Impact of Polymer-Coated Urea Application Timing on Corn Yield in an IoT-based Smart Farming Application

by

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Thesis submitted to the University of Ottawa
in partial fulfillment of the requirements for the degree of
M.Sc. in Systems Science
in the
Department of Electrical Engineering and Computer Science
Faculty of Systems Science and Engineering
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Abstract

The population of the world is increasing exponentially each year with a large population base. Agricultural fields are facing the pressure of dealing with food insufficiency, whereas the challenges of limited resources of arable land and fresh water on the earth should be taken into account at the same time. Smart farming was born at the right time to cope with the problem and has become one of the most powerful approaches to reducing the ecological footprint of farming and improving agricultural yield.

The four most important variables that impact crop yield are soil productivity, the accessibility of water, climate, and pests or diseases. This thesis emphasizes the application of chemical fertilizers to corn and disregards the impact of water, pests, and disease for the moment. In this study, three scenarios are explored deeper one by one. The only factor that varies among the three scenarios is the nitrogen amount available to the plant. Fertilizers have outstanding performance in improving the yield and quality of plants in agricultural fields, and this is the emphasis of this thesis. Compared with the fertilizer properties and characteristics of frequently used commercial fertilizers, polymer-coated urea was selected as the fertilizer in this study because feature of nitrogen can be released into the soil slowly and in a controlled manner.

Scenario 1 created an ideal condition where unlimited nitrogen was provided to the corn. Scenario 2 assumed that a fixed amount of polymer-coated urea was applied at the beginning of the sowing season only. Scenario 3 figured out an optimal yield by separating the fertilizer application at the beginning and in the middle of the growing days with same amounts of fertilizer used in Scenario 2. The model was performed based on historical data from Oklahoma and Ottawa using IoT sensors. The simulation model generated with Python figured out that approximately the end of June to the start of July is the best time to apply the remaining fertilizer, assuming that the sowing stage starts on May 1. The percentage of polymer-coated urea applied initially was found to usually be around 10% in the tested regions. The model was used to predict the yield in Ottawa using from 40.94 g/m^2 in Scenario 2 to 55.43 g/m^2 in Scenario 3, achieving an outstanding increasing rate of 35.38%.

Keywords: smart farming, fertilizer optimization, yield prediction

Acknowledgements

I would like to sincerely thank my supervisors, Dr. Tet Yeap and Dr. Iluju Kiringa, for their patient guidance and support and valuable time. Although face-to-face meetings were restricted during the pandemic, they generously provided help through online meetings. Their constructive feedback on this thesis encouraged me in the development of my idea from zero to completion.

I would also like to show my appreciation to my parents for the enormous financial support and generous advice they gave me through countless video calls. I am also grateful to all my colleagues and friends for sharing their ideas with me throughout the development of this project. Finally, I am dearly obliged to my cousin Lorraine, who shared her experience and provided a residence for me. Without all this support, I could not have succeeded in completing this project.

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Abbreviations

A fully expanded area of each leaf 22

AM Area of the largest leaf 22

ATU Accumulated Thermal Units 21–23, 30, 31, 57, 61, 70, 71

BM Biomass 25, 26, 33

CRF Controlled-Release Fertilizer 50, 51

DVTN Daily Nitrogen Translocation 33

FAS Fraction of total leaf Area was Senesced 22, 23, 70

fertilizer amount of fertilizer applied to the plant 31

FM Fraction of soil organic nitrogen available for Mineralization 29, 30, 62

FTSW Fraction Transpirable Soil Water 30, 31, 62, 63

GN total Grain Nitrogen concentration 33

Grain yield of the plant 25, 26, 33

GRAINN daily total amount of Nitrogen Accumulated in the Grain 33, 34

HI Harvest Index 25, 26, 70, 71

IoT Internet of Things 2, 7, 9

KS temperature response coefficient for Nitrogen mineralization 30, 62

LAI Leaf Area Index 22, 23, 62, 73

LFN amount of Leaf Nitrogen 31, 63

LN Leaf Number 22

LNM Leaf Number Maximum 22

LNT Nitrogen per unit Leaf area 31–33, 63

NCON1 solvable soil mineral Nitrogen concentration for the top layer of soil 30

NMIN1 daily Nitrogen mineralization for the top layer of soil 29, 30, 59, 62

NORG soil organic Nitrogen content 29

NU Nitrogen Uptake 30, 31

NUP daily Nitrogen Uptake Potential rate 30, 55, 59, 63

PCU Polymer-Coated Urea 51, 52, 60, 66–68, 72, 73, 76, 77, 79, 80, 83

PHS Photosynthesis 25, 33, 70, 73

PLA Plant Leaf Area 23, 71, 73

PNU total Potential Nitrogen Uptake 30, 63

Popu plant population 23

PROPLFN Percentage of the accumulated Nitrogen during vegetative development went to the leaves 31, 63

