CONSTRUCTING A SYSTEM DYNAMIC MODEL FOR WASTEWATER IRRIGATION

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CALIFORNIA POLYTECHNIC STATE UNIVERSITY, SAN LUIS OBISPO

Advisor: Dr. Yi-Wen Chiu

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Rachel Seidner

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Constructing a System Dynamic Model for Wastewater Irrigation

R. Seidner[a]

[a] California Polytechnic State University, San Luis Obispo racheliseidner@gmail.com

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1. *Executive Summary*

The objective of this study is to develop a model for illustrating the dynamics of water balance, biomass accumulation, and nitrogen cycle within a dairy-crop co-production system where animal wastewater was applied as irrigation and nutrient supplies. The dairy facility and crop fields operated by California Polytechnic State University, San Luis Obispo (Cal Poly) were analyzed as a study case. The focus of the model is to understand the feedback loop weaving together the water, nitrogen, and plant biomass. To meet the study goal, a system dynamic modeling approach was adopted to create an analytical framework. The model can simulate the dynamics of water-nutrient-crop nexus on a daily basis. The modeling tool can be utilized as a decision-making tool to advance the dairy-crop co-production system by optimizing water-use efficiency and fertilizer reduction.

2. *Project Objectives*

The original goals of the project were to create a numerical model which can be adopted as a tool to support decision-making process for sustaining the dairy operation in Cal Poly by determining potential opportunities to improve the efficiency of irrigation water consumption and reducing fertilizer application rate. I was to meet this goal by conducting my own field research of the project area, however that proved infeasible. Therefore, much of the success of the project relied on intensive data mining and the integration of existing empirical models proposed in various literatures. The goal of creating a model remained the same for the project, but different sources were used.

The project also provided valuable education opportunity by allowing me to engage in advanced scientific studies. The involvement in this project led me to pursue further education in the area of water resources and hydrology. I have developed a professional educational track and will soon pursue a master's program upon graduation. I hope to use my skills to protect the environment, such as through the USDA.

3. *Introduction*

Throughout the world, manure lagoons are used as a sustainable replacement for fertilizer when growing crops and to dispose of unwanted livestock waste. The United States Department of Agriculture estimates that confined livestock and poultry animals generate about 500 million tons of solid and liquid waste annually (EPA 2003). On a global scale, seven billion tons of manure are produced across the world annually (Ramya Thangarajan 2013).

The wastewater irrigation study case is located at California Polytechnic State University, San Luis Obispo (Cal Poly) in California, USA. San Luis Obispo County, which includes the city of San Luis Obispo, heavily relies on agriculture to support the economy. In San Luis Obispo County, the total gross crop value for 2017 was reported to be $924,698,000 (Measures 2017). The average price for California milk producers in California is $16.50 per hundredweight, which is equal to 11.6 gallons (CDFA 2017). The Cal Poly dairy produces 1,600 gallons of milk per day, which would sell for about 2270 dollars a day or 829 thousand dollars a year.

The study of wastewater irrigation is relevant on a broader scale because wastewater irrigation could support agriculture. Crops rely on soil nutrients for growth, and fertilizers are used for additional nutrition. In 2013, San Luis Obispo County was reported to have 57,000 cattle (USDA 2013). Cattle and calves are seventh in leading commodities for gross value of agricultural production within San Luis Obispo County, with a value of $39,984,000 (USDA 2019). Wastewater irrigation provides a solution to the problems of unwanted livestock waste and soil nutrient depletion.

The objective of this study is to develop a model for wastewater irrigation at Cal Poly. The focus of the model is to understand how the water and nitrogen from the system influence plant biomass for the Cal Poly agricultural fields. The scope of the analysis will cover the daily waste of the animals at the dairy, the wastewater produced, and the irrigation of the Cal Poly crop fields.

4. Methodology

Through the construction of the model, I have improved my skills reviewing literature, building mathematical models, and working with new modeling software. I read multiple scientific journal articles to find the information for both understanding wastewater irrigation as a whole and for each individual variable. I had to create mathematical models in Vensim, and I also used Excel to change the units on some of the variables. While I have previously worked with Excel, I have had no classes that used Vensim.

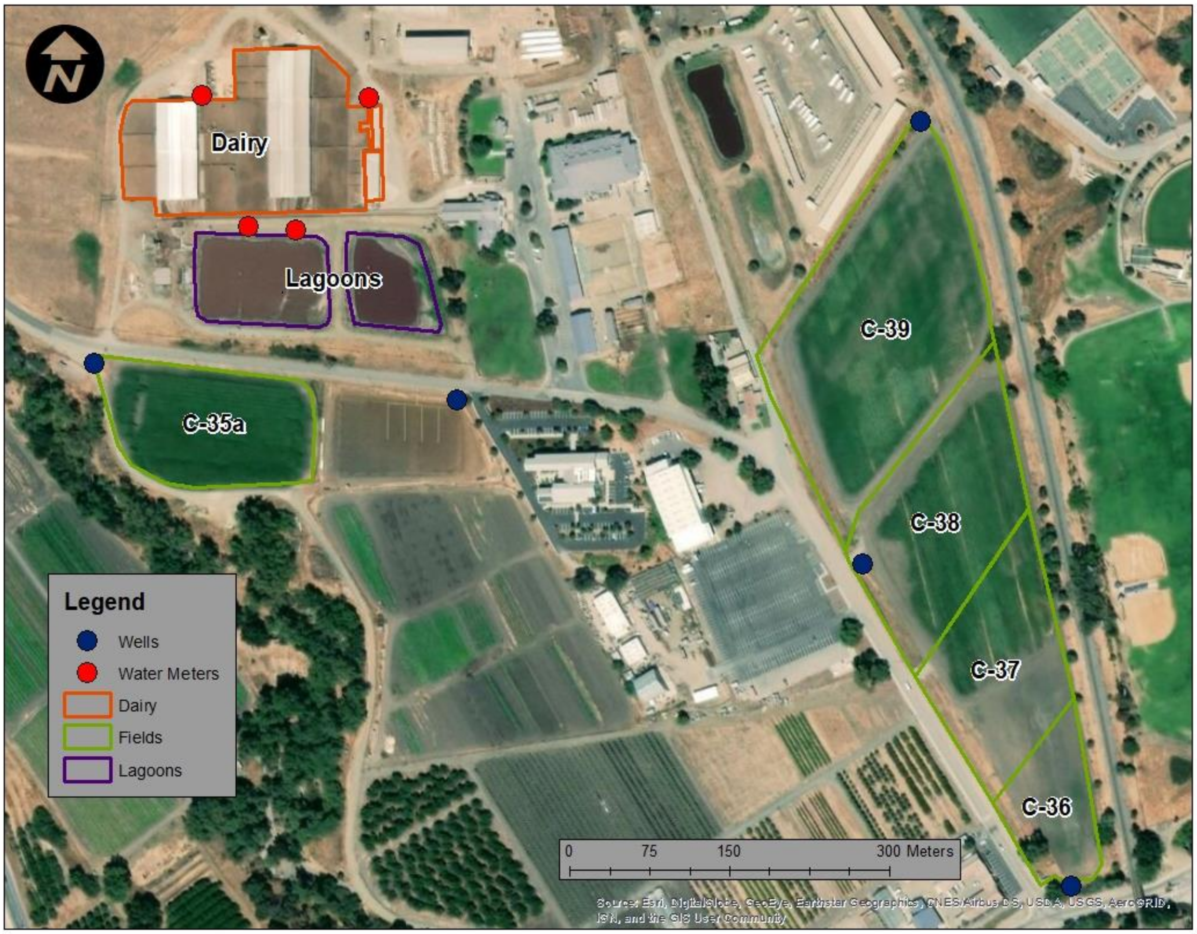
System Dynamic Modeling

System Dynamic Modeling (SDMing) is used for simulating long-term dynamic management problems (Venkatesan AK 2011). System users are better able to understand a system by giving insight into feedback processes using SDMs (Swanson 2002). Given this information, SDMing was chosen in this study as the way to display the long-term dynamic management of wastewater irrigation.

Vensim was the software chosen to create the SDMs because it improves the quality and understanding of models and is useful for novices (Robert L.Eberlein 1992). SDMing through Vensim is a visual model that shows how the different variables interact. SDMs are developed using stocks and flows. Stocks are variables that can be depleted and accumulated, and flows fill and drain stocks (Venkatesan AK 2011). An example of a stock seen in this model is lagoon wastewater. Lagoon wastewater decreases when wastewater irrigation increases and also increases with inputs of liquid cow waste.

Research Site

The site is part of the Cal Poly campus and has a latitude/longitude of 35°18’26”, -120°40’22”. An aerial photo of the site is shown below in *Figure 3-A*. The parts of the site that will be analyzed for the model are the wastewater lagoons, agriculture fields, and dairy farm. The manure lagoons at Cal Poly result from waste removed from the nearby dairy farm. Due to a filtration process, primarily liquid cow waste diluted by water enters the lagoon. The lagoon water along with tap water is used to irrigate fields of corn and triticale, a hybrid between wheat and rye (Schultes 1984). The corn and triticale crops are used as food for the dairy farm animals. The site is important for determine the variable values for the three modules that are specific to the Cal Poly location.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3-A An aerial view of the dairy farm area. The agriculture fields, dairy farm, and manure lagoons are visible. Fields C-35a, C-36, C-37, C-38, and C-39 are used for growing the corn and triticale for the dairy.

Model Development

The first step of model development was the literature review for topics including wastewater irrigation, soil nitrogen, and manure lagoons. These journal articles increased the understanding of how the manure lagoons are used for irrigation and were used for the first draft of the model. The next step was to visit the Cal Poly dairy farm, manure lagoons, and agriculture fields. The site visit helped with adding variables that were relevant to the site and removing variables that were not part of the Cal Poly system. With the information obtained from the articles and the site, a draft model was built to describe the general relationship between nitrogen, water, and plant biomass. The model was then broken up into three modules; the nitrogen module showed the nitrogen cycle and processes, the water module the water cycle and processes, and the biomass module the changes in crop biomass.

More research was done for each individual module through additional literature review and sources at Cal Poly. Literature review was used to determine the empirical equations and the variables necessary for the empirical equations. Empirical equations that were researched in scientific journal articles include those for evapotranspiration, evaporation, and crop biomass. To determine the values of the variables for empirical equations, it was important to understand the project site.

5. Methods

Overview of model structure

The nitrogen module (*Figure 3-B*) includes processes that determine the input of soil nitrogen used to maintain optimal plant biomass. The module includes the dairy farm animals, cow food, and the nitrogen in the soil. The water module (*Figure 3-C*) uses the input of water to maintain optimal plant biomass. The main stocks are lagoon wastewater and field soil water. The water module also encompasses weather variables to determine loss of water from evaporation and evapotranspiration. The biomass module (*Figure 3-D*) displays how the nitrogen and water quantities in the soil influence plant biomass.

The “step” for the model is evaluated at daily over the span of a year, shown in the model as Day 0 to Day 364. For stock variables that would not typically start at 0 on January 1 (Day 0), the value on December 31 (Day 364) is used as an initial value.

