DEVELOPMENT OF A WHOLE FARM GROW-FINISH SWINE OPERATION DECISION SUPPORT TOOL THROUGH MODELLED NUTRIENT LOSS

By

Brooke Latack

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ABSTRACT

DEVELOPMENT OF A WHOLE FARM GROW-FINISH SWINE OPERATION DECISION SUPPORT TOOL THROUGH MODELLED NUTRIENT LOSS

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The need for animal production decision-making tools is essential to ensuring sustainable animal protein production. Of the decision-making tools available, there is a lack of consideration for year-after-year consequences of and the interaction between animal production, manure storage, manure land application, and crop nutrient uptake. A model was created to address this gap using a grow-finish swine system with respect to nitrogen and phosphorus losses. Empirical formulas and published information of nutrient retention or losses were used in the development of a management decision driven model. Observed results from a previous study at Michigan State University were compared to calculated results to assess the validity of model outputs. Calculated outputs for total manure excretion, nitrogen excretion, and nitrogen loss from the system were within the error found in the observed data. The model was tested further by modifying the baseline scenario to test model sensitivity. Changes in manure storage and dietary phosphorus concentrations had a greater impact on management longevity than manure application method and field location. The results of the model assessment indicate high variability in outputs, but this may reflect high variability in animal production observation, indicating that model outputs still portray a realistic vision of a grow-finish swine facility. This model allows the identification of critical control points within the system to help direct future research and support producers and advisors in creating a long-term, sustainable animal protein production system.

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1 Introduction

The need for animal production decision-making tools is essential to ensuring sustainable production. Of the decision making tools available, there is a lack of consideration for year-after-year consequences of and the interaction between animal production, manure storage, manure land application, and crop nutrient uptake. The ability of a decision-making tool to address this gap can influence management decisions and, therefore, long-term farm sustainability.

Two nutrients of specific interest are nitrogen (N) and phosphorus (P) because of their negative environmental impact (i.e. leaching to groundwater and runoff leading to pond or lake eutrophication). Both nutrients are important for animal growth. If fed in insufficient quantities production decreases significantly. If fed in excess of nutrient needs animals may meet production goals, but additional land is needed to apply these excess nutrients in order to avoid negative environmental consequences. Manure storage contributes to greater air emissions, including nitrous oxide and ammonia. State-specific nutrient application thresholds influence producer decisions. Access to improved decision tools will make it easier to make better decisions that are consistent with state guidelines.

A software program that follows N and P flows through a swine production system from excretion of nutrients through manure storage, manure land application, and crop nutrient uptake allows researchers opportunities to identify areas for further research to improve understanding of sustainable animal production. While many programs currently available offer portions of the complete system, a comprehensive program to analyze the entire system does not exist. There is a need for a tool that analyzes a complete system through the four main stages of manure handling. Advanced software to simulate a farm and to estimate the nutrients remaining in each field following crop harvest and the number of years the current management practices could continue before soil nutrient concentrations reach regulatory thresholds will improve the system sustainability.

2 Objective

The objective of this work is to use reference equations and data to model the flow of N and P through grow-finish swine operations including nutrient absorption during growth, losses during manure storage and land application, and crop nutrient uptake. Unlike other tools available, a goal of the model development is to integrate feedback mechanisms at various points of the system, providing a dynamic understanding of how components of the system directly or indirectly interact over a multi-year time-frame (iterative process).

The following goals were critical in the development of the model:

- Identify impacts and consequences of management decisions with respect to N and P;
- Reveal critical control points to increase the sustainability of animal protein production;
- Aid in the development of a collaborative model to understand the broader context of a sustainable of animal protein production system (social and economic impacts).

3 Literature Review

3.1 Livestock production in the United States

The anticipated 33% to 71% population increase between now and 2050 calls into question food security (Gerland et al., 2014). Because of the expected increase in demand for livestock products it is important to find sustainable livestock and crop management systems (Nardone et al., 2010; Wu et al., 2014). Balancing economic, environmental and social factors is key to achieving efficient livestock production while leaving the smallest environmental impact and adhering to social constructs (Hansmann et al., 2012; Hoffmann, 2011; Honeyman, 1996). Excess nutrients, emitted through air, land, and water, create ecosystem imbalances and poor living conditions (Jongbloed and Lenis, 1998).

3.2 Swine Production

Modern swine production systems group animals by production phase often with separate buildings for different phases (breeding/gestating, nursery, and grow-finish life stages) and each phase is fed N levels appropriate for productive lean growth at that life phase (Kliebenstein and Lawrence, 1995). An essential nutrient for both animals and plants is N (Havlin et al., 2014; Wu et al., 2014). It is used animals to build amino acids and subsequently construct proteins (Wu et al., 2014). Each production phase has specific N and P needs to maximize productivity without excessive nutrient excretion in urine and feces (Lange, 2013). Phase feeding has been shown to reduce N excretion by 4.4% (Sutton et al., 1999). The difference in nutrient recommendations between production phases is based on the differing N retention values for the different phases.

Gilts retain less N, at a rate of protein deposition of 234 g/day, than barrows with a retention of 277 g/day. Thus, if gilts are fed a level of N similar to barrows, the gilts would excrete more N compared to the barrows (Lange, 2013).

3.3 Animal Housing

Many factors in swine housing will affect nutrient losses, such as manure collection methods, time between manure collections, and housing management. Flooring in the swine housing will affect how and how often of manure collection occurs (Olesen and Sommer, 1993). Common styles of flooring include partially or fully slatted flooring or solid flooring covered in shavings or straw (Arogo et al., 2003). Slatted floors allow manure to collect for hours to months following excretion depending upon depth of storage below the slatted floor (Arogo et al., 2003). Litter from solid floors may also be collected at different time periods (Arogo et al., 2003). Philippe et al. (2007) found that slatted floor collection systems emitted 6.2 g/day of ammonia while solid floor covered with straw emitted 13.1 g/day when left for a full 120 day grow-finish phase. The differences in flooring and in-house manure storage will lead to differences in the build-up of ammonia (Herber et al., 2000; Lim et al., 2002; Zhu et al., 2000). Drummond et al. (1980) observed that ammonia levels of 50, 100, and 150 ppm reduced swine growth by 12, 30, and 29 percent, respectively, compared to a well-ventilated chamber with minimal aerial ammonia present. The decrease in swine growth due to ammonia levels is primarily in lean muscle accretion, resulting in an increased excretion of nutrients consumed.

3.4 Manure Storage

Manure storage method and structure varies by farm and each type of storage reflects different rates of N emission (Liu et al., 2014). Collection conditions (e.g. warm or cool temperatures, air flow over the surface of the storage area, and time stored) impact the N gas lost as nitrous oxide and ammonia (Havlin et al., 2014; Liu et al., 2014). One study found that uncovered manure storage lost 14.7% of the initial N while covered manure storage lost only 5.6% of initial N due to active air movement over the uncovered manure (Hansen et al., 2006). A meta-analysis of available data revealed that a lagoon storage system at a finishing farm emitted a mean of 3.70 ± 3.74 kg/year/pig while a slurry tank at a finishing farm emitted a mean of 1.85 ± 2.28 kg/year/pig (Liu et al., 2014). Warmer storage systems will emit more ammonia than a cooler storage system (Liu et al., 2014). These differences in emissions are an integral part of understanding the whole system and where N losses occur.

3.5 Land Application of Manure

Movement from manure storage into the manure spreader and onto the field will result in some gaseous N loss. Differing manure application methods result in greater variation in N emissions (Havlin et al., 2014). Ammonia loss following land application of manure using surface broadcast, surface incorporation, and deep placement methods was 68%, 17%, and 2% of total N applied, respectively (Huijsmans et al., 2003). The same study found that increasing ambient temperature increased the N lost from 35.3% at 10ºC to 56.2% at 20ºC when manure was surface broadcasted (Huijsmans et al., 2003). Incorporation and deep placement methods resulted in similar increases in N lost as ambient temperature increased (Huijsmans et al., 2003). Precipitation around the time of manure spreading contributes to leaching and runoff because nutrient-rich water moves faster than the rate at which plants take up N (Innes, 2000). Excess P in the soil increases the chance of run off, ultimately increasing the chance of eutrophication in nearby water sources (Havlin et al., 2014).

3.6 Crop Nutrient Use

Crops absorb nutrients throughout the growing season (Havlin et al., 2014). Each crop has a specific timeframe during which nutrient absorption rate is greatest (Havlin et al., 2014). Similarly, each crop has a different rate of nutrient uptake and nutrient requirement so it is imperative to be able to make crop-specific nutrient recommendations. At the time of greatest nutrient absorption, the crop will absorb more N at a faster rate reducing environmental risks (Havlin et al., 2014). Soil type also plays a role in the availability of nutrients for crop uptake. Fields with sandy or loam types of soil had less N and P available for crop uptake than the fields composed mainly of clay, though sandier soils had higher N availability in the winter compared to clay soil (Havlin, et al., 2014). All of the variables affecting N uptake by crops are essential when understanding the amount of N being used in a system and remaining amount of N is left in the soil. Excess N in the soil is absorbed by a plant and can cause weakened fiber within the plant due to increased carbohydrate movement (Havlin et al., 2014). Excess N uptake can cause delayed maturity in plants (Havlin et al., 2014). If the soil is in excess of N to the extent that the crop is no longer absorbing N, a stock will be left in the soil (Havlin et al., 2014).

3.7 Nitrogen and Phosphorus Impacts on the Environment

Leaching and runoff of N are damaging to the environment (Daniel et al., 1994). If leaching occurs vertically it can drain into the water supply, making it dangerous for human consumption. If leaching or run off occurs into a river, lake, or pond the N will cause eutrophication resulting in uncontrolled algae growth and depletion of the oxygen in the water supply (Daniel et al., 1994).

Gaseous emissions of N are mainly in the form of nitrous oxide, a greenhouse gas, and ammonia (Havlin et al., 2014). Both can be emitted during manure storage and manure land application (Brunke et al., 1988; Havlin et al., 2014; Morken and Sakshaug, 1998). Emissions can also create human health issues. Studies found that prolonged exposure to even low levels of ammonia led those working within the barns to be susceptible to regular upper respiratory irritation, inflammation, and infections (Crook et al., 1991).

An important nutrient in crop growth is P. It is important to keep fields supplied with P, but not all P is in a form that can be used by plants readily (Havlin et al., 2014). For this reason crops may appear deficient when the soil has adequate amounts of P (Havlin et al., 2014). Over applying manure to fields can lead to dangerously high levels of P in the soil, which could move into nearby water and cause eutrophication (Jongbloed and Lenis, 1998; van der Werf and Petit, 2002).

Soil P concentration is often used as the benchmark for constructing manure application regulations because P concentrations often pose an environmental risk well before N or potassium concentrations (Ribaudo et al., 2003). Many states employ maximum P application rates, including allowance for multiple years' worth of P application allowed provided the field is not returned to for a period of time and the starting soil P concentration does not exceed a prescribed threshold.