RS soil water response coefficient for N mineralization 30, 62

RUE Radiation Use Efficiency 25, 32, 33

SN Nitrogen available in the Soil 30, 31, 59, 60, 62, 71, 73, 75

SR Solar Radiation 25

STEMN amount of Stem Nitrogen 31, 63

topdepth soil depth of the top layer 31

TU Thermal Units on a daily basis 21, 26, 30, 55, 57, 59, 61

TVN total amount of vegetative Nitrogen available for Translocation to seed 32, 34

Chapter 1

Introduction

The global population has accelerated at a speed to be reckoned with, from 1 billion in 1800 to 7.9 billion in 2020 [9]. Although the total fertility rate has now declined (to 1.1% in 2020), it cannot be denied that the population is still increasing with a huge base number. Determining how to feed such a large amount of people has become a contentious issue in today's world, especially considering the limited resources on Earth. As such, addressing food insufficiency should be a priority in economic development in both developing and developed countries. This chapter introduces the necessity of agriculture development, why the topic has been chosen and the main objectives and contributions of the work.

1.1 Background and Motivations

According to Maslow's hierarchy of needs, only when physiological needs such as food and water are sufficiently met, can a human, or even a country, start to consider other levels of needs [10]. This statement clearly expresses the importance of food supply.

To solve the problem of food insufficiency, great hope is placed on the agricultural industry. However, the challenges of finite arable lands and freshwater resources versus population pressure result in agricultural development bearing the brunt. Globally, there are approximately 31 million km^2 of arable land, with 148 million km^2 of land in total.

However, arable land is being lost at the rate of over 100,000 km^2 per year [11]. It cannot be forgotten that consumable fresh water only comprises 0.5% of the Earth's water, with other freshwater sources locked up in glaciers, polar ice caps, atmosphere, and soils [12]. Considering the limitation of available resources, improving the use ratio of water, soil and other elements is imperative.

Humans have been developing and innovating agricultural technologies and techniques for thousands of years. The goal is to achieve greater crop yield with less human labour. Some of the most notable steps forward were the inventions of the steam engine and the seed drill in the early 1800s, which promoted farming productivity to a much higher level. Another important step was the introduction of optimized smart agricultural systems with artificial intelligence technology. This is required to face the challenges of an increasing global population and the gradual reduction of arable land. A study shows that 68% of the world's population will live in urban areas, while the current percentage is 55% [13].

Fortunately, smart farming was born at the right moment. With the application of modern information and communication technologies in agriculture, farm management now has one of the most powerful approaches to reducing the ecological footprint of farming and providing the agricultural industry with the infrastructure to leverage advanced technology. Cutting-edge technologies such as big data, the cloud, and the Internet of Things (IoT) are used for tracking, monitoring, automating, and analyzing farming steps, such as site-specific application of inputs, fertilizers, and pesticide management [14]. In other words, smart farming aims to reorganize the entire agricultural system towards low-input, high-efficiency, and sustainable agriculture [15].

As one of the most highly produced cereals in the world, maize provides at least 30% of food calories to more than 4.5 billion people in 94 developing countries, together with rice and wheat. Maize grains have great nutritional value as they contain 72% starch, 10% protein, 4.8% oil, 8.5% fibre, 3.0% sugar, and 1.7% ash [16]. Maize is globally significant due to its nutritional value, but its usefulness goes beyond just food — its waste also has unique importance in industries and for animals. Maize plays a key role in industrial products, including the production of biofuels. Multiple applications reflect the increasing demand for and production shortfalls in global maize supplies, such as the tremendous growth in demand for maize as livestock feed over the past decade [17]. Therefore, research on raising the yield of corn is currently of great importance.

As one of the most significant elements in farming, fertilizers are frequently used to boost the fertility of the soil and increase the yield of crops. Fertilizers are natural or artificial substances containing essential chemical elements that improve the growth and productiveness of plants on existing farmland. Nitrogen, phosphorus, and potassium are mostly used in modern chemical fertilizers.