Nitrogen module

The nitrogen module (*Figure 3-B*) encompasses three smaller modules: the dairy farm module, cow food module, and the soil nitrogen module. The variables for the nitrogen module are shown in detail in Table A-1. The variables in the nitrogen module explained in three categories: Dairy Animals, Food, and Nitrogen in Soil.

Dairy Animals

The dairy farm variables primarily used information from a stakeholder interview with a professor that specializes in dairy from the Animal Science Department at Cal Poly. The stakeholder provided a better understanding of the dairy farm, such as the number of the different categories of animals.

The dairy farm module shows the population of each age group of cows. Calves are male and female cattle that are under 1 year old, heifers are female cattle that have not had a calf, and cows are female cattle that have had a calf (Berning 2018). After the male animals have reached one year, they are removed from the dairy farm while the females remain. The cull rate is the rate cows are removed from the dairy farm for any reason (including death).

Food

The consumption of cow food in the module is determined by the number of cows and is a result of the outside food sources and crops used. The “Outside Food Sources” flow is cow food, while the “Crops Used” is the harvested crops (*Figure 3-B*). Outside food is decided by the harvested crops available as well as amount of food required to sustain cows. Once the cow food depletes, it is assumed that a large quantity of outside cow food is bought to feed the cows.

Nitrogen in Soil

The nitrogen in soil category decides if there is enough nitrogen for crops to uptake to ensure maximum crop growth. The amount of nitrogen introduced to the system is determined by the number of cows producing liquid cow waste. The solid waste produced by the cows is outside the bounds of the project and is not included in the model. The liquid waste enters the lagoon which is used to irrigate the fields. The amount of nitrogen added to the fields through irrigation is determined proportionally using the total lagoon wastewater, nitrogen in the lagoons, and the amount supplied.

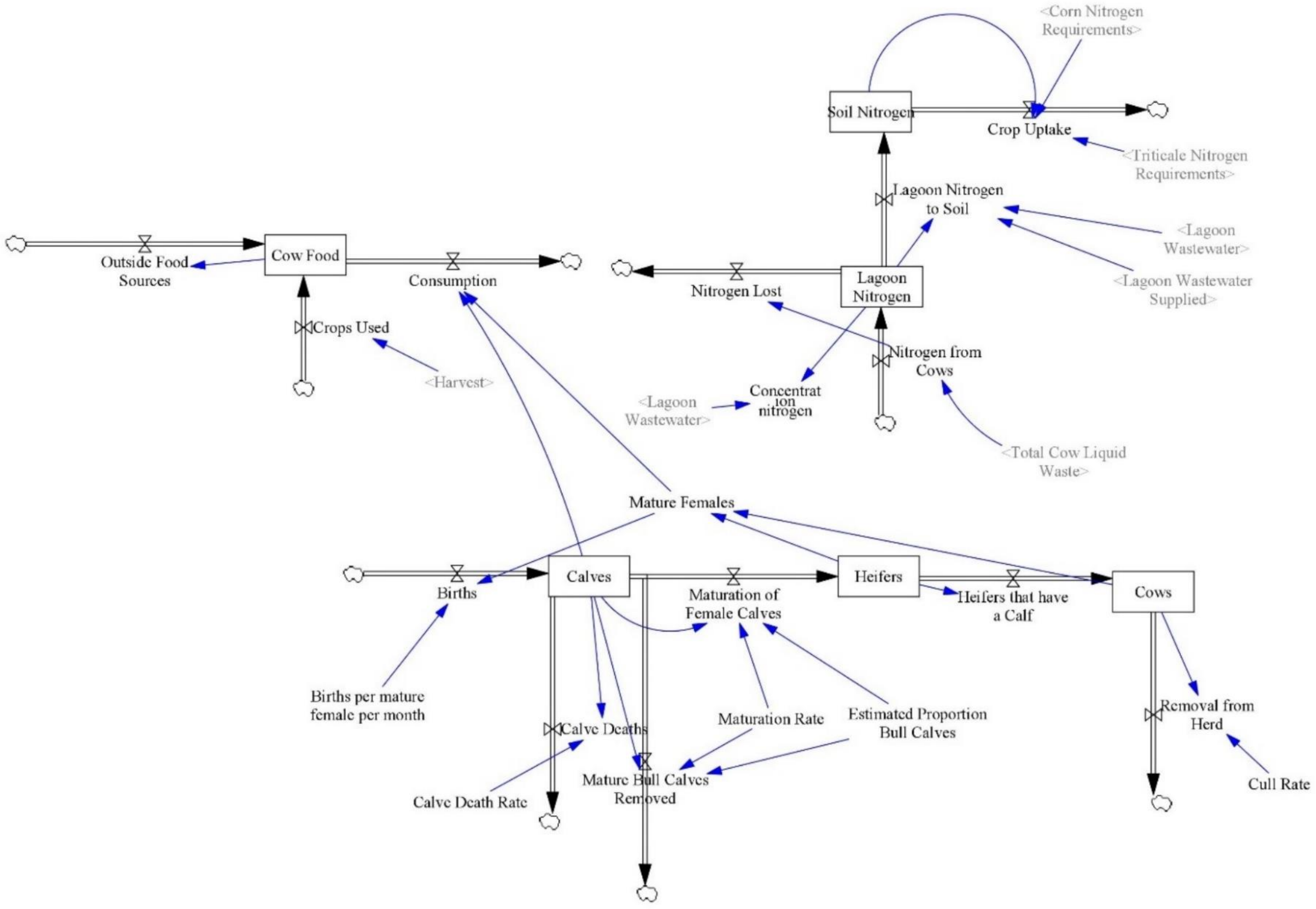


Figure 3-B Nitrogen module which includes processes that determine the inputs of the soil nitrogen used to increase plant biomass.

Water Module

The water module (*Figure 3-C)* displays the water in the soil of the agricultural fields and manure lagoons. The variables for the water module are shown in detail in Table A-2. The agricultural fields are irrigated with both the wastewater from the lagoons and tap water. The fields grow two crops that feed the cows: corn and triticale. Young corn is unable to be irrigated with high proportions of the lagoon water, while triticale is more resistant to the high salinity of the wastewater. Triticale is grown during the winter season, and no freshwater is applied during the growing season for triticale. The variables in the water module are broken up into five categories: Water in Soil, Wastewater Lagoons, Evaporation, Evapotranspiration, and Weather and Other.

Water in Soil

The water content of the fields was calculated using an initial value of 200mm. The variables that increase the water in the soil are wastewater and tap water irrigation, and precipitation over the fields. Water in the fields is lost through evapotranspiration and percolation to the groundwater. The tap water ratio determines the amount of public supply water used for irrigation as opposed to wastewater and was found from past Cal Poly dairy- crop co-production research.

Wastewater Lagoons

The lagoon wastewater encompasses the water in the two wastewater lagoons located at the dairy (Figure 3-A). The initial value is determined by estimating a depth of 8 feet in each lagoon, or 2.4 meters. The lagoon wastewater is increased by tap water used for cleaning and cooling in the milking process, liquid cow waste, and precipitation. The lagoon wastewater is lost through wastewater irrigation and evaporation. The tap water used in the milk process is used for both cleaning the milking area and cooling the milk, which afterwards drains to the lagoons. The precipitation measured includes both the area over the lagoons as well as the dairy because the dairy has roofs that collect the rain and transfer it to the lagoons.

Evaporation

Evaporation is calculated using the Turc equation shown below (Abtew 1996). The Turc equation uses the maximum daily temperature, solar radiation, and FRH (adjusted relative humidity) to determine evaporation. The Turc equation is

$$ET = 0.013 * \frac{T}{T+15}(R_s + 50) \quad for\ \ RH\ \geq 50$$

$$ET = 0.013 * \frac{T}{T+15}(R_s + 50)\left(1 + \frac{50 - RH}{70}\right) \quad for\ \ RH\ < 50$$

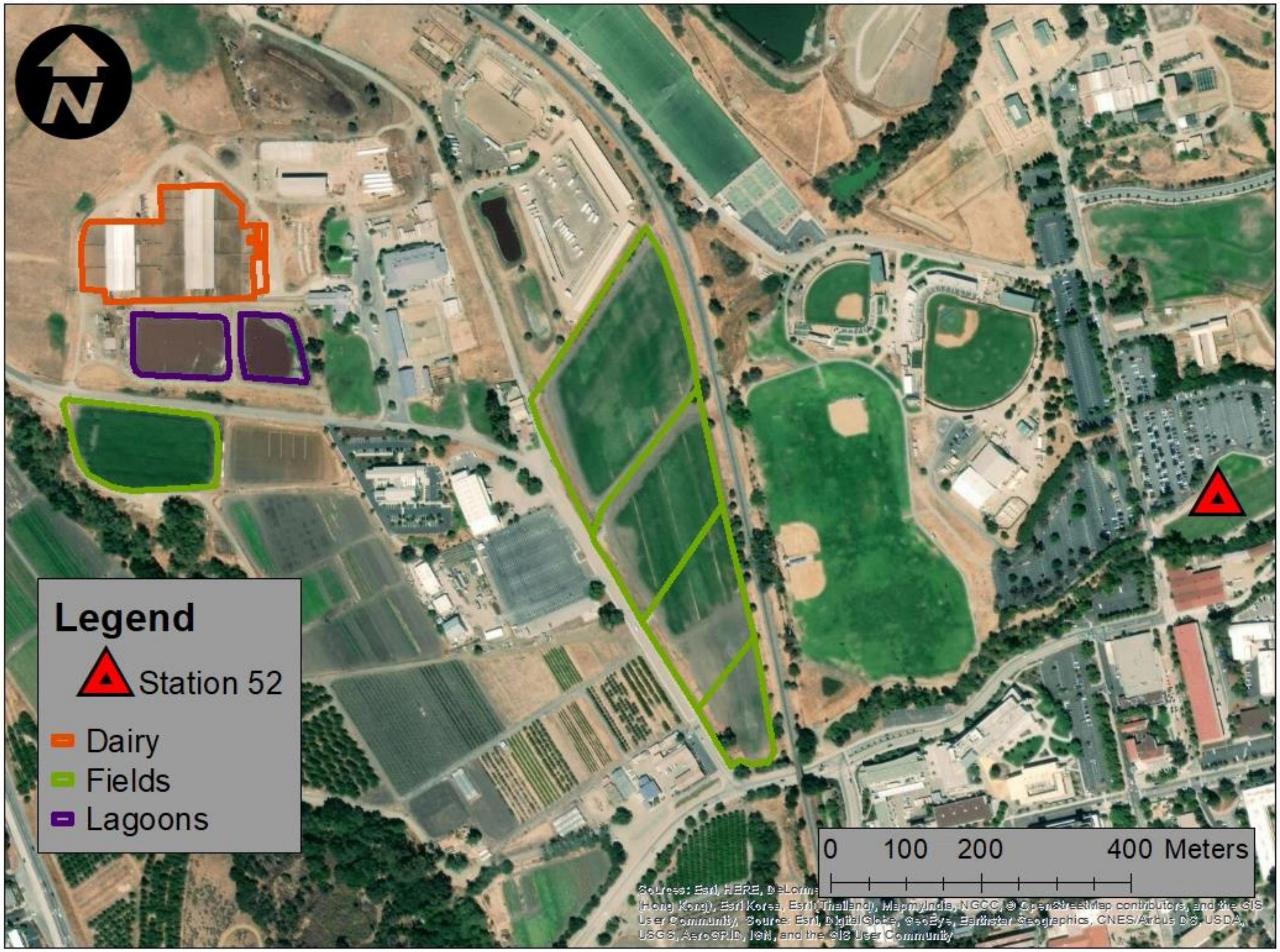
where T is the air temperature (Celsius), R_s is the solar radiation (cal/cm^2/day), and RH is the relative humidity (percent) (Abtew 1996).

