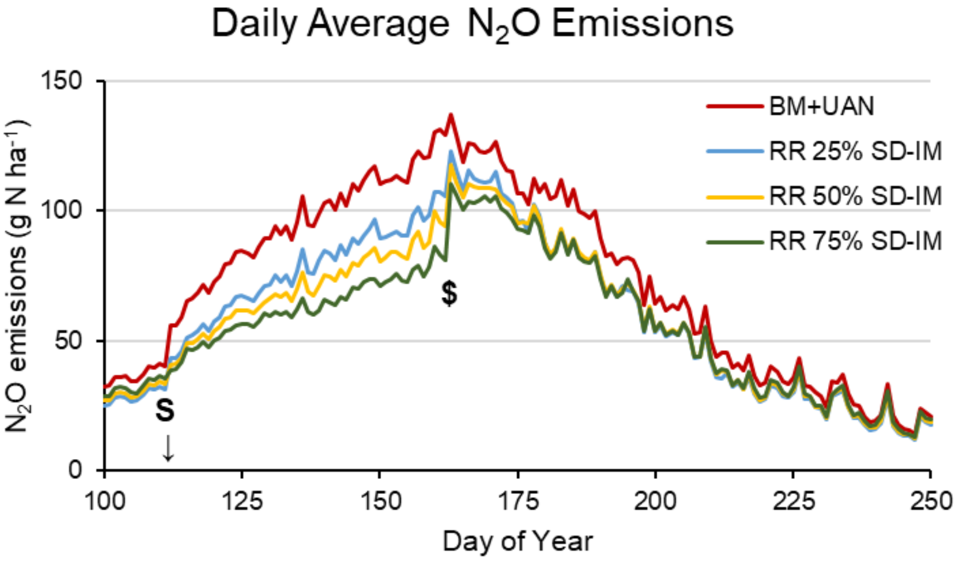

Figure 6: Daily average N_2O emissions (1980-2016) between DOY 100 and DOY 250 from the following agronomic managements: BM+UAN at total rate 255 kg N ha^{-1} and injected manure at side-dress with 25%, 50%, and 75% of 199 kg N ha^{-1}. ↓ indicates when corn was planted, S indicates when manure was applied, and $ indicates when side-dress manure was injected on DOY 163.

In Chapter 2, we found that Cycles underestimated N_2O fluxes after injected manure application events by 38.2% to 52.8% (Table 1). To compensate for the underestimated results, a correction factor of 1.455, calculated from the mean of 38.2% and 52.8%, was multiplied to the N_2O fluxes after side-dressing on DOY 163 for seven days (emissions remained elevated for approximately seven days in Ponce de Leon, 2017). After applying the correction factor, the cumulative N_2O emissions were still less than BM+UAN by a range of 95.6 to 106 kg N ha^{-1} across all three side-dress scenarios (Table 6). However, the IM treatments simulated in Chapter 2 were applied early in the season before corn was taking up N, and so the correction factor represents a time that is earlier than what is necessary for this experiment. The correction factor reflects a time when the corn N uptake was not well synchronized with manure application. In comparison, injected manure was applied when V3 stage corn was taking up N in this chapter, so the emissions would likely be less than the corrected results. There are differences in climate and plant factors between spring and early summer conditions that affect the accuracy of the correction factor for this chapter's purpose. These factors could reduce the correction factor, and so the correction factor 1.455 was a conservative correction just for estimation purposes since we do not know exactly how much to adjust the correction factor. In addition, the N_2O emissions during this time were not just due to the side-dress N, but we assumed that the major N input driving emissions at that time was from the side-dress manure.

After applying the correction factor to account for Chapter 2's finding that Cycles underestimated injected manure N_2O emissions in spring prior to corn planting, the cumulative N_2O emissions of side-dress were still reduced in Experiment 2 with injected manure side-dress because of the reduced total N rate (Table 6).

Table 6: Cumulative nitrous oxide emissions from 1980 to 2016 before and after a correction factor of 1.455 applied to nitrous oxide fluxes from DOY 163 to DOY 170 from the following agronomic managements: side-dress injected manure at 25%, 50%, and 75% of reduced rate 199 kg N ha^{-1}.