1.2 Objectives

The primary aim of this thesis is to investigate the simulation model using polymer-coated urea to improve the yield of corn (*Zea mays L.*). In the pages that follow, we seek to:

- Discuss and determine the variety of chemical fertilizers selected for this project.
- Establish three step-by-step scenarios analyzing and simulating corn growth situations.
- Develop mathematical corn growth models investigating the usage of polymer-coated urea to improve corn yield for each scenario.
- Calculate the optimal application time of the selected chemical fertilizer to achieve the highest yield based on Oklahoma (in the United States) historical climate data and Ottawa (in Canada) climate data from last year.

Considering the reality that fertilizer amounts are typically purchased at a fixed value, nitrogen resources are restricted, but a higher yield can be achieved by determining the optimal time to fertilize crops.

1.3 Methodology

The thesis aims to develop mathematical simulation models to predict corn yield with additional amounts of fertilizer. Python was used as the main tool to develop and simulate the model.

1.4 Contributions

The main contributions of this thesis are:

1. Consideration of the effect of chemical fertilizer on plant growth
2. Development of a mathematical model to simulate the yield of corn growth in three respective scenarios with input weather data collected from IoT sensors
3. Determination of an appropriate model to calculate the exact timing and amount of fertilizer to be applied in the middle of the growing season
4. Calculation of the optimal time to apply fertilizer at the beginning of the sowing stage and in the middle of the growing season

1.5 Organization

The remaining parts of this thesis are organized as follows:

- Chapter 2 mainly discusses relevant theories and related previous works, including the explanation of precision agriculture, why corn is chosen as the target, and how corn grows physiologically. Corn growth in this thesis is explained based on three scenarios, with each scenario being more complex than the previous one. In regular corn growth, referred to as Scenario 1, the model is explained following a precise flow chart, which is developed under the most ideal situation. No constraints imply sufficient sunshine, water, and nutrients in the soil, with no diseases or pests. In Scenario 2 corn growth, the model is explained considering the nitrogen effect. Scenario 2 is more precise because the nitrogen-fertilizer is considered and applied at the beginning of the growing season.
- Chapter 3 provides further explanation about fertilizers. The properties, characteristics, and significance of fertilizers are introduced in detail, as well as the benefits and disadvantages. The selection of fertilizers among the frequently used varieties in the designed model is also considered.

- Chapter 4 sets out to explain the model designed in Scenario 3, which is the most precise among the three scenarios. The difference is in the amount of artificial nutrients and the fertilizer application timing. The theoretical basis and formulas are explained and discussed. The chemical fertilizers would be applied twice, at the start of the sowing stage and during the growing season. The process and effect of the specific aspects of this model are described and explained in detail.

- Chapter 5 shows the experiment results of Oklahoma and Ottawa using the model developed in the three scenarios from Chapter 4. Data of Oklahoma were captured from Daymet and USDA-NASS, and data of Ottawa were collected from the IoT-based sensors set in the farms. Mainly, the results in both ideal conditions and realistic conditions (Scenario 2 and Scenario 3) are compared. Furthermore, Ottawa-based data is used on the model to see the simulated yield. The results are then compared to see the accuracy of the model.

- Finally, Chapter 6 summarizes the essential points in this thesis and discusses potential future work.

Chapter 2

Theory and Related Works

Throughout human history, agriculture has always played a critical role in the support of livelihood. Humanity cannot survive and multiply without the development of agriculture due to its crucial nature as a reliable source of life. Agriculture was a primary economic source prior to the industrial revolution, providing food and raw materials to support people with their basic needs. The agricultural industry also provided employment opportunities to a large percentage of the population. Despite the passage of time and development, in many ways, this industry is still the backbone of the economic system of a country. For decades, agriculture was associated with the production of essential food crops. These days, agriculture is widely expanded to include areas such as forestry, poultry, and fruit cultivation. With the help of technological advancement, agriculture is facing a revolution in the industry. Smart farming is being defined as the new era. In the following sections, smart farming will be explained in detail. The reason corn was chosen as the target crop will also be expanded upon. Furthermore, previous research regarding corn growth and the factors that affect crop growth will be explained one by one.

2.1 Smart Farming

As mentioned in Chapter 1, human beings are facing challenges due to increasing global population, food shortages, and inevitable production costs. The target is to improve agricultural yield with fewer resources and labour efforts. For this to be feasible, we are in urgent need of substantial innovations. The term “smart farming” refers to the integration of advanced technologies into existing agricultural practices to achieve fine-grid crop management [18]. Smart farming aims to empower today’s farmers with meaningful real-life environmental data from the cultivation fields and boost competitiveness and profit. Automation technologies integrate products seamlessly, providing knowledge and services for improved productivity, quality, and profit to farmers. Primarily, the purpose of applying innovative tools in agriculture is to sustainably secure the yield potential. Other than that, increasing crop production efficiency and reducing natural resource inputs are two additional benefits of implementing such technology.