Evapotranspiration

Evapotranspiration is determined from multiple variables used in “Water footprint of biofuel produced from switchgrass and miscanthus under projected scenarios” (Yi-Wen Chiu 2013). Detailed equations for evapotranspiration are listed in Table A-2.

Weather and Other

Weather conditions including average temperature, maximum temperature, relative humidity, and solar radiation were determined using weather station 52 (Resources). Station 52 (shown in *Figure 3-1*) is located at Cal Poly a short distance from the dairy farm and provides a good estimate for the weather variables required for the evapotranspiration equation. The data used is from part of year 2018 and part of 2019 (one year of weather data from the time the data was downloaded). Weather variables determined from other sources include precipitation and wind. The surface area of the fields was determined using ArcMap (ESRI 2017).



Sources: Esri, HERE, DeLorme
(Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, NGCC, © OpenStreetMap contributors, and the GIS User Community, Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3-1 *Station 52 in relation to the dairy site.*

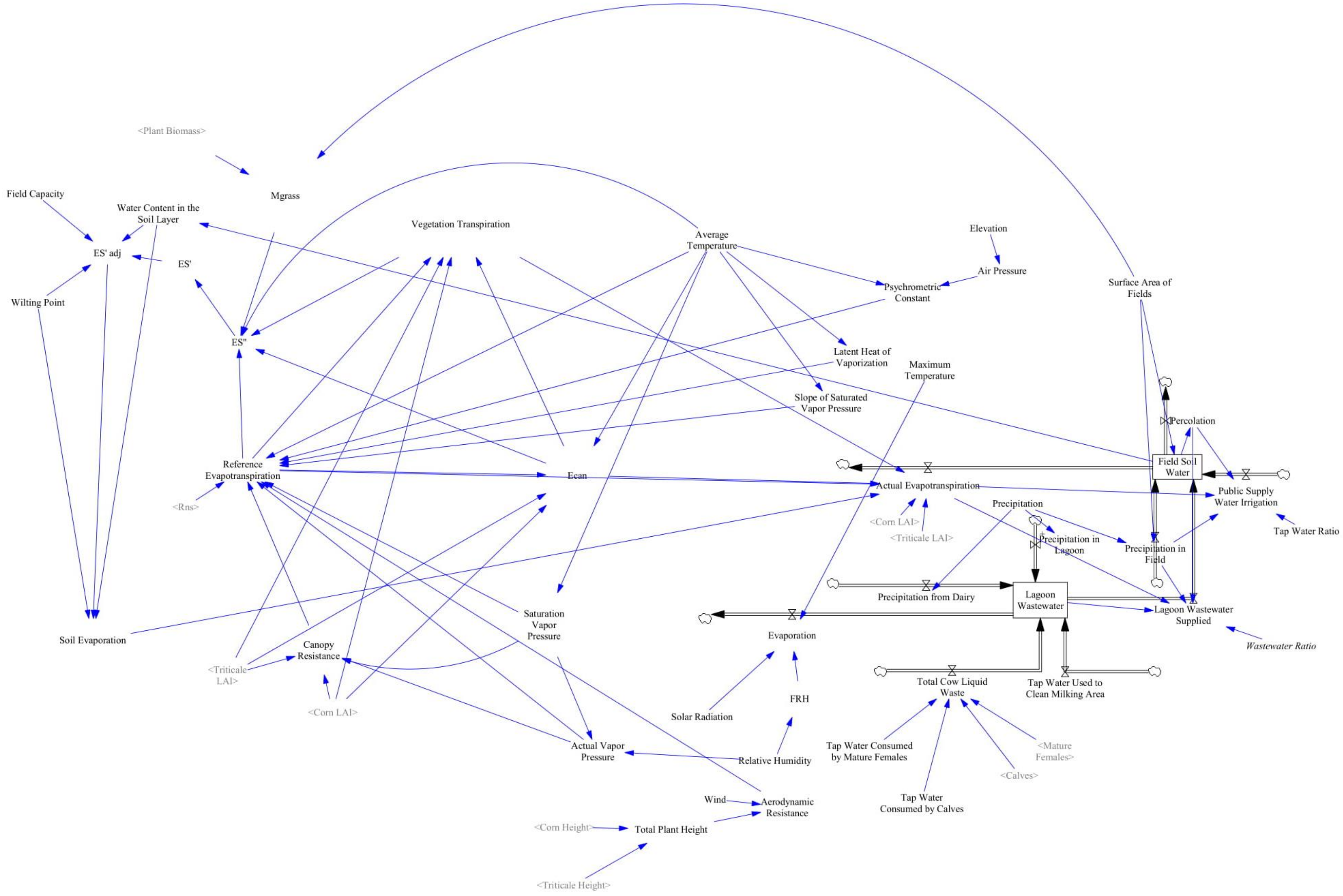


Figure 3-C Water module which includes processes that determine the inputs of the soil water used to determine plant biomass.

Biomass Module

The biomass module (*Figure 3-D*) uses the input of nitrogen and water into the crops to determine the plant biomass. The variables for the water module are shown in detail in *Table A-3* in the appendix section. The variables in the biomass module are broken up into three categories: Biomass and Other, Corn, and Triticale. Corn and triticale biomass use the same equation and will be discussed together.

Biomass and Other

The total crop biomass in the fields is determined by adding the cumulative daily growth and subtracting the harvest, which occurs twice a year. The triticale is harvested at the end of April while corn is harvested at the end of October.

Corn and Triticale

The biomass is determined as a function of RUE, RIPAR, and radiation efficiency for each respective crop. RUE is the intercepted radiation use efficiency adjusted by the difference between the saturation vapor pressure and actual vapor pressure and RIPAR is the intercepted photosynthetically active radiation (Yi-Wen Chiu 2013). The Nitrogen Limiter decreases biomass as the crop lacks nitrogen.

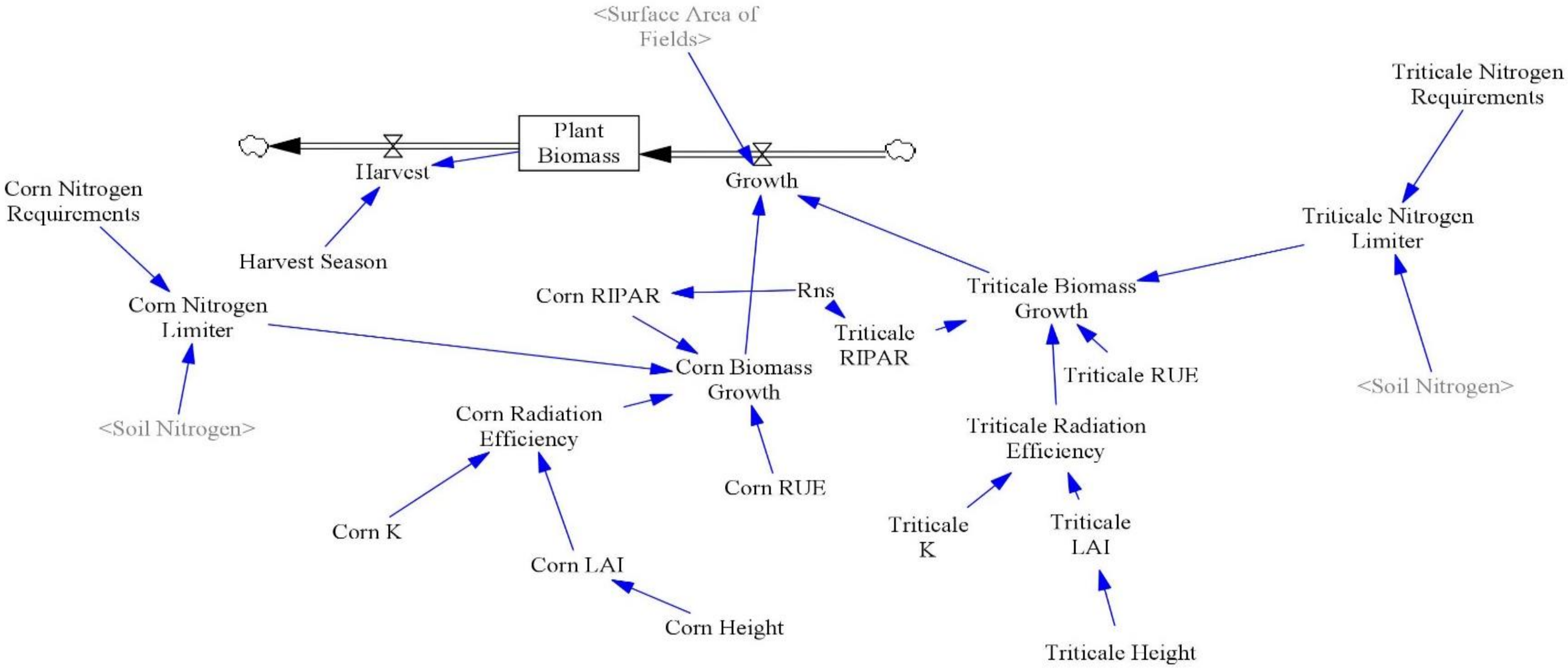


Figure 3-D Biomass module to measure the combined weight of the corn and triticale grown in the fields.

6. Results and Discussion

Results

Nitrogen Module

As shown in *Figure 5-1*, the number of cows is shown to be increasing over the year. The birth rate is high enough to compensate for the calve death rate and the removal of bull calves. The increasing number of cows leads to more nitrogen available for the crops, and an increase in consumption of cow food.

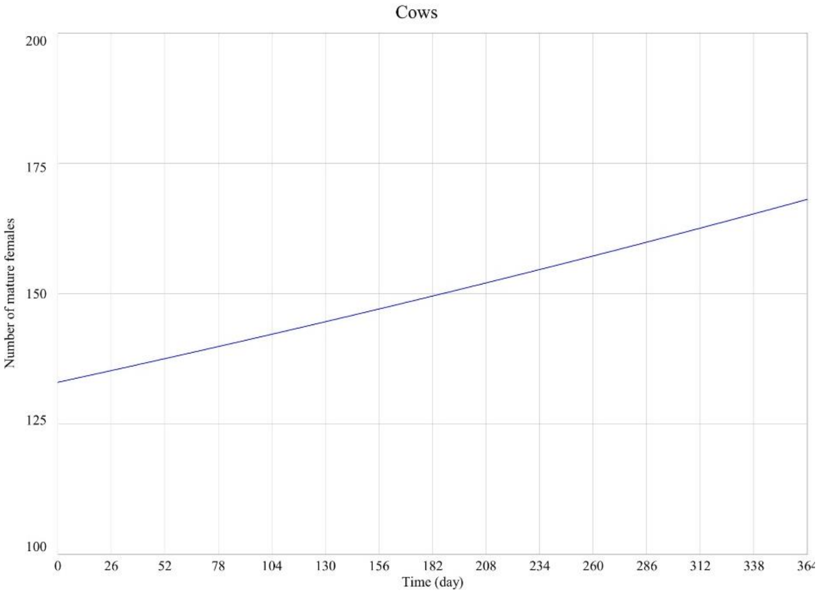


Figure 5-1 *Number of cows (mature female cattle that have had a calf) within the dairy farm.*

Figure 5-2 shows that the model keeps the cow food very consistent, except for the large increase when the corn is harvested. Consumption continues to increase as the number of cows at the farm increases.