3.8 Computer modeling of nutrient flow of swine production

Understanding the flow of nutrients through a swine production system is an important step in identifying ways to reduce environmental impact of meat production. Equations from well-developed methods can be used to predict animal nutrient retention and excretion (National Research Council, 2012), manure storage losses, manure land application (Midwest Plan Service), and plant nutrient uptake (Havlin et al., 2014; Lange, 2013). Optimization of management practices contribute to decreases in nutrient leaching, air emissions, and soil fertility issues – all major environmental concerns for livestock and crop production (Salois, 2015; Tilman et al., 2011).

3.9 Attributes for nutrient flow through animal production

Multiple tools exist to consider management practices in place on the farm and follow the flow of nutrients through the farm. Each program has specific attributes that make the software program beneficial to users. However, currently available programs lack essential features that result in a complete understanding of nutrient movement and flows. The Purdue Manure Management (MMP) software program allows the user to enter nutrient and field information and receive manure management plans for spreading on fields, but does not allow for a long term assessment of the environmental impacts of the management practices and does not account for any feedback within a system (Karmakar et al., 2007). Other programs, like the Ammonia Emissions Estimator, provide an understanding of emissions from animal production facilities though no other losses or manure calculations are included (Koelsch et al., 2005). Whole farm nutrient balance software developed by Cornell University (version 2.0, 2012) provides a whole farm nutrient balance, but lacks the ability to project years into the future as to the sustainability of the management practices. Other software exists that have similarities to the programs outlined, but all programs available lack the year-to-year environmental analysis necessary for understanding longer term implications of management.

The capability of the software platform to allow the following calculations and input variables to be used are important for mapping nutrient flow:

- Animal management: feed composition, growth modifiers used, number of animals produced, animal nutrient needs for stage of production
- Manure storage: collection, storage, time manure is stored
- Manure field application: application method, soil conditions, ambient temperature, precipitation patterns, dominant soil texture
- Nutrient removal by crops: soil nutrients content, soil nutrient availability, crop, crop yield, crop nutrient needs
- Detailed output depicting management impacts: Amount of manure produced by animals, nutrient loss during manure storage, nutrient loss during field

application of manure, manure application quantities (i.e. a spreading plan), soil nutrient concentrations after each crop harvest, and number of years until soil nutrient levels approach a specified limit.

3.10 Choosing software for the model

The user interface of a model is an important attribute of model acceptance by the intended audience. Accessibility and familiarity are additional important considerations when choosing the model platform. Widely-used software, such as Microsoft Excel, gives the general public easy access. Because Excel is user-friendly programs that interface with Excel are advantageous. Because Excel does not incorporate some of the more complicated mathematical structures, a more complicated and robust program is required.

Some software programs offer a wide range of programming capabilities. MATLAB offers programming options as far as computation, data analysis, programming, and developing models. This system is ideal for many hoping to program more complex models. LabVIEW (2012) offers similar programing capabilities. Both programs allow the user to delve deeper into more complex modeling options, but both programs require purchasing of the software. Neither program is widely used outside of the engineering discipline. The general public is unlikely to purchase software for the sole purpose of a single model.

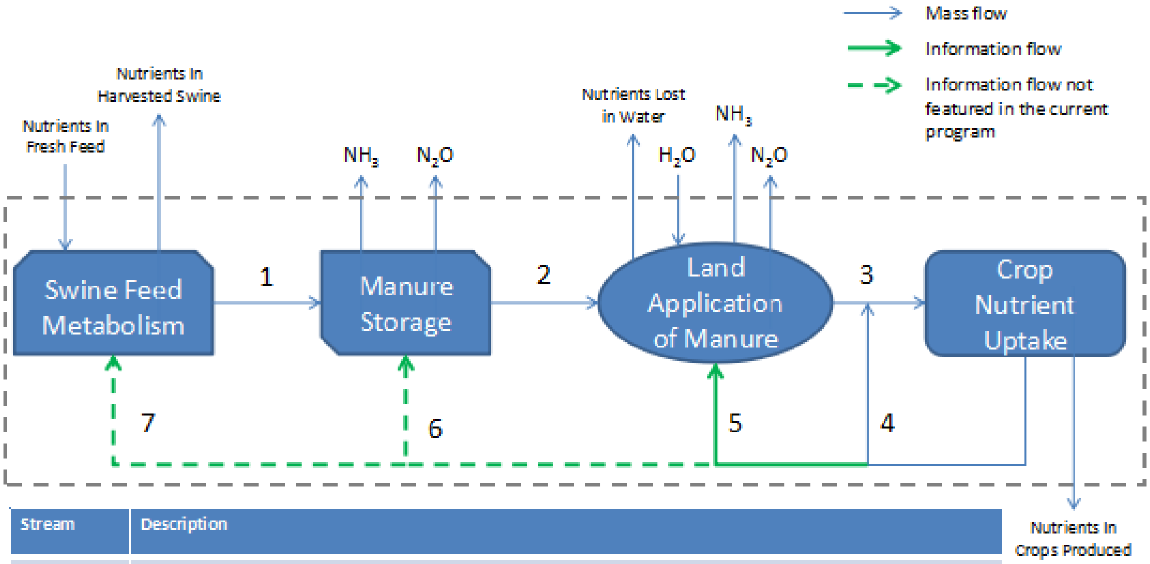
For the purposes of following N and P from animal production to manure storage to manure application and finally crop nutrient uptake, software with robust modeling capabilities, such as LabVIEW (2012), have the ideal user interface and mathematical capabilities. Because the model intent is as a tool to further future research, software cost was not deemed a critical decision point. Using the abilities of LabVIEW to export data calculated into an Excel file and ultimately being able to import the data into visual representation software allows a robust model to be built that aggregates four primary sources of N and P movement on a swine operation. With these concepts at the forefront in the need for a comprehensive software program, creating a program to integrate animal N and P excretion, losses during manure storage and land application, and residual nutrients remaining in soil after crop nutrient uptake is prudent to creating a better understanding of the sustainability animal protein production practices over multiple years.

4 Materials and Methods

4.1 Project Scope

Project boundaries are illustrated in Figure 1. The scope of this project is the farmstead boundary and includes swine feed metabolism, on-farm manure storage, land application of manure, and crop nutrient uptake. Nutrients considered are N and P. Nutrient retention by pigs, nutrients lost to overland flow into surface waters and leachate into groundwater, N lost to the atmosphere as NH_3 and N_2O, and nutrients removed from the soil by crops are within the scope of this project. All feedstock used in the swine production portion of the system is assumed to be brought in from outside the system. The fate and impact of nutrients in harvested swine, soil and manure emissions of NH_3 and N_2O emitted, and nutrients in crops grown that leave the system after the crop growing season are not within the scope of this project. Site specific location is important for determining nutrient loss based on dominant soil texture. The geographic scope of the project is the United States (including Hawaii and Alaska), where dominant soil texture data have been incorporated into the program.

Figure 1. Model boundaries and scope

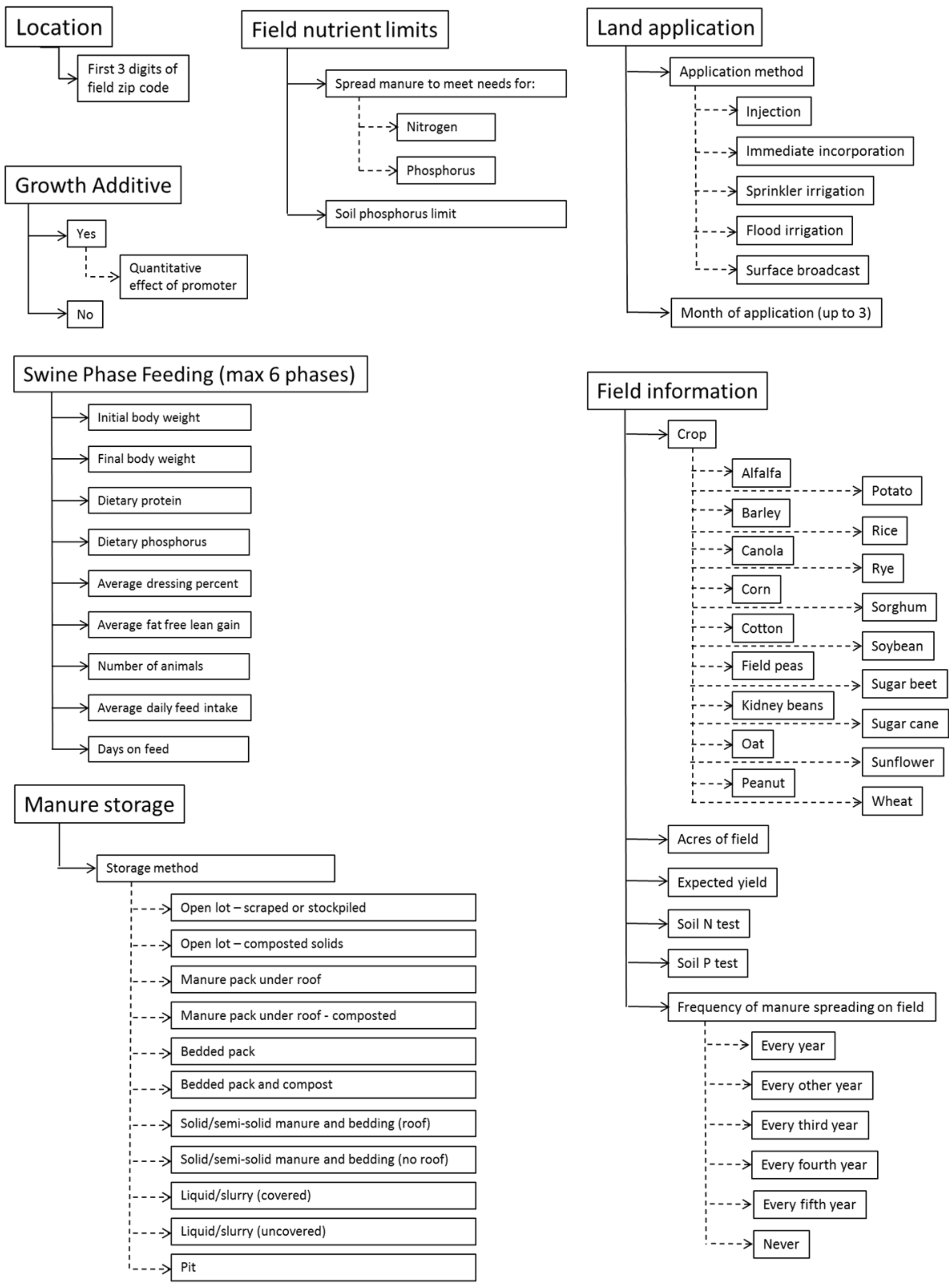


Stream	Description
1	Nutrients excreted in manure
2	Nutrients remaining in manure after storage
3	Nutrients available in soil after land application
4	Nutrients left in soil for subsequent years
5	Information feedback of remaining nutrient values in soil used to adjust land application of manure in subsequent years
6	Information feedback of remaining nutrient values in soil used to adjust manure storage management in subsequent years – Not featured in current program but potential growth of program to include this information feedback
7	Information feedback of remaining nutrient values in soil used to adjust swine management in subsequent years – Not featured in current program but potential growth of program to include this information feedback

4.2 Functionality criteria of the model

The model estimates manure excreted, nutrient loss from storage and land application, nutrient uptake by crops, and the resulting amount of manure that needs to be applied to each field to fulfill crop N or P needs. Feedback loops adjust spreading habits until P threshold limits (specified by the user) are met. User inputs required by the model are shown in Figure 2. The variables needed reflect primary management considerations in swine production farms and within crop management. All variables included have an impact on nutrient loss throughout the system. Default values for variables within the swine phase feeding, manure storage, and land application sections of the model are pre-programmed with an override option by the user. Model outputs export into a Microsoft Excel file for the user.