Smart farming has been developed with the goal to reduce production costs and improve crop yield. As a rising area, smart farming offers far more than the mere use of information and communication technology, and precision agriculture is one of the core branches of this modern industry. Modern devices are introduced into agriculture to process and analyze data. As a result, rational and reasonable decisions can be made or semi-automatically prepared based on the rise of new technologies, such as big data, the IoT, and artificial intelligence in all stages of agriculture.

Targeting more than conventional farming exploitations, smart farming applications enhance and boost respected and transparent farming in small and complex areas or spaces with specific cultures and cattle. There are also environmental benefits because of the monitoring and control of water usage and chemical treatments with the help of smart farming decision-making tools [19]. It is obvious that almost every aspect of the agricultural field can benefit from technological advancements, ranging from planting and irrigation processes to plant protection and harvest methods. Conventional agriculture benefits from the development of smart farming and leads to improvement in these aspects. Conversely, these improvements also promote the development of smart farming.

2.1.1 Precision Agriculture

In the past, farmers had to plant and harvest solely based on experience. Thanks to the industrial age, agriculture began to incorporate mechanization and the application of synthesized fertilizers to plants. Modern agricultural systems have benefited from the development of technology, genetic engineering, and automation that work to greatly bolster the yield of crops. Precision agriculture has the potential to be a powerful approach in farm management that reallocates farm resources to produce lower input, higher efficiency, and sustainability [20]. Besides, with concerns surrounding crop yield for agricultural stakeholders, crop yield prediction plays a significant role in agricultural decision-making and global trade trend predictions.

With the establishment of agricultural mechanization, farmers are released from applying manual treatments. Cutting-edge technologies currently applied to agriculture include the Global Positioning System (GPS), mobile computing, telecommunications, and in-field sensing devices. Data can be generated and analyzed based on spatial and temporal dimensions to reasonably organize agricultural resources. Moreover, precision agriculture manages the improvement of spatial and temporal variability to increase economic benefits. The decision support system (DSS) aims to optimize the process by preserving resources and facilitating the widespread use of modern technologies such as GPS, aerial images by drones, and hyperspectral images provided by sentinel satellites. A wide range of spatial variables can be measured containing terrain features, topography, moisture content, nitrogen levels, and crop yield, among others [19]. As such, it is now possible for more comprehensive data on production variability to be collected in order to analyze influential aspects, including historical and present yield distributions, field topography, soil fertility, soil physical properties, crop density, and management variabilities [15].

Precision agriculture technology benefits agricultural production in two ways: ecological and environmental benefits for the public, and economic profitability for the producers. An increasing number of countries have realized the importance of environmental protection, introducing strict environmental legislation, including restrictions on the usage of agrochemicals. While this is necessary for sustainable development, it is difficult for farmers to follow. Precision agriculture offers assistance in the enforcement of such legislations by using the accurate information and methods of the targeted application, such as recording field treatments, keeping track of operations on the field, and transferring all saved data to a platform for further analysis [21].

On the other hand, farm production can be precisely tracked and monitored with precision agriculture techniques, and accurate assessments can be concluded with the collected data. Inputs such as fertilizer amounts, the timing of fertilizer applications, and the distribution of fertilizers are controllable and adjustable based on spatial and temporal variability in a field. These statistical conclusions provide clear ideas on the costs of inputs and cash return over the costs for each hectare, which are essential variables for calculating economical earnings [22]. Furthermore, they serve as a basis for decision-making in the field of agricultural management.

2.1.2 Internet of Things

The IoT is a large communication network involving a vast number of distributed devices around the network, designed to recognize and notify users instantly about real-time events. These devices have basic computational skills and are called smart objects.

IoT is widely applied in precision agriculture with the presence of systematic architecture and a distributed data processing approach. To enhance operational efficiency and productivity in the agriculture sector, the use of IoT is employed, and several existing modern technologies are integrated, such as cloud computing, wireless sensor network, and radio frequency identification [1]. In detail, the data processing approach aims to distribute the monitoring of crops and soil where hierarchical aggregation and modeling primitive sand contribute to the robustness of the network by alleviating communication bottlenecks and reducing the energy required for redundant data transmissions. By exploiting the dense spatial and temporal distributions of the sensing nodes, intelligent data reduction through aggregation and model reconstruction is illustrated for significant benefits in improving network congestion and energy efficiency. Eventually, IoT-enabled distributed data achieves the purpose of extensive evaluation for online decision-making by domain experts to improve the reconstructed data quality [23].