	BM+UAN	RR 25% SD-IM	RR 50% SD-IM	RR 75% SD-IM
Original cumulative N_2O emissions (kg N ha^{-1})	614.8	505.8	502.2	496.4
Corrected cumulative N_2O emissions (kg N ha^{-1})	NA	519.2	515.2	508.7

Chapter 4 : Conclusion and Recommendations

Conservation agriculture practices and nutrient management strategies have great potential to reduce nitrous oxide emissions in agronomic cropping systems in Pennsylvania. Some strategies require new equipment, technology, and practices, and therefore preliminary computer models can evaluate their drawdown potential. Chapter 2 evaluated how well Cycles can model a no-till corn system with dairy slurry manure fertilizer, and we concluded that Cycles can currently model corn following soybean with broadcast manure and inorganic fertilizer (UAN) better than corn following soybean with injected manure and corn following alfalfa and orchard grass with broadcast manure. While the modelling of cover crop residues and N_2O fluxes from injected manure needs improvements, we expected from the results in Chapter 2 that Cycles would be capable of producing models of N_2O emissions with the new agronomic management strategies in Chapter 3.

In Chapter 3, we conducted two experiments and found that by implementing the management strategies of side-dressing manure and applying a reduced and “right” rate of nitrogen to crop needs, farmers can maintain grain yields while lowering nitrogen inputs to soil and reducing nitrous oxide emissions. The total nitrogen application rate can be reduced from 255 kg N ha^{-1} to 199 kg N ha^{-1} when manure is side-dressed and injected. The results showed that reducing the total nitrogen input to a cropping system further reduces the total nitrous oxide emissions while grain yields remained similar. More efficient use of dairy manure as fertilizer can reduce the need for commercial inorganic fertilizer, which can reduce costs and save money.

It is recommended for there to be financial incentives that encourage farmers to adopt manure side-dressing practices and equipment. More technological innovations to manure side-dressing equipment can help to lower purchasing costs and promote widespread adoption of the equipment. Overall, overapplication of manure and nitrogen fertilizers need to be discouraged to reduce nitrous oxide emissions and to help achieve Drawdown.

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ACADEMIC VITA

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EDUCATION

The Pennsylvania State University: University Park, PA — Graduation: **May 2020**

Schreyer Honors College
B.S. in Environmental Resource Management
Minors: Entrepreneurship & Innovation
Environmental & Renewable Resource Economics

Danish Institute for Study Abroad: Copenhagen, Denmark — **Spring 2019**

WORK EXPERIENCE & RESEARCH

Student Farm Production Intern — **February 2017 – May 2020**

Student Farm at Penn State, The Pennsylvania State University, PA

- Produced, harvested, & delivered 34 types of plant produce at the student-run farm
- Hosted volunteers, planned events, engaged with the community through service days & tours
- Conducted 30 interviews for the Student Farm internship program

Sustainability Intern — **January – May 2020**

Centre Region Planning Agency, State College, PA

- Assisted the Sustainability Planner with preparing a Climate Action and Adaptation Plan
- Identified and researched strategies to reduce greenhouse gas emissions

Drawdown Undergraduate Research Scholar — **June – July 2019**

Penn State Research Experience for Undergraduates, Pennsylvania State University, PA

- Researched & modelled nitrous oxide emissions produced from fertilizers on farms
- Presented poster at the international conference of Drawdown at Penn State in Sept. 2019

Community Engagement Intern — **June – August 2018**

Penn State Extension Center Philadelphia, Philadelphia, PA

- Supervised the weekly farmer's market of an urban farm and managed high school volunteers
- Researched and began creating a rain garden and French drain for rainwater management
- Engaged in dialogues about power, privilege, and race within the context of urban agriculture

Chesapeake Bay Program Office Intern — **June – Aug 2017, Dec 2017 – Jan 2018**

Pennsylvania Department of Environmental Protection, Harrisburg, PA

- Updated tracking database with new data entries and assisted in developing administrative forms
- Created tracking spreadsheet to record budget & expenditure for two Bay Program federal grants
- Collated funding information for Phase 3 Watershed Implementation Plan Funding Workgroup

ACTIVITIES

Student Farm Club — **Aug 2016 – May 2020**

- Executive Director, Club Programming Director, Club Engagement Coordinator

Volé Penn State Dance Company, Dancer — **Fall 2016 – May 2020**
Penn State Alternative Breaks, Participant — **Nov 2019**
Music Service Club, Secretary, Co-President, Historian — **Fall 2016 – Dec 2018**
Council of LionHearts, Vice President — **Fall 2018**
Happy Valley LaunchBox, Idea TestLab Participant — **Spring 2018**
Net Impact, Service Corps Member — **Fall 2016 – Spring 2017**
AURORA Penn State Outdoor Orientation Program, URSA Participant — **Summer 2016**