Figure 2. User inputs required by the model



4.3 Software platform identification

Table 1 shows the requirements for the software platform. LabVIEW (National Instruments, Austin, TX), Matlab (MathWorks, Natick, MA), and Stella (isee systems, Lebanon, NH) were compared. LabVIEW (2012) programming software was selected as the best option. Because feedback is a critical component to the model created and future modification of equations is necessary to keep the model up to date, Matlab was removed from consideration as a candidate for the model. Stella contains the mathematical and modeling capabilities but lacks the ease of use needed. LabVIEW programming software is deficient in visual friendly outputs, but the limitation was circumvented by exporting data to Microsoft Excel.

Table 1. Modeling software platform requirements and the applicability of LabVIEW, Matlab, and Stella programming software on each requirement

Requirement	LabVIEW	Matlab	Stella
Simple user interface	x	x	
Capable of complicated mathematical structures	x	x	x
Feedback capabilities	x		x
Robust modeling capabilities	x	x	x
Visually friendly outputs		x	x
Ease of equation modification and update	x		

4.4 Modeling process

In order to accurately model the behavior of the grow-finish swine operation, equations outlining mass balances of nutrients were necessary for each process. This section documents the equations used to calculate nutrient loss and remaining nutrients at each step in the process and the variable assumptions used in an example scenario. When the user identifies either N or P of which to meet the needs of crops when applying manure to fields, the model performs separate functions. When spreading to meet N needs, the program runs until all fields exceed the critical P soil concentrations specified by the user. When spreading to meet crop P needs, the model runs for 50 years and specifies how much additional N fertilizer is required to meet crop needs.

4.4.1 Soil texture determination through zip codes

The model identifies the dominant soil texture when the user inputs the first three digits of the field zip code. By using a zip code data base (Fry, 1999) the general area of each three digit code was determined. The Web Soil Survey (NRCS, 2016) outlines the area of the zip code and identifies the dominant soil texture. A case structure was coded to allow the program to search for the soil texture within the three digits of the area code and output a coefficient calculated by Griffin et al. (2002) and Powell et al. (1994) for nutrient loss during manure application to fields based on identified soil texture.

4.4.2 Nutrient excretion and resulting manure composition and assumptions

Excreted manure mass and nutrient composition were estimated using ASABE Standard D384.2 (2005) equations and the following input variables: initial and final body weight (kg), average dressing percentage (%), fat free lean percentage (%), average daily feed intake (kg), crude protein in feed (%), P content in feed (%), number of animals, and days on feed. An option was included to account for inclusion of growth promoting additives. Up to six feeding phases period can be programmed into the model. If fewer than six phases are fed, the program omits the unused phases from calculations. User inputs drive the conditional structures that process N and P consumption and retention. The equations derived from ASABE Standard D384.2 (2005) are used to calculate total manure excretion (kg) based on N intake (kg), N retention (kg), P intake (kg), and P retention (kg) as subroutines of the program. Outputs of total manure excretion, N excretion, and P excretion flow into the manure storage phase of the program.

4.4.3 Nutrient loss during manure storage

The manure storage method drives nutrient loss. The program calculates the number of days that manure is stored based on the user-defined times of manure application. By calculating the days between manure spreading, nutrient loss during storage is quantified. Based on storage method and time the manure is stored, conditional structures apply literature values for N and P losses (Benham et al., 2009). The nutrients remaining after storage are available for spreading onto fields for crop nutrient uptake.

4.4.4 Land application of manure

Manure spreading practices will affect nutrient losses during the application process. The model prompts the user to choose whether the program is spreading to meet N or P needs. In the case of spreading to meet N needs of the crop, P is typically over-applied, which leads to a shorter time period before the field P content exceeds the critical P limits. When applying to meet the P needs of crops, N needs are typically not met, requiring additional N fertilizer to make up the deficiency. An output is created by the program indicating the number of years before the critical P limit is met or the amount of additional N needed to satisfy the crop needs. Manure spreading methods and seasonal timing of manure spreading influence nutrient losses. By implementing the user defined management decisions, seasonal data using conditional structures determine soil moisture and soil temperature and estimates the loss of nutrients primarily due to N volatilization (MWPS, 1993). Using the nutrients available after land application and the dominant soil texture determined by the program, losses due to dominant soil texture are calculated (Griffin et al., 2002; Powell et al., 1994). Nutrients not lost to air emissions, overland flow into surface water, or leachate into groundwater remain available for crop growth.

4.4.5 Plant nutrient uptake

Nutrients removed from the soil during crop growth are largely dependent on the crop being grown, soil nutrients, and the nutrients available from the manure plus any additional fertilizer applied. The model was programmed to consider initial soil nutrient level inputs relative to specific crop needs and acreage to perform conditional processes that calculate crop nutrient removal using International Plant Nutrition Institute equations. If a field is initially over the user-defined critical nutrient concentration, the program does not allow additional spreading of manure onto that field. Because the field does not receive manure, the growing crops can only use nutrients accumulated in the soil from previous fertilization. The program advances nutrient concentration data into the sub-program for each consecutive calendar year until all fields exceed the maximum nutrient concentration. When spreading to meet crop N needs, when all the fields reach critical the P concentration, the program terminates, calculating the number of years the management practices occurs until the endpoint is reached. When spreading to meet crop P needs, the model iterates 50 years to estimate the annual manure spread and the annual amount of supplemental commercial N fertilizer needed for maximum crop production.

4.4.6 Data outputs

Because user skills and platform experience will vary, clarity of output data is essential. Coding was developed for automatic export of some data to Microsoft Excel. These data include:

- Gallons of manure excreted per year (gal/year)
- N excreted (kg/year)
- P excreted (kg/year)
- Quantity of manure spread on each field annually (gal/acre)
- Annual excess or deficiency in manure excreted (kg)
- Number of years a management practice can be used before soil nutrient thresholds met

4.4.7 Validation of the model

Data from a swine feeding study was used to assess model validity. Two scenarios were considered, each representing one of two diets fed to 60 barrows weighing approximately 91 kg at approximately 140 d of age (5 pigs per group; 6 groups per diet) in a grow-finish swine study conducted at the Animal Air Quality Research Facility at Michigan State University. The two diets contained different amounts of growth additive; 0 g/ton and 9 g/ton. The animals were fed for 28 days then harvested. Collected data was scaled to 4,000 animals in order to provide sufficient manure for model-simulated field application. Example baseline validation parameters for the two diets, based on study data, are depicted in Table 2.

Table 2. User inputs for baseline validation scenarios

Diet Name	Number of Animals	Quantitative Effect of Growth Additive	Diet N Conte nt (%)	Diet P Content (%)	Fat Free Lean Gain (%)	Start Weight (kg)	End Weight (kg)	Average Dressing Percentage (%)	Daily Average Feed Intake (kg/animal)	Days on Feed
A	4,000	0	16.2	0.5	56	91.7	133	74	3.1	35
B	4,000	0.2	16.2	0.5	56	92.8	140	74	3.1	35

The model requires user inputs for manure storage method, manure spreading method, and timing of spreading in addition to the location of the fields. Table 3 outlines an example baseline scenario of inputs.

Table 3. Baseline scenario inputs for manure storage and land application

Field Location	Nutrient to Base Spreading On	Soil P Limits (ppm)	Storage Method	Application Method	Timing of Application
Lansing, MI	N	150	Liquid/slurry uncovered	Surface broadcast	August/May

The baseline scenarios represented the study parameters as well as a realistic extension of the observed study data to include manure management. Assumptions for cropping inputs reflect common industry practices geographically proximate to the study location (Table 3). Table 4 depicts the crop production inputs used for both baseline scenarios.

Table 4. Baseline scenario inputs for crop growth

Field ID	Crop	Acres of Field	Expected Yield (bu/acre)	N Soil Test (lb/acre)	P Soil Test (ppm)	Frequency of Manure Spreading
1	Soybeans	50	45	50	25	Every year
2	Corn	50	160	50	25	Every year
3	Soybeans	75	45	75	35	Every year
4	Corn	75	160	75	35	Every year
5	Soybeans	100	45	30	20	Every year

To test the sensitivity and behavior of the model a series of scenarios using data in Tables 1, 2, and 3 were developed as model inputs. Table 5 outlines the scenario assumptions for each of the two study diets (baseline scenarios). Scenario 2 used the same inputs as the baseline scenario, but altered the method of manure application onto fields; changing the application from surface broadcast to injection, which have different volatilization rates and will affect nutrients available for crop use. Scenario 3 altered the field location from Lansing, MI (baseline) to Greenville, MS (Scenario 3). Regulations on field P limits vary by state, therefore the soil P limit was modified to reflect regulations applicable to Greenville, MS. This scenario was intended to illustrate the impact soil texture and P limits have on management longevity, so a location that differed in both respects was selected. Scenario 4 modified the manure storage method from uncovered liquid/slurry storage to bedded pack while keeping the other baseline inputs the same. These two manure storage methods are very different with respect to nutrient loss and would provide an understanding for system sensitivity to change in manure storage method. The final modified scenario (5) used the same inputs as the baseline scenario with a change in the P content of both diets. The modified scenario increased the dietary P from 0.5% to 0.75%. These modified scenarios are important to exhibit how the program responds to changing situations and its applicability to different management practices.

After determining the validity of model outputs for situations where manure was applied to meet N needs of the crops, the same scenarios were considered using manure based on crop P needs. This provided a better understanding of program sensitivity for both management decisions.