These days, the application of IoT in the agricultural sector is mainly about empowering farmers with tools to make real-time decisions and incorporating automation technologies to integrate services for better productivity. Figure 2.1 visually illustrates the process of the IoT ecosystem for agriculture. Real-time data is collected from embedded devices, such as temperature and humidity sensors, to detect soil conditions, alarm systems, SOS-light controls, and ultrasound controls. After the first step of data collection, the data is transferred using IoT devices and communication technology, then uploaded to the cloud IoT platform. Data, including real-time raw data and images taken from cameras, is saved and analyzed through the application server. This cloud IoT platform provides device management services and connectivity management services. After data analysis, raw data is visualized and managed through different applications and operations to assess current farming conditions and make real-time decisions to monitor and control crop growth. [1]

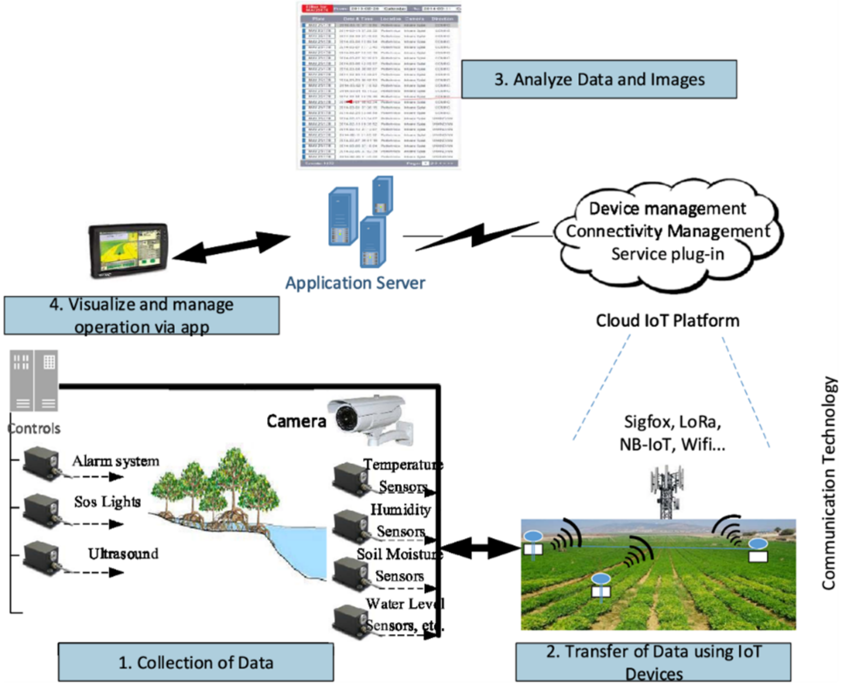


Figure 2.1: Illustration of IoT ecosystem for agriculture [1]

2.1.3 Benefits, Challenges, and Characteristics of IoT Devices

The use of IoT in agriculture creates a wide range of benefits. Firstly, IoT allows common data storage and data sharing. The sharing aspect of the information system undoubtedly increases the interaction between farmers and agricultural experts, which promotes the development of community farming through the use of mobile apps and IoT facilities equipment. On this basis, the logistics traceability and qualitative traceability of food can be addressed with the application of IoT technology to achieve the goal of product safety control and fraud prevention. Meanwhile, when and where to apply the exact quantity of fertilizer or pesticide are decisions that should be made by farmers and agricultural experts.

These real-time decisions are usually made depending on real-time data for optimal crop management. The enabling of data-driven agriculture using IoT promotes a brand-new direction to lower costs and reduces wastage of farm inputs, such as fertilizers and pesticides. Since data can be easily collected and saved on the IoT cloud platform, these pieces of information are easily accessed through mobile apps and are readily analyzed. Time and money are two outstanding aspects that are reduced and saved because of the remote monitoring of IoT devices and equipment, especially in a large field. The supply chain of agricultural products can be optimized with the use of IoT systems, which provide a real-time balance between the demand and supply related to farmers and decision-makers in agricultural sectors such as government and non-governmental agencies.

As discussed above, data collection depends on IoT devices, which consist of sensors and actuators. Sensors typically aim to monitor and measure variables in agriculture, including soil nutrients and weather data. To meet the requirements of agricultural applications, IoT devices should meet several key characteristics. Reliability can be the priority because the confidentiality of data is the basis of data analysis. IoT devices should also be able to achieve high power and computational efficiency. Consequently, these facilities can be used for a long time and meet the requirement of durability. Moreover, the entire farm should be monitored and covered by the devices, and there should be enough memory to store the collected data [1].