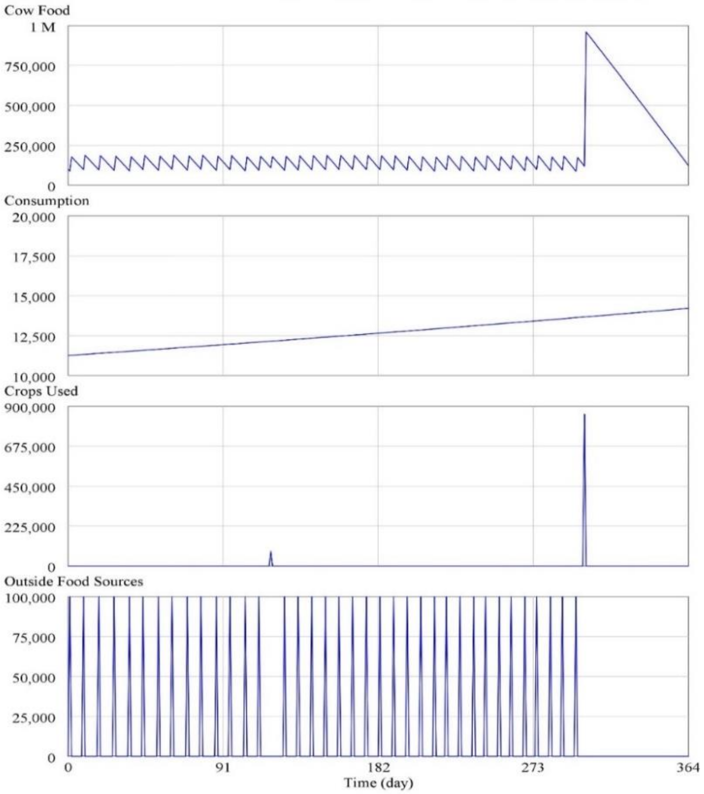


Figure 5-2 *Cow food (kg) consisting of harvested campus grown crops and outside food sources required for cow consumption.*

While the nitrogen in the lagoon is steadily increasing from the increase of cows, other variables decrease the nitrogen content in the lagoon (*Figure 5-3*). Between November and May, triticale uses large amounts of wastewater and results in a decrease of the total nitrogen in the lagoons.

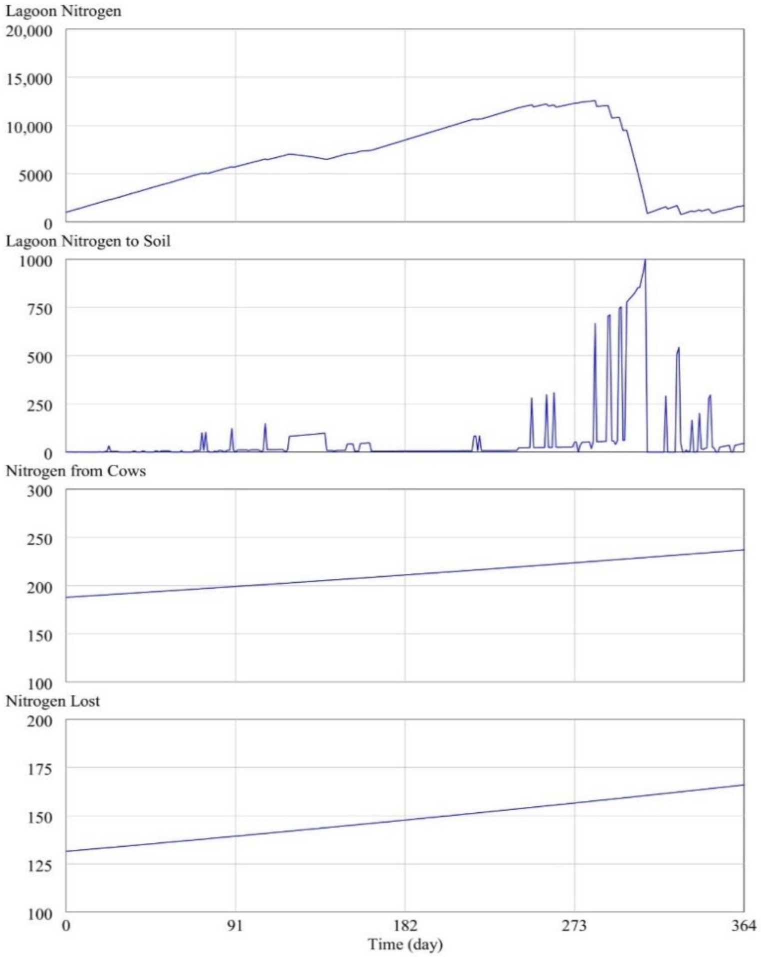


Figure 5-3 *The amount of nitrogen in the wastewater lagoons (kg).*

Although more wastewater is applied to triticale rather than corn, corn requires more nitrogen uptake as shown by the increasing in crop uptake between May and November (*Figure 5-4*).

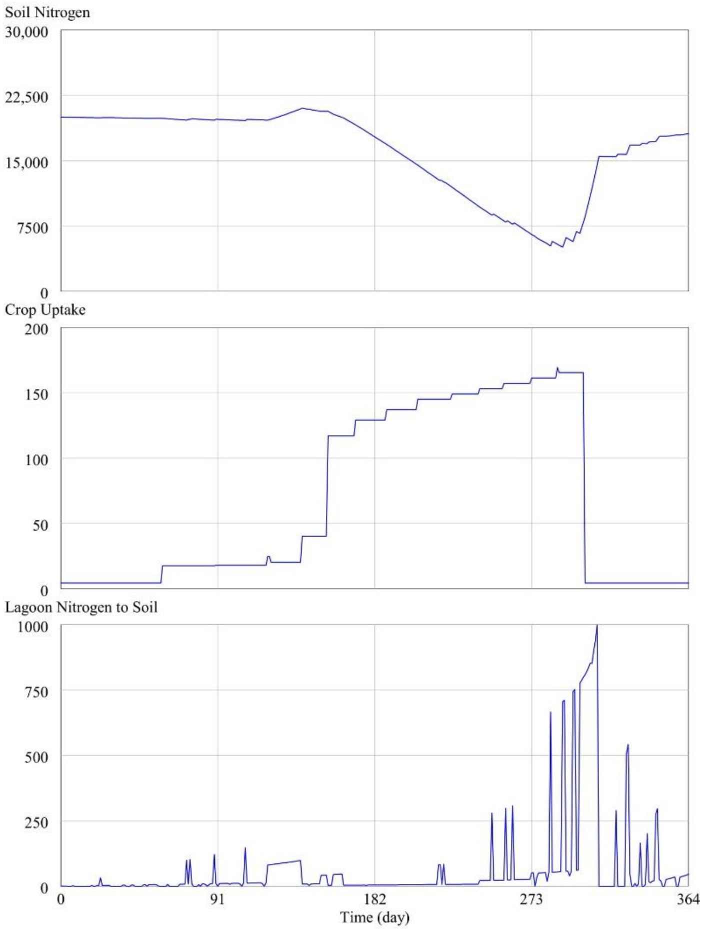


Figure 5-4 *The amount of nitrogen in the soil of the crop fields (kg).*

Water Module

Figure 5-5 displays how the lagoon wastewater changes over the course of a year. Although the amount of liquid cow waste is increasing, lagoon wastewater is shown to dynamically increase and decrease. The rapid decreases of wastewater appear to be primarily caused by wastewater irrigation. Precipitation causes small increases in lagoon wastewater as seen at points when there is heavy precipitation, such as at Day 326.

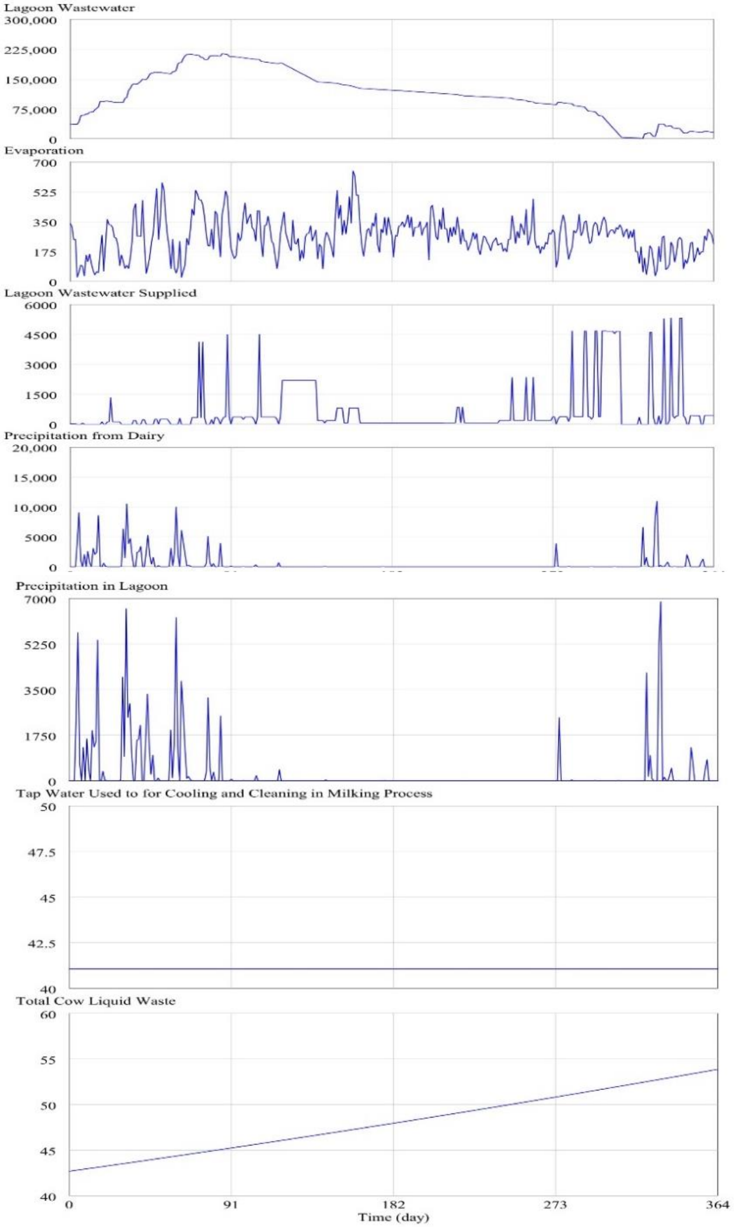


Figure 5-5 *Wastewater in the lagoons (m^3).*

The Ecan, or rain captured and evaporated from the crop canopy, in *Figure 5-9* is influenced by both the LAIs of the different crops and the average temperature. The graph takes the general shape of each in-season crop LAI, and the peaks of the Ecan resemble the daily average temperature.