Table 5. Modification scenarios to test sensitivity of the model

Trial name	Number of animals	Growth additive	Diet N content (%)	Diet P content (%)	Fat free lean gain (%)	Starting weight (kg)	End weight (kg)	Average dressing percentage (%)	Daily average feed intake (kg/day)	Days on feed	Field location	Nutrient to base spreading on	Soil P limits (ppm)	Manure storage method	Manure application method	Time(s) of manure application	Number of fields	Crops	Acres of fields	Expected crop yield (bu/acre)	N soil test (lbs/acre)	P soil test (ppm)	Frequency of manure spreading on field
1A[1,2]	4000	0	16.2	0.5	56	91.7	133	74	3.1	35	Lansing, MI	N	150	Liquid/Slurry Uncovered	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
1B[1,2]	4000	0.2	16.2	0.5	56	92.8	140	74	3.1	35	Lansing, MI	N	150	Liquid/Slurry Uncovered	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
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																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
2A[3]	4000	0	16.2	0.5	56	92.8	140	74	3.1	35	Lansing, MI	N	150	Liquid/Slurry Uncovered	**Injection**	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
2B[3]	4000	0.2	16.2	0.5	56	92.8	140	74	3.1	35	Lansing, MI	N	150	Liquid/Slurry Uncovered	**Injection**	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
3A[4]	4000	0	16.2	0.5	56	92.8	140	74	3.1	35	**Greenville, MS**	N	**100**	Liquid/Slurry Uncovered	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
3B[4]	4000	0.2	16.2	0.5	56	92.8	140	74	3.1	35	**Greenville, MS**	N	**100**	Liquid/Slurry Uncovered	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
4A[5]	4000	0	16.2	0.5	56	92.8	140	74	3.1	35	Lansing, MI	N	150	**Bedded Pack**	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
4B[5]	4000	0.2	16.2	0.5	56	92.8	140	74	3.1	35	Lansing, MI	N	150	**Bedded Pack**	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
5A[6]	4000	0	16.2	**0.75**	56	92.8	140	74	3.1	35	Lansing, MI	N	150	Liquid/Slurry Uncovered	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year
5B[6]	4000	0.2	16.2	**0.75**	56	92.8	140	74	3.1	35	Lansing, MI	N	150	Liquid/Slurry Uncovered	Surface Broadcast	August May	5	Soybeans	50	45	50	25	Every year
																		Corn	50	160	50	25	Every year
																		Soybeans	75	45	75	35	Every year
																		Corn	75	160	75	35	Every year
																		Soybeans	100	45	30	20	Every year

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table.
2 The baseline scenario tested by the model. The scenario variables include a phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI
3 All variables for the second scenario are the same as the baseline scenario except for manure application method. Manure application method is modified from surface broadcast to injection.
4 All variables for the third scenario are the same as the baseline scenario except for the location of the fields and field phosphorus limits. The location of the fields is modified from Lansing, MI to Greenville, MS. Due to differences in state regulations the field phosphorus limit was modified from 150 ppm to 100 ppm.
5 All variables for the fourth scenario are the same as the baseline scenario except for manure storage method. The manure storage method is modified from liquid/slurry to bedded pack.
6 All variables for the fifth scenario are the same as the baseline scenario except for the phosphorus levels in the diet. Diet phosphorus levels were modified from 0.5% to 0.75% for both diets.

4.4.8 Monte Carlo analysis

Because the model represents a conglomeration of many variables impacting the behavior of the much larger system, outputs from each scenario model run was compared to literature values from studies addressing similar practices. These comparisons provided a sense of suitability of the model to represent observed situations. To understand the total margin of error the model creates through each run, maxima and minima for selected variables were drawn from literature in order to run Monte Carlo simulations. Using a random number generator to select values within the maximum and minimum of the variable based on literature values (Table 6), the model was run 1000 times. The data from the model runs were fit to a histogram to test the normalcy of the distribution and variability of the model outputs.

Table 6. Monte Carlo assumptions for analysis

Variable	Default	Min	Max
Dietary N (%)	16.2	14	17
Dietary P(%)	0.5	4	7.5
Fat Free Lean Gain (%)	56	52	58
Start Weight (kg)	91.7	90	105
End Weight (kg)	133	120	135
Average Dressing Percentage	74	72	78
Daily Feed Intake	3.1	2.5	3.5

5 Results

5.1 Baseline Scenarios

Based on the calculations from the model, the diet containing the feed additive resulted in less manure, reduced N excretion resulting in less N available for crop use. Both diets produced the same P outputs (table 7). Manure excreted, N excreted, P excreted, and N and P available for crop uptake is similar whether running the model to spread manure to meet crop N needs or to meet crop P needs for the baseline scenario as well as the subsequent scenarios analyzed. Figures 3 and 4 compare model outputs to the observed data for both baseline diets. The model was able to generate outputs similar to those observed in the study. Differences between the calculated values and the observed values fall within the error of the observed data, though the calculated values are very close to the high end allowed by the observed data plus standard deviation (figure 3). This indicates that the data generated by the model is an acceptable representation of what may be seen in a real world situation. Both calculated outputs and observed data depict that diet B predicted less N excretion than that of diet A (figure 4) due to the metabolic enhancing additive used in diet B increasing muscle accretion, thus increasing N retention.

Table 7. Model outputs for baseline scenarios

Scenario	Manure Excreted (MM gal/year)	Nitrogen Excreted (Mg/year)	Phosphorus Excreted (Mg/year)	Nitrogen Available for Crop Uptake (Mg/year)	Phosphorus Available for Crop Uptake (Mg/year)	Model outputs when spreading to meet nitrogen needs: Years Before Critical P Limits Met	Model outputs when spreading to meet nitrogen needs: Total Acres Required to Use All Manure Excreted	Model outputs when spreading to meet phosphorus needs: Additional Nitrogen Fertilizer Required (lb)
1A[1,2]	2.3	64.0	13.1	24.0	12.4	38	470	6900
1B[1,2]	1.8	53.3	13.1	20.0	12.4	20	450	10200

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table
2 The baseline scenario tested by the model. The scenario variables include phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI

Figure 3. Model outputs and observed study data comparison for annual manure production

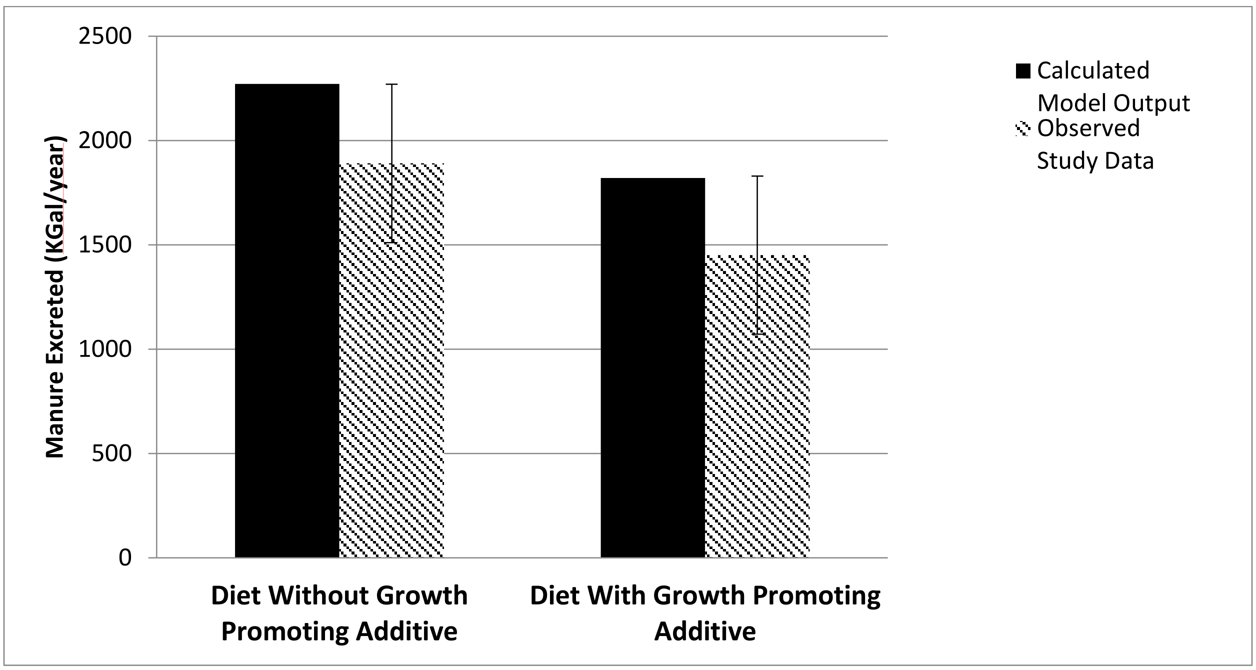
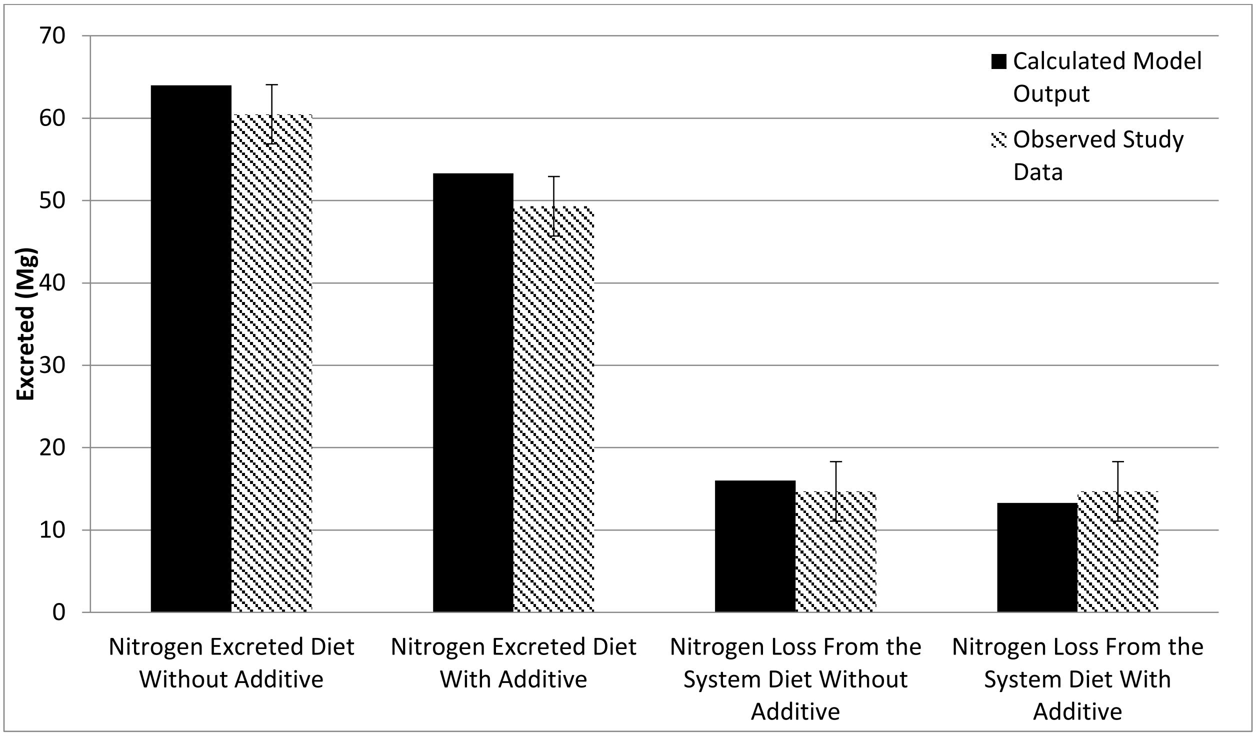


Figure 4. Model outputs and observed study data comparison for annual N excretion and N loss



5.2 Manure Spreading Method Modification (Scenario 2) Outputs

The modification of the manure spreading technique affected the N and P available to crops. The calculated values are shown in table 8. By changing the method from surface broadcast to injection, the nutrients available for crop uptake were increased. Because surface broadcast allows for greater volatilization, more of the N was lost. Given the manure spreading parameters of the baseline scenario, the model was programmed to calculate a loss of 58% of the available N using surface broadcast manure spreading. By modifying the manure spreading method to injection, the model calculated that the N loss was decreased to 1% of available N.