However, there are still several unresolved issues and key challenges in the deployment and adoption of IoT in agriculture. These issues can be classified into three main categories: business, technical, and sectoral.

Firstly, the expenses associated with IoT equipment involve setup costs and running costs, including the purchase of hardware such as IoT devices, gateways, and base station infrastructure. The running cost includes the continuous subscription for the use of centralized services or IoT platforms and the exchange of data between IoT devices and cloud platforms. Although some of the platform providers provide free subscription services, the functionality of the services and the number of connected IoT devices are limited, which means complete and comprehensive functionality and services require a higher subscription fee. The high cost leads to a burden upon farmers as a long-term improvement expense. What's more, the companies with mature IoT technologies usually have developed business models that support revenue generation from data accumulated from their farms. However, these business models may not perfectly adapt to the farmer's field. Also, the issue of data control and ownership remains an area of contention between farmers and IoT service providers. Lastly, another challenge from the business aspect is the lack of adequate knowledge of IoT applications. This is a severe and common barrier in rural areas of developing countries, where major farmers are mostly unable to use IoT devices.

Second are the category of challenges that are technical in nature, which need to be resolved to promote the development of IoT. This includes interference problems associated with the massive deployment of IoT devices, security and privacy issues that need to be addressed at different levels, and the reliability of IoT devices in harsh environmental conditions. It also includes challenges with scalability to support a large number of IoT nodes, localization of IoT devices to support place-and-play functionality, and the development of complex algorithms and mathematical models to minimize the cost and maximize agricultural products and profits.

Thirdly, sectoral issues surrounding regulatory challenges and interoperability are another category that presents potential complications. The regulations regarding the control and ownership of farm data between farmers and companies may differ from country to country. Policies on data privacy and security across regions can affect the application of IoT in different cases. Moreover, the protocol and standards of IoT device operations are still under construction and normalization. Interoperability refers to the ability to communicate and transfer data successfully and effectively, regardless of infrastructure or geographic region. To successfully achieve interoperability, access to standard return formats and appropriate interchange gateways is required.

It is apparent that IoT technology benefits the development of modern farming, especially by increasing operational efficiency and productivity. The identified open challenges discussed in this chapter are expected to be resolved, such as the affordability of IoT devices for small and medium-scale farmers and the security and cost issues. In all cases, the implementation of IoT technology would make a big change in the future pattern of agriculture.

2.2 Corn Growth

Corn plays an important role in human history and has one of the highest production rates of all cereals in the world. As a crop, corn is widely used as food for humans and offers various health benefits. The demand for its usage as livestock feed is increasing as well. Recently, the employment of corn as a source of biofuel has also gained traction. It can now be processed into a wide range of useful chemicals, contributing to the improvement of farmers' livelihood. Due to its importance and far-reaching benefits, corn is used as the basis of this thesis to discuss and determine the growth process and improve yield.

Corn is a typical plant that is more adapted to cooler temperatures compared to other crops. Therefore, the yield performs better than other plants growing in Ottawa, Canada. Understanding the steps of corn growth from the first emergence through to harvest would help benefit the growth process and recognize issues.

2.2.1 Corn Growth Stages

Generally, there are four distinct stages of corn growth from seed to harvest: planting, germination, vegetative, and reproductive. The latter two stages are centered around the process of growth and development. Understanding the growth stages of corn can inform the methods needed to enhance the corn crop and apply the appropriate timing of fertilization, irrigation, cultivation, and pesticide application that significantly improve the yield.

As can be seen from Figure 2.2, the corn growth stages and development processes are visualized from the vegetative stages to the reproductive stages. The vegetative stages start from emergence to tassel. Emergence occurs when the first leaves appear above the soil surface. Ideally, the emergence stage performs at 10-13°C and moisture conditions promote rapid emergence 5 to 7 days after planting. The seed is placed at a depth of around 1 to 2 inches from the surface of the soil. The temperature, soil moisture conditions, and depth of seed placement can vary the timing of emergence by several days. Leaf development of the first leaf, known as the V1 stage, occurs about one week after the emergence stage. Full development of the first leaf is completed when its collar becomes fully visible, and the collar of the leaf can be found at its base. The higher concentration of soil nutrient levels stimulates early plant growth.