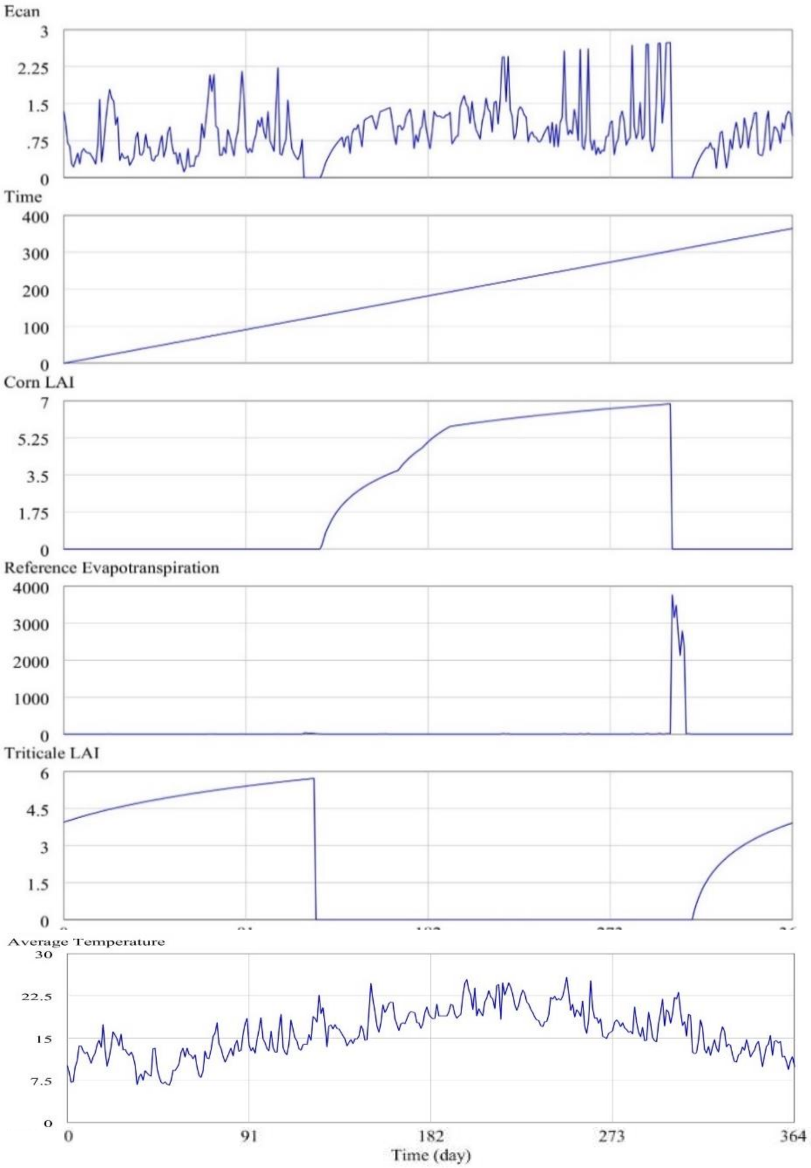


Figure 5-6 *The rain captured and evaporated from the crop canopy (Ecan) in mm/month.*

Figure 5-7 shows the variables contributing to vegetation transpiration. Many of the peaks shown in vegetation transpiration are at the same locations of the Ecan graph, which shows that Ecan may heavily influence vegetation transpiration. The peaks are higher when corn is grown as opposed to triticale and is likely because corn has a higher maximum LAI.

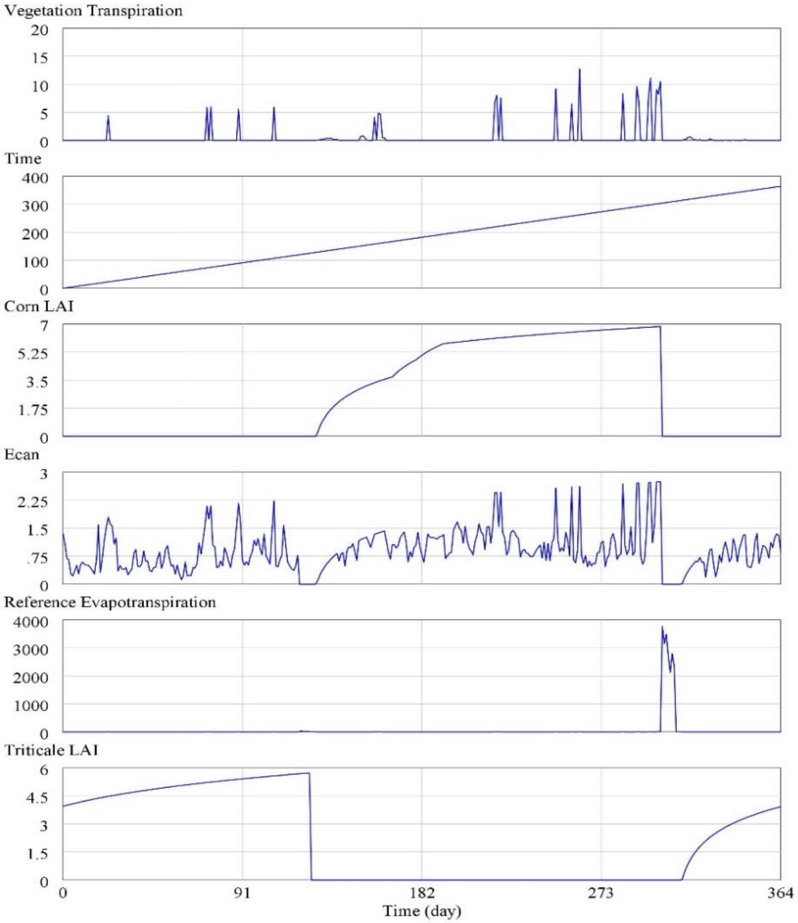


Figure 5-7 *Vegetation Transpiration (mm) estimates the water lost from the crops.*

In *Figure 5-8*, the graph of soil evaporation appears to be heavily influenced by the water content in the soil layer, as shown by the similar shapes of the graph. There are no obvious signs of impacts to soil evaporation from the large spike in the ES' adj graph.

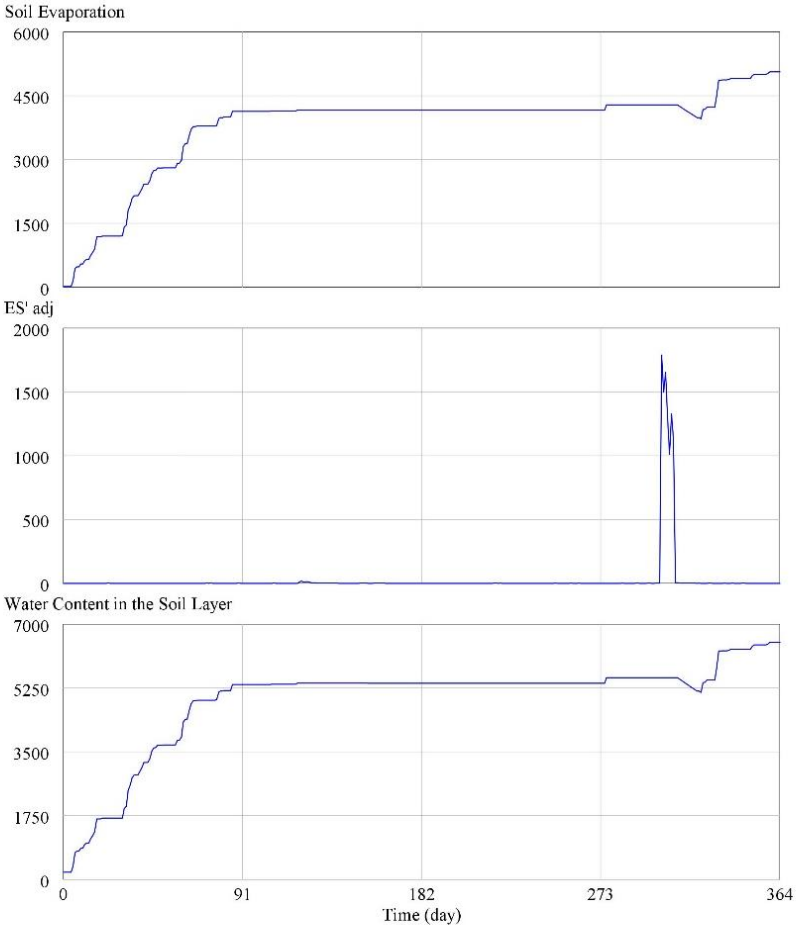


Figure 5-8 *Evaporation from Soil (mm).*

The actual evapotranspiration in *Figure 5-9* is determined by the crop LAI, evaporation from the crop canopy, reference evapotranspiration, soil evaporation, and vegetation transpiration. As there are multiple variables determining actual evapotranspiration, it is difficult to tell from the graph the impact of each variable. There are no obvious signs of actual evapotranspiration being impacted by the spike in reference evapotranspiration.

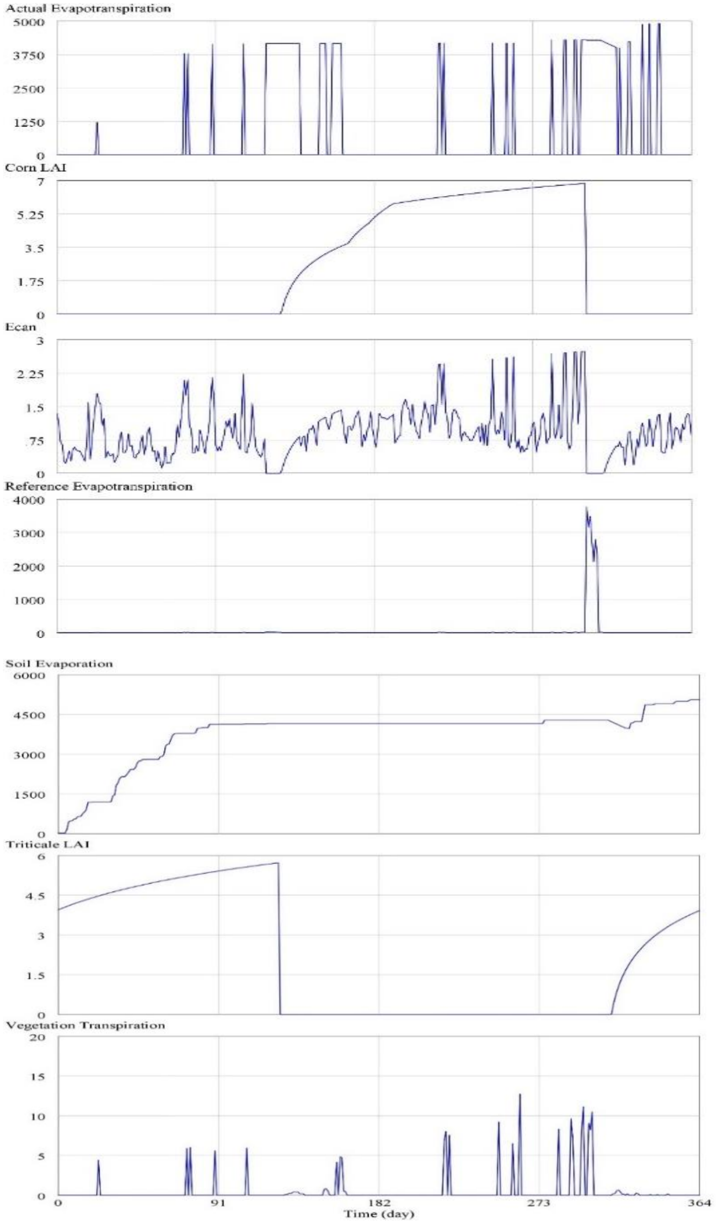


***Figure* 5-9** *Actual Evapotranspiration (mm).*

Biomass Module

As shown in *Figure 5-10* and *Figure 5-11*, most of the crop biomass is produced by corn. The model predicts the harvest of triticale to be 52,480 kilograms and the corn harvest to be 855,000 kilograms, which is over 16 times that of triticale.