Table 8. Model outputs for scenario altering manure application method from surface broadcast to injection (scenario 2)

						Model outputs when spreading to meet nitrogen needs		Model outputs when spreading to meet phosphorus needs
Scenario	**Manure Excreted (MM gal/year)**	**Nitrogen Excreted (Mg/year)**	**Phosphorus Excreted (Mg/year)**	**Nitrogen Available for Crop Uptake (Mg/year)**	**Phosphorus Available for Crop Uptake (Mg/year)**	**Years Before Critical P Limits Met**	**Total Acres Required to Use All Manure Excreted**	**Additional Nitrogen Fertilizer Required (lb)**
1A[1,2]	2.3	64.0	13.1	24.0	12.4	38	470	6900
1B[1,2]	1.8	53.3	13.1	20.0	12.4	20	450	10200
2A[1,3]	2.3	64.0	13.1	48.0	13.0	40	940	3400
2B[1,3]	1.8	53.3	13.1	34.0	13.0	36	765	5500

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table
2 The baseline scenario tested by the model. The scenario variables include phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI
3 All variables for the second scenario are the same as the baseline scenario except for the manure application method. Manure application method is modified from surface broadcast to injection

Huijsman (2003) conducted a study comparing various manure management and application methods to understand N loss after manure application to fields. The study used production methods similar to those used in the model calculations and found that surface broadcast application methods had a mean loss of 56.2% of the total N applied to the fields. Total N loss values observed in the study ranged from 44% to 70% of the total N applied. Injecting manure resulted in a mean loss of 0.87% of the total N applied to the field, with the 95% confidence interval range of 0.58% to 1.15% loss of total applied N. Bittman et al. (2005), Hansel et al. (2003), and Smith et al. (2000) observed similar ranges in total N lost, all of which comfortably encompass the total N losses due to the injection manure method calculated by the model. The ranges reported in literature indicate that the calculated outputs and equations to estimate N losses due to land application method appropriately represent what would be reasonably be expected in field observations. Losses are attributed to the volatilization of ammonia. The greater extent of volatilization resulting from the surface broadcast technique reflects greater exposure to wind, rain, and sun, leading to increased mass transfer and, ultimately, N loss. Manure injection decreased exposure to the elements that increase mass transfer and N loss.

5.3 Field Location and Critical P Threshold Modification (Scenario 3) Outputs

The third scenario assessed the location of production as well as the critical threshold of field P concentration. By modifying the location of the fields, the dominant soil texture was changed from loam, found in Lansing, MI, to sandy loam, found in Greenville, MS. The critical threshold of P decreased from 150 mg/kg in Michigan to 100 mg/kg in Mississippi. Due to the change in the dominant soil texture, the model assumed N losses during manure spreading increased to approximately 68% from the 58% loss estimated in the baseline scenario.

Table 9. Model outputs for scenario altering field location and P critical limits (scenario 3)

						Model outputs when spreading to meet nitrogen needs		Model outputs when spreading to meet phosphorus needs
Scenario	**Manure Excreted (MM gal/year)**	**Nitrogen Excreted (Mg/year)**	**Phosphorus Excreted (Mg/year)**	**Nitrogen Available for Crop Uptake (Mg/year)**	**Phosphorus Available for Crop Uptake (Mg/year)**	**Years Before Critical P Limits Met**	**Total Acres Required to Use All Manure Excreted**	**Additional Nitrogen Fertilizer Required (lb)**
1A[1,2]	2.3	64.0	13.1	24	12.4	38	470	6900
1B[1,2]	1.8	53.3	13.1	20.0	12.4	20	450	10200
3A[1,4]	2.3	64.0	13.1	20.4	11.1	42	400	8300
3B[1,4]	1.8	53.3	13.1	17.0	11.1	45	383	11000

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table
2 The baseline scenario tested by the model. The scenario variables include phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI
4 All variables for the third scenario are the same as the baseline scenario except for the the location of the fields and field phosphorus limits. The location of the fields is modified from Lansing, MI to Greenville, MS. Due to differences in state regulations the field phosphorus limit was modified from 150 ppm to 100 ppm

Loam texture, being a finer soil, allows smaller amounts of nutrients deeper in the soil, leaving more N and P available for plant use. Due to the addition of sand in the sandy loam soil found in Greenville, MS, N and P readily move through the larger pores in the soil, allowing for less of the applied nutrients to be available to the crops. Because of the increase in nutrient movement in the soil for the modified scenario, the field accumulated P at a slower rate due to the nutrient losses, which led to critical limits being met later. The program took all of these factors into account when calculating the availability of nutrients for uptake by crops after application. Griffin et al. (2002) applied swine manure to both sandy loam soil and loam soils. The study found a difference of volatilized N between the soil types, with loam soil associated with 77% of total N applied volatilized while sandy loam corresponded to, on average, 99% of total N applied volatilized. Similarly, Huijsmans et al. (2003) found that a range between 37% and 100% of total applied N to sandy loam soils was volatilized. The values found in these studies are greater than those calculated by the model, but the model calculations fell within the error of both study values.

5.4 Manure Storage Modification (Scenario 4) Outputs

The fourth scenario compares N losses from an uncovered liquid/slurry system versus a bedded pack. Cortus et al. (2009) found that by storing manure as a liquid/slurry, N losses ranged from 17% to 137%. Model estimates fall within this range, a range that was observed by Portejoie et al. (2003). The model estimated N losses from an uncovered liquid/slurry system at 25% while it estimated that a bedded pack lost 50% of available N. Thus, the developed model produced outputs within reported values.

Table 10. Model outputs for scenario altering manure storage method (scenario 4)

						Model outputs when spreading to meet nitrogen needs		Model outputs when spreading to meet phosphorus needs
Scenario	**Manure Excreted (MM gal/year)**	**Nitrogen Excreted (Mg/year)**	**Phosphorus Excreted (Mg/year)**	**Nitrogen Available for Crop Uptake (Mg/year)**	**Phosphorus Available for Crop Uptake (Mg/year)**	**Years Before Critical P Limits Met**	**Total Acres Required to Use All Manure Excreted**	**Additional Nitrogen Fertilizer Required (lb)**
1A[1,2]	2.3	64.0	13.1	24.0	12.4	38	470	6900
1B[1,2]	1.8	53.3	13.1	20.0	12.4	20	450	10200
4A[1,5]	2.3	64.0	13.1	16.0	9.8	18	313	8200
4B[1,5]	1.8	53.3	13.1	13.3	9.8	3	299	14000

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table
2 The baseline scenario tested by the model. The scenario variables include phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI
5 All variables for the fourth scenario are the same as the baseline scenario except for the manure storage method. The manure storage method was changed from liquid/slurry to bedded pack

5.5 Dietary P Modification (Scenario 5) Outputs

The final scenario assessed the impact of increasing dietary P content from the baseline 0.5% P to 0.75% P. This increase in dietary P content increased the P excreted by the animals and subsequently the P available in soil for crop uptake. Table 11 shows the model outputs for the Scenario 5.

Table 11. Model outputs for scenario increasing dietary P (scenario 5)

						Model outputs when spreading to meet nitrogen needs		Model outputs when spreading to meet phosphorus needs
Scenario	**Manure Excreted (MM gal/year)**	**Nitrogen Excreted (Mg/year)**	**Phosphorus Excreted (Mg/year)**	**Nitrogen Available for Crop Uptake (Mg/year)**	**Phosphorus Available for Crop Uptake (Mg/year)**	**Years Before Critical P Limits Met**	**Total Acres Required to Use All Manure Excreted**	**Additional Nitrogen Fertilizer Required (lb)**
1A[1,2]	2.3	64.0	13.1	24.0	12.4	38	470	6900
1B[1,2]	1.8	53.3	13.1	20.0	12.4	20	450	10200
5A[1,6]	2.3	64.0	24.4	48.0	18.3	16	940	8500
5B[1,6]	1.8	53.3	24.4	40.0	18.3	3	900	14000

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table
2 The baseline scenario tested by the model. The scenario variables include phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI
6 All variables for the fifth scenario are the same as the baseline scenario except for the phosphorus levels in the diet. Diet phosphorus levels were modified from 0.5% to 0.75% for both diets

Because the crops produced in both scenarios were the same, nutrient needs were the same. As a result, the modified scenario accumulated P in the soil at a faster rate than the baseline scenario, resulting in the cessation of the management practice in fewer years. The calculations yielded an 83% increase in P excretion from swine when increasing the dietary P to 0.75%. Rodehutscord et al. (1999) found that when increasing the dietary P that there was up to a 81% increase in P excretion when fed diets containing 0.70% dietary P. Vipperman et al. (1974) observed an increase in P output of 60% to 110% as a result of increasing dietary P by 50%.

5.6 Management practice influence on long-term sustainability

5.6.1 Manure spreading to meet crop N needs

Model outputs for the scenarios depict that the number of years a practice can be used before critical P limits are met varies widely by management and site variables. Due to the fact that all of the scenarios spread manure to meet N needs of crops, P was always over-applied to the fields, allowing each scenario to hit the critical P thresholds at different time frames. When compared to the baseline scenario for the diet not containing growth additive, the scenario modifying manure application from surface broadcast to injection (scenario 2A) and the scenario modifying field location and critical P limits (scenario 3A) both have less than a 10% change in longevity of practice from the baseline scenario. Longevity for the scenario modifying manure storage from uncovered liquid/slurry to bedded pack (scenario 4A) and the scenario increasing dietary P (scenario 5A) decreased longevity 53% and 57%, respectively, when compared to the baseline scenario for the diet with no feed additive. This indicates that management changes earlier in the system (manure storage and dietary changes) have a greater effect on nutrient loss and management efficacy than those further post-excretion in the system.

The model calculated that management decisions could continue for 80% and 125% more time for the scenario modifying manure application from surface broadcast to injection (scenario 2B) and the scenario modifying field location and critical P limits (scenario 3B), respectively, when compared to the baseline scenarios of diet B. Longevity of practices decreased 85% in both the scenario modifying manure storage from uncovered liquid/slurry to bedded pack (scenario 4B) and the scenario increasing dietary P (scenario 5B) compared to the baseline of diet B. These factors indicate that the addition of metabolic enhancing feed additives create more sensitivity within the system, allowing for more options and modifications having a greater effect when practiced.

The results indicate that the growth additive regularly decreases the amount of time the management style could be used, which is most evident in the scenario modifying manure storage from uncovered liquid/slurry to bedded pack (scenario 4) and the scenario increasing dietary P (scenario 5). The baseline scenario saw a similar discrepancy between the two diets. When the growth additive was fed, less N was excreted, so the concentration of N relative to the mass of manure excreted decreased while the concentration of P relative to the mass of manure excreted increased. Because manure was spread to meet the N needs of the crops produced, more mass of manure was growth additive was fed, which meant that a greater amount of P was applied yearly, leading to faster P accumulation in the soil compared to the scenario without the addition of growth additive. The exception to this effect is the case of the scenario changing farm location and critical P limits (scenario 3), where the diet with growth additive can be practiced for a slightly longer period (45 compared 42 years); as much due to state policy as any biological determinant.