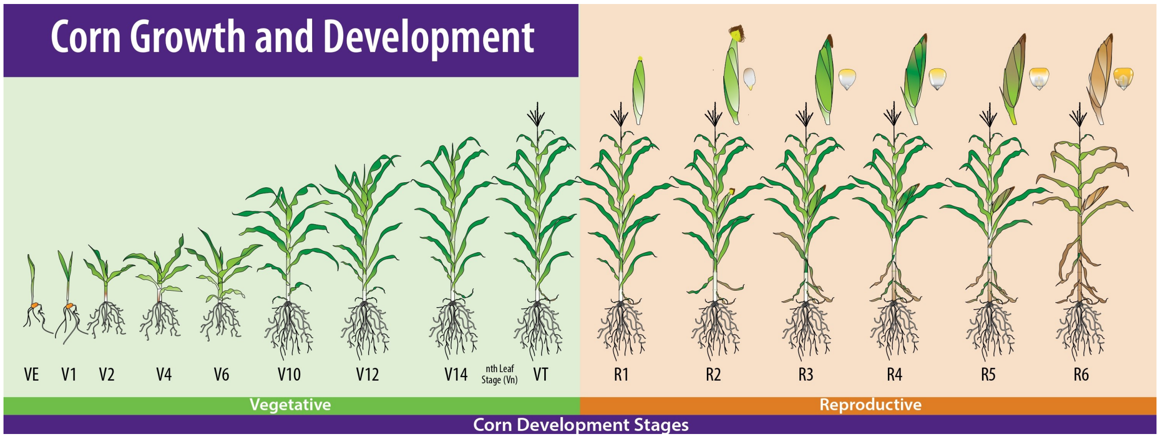


Figure 2.2: Stages of corn growth [2]

The following components in the vegetative stage are named by the full emergence of the number of leaves. To complete a vegetative stage, an exact number of fully visible and expanded leaf collars must be present on the new growth. There are approximately 14 to 18 leaves in a plant. The tassel stage occurs after the leaves are fully expanded, which means the potential kernels per row are set. Meanwhile, the final potential grain number and potential ear size are determined at their maximum height at this stage. The end of leaf production is characterized by tassels that are fully extended, but the silks have yet to emerge. Usually, it takes 2 to 3 days for the tassels to be completely visible before the emergence of the silk. At this point, there is no new vegetative growth on the crop. Although the leaves of the plant may grow larger during the following reproductive growth stages, there will be no increase in the number of leaves. At this stage, a complete leaf loss would cause nearly complete yield loss.

The first reproductive stage is marked by the emergence of silk from the ends of the husk. At this point, there are several features worth noting: the corn has grown fully, the ears are still maturing, and the total number of kernels and rows on the ears is fully determined. The silks aim to gather any pollen that falls from the fully matured tassel and capture the pollen that moves down into the ovule where pollination takes place. In other words, this is the stage where silk is visible outside the husks and flowering begins. At this stage, the potential kernel number is determined, and the maximum plant height is achieved. Nutrients are required during this growing stage, and water demands are at their peak. Close attention should be paid to heat and drought conditions because these factors will affect pollination and the final grain number.

In addition, defoliation by hail or other factors such as insects will produce a large yield loss. During this stage, the plant is at its most vulnerable. The biggest culprit is moisture stress, since the drought dries the silk out and compromises its ability to collect the pollen falling from the tassels. As such, environmental conditions can greatly affect how well the corn pollinates, and careful consideration of such factors is paramount.

The next stage is called blister, which is where silks darken and begin to dry out about 12 days after silking. At this point, kernels contain a clear fluid with white colour and a blister-like shape. The embryos start to develop in each kernel, in which the moisture levels reach approximately 85%. The process of cell division is complete at this stage, and the process of grain filling commences.

After around 20 days of the silking stage, the milk stage starts when silks dry out. A test consisting of crushing and squeezing the milk-like fluid out of the kernels between one's fingers confirms the start of the starch accumulation process. The dough stage occurs after the milk stage, approximately 26 to 30 days after the silking stage. This stage is thus named due to the starchy material within the kernels, which have a dough-like consistency. It can also be proven by the finger squeeze test that the material squeezed out of the kernel has a dough-like consistency. At this point, the rapid accumulation of starch and nutrients occurs, and kernels have 70% moisture and begin to dent on the top. Most of the kernels are dented at the dent stage during the reproductive process about 38 to 42 days after the silking stage. The moisture level inside of the kernel declines to approximately 55% as the starch content increases.