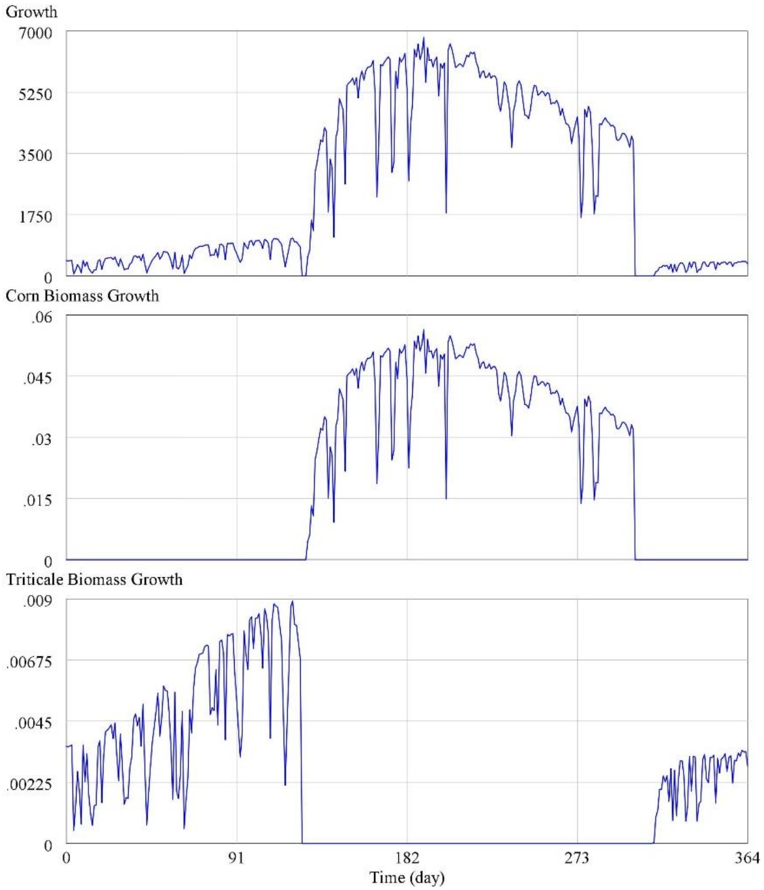


Figure 5-10 *Crop growth (kg).*

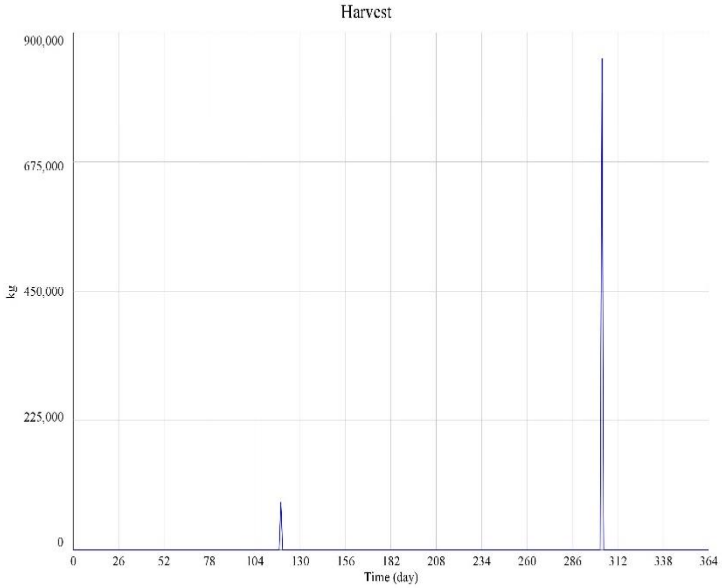


Figure 5-11 *Crop harvest in kilograms. The model has triticale harvested on April 30th (Day 119) and corn harvested on October 31st (Day 303).*

Discussion

The model can predict the water and nitrogen necessary for the optimal dairy-crop co-production system. It can also predict crop harvest quantities to estimate how much outside food is necessary to support the dairy. Some of the model variables are validated and potential variable issues are analyzed to assist with future model calibration. Future research will benefit from finding out true values of variables instead of being theoretical through more field examination at the project site.

Data Validation and Problems

Data validation was performed to analyze the how the model variables deviate from accepted values. Validated variables are listed below as well as the shortcomings of the model.

Nitrogen Module

Cow Food

The Cow Food variable was validated using information from "Environmental Performance of Livestock-crop Water Recycle System" (Chiu 2016). The presentation claimed that 13 to 15 percent of dairy cow food is composed of crops harvested from the on-campus fields while the model portrays the amount as being close to 20 percent. Assuming the true value for crops used is lower than predicted, there are multiple reasons the model could be overestimating the amount used. The consumption of the cows could be underestimated, which would cause less outside food to be bought. Another possibility is that the crop harvest is overestimated.

Nitrogen Concentration

The nitrogen concentration variable is used to determine if the nitrogen concentration for the wastewater lagoons are within the typical nitrogen concentration range for dairy cow lagoons. The model determined an average nitrogen concentration of 0.088 kilograms per square meter with a minimum concentration of .02 kilograms per square meter and a maximum of 0.985 kilograms per square meter. *Figure 5-12* displays the simulated nitrogen concentration over a year. The average nitrogen concentration for a dairy wastewater lagoon should be between 0.35 to .66 kilograms per cubic meter (John D. Harrison 2004). The nitrogen concentration simulated by the SDM is not within the typical nitrogen concentration range for dairy lagoons. The simulated concentration may be an indicator that the model needs to adjust for one of the variables that determine the nitrogen in lagoon wastewater or the wastewater itself. If 0.08 kilograms per square meter is true for the studied dairy lagoons, it can be from multiple factors. Cal Poly may have less cows that a typical dairy farm in the referenced study for the volume of lagoon water, resulting in a lower nitrogen concentration. The brief time that the model overpredicts the nitrogen concentration is likely caused by the large decrease in wastewater.

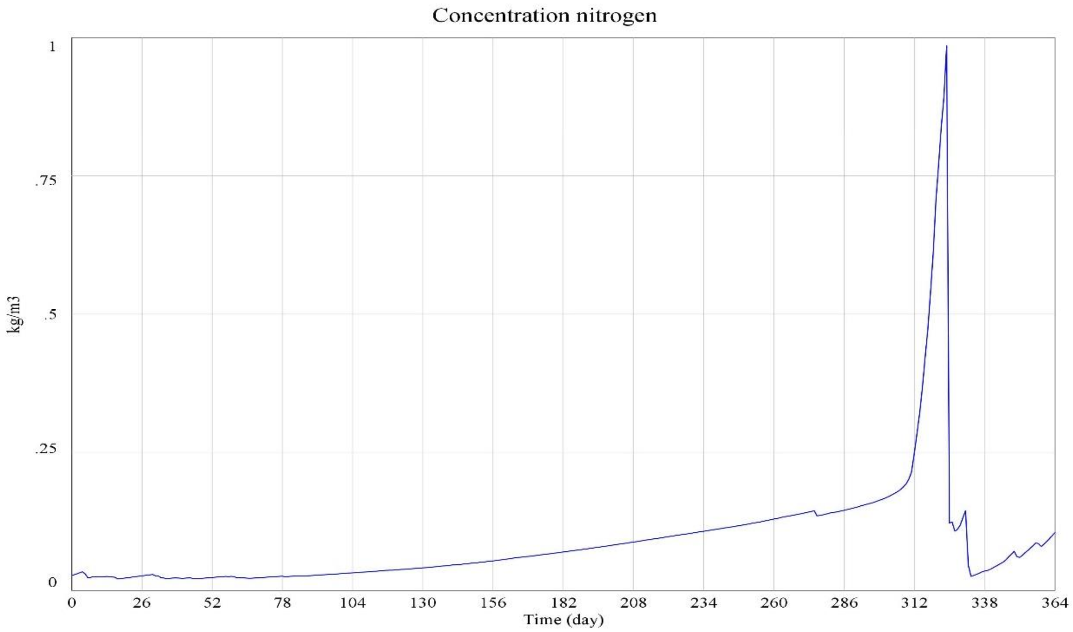


Figure 5-12 Nitrogen concentration of the lagoon wastewater over the simulated year.

Water Module

Reference Evapotranspiration

Figure 5-13 displays the simulated reference evapotranspiration (mm/ day) over a year. Throughout most of the year, the reference evaporation stays between 0 and about 10 mm/day, with an average of 2 mm/day. However, the reference evapotranspiration drastically increases between Day 304 and Day 310 to an average of 3065 mm/ day. The increased in reference evapotranspiration is caused by the aerodynamic resistance reaching its minimum in the equation, 0.1 s/m. In future models, a different equation for aerodynamic resistance may reduce irregularities with reference evapotranspiration. Reference evapotranspiration is used to calculate the first variable (ES”) in the set of variables (ES”, ES’, ES’ adj) used to calculate soil evaporation. Upon reaching soil evaporation, there are no signs of obvious irregularities in the graph (*Figure 5-8*).

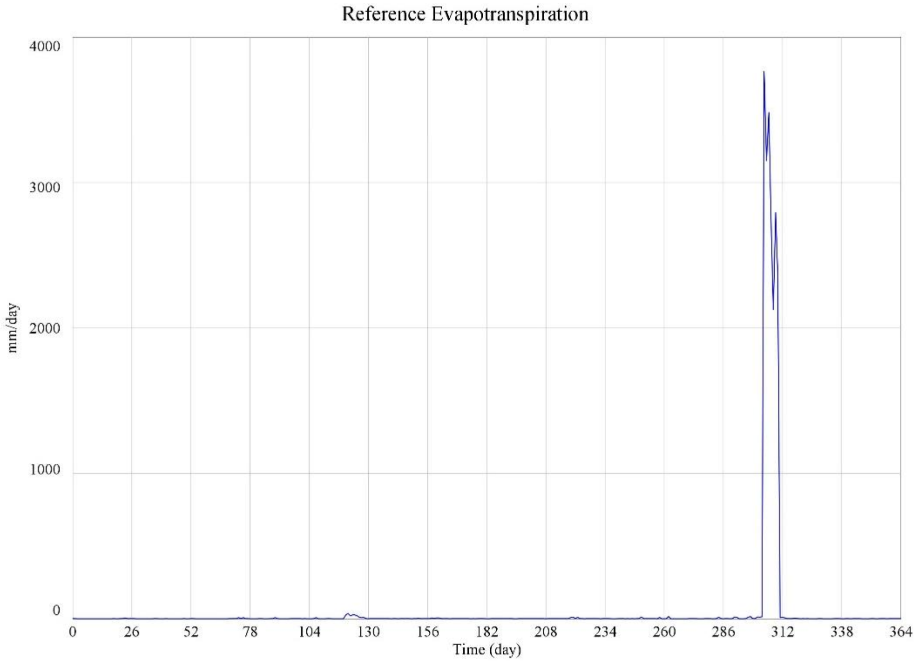


Figure 5-13 Nitrogen concentration of the lagoon wastewater over the simulated year.