5.6.2 Manure spreading to meet crop P needs

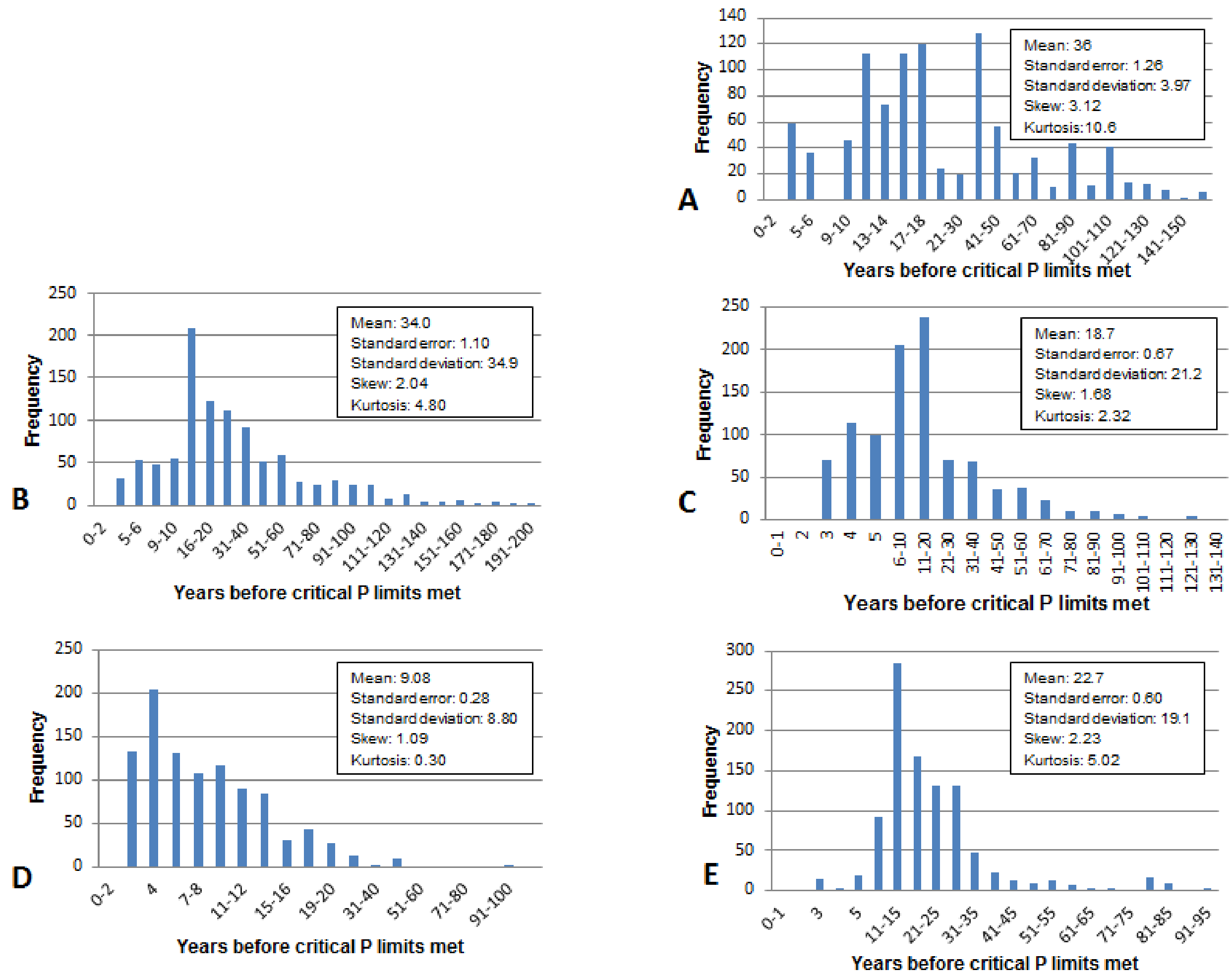
Baseline scenario calculations when spreading manure to meet P needs revealed that the scenario supplying a growth additive to the animals ultimately required a greater amount of additional N fertilizer after spreading due to lower N concentration in the manure. The fields producing soybeans, for all scenarios assessed, did not require additional N fertilizer due to N fixation by soybeans. The scenario modifying manure spreading from surface broadcast to injection required less additional N fertilizer due to the higher concentration of N in the manure, leading to a greater amount of N applied when meeting phosphorus needs, when compared to the baseline. Changing farm location and dominant soil texture, manure storage, and dietary phosphorus content all increased the requirement for additional N fertilizer relative to the baseline scenarios. This was due to the concentration of N in the manure as a percentage of total manure content decreasing while P concentrations remained similar. This change in the N to P ratio resulted in less N being applied when spreading manure to meet crop P needs, thus requiring more supplemental N to be applied to the field.

All of the information gleaned from the comparison of the scenarios show that there are distinct sensitivities found with each of the scenarios which ultimately affect how the model behaves. The differences in spreading techniques, whether spreading to meet N or P needs, and the supplemental fertilizer needed will be important when deciding management options.

5.6.3 Monte Carlo results

Monte Carlo results for each scenario spreading manure based on N crop needs are depicted in figure 5. From these figures, all scenario analyses show a non-normal distribution of model outcomes. All analyses depict a skew in the model outputs. This indicates that the model generates outputs with high variability. This is due to the high variability in observed data used to develop the model.

Figure 5: Monte Carlo analysis histograms for A: Baseline scenario, B: Scenario 2 (modified manure application), C: Scenario 3 (modified field location), D: Scenario 4 (modified manure storage), and E: Scenario 5: (modified dietary P)



5.7 Software Platform Efficacy

The LabVIEW programming software presented challenges and benefits throughout programming that may persist beyond the completion of the model. By using LabVIEW software, multiple methods to achieve the same goal were found, allowing for more flexibility during the programming phase. LabVIEW also allowed for sub-programs to be created facilitating a more organized design, while making it easier for users to navigate the wire diagram of the program. Though LabVIEW programming was beneficial during the programming phase, the complexity of the method needed to import and use large data sets as a way to create new equations or update out-of-date equations within the LabVIEW program may be a deterrent for those who may update the program down the road. If the user does not desire to invest the time to learn the LabVIEW software enough to use the complex methods, creating an equation in Microsoft Excel and then importing that equation in the LabVIEW program would be required. Additionally, due to the complexity of the model created, many case structures were used to drive the program based on user inputs. Because of this, there may be difficulties encountered by users in following the logic of the wire diagram. In order to counter this issue, it was necessary to ensure that all structures were labeled adequately in order to make very clear what the role of each structure was. Overall, the difficulties encountered in the process of programming and that may be encountered by future users are largely due to the fact that the LabVIEW software was not developed as a platform to build decision making tools. These difficulties were minimal compared to the power the LabVIEW software afforded in making many calculations simultaneously and iteratively. While users may encounter difficulties in modifying the program, the user interface was programmed to allow ease of use while using it as a decision making tool, satisfying the need for a program with an accessible, easy to understand user interface.

6 Conclusions

The developed model demonstrated an ability to accurately portray a realistic vision of a long term whole farm nutrient balance for a swine grow-finish facility under different management and site characteristic scenarios. When tested against literature values, the outputs accurately depicted what was observed. Monte Carlo analyses revealed high variability in the output of the model that mimicked observed variation. The model allows the user to observe the behavior of the system at a level that facilitates understanding of what variables impact nutrient loss and long-term sustainability of management practices. Through model runs depicting different management options, the model demonstrated its sensitivity to site management conditions. This sensitivity allows the user to understand the downstream effects of management. Based on the scenarios considered, the model has a greater sensitivity to the on-farm management practices modified earlier in the system (i.e swine feed/metabolism and manure storage) compared to off-farm practices and influences (i.e. crop uptake and losses due to manure spreading). Given the ability of the model to demonstrate the critical points of control within the system, this program has the ability to lend an understanding not only to those aiming to expand the research of variables within the system, but also to producers and advisors who aim to enhance adoptions of practices and behaviors to create a long-term sustainable food system.

While the model created brought together many variables in order to give users the ability to visualize the system as a whole and understand the feedback influences, there is still much that could be developed to enhance the tool. Upstream decisions had large influence on downstream losses and longevity; the model would benefit from to enhanced feedback that ties to animal production decisions (i.e. decisions of herd size and dietary modification based on performance).

Further research of the variables not validated by observed data from a study, namely those associated with manure storage, manure application, and crop uptake, would allow the model to increase the accuracy of the outputs and increase the ability to accurately represent the system. Including an economic factor and environmental factors beyond the current scope that will affect the system would provide a broader understanding of the system.

The overarching goal of this model is to be able to use it in a much larger model in order to understand the suitability of animal protein production through the systems behaviors. Given the capabilities the model has demonstrated, there still remains potential to expand the model to include more variables and feedback as well as include more species involved in protein production in order to provide greater depth when used in the more expansive model, though the software platform used may cause difficulties when moving forward with the model.

APPENDICES

APPENDIX A – Full table of all scenario outputs

Table 12. Complete table of all scenario outputs analyzed

Scenario	Manure Excreted (MM gal/year)	Nitrogen Excreted (Mg/year)	Phosphorus Excreted (Mg/year)	Nitrogen Available for Crop Uptake (Mg/year)	Phosphorus Available for Crop Uptake (Mg/year)	Years Before Critical P Limits Met	Total Acres Required to Use All Manure Excreted
1A[1,2]	2.3	64	13.1	24	12.4	38	470
1B[1,2]	1.82	53.3	13.1	20	12.4	20	450
2A[1,3]	2.3	64	13.1	48	13	40	940
2B[1,3]	1.82	53.3	13.1	34	13	36	765
3A[1,4]	2.3	64	13.1	20.4	11.1	42	400
3B[1,4]	1.82	53.3	13.1	17	11.1	45	383
4A[1,5]	2.3	64	13.1	16	9.8	18	313
4B[1,5]	1.82	53.3	13.1	13.3	9.8	3	299
5A[1,6]	2.31	64	24.4	48	18.3	16	940
5B[1,6]	1.83	53.3	24.4	40	18.3	3	900

1 Label of A and B indicate the diet differences for each scenario. Label A indicates the diet that does not include a growth promoting additive. Label B indicates a diet that does include growth at a level indicated further in the table.
2 The baseline scenario tested by the model. The scenario variables include a phosphorus field concentration limit of 150 ppm, uncovered liquid/slurry manure storage, surface broadcast manure application, feed phosphorus concentrations of 0.5%, and a field location of Lansing, MI
3 All variables for the second scenario are the same as the baseline scenario except for manure application method. Manure application method is modified from surface broadcast to injection.
4 All variables for the third scenario are the same as the baseline scenario except for the location of the fields and field phosphorus limits. The location of the fields is modified from Lansing, MI to Greenville, MS. Due to differences in state regulations the field phosphorus limit was modified from 150 ppm to 100 ppm.
5 All variables for the fourth scenario are the same as the baseline scenario except for manure storage method. The manure storage method is modified from liquid/slurry to bedded pack.
6 All variables for the fifth scenario are the same as the baseline scenario except for the phosphorus levels in the diet. Diet phosphorus levels were modified from 0.5% to 0.75% for both diets.