Biomass Module

Harvest

A standard harvest of triticale is expected to yield a range of 710 to 2030 kilograms per acre (Seed 2010). The total simulated triticale harvest is 52,480 kilograms (*Figure 5-11*), totaling to 1760 kilograms per acre, which falls within the expected yield range. The triticale harvest is expected to be at the lower end of the range, so despite being in a standard range the model may be still overestimated triticale production.

In California counties, the range of corn planted for all purposes is between 16,000 and 29,000 kilograms per acre (Agriculture 2017). The total simulated corn harvest is 855,000 kilograms (*Figure 5-11*), totaling to 28,620 kilograms per acre, which falls within the upper end of the expected yield range. However, the average production for Central California is at the lower end of the range, producing only 16 thousand kilograms per acre. In addition, an estimate from a previous year predicted the Cal Poly corn silage production to be 17 thousand kilograms per acre (Chiu 2016). Therefore, it appears that the model likely overestimates the Cal Poly corn production.

Data Validation Conclusions

From the validated variables, it appears clear that the model is likely overestimating the weight of the crops produced. There is more cow food produced than expected, which could be from the increased size of simulated crop biomass. There is an on average smaller nitrogen concentration than expected in the lagoons, which could be because the simulation estimates a larger crop biomass than the true value. The triticale and corn harvest also appear to be overestimated, because it is assumed that Cal Poly produces a smaller than average biomass per acre in California. Future research should validate the equations for the triticale and corn biomass to ensure the correct simulation of biomass.

7. Conclusion

The objective of this study was to develop a model to simulate the dynamics of water, nitrogen, and biomass within a dairy-crop co-production system. The use of unwanted animal wastewater from manure lagoons has found a valuable use in the fertilization of crops. SDMing was used to simulate the dairy-crop co- production system which uses wastewater irrigation at Cal Poly, San Luis Obispo in California. The dairy system included the dairy farm, wastewater lagoons, and agricultural fields. Three modules were developed to model the accumulation of plant biomass from wastewater irrigation at Cal Poly. These modules were the nitrogen module, water module, and biomass module. The modules were able to show the impact of different variables towards the harvested plant biomass and determine the optimal amounts of nitrogen and water in the soil for plant growth. The results show that the SDM was an effective tool to describe and explain the connection between wastewater and the increase of plant biomass, and the results can be used to advance the dairy-crop co-production system by optimizing water-use efficiency and fertilizer reduction.

More research for this project should be conducted for the real variable values that can only be obtained in the field rather than through literature review. This research has furthered my career goals by helping navigate the direction I plan to go with a career. I would like to do more research related to soil and wastewater in the future, possibly through a career in the USDA.

8. Acknowledgements

This project was supported by Hispanic-Serving Institution's Education Program Grant no. 2015-38422- 24058 from the USDA National Institute of Food and Agriculture, and Water Use Efficiency Program administrated by California Department of Water Resources (award number 4600011907)

Thank you to Dr. Berning for providing the information regarding the Cal Poly dairy.

Special thanks to Dr. Chiu for her valuable advice throughout the development of this project. Her help is much appreciated.

9. *Appendix*

Table A-1 Data collection variables and sources for the nitrogen module.

Nitrogen Module				
Category	**Variables**	**Units**	**Equations**	**References**
Dairy Animals	Births	Number of Births	Births per mature female per day*Mature Females	
	Births per mature female per day	Percent of cows that give birth each day	(1+ 0.9)^(1/365)-1	(Berning 2018)
	Calves	Calves	164	(Berning 2018)
	Calve Death Rate	Calves dead per year	(1+ 0.015)^(1/365)-1	(Berning 2018)
	Calves Deaths	Number of dead calves	Calves * Calve Death Rate	
	Cows	Number of mature females	*Initial Value:* 133 Heifers that have a Calf - Removal from Herd	(Berning 2018)
	Cull Rate	Percent of cows removed	(1+ 0.325)^(1/365)-1	(Berning 2018)
	Estimated Proportion of Bull Calves	Percent of calves	29/ 164	(Berning 2018)
	Heifers	Number of heifers	*Initial Value:* 107 Maturation of Female Calves - Heifers that have a Calf	(Berning 2018)
	Heifers that have a Calf	Number of heifers	Heifers * ((1+ 0.9)^(1/365)-1)	(Berning 2018)
	Maturation of Female Calves	Number of female calves	Calves*Maturation Rate*(1-Estimated Proportion Bull Calves)	
	Maturation Rate	Days until calves mature	(1+ 1)^(1/365)-1	(Berning 2018)
	Mature Females	Number of mature females	Heifers + Cows	
	Mature Bull Calves Removed	Number of bull calves	Calves*Maturation Rate*Estimated Proportion Bull Calves	
	Removal from Herd	Number of cows	Cows * Cull Rate	

Food	Consumption	kg	2.27*Calves + 45.36*Mature Females	(Arkansas 2013) (Afimilk 2013)
	Cow Food	kg	*Initial Value:* 100,000 Crops Used + Outside Food Sources - Consumption	
	Crops Used	kg	Harvest	
	Outside Food Sources	kg	IF THEN ELSE(Cow Food < 100000, 100000 , 0)	
Nitrogen in Soil	Crop Uptake	kg	IF THEN ELSE(Soil Nitrogen > Corn Nitrogen Requirements (Time) *Surface Area of Fields + Triticale Nitrogen Requirements(Time)*Surface Area of Fields, Corn Nitrogen Requirements(Time)*Surface Area of Fields + Triticale Nitrogen Requirements (Time)*Surface Area of Fields, Soil Nitrogen)	
	Lagoon Nitrogen	kg	*Initial Value:* 1000 Nitrogen from Cows-Lagoon Nitrogen to Soil-Nitrogen Lost	
	Lagoon Nitrogen to Soil	kg	Lagoon Wastewater Supplied/Lagoon Wastewater*Lagoon Nitrogen	
	Nitrogen from Cows	kg	(4.4/1000) * (Total Cow Liquid Waste*1000)	(CJ Hoogendoorn 2010)
	Soil Nitrogen	kg	*Initial Value:* (((14.067/62.0049)*1.71055e-005)/1000)*Surface Area of Fields Lagoon Nitrogen to Soil-Crop Uptake	(Obispo 2013)

Table A-2 Data collection variables and sources for the water module.

Water Module				
Category	**Variables**	**Units**	**Equations**	**References**
Water in Soil	Field Soil Water	mm	*Initial Value:* 200 1000* (Lagoon Wastewater Supplied-Actual Evapotranspiration -Percolation + Precipitation in Field + Public Supply Water Irrigation) / Surface Area of Fields	200 mm for initial was suggested by Dr. Chiu
	Percolation	mm/day	IF THEN ELSE(Field Soil Water<=0,0,Field Soil Water/15)	(May M Wu 2014)
	Precipitation in Field	Cubic meters	Precipitation(Time) *Surface Area of Fields	
	Public Supply Water Irrigation	Cubic meters	MAX((Actual Evapotranspiration+ Percolation - Precipitation in Field)* Tap Water Ratio(Time), 0)	
	Tap Water Ratio	Percent	GET XLS LOOKUPS('DailyData.xlsx', 'Sheet1', 'D' , 'AK2')	Estimated using previous ratios obtained from past research
Wastewater Lagoons	Lagoon Wastewater	Cubic meters	*Initial Value:* 15240.6 * 2.4384 Tap Water Used to for Cooling and Cleaning in Milking Process + Total Cow Liquid Waste - Lagoon Wastewater Supplied - Evaporation + Precipitation from Dairy + Precipitation in Lagoon	Initial value is an estimate

	Lagoon Wastewater Supplied	Cubic meters	IF THEN ELSE((Actual Evapotranspiration+ Percolation - Precipitation in Field)*Wastewater Ratio(Time) > Lagoon Wastewater, 0, MAX((Actual Evapotranspiration+ Percolation - Precipitation in Field)*Wastewater Ratio(Time),0))	
	Tap Water Used to for Cooling and Cleaning in Milking Process	Cubic meters	10850/264.172	(Chiu 2016)
	Tap Water Consumed by Calves	Cubic meters per calf	0.13249/2	From past research in this study
	Tap Water Consumed by Mature Females	Cubic meters per mature female	0.13249	From past research in this study
	Total Cow Liquid Waste	Cubic meters	Calves * Tap Water Consumed by Calves + Mature Females * Tap Water Consumed by Mature Females	
	Precipitation from Dairy	Cubic meters	24281.1 * Precipitation(Time)	
	Precipitation in Lagoon	Cubic meters	15240.6*Precipitation(Time)	
	Wastewater Ratio	Percent	GET XLS LOOKUPS('DailyData.xlsx', 'Sheet1', 'D' , 'AJ2')	Estimated using previous ratios obtained from past research
Evaporation	Evaporation	Cubic meters	IF THEN ELSE(Maximum Temperature (Time) = 0, 0, 15240.6/1000* (0.0123*(23.89 *Solar Radiation(Time) +50) *	(Abtew 1996)

			Maximum Temperature(GET TIME VALUE (0,0,3))/(Maximum Temperature(Time) + 15)*FRH))	
	FRH	Unitless	IF THEN ELSE(Relative Humidity(Time) > 50 , 1+ ((50 - Relative Humidity(Time))/70) , 1)	(Abtew 1996)
Evapotranspiration	Actual Vapor Pressure	kPa	(Relative Humidity (Time) / 100) *Saturation Vapor Pressure	(Yi-Wen Chiu 2013)
	Aerodynamic Resistance	Siemen/ Meter	IF THEN ELSE(Total Plant Height = 0, 0.1, MAX(5 , LN((170 - 0.67* Total Plant Height)/(IF THEN ELSE(Total Plant Height<200 , Total Plant Height*0.123 , 0.058*Total Plant Height^1.19))) * LN((170 - 0.67*Total Plant Height)/ (0.1* IF THEN ELSE(Total Plant Height<200, Total Plant Height*0.123, 0.058*Total Plant Height^1.19))) / (0.412*Wind(Time))))	(Yi-Wen Chiu 2013)
	Air Pressure	kPa	101.3-0.01152 * Elevation+0.544* 10^(-6)*(Elevation)^2	(Yi-Wen Chiu 2013)
	Actual Evapotranspiration	mm/ day	IF THEN ELSE(Reference Evapotranspiration<0.0004*(Corn	(Yi-Wen Chiu 2013)

			LAI+ Triticale LAI) *1000 , Reference Evapotranspiration , Ecan+ Soil Evaporation+ Vegetation Transpiration)	
	Canopy Resistance	Siemen/ Meter	IF THEN ELSE(Corn LAI = 0, 0 , 1/(0.5*(IF THEN ELSE(Saturation Vapor Pressure-Actual Vapor Pressure<=1, 0.005 , 0.005*(1-0.08333*(Saturation Vapor Pressure-Actual Vapor Pressure-1))* Corn LAI)))) * Corn Season(Time) + IF THEN ELSE(Triticale LAI = 0, 0 , 1/(0.5*(IF THEN ELSE(Saturation Vapor Pressure-Actual Vapor Pressure<=1, 0.005 , 0.005*(1-0.08333*(Saturation Vapor Pressure-Actual Vapor Pressure-1))* Triticale LAI)))) * Triticale Season (Time)	(Yi-Wen Chiu 2013)
	Ecan	mm /day	IF THEN ELSE(Average Temperature(Time) < 0, 0 , IF THEN ELSE(Reference Evapotranspiration < (0.0004*Corn LAI*1000) , Reference Evapotranspiration , 0.0004*Corn LAI*1000)) * Corn Season(Time) +	(Yi-Wen Chiu 2013)

			IF THEN ELSE(Average Temperature(Time) < 0, 0 , IF THEN ELSE(Reference Evapotranspiration < (0.0004*Triticale LAI*1000) , Reference Evapotranspiration , 0.0004*Triticale LAI*1000)) * Triticale Season(Time)	
	ES’	Unitless	ES"* (100/(100+ EXP(2.374-0.00713*100)) -(10*0.95)/(10+ EXP(2.374-0.00713*10)))	(Yi-Wen Chiu 2013)
	ES’ adj	Unitless	IF THEN ELSE(Water Content in the Soil Layer < Field Capacity ,ES'*EXP((2.5*(Water Content in the Soil Layer- Field Capacity))/ (Field Capacity- Wilting Point)), ES')	(Yi-Wen Chiu 2013)
	ES"	Unitless	IF THEN ELSE(Average Temperature (Time) =0 :OR: Reference Evapotranspiration-Ecan=0, 0, MAX((Reference Evapotranspiration-Ecan)* EXP(-5*10^(-5)* Mgrass), ((Reference Evapotranspiration-Ecan)* EXP(-5*10^(-5)* Mgrass)*Reference Evapotranspiration-Ecan))/ ((Reference Evapotranspiration-Ecan)* EXP(-5*10^(-5)*Mgrass)+Vegetation Transpiration))	(Yi-Wen Chiu 2013)
	Elevation	meters	92	(FreeMapTools)

	Field Capacity	mm	406	(May M Wu 2014)
	Latent Heat of Vaporization	MJ/ kg	2.501-2.361 * 0.001 * Average Temperature(Time)	(Yi-Wen Chiu 2013)
	Mgrass	kg/ ha	Plant Biomass/(Surface Area of Fields/10000)	(Yi-Wen Chiu 2013)
	Psychometric Constant	kPa/ C°	0.001013*Air Pressure/(0.622*(2.501-0.002361*Average Temperature(Time)))	(Yi-Wen Chiu 2013)
	Reference Evapotranspiration	mm / day	MAX(0.01,((Slope of Saturated Vapor Pressure* (Rns(Time)) +Psychrometric Constant* (1710-6.85*Average Temperature(Time))*((Saturation Vapor Pressure-Actual Vapor Pressure))/ Aerodynamic Resistance) / (Slope of Saturated Vapor Pressure +Psychrometric Constant*(1+Canopy Resistance/Aerodynamic Resistance)))/ Latent Heat of Vaporization)	(Yi-Wen Chiu 2013)
	Saturation Vapor Pressure	kPa	MAX(EXP((16.78* Average Temperature(Time) -116.9)/(Average Temperature(Time) +237.3)), 0)	(Yi-Wen Chiu 2013)
	Slope of the Saturated Vapor Pressure	Unitless	IF THEN ELSE(Average Temperature (Time) > -237.3 , (2503*	(Yi-Wen Chiu 2013)

			EXP((17.27*Average Temperature(Time))/(Average Temperature(Time) +237.3)) /(Average Temperature(Time) +237.3)^2), 0)	
	Soil Evaporation	mm	MAX(ES' adj , 0.8 *(Water Content in the Soil Layer- Wilting Point))	(Yi-Wen Chiu 2013)
	Total Plant Height	cm	Triticale Height(Time)+ Corn Height(Time)	
	Vegetation Transpiration	mm	IF THEN ELSE(Corn LAI<= 3 , (Reference Evapotranspiration-Ecan) * Corn LAI/3 , (Reference Evapotranspiration - Ecan)) * Corn Season(Time) + IF THEN ELSE(Triticale LAI<= 3 ,(Reference Evapotranspiration-Ecan) * Triticale LAI/3 , Reference Evapotranspiration - Ecan) *Triticale Season (Time)	(Yi-Wen Chiu 2013)
	Water Content in the Soil Layer	mm	Field Soil Water	
	Wilting Point	mm	177	(May M Wu 2014)
Weather and Other	Average Temperature	C°	GET XLS LOOKUPS('DailyData.xlsx', 'Sheet1', 'D' , 'S2')	(Resources) Missing temperatures were taken from (timeanddate 2018) using month average
	Maximum Temperature	C°	GET XLS LOOKUPS('DailyData.xlsx', 'Sheet1', 'D' , 'O2')	(Resources)

	Precipitation	Meters	GET XLS LOOKUPS('DailyData.xlsx', 'Sheet1', 'D' , 'AL2')	(ITRC 2018)
	Relative Humidity	Percent	GET XLS LOOKUPS('DailyData.xlsx', 'Sheet1', 'D' , 'Y2')	(Resources) Missing relative humidity values were taken from (timeanddate 2018) using month average
	Solar Radiation	Megajoule/ Square meter/ Day	GET XLS LOOKUPS('DailyData.xlsx', 'Solar and Rns', 'A' , 'C2')	(Resources)
	Surface Area of Fields	Square meters	120890	(ESRI 2017)
	Wind	m / sec	GET XLS LOOKUPS('DailyData.xlsx', 'Wind', 'A' , 'C2')	(Windfinder)

Table A- 3 Data collection variables and sources for the biomass module.

Category	**Variables**	**Units**	**Equation**	
Biomass and Other	Growth	Kilograms	MAX((Corn Biomass Growth+Triticale Biomass Growth)*Surface Area of Fields, 0)	
	Harvest	Kilograms	Harvest Season(Time) *Plant Biomass	
	Harvest Season	Unitless	GET XLS LOOKUPS('DailyData.xlsx', 'Seasons', 'A' , 'E2')	
	Plant Biomass	Kilograms	*Initial Value:* 15170 Growth-Harvest	The initial value is calculated using the final day of the year in simulation
	Rns	Megajoule/ Square meters/ Day	GET XLS LOOKUPS('DailyData.xlsx', 'Solar and Rns', 'A' , 'E2')	Calculated from the solar radiation taken from (Resources)
Corn	Corn Biomass Growth	Kilogram/ Square meter/ Day	(Corn RUE* Corn RIPAR* Corn Radiation Efficiency* 0.001)* Corn Nitrogen Limiter	(Yi-Wen Chiu 2013)
	Corn Height	Centimeters	GET XLS LOOKUPS('DailyData.xlsx', 'Crop Heights', 'A' , 'C2')	(R. K. Teal 2006) (Work 2017) (Dieter 2012)
	Corn K	Unitless	0.49	(John L. Lindquist 2005)

Corn LAI	Unitless	MAX(IF THEN ELSE(Corn Height(Time) > 0 , 1.5*LN(Corn Height(Time))-1.4, 0), 0)	(Yi-Wen Chiu 2013)
Corn Nitrogen Limiter	Percent	IF THEN ELSE(Corn Nitrogen Requirements (Time)* Surface Area of Fields * 0.83 > Soil Nitrogen , (IF THEN ELSE(Corn Nitrogen Requirements (Time)* Surface Area of Fields*0.5 <= Soil Nitrogen :AND: Soil Nitrogen < Corn Nitrogen Requirements (Time)* Surface Area of Fields*0.83 , 0.75 , (IF THEN ELSE(Corn Nitrogen Requirements (Time)* Surface Area of Fields* 0.17 <= Soil Nitrogen :AND: Soil Nitrogen<Corn Nitrogen Requirements (Time)* Surface Area of Fields* 0.5 , 0.46 , 0.1)))) , 1)	(Sharon A. Clay 2006)
Corn Nitrogen Requirements	Kilogram / Square meter	GET XLS LOOKUPS('DailyData.xlsx', 'Seasons', 'A' , 'H2')	(Triferto)

	Corn Radiation Efficiency	Percent	1- EXP(-Corn K* Corn LAI)	(Yi-Wen Chiu 2013)
	Corn RIPAR	Megajoule/ Square meter/ Day	0.8*Rns (Time)	(C. Wayne Smith 2004)
	Corn RUE	Gram/ Megajoule	3.8	(John L. Lindquist 2005)
Triticale	Triticale Biomass Growth	Kilogram/ Square meter/ Day	Triticale RUE * Triticale RIPAR * Triticale Radiation Efficiency* 0.001*Triticale Nitrogen Limiter	(Yi-Wen Chiu 2013)
	Triticale Height	Centimeter	GET XLS LOOKUPS('DailyData.xlsx', 'Crop Heights', 'A' , 'D2')	(J. P. GUSTAFSON and Y. P. PURI 1972) (E.A. Oelke 1989)
	Triticale K	Unitless	0.65	(F. Giunta 2004)
	Triticale LAI	Unitless	MAX(IF THEN ELSE(Triticale Height(Time) > 0 , 1.5*LN(Triticale Height(Time))-1.4, 0), 0)	(Yi-Wen Chiu 2013)
	Triticale Nitrogen Limiter	Percent	IF THEN ELSE(Triticale Nitrogen Requirements (Time)* Surface Area of Fields*0.9 > Soil Nitrogen , IF THEN ELSE(Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.9 >= Soil Nitrogen :AND:	(Crops 2016)

		Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.7 < Soil Nitrogen , 0.88 , IF THEN ELSE(Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.7 >= Soil Nitrogen :AND: Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.5 < Soil Nitrogen , 0.66 , IF THEN ELSE(Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.5 >= Soil Nitrogen :AND: Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.3 < Soil Nitrogen , 0.46 , IF THEN ELSE(Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.3 >= Soil Nitrogen :AND: Triticale Nitrogen Requirements (Time)* Surface Area of Fields *0.1 < Soil Nitrogen , 0.21 ,	

			0.1)))), 1)	
	Triticale Nitrogen Requirements	Kilogram/ Square meter	GET XLS LOOKUPS('DailyData.xlsx', 'Seasons', 'A' , 'J2')	(Seed 2010)
	Triticale Radiation Efficiency	Percent	1- EXP(-Triticale K* Triticale LAI)	(Yi-Wen Chiu 2013)
	Triticale RIPAR	Megajoule/ Square meter/ Day	0.45* Rns(Time)	(Yi-Wen Chiu 2013)
	Triticale RUE	Gram per Megajoule	1.04	(F. Giunta 2004)

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