APPENDIX B - Monte Carlo Yearly Output Statistics

Table 13. Output statistics for monte carlo analysis for all scenarios

Scenario	1	2	3	4	5
Mean	36	28.3	19.6	8.17	20
Standard Error	1.26	1.13	0.86	0.25	0.58
Median	17	14	10	4	14
Mode	12	4	4	4	3
Standard Deviation	39.7	35.9	27.2	7.96	18.4
Kurtosis	10.6	4.93	2.08	10.7	5.29
Skewness	3.12	2.27	1.84	3.05	2.26
Range	378	378	177	94	171
Minimum	3	3	3	3	3
Maximum	381	381	180	97	174
Count	1000	1000	1000	1000	1000

APPENDIX C - Program Screenshots

Figure 6. Front panel user interface for location, manure spreading, growth additive, and animal performance data inputs

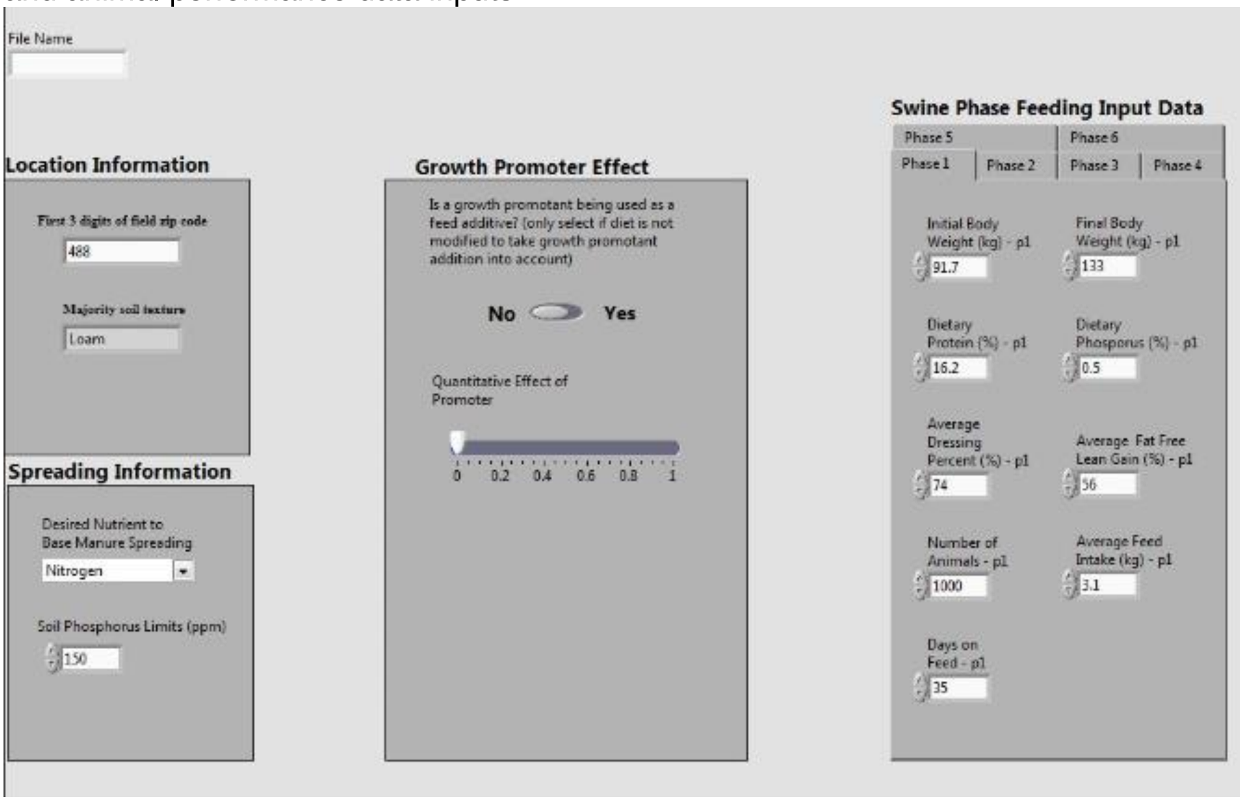


Figure 7. Front panel user interface for manure storage, manure application, and field information. Image shows inputs for only 5 fields, but the model is programmed to allow up to 30 fields.

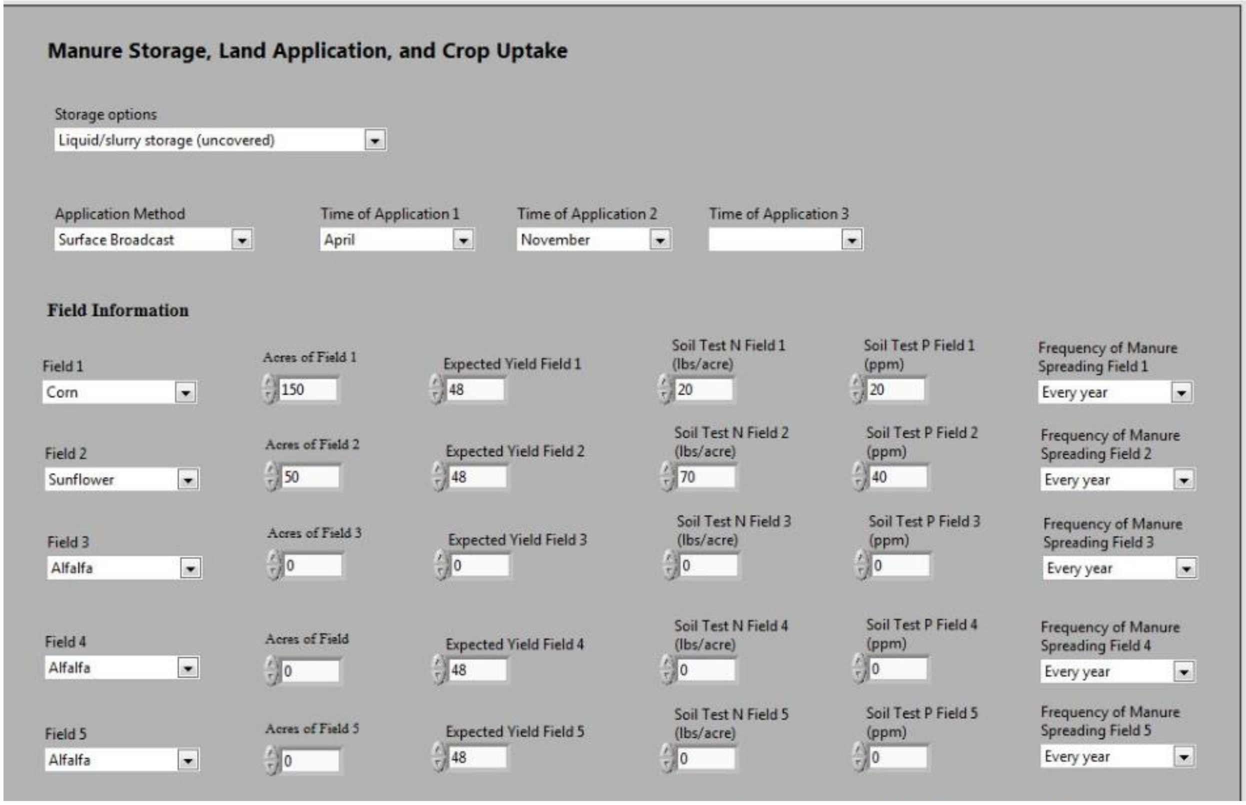


Figure 8. Model outputs as seen on front panel of the program.

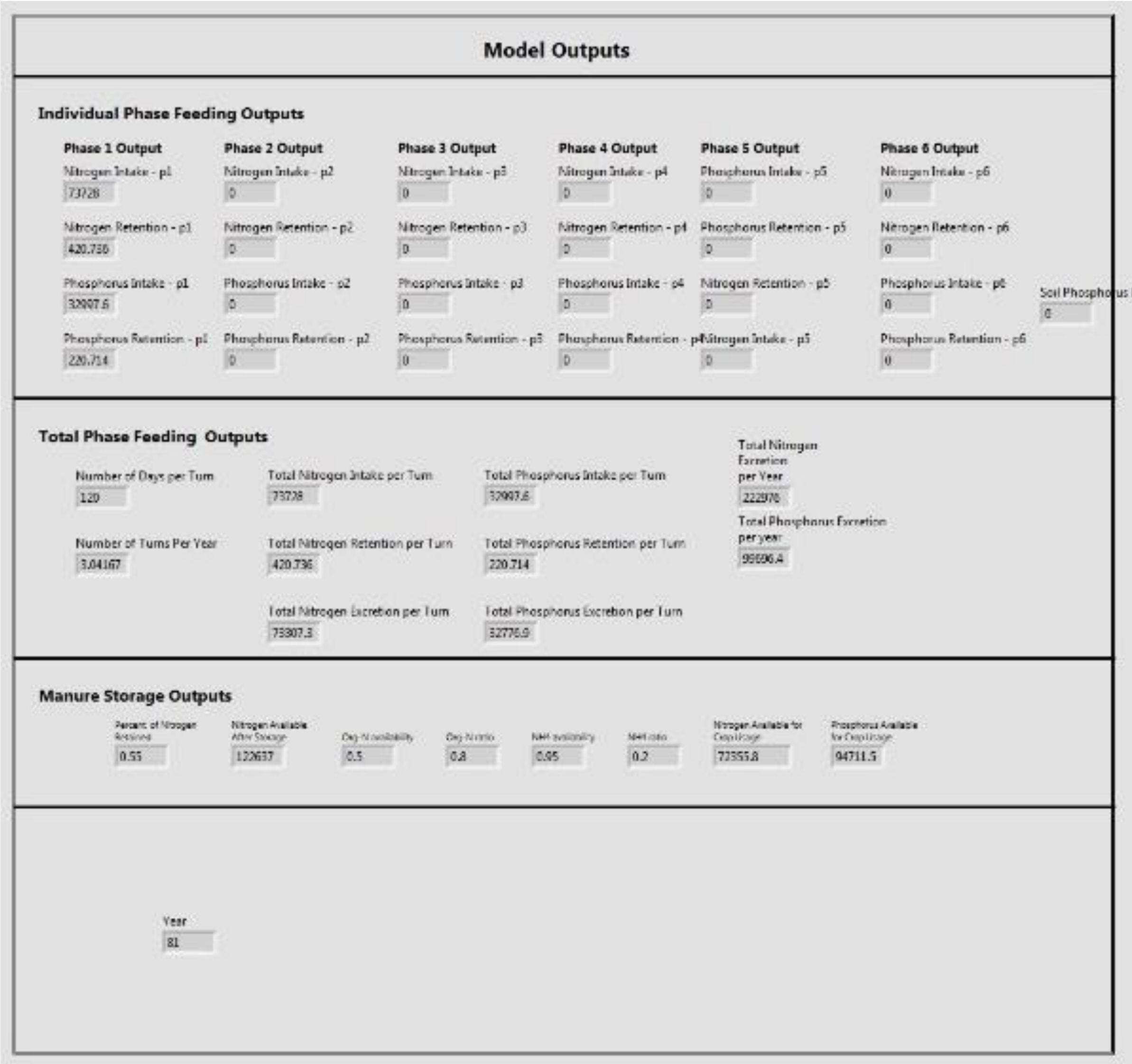


Figure 9. Block diagram of one of six available phase available in the program. The inputs (seen on the left of the case structure) are dictated by the user on the front panel. The inputs feed into a case structure to calculate N and P excretion.

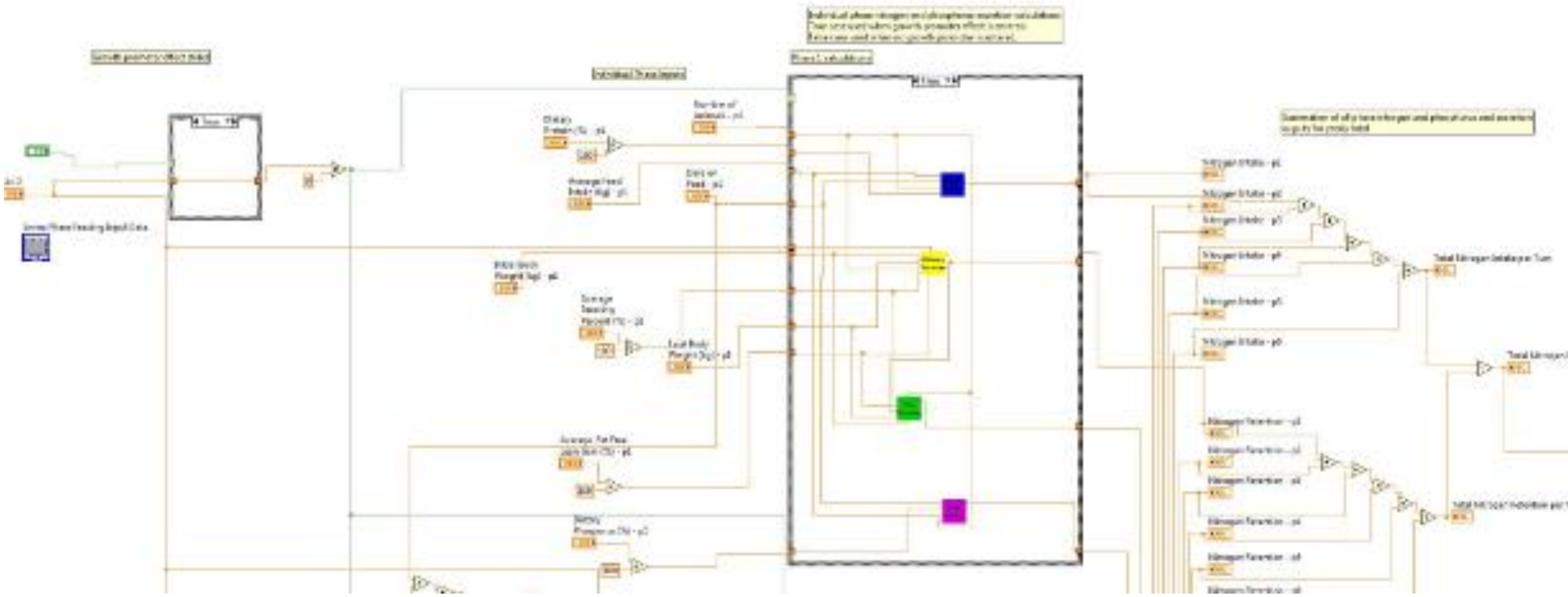


Figure 10. Nutrient loss calculation due to manure storage and land application block diagram

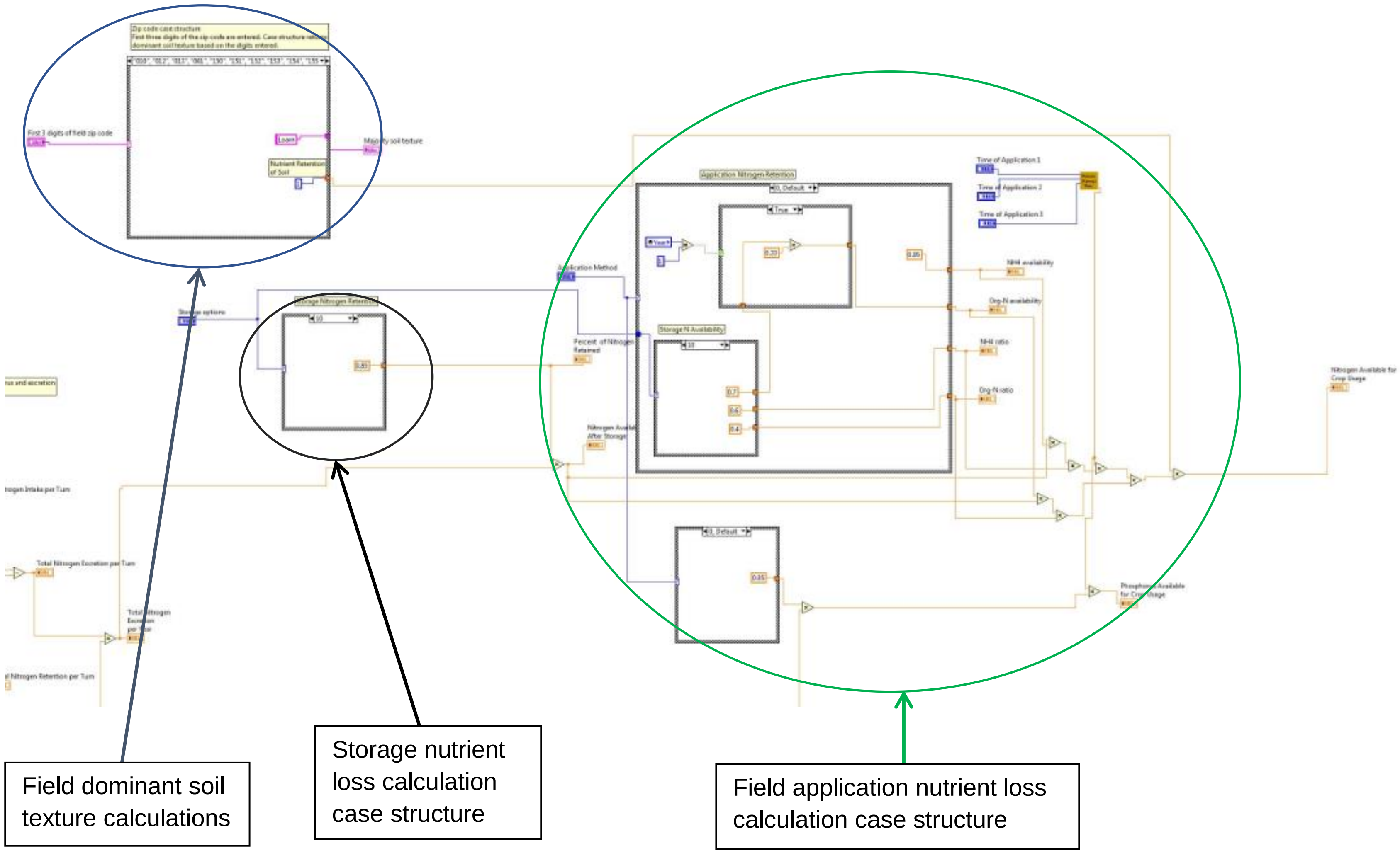
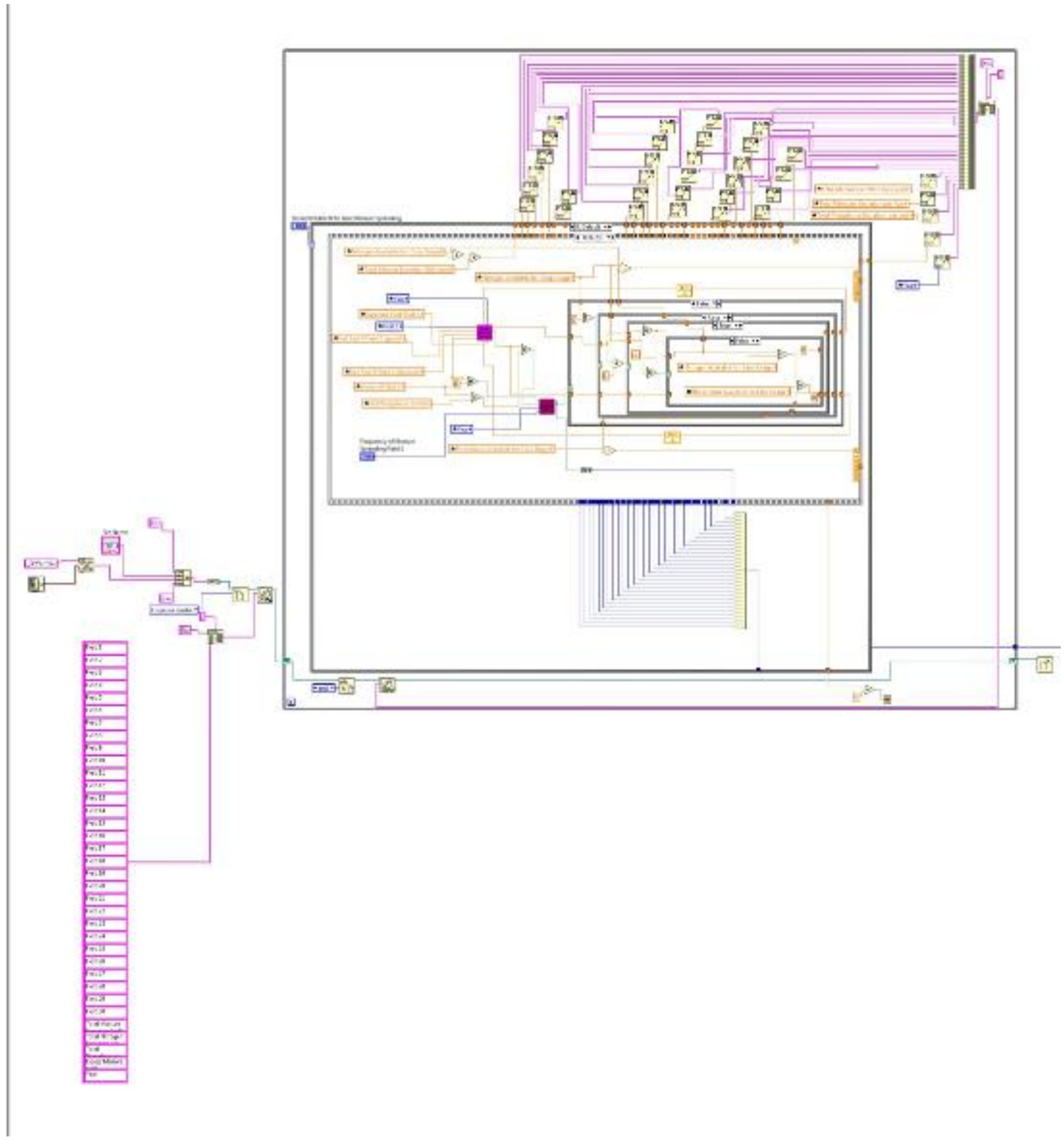


Figure 11. Crop nutrient uptake and write to file portion of the block diagram. Remaining nutrients flow to this section and crop nutrient use is calculated for each yearly iteration.



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