The symbol of the stage of maturity is the occurrence of a black layer forming at the base of the kernel, blocking the movement of dry matter and nutrients from the plant to the kernel. This stage normally occurs 50 to 60 days after silking, and the moisture level inside the kernel is 30% to 35%. The kernels that achieve maximum dry weight are physiologically mature. Although frost or any biotic or abiotic stress does not impact yields after this development stage, lodging from disease, insect damage, or hail can still result in the physical loss of yield. Grain is not ready for safe storage at this stage since the recommended moisture level for long-term storage is 14.5% [24] [2].

Knowledge of plant growth and plant symptoms that occur during certain stages is essential in helping farmers determine the background and impact of crop problems such as fruit deficiency and disease. Corn growth undergoes both physical and biochemical changes, and awareness of these changes greatly impacts the efficiency of the response to different management decisions during the growth process.

2.2.2 Factors Affecting the Farming and Yield

Growth and development stages are different depending on plant varieties. Whether it is directly or indirectly, environmental factors greatly affect plant growth and distribution.

Since the importance of yield promotion has been explained in detail above, factors that affect crop growth and yield are taken seriously into account. Generally, the four environmental factors that could affect the growth of plants include light, temperature, water, and nutrition. Since the four factors go through the entire growing season, agricultural development should recognize the roles of these factors to diagnose plant problems and manipulate plants to increase leaf, flower, or fruit production.

Sunshine is the source of light, providing solar radiation to promote photosynthesis. Water is usually acquired from precipitation. And nutrition comes from the soil and extra artificial nutrition, such as fertilizers. The factor of temperature impacting the plant growth is expanded on in Chapter 2.3, and the factor of nutrition affecting the development of the crop is discussed in Chapter 2.4.

As one of the core components of crop production, water is essential to improve both the yield and quality. The water requirements and irrigation systems will be introduced as follows considering the monitoring of soil moisture. Besides, water quality and irrigation auditing will be talked about.

Usually, the irrigation amount varies in seasons. During the summertime, surface water can be used for irrigation directly. Meanwhile, reservoirs are required to store the predicted annual water requirement. For each farm, there needs to be a specially designed irrigation system. Water needs to be adequately filtered, especially to prevent trickle irrigation from blockages. The frequency of water application must be decided on depending on different applications by soil moisture deficit.

To plan the most efficient systems, fields need to be individually considered for the soil type, slope, and especially row length. Where trickle irrigation is used in conjunction with other application systems, a separate lower pressure main with dedicated pumps may be the right solution. This will depend on the relative scale of the operations, when and how the trickle operates, and at what distance. Water quality is an important factor in corn irrigation. It is crucial for the success of trickle irrigation. Simple mesh filters can be used for smaller schemes, but sand filters and particularly disc filters are now increasingly common, as they offer a self-cleaning option.

Potentially, saline water sources that are used for irrigation purposes should be regularly tested for their chloride levels. Chloride can scorch foliage directly and reduce water uptake by the roots. Potentially, the most water-efficient method of application is trickle irrigation, but apart from use on high-value corn crops, or where water supplies are very limited, the investment is currently difficult to justify. Added to this, some recent reports and experience suggest that the potential water savings expected do not always materialize in practice. Their advantages are great flexibility and adaptability, with a wide range of sizes and outputs available. It aims to make more efficient and more accurate use of the water. Growers are increasingly looking to use booms. Besides, booms have smaller droplet sizes compared with a rain gun, reducing the impact effect on the soil and crop. Also, they improve the accuracy. Other ways include center pivot and linear machines, and sprinkler irrigation.

Two main irrigation methods are using these days. Theoretically, trickle irrigation is a more efficient use of water than overhead systems. Less energy is used compared with hose reel systems – in the order of 50%. The design and layout are very flexible, fitting almost any shape of field. Less labour is required during the growing season. High costs and the practicalities of handling reusable trickle pipes are disadvantages of this method. However, separate mains and pumps or pressure regulating valves may be required when trickle systems are being run alongside an existing overhead irrigation system.

The importance of water is revealed in many aspects: photosynthesis, respiration, and other plant physiological functions; the transport of minerals and photosynthetic products; the turgidity of plant cells; and the transpiration and regulation of leaf temperature. Compared to many other crops, the corn plant is sensitive to both the lack of and an excess of water. If facing a lack of water, which is the most common stress, the corn does not compensate for drought periods with prolonged growth. Drought influences the yield directly by restricting transpiration and photosynthesis. Dry soils form clods that make soil and crop management difficult and cause tuber damage at harvest. Drought early in the growing season restricts canopy expansion and therefore light interception and yield. Moist soils encourage root growth.

The aim of irrigation scheduling and application for maximum common scab control is to maintain soil water reserves close to field capacity. Excess nutrient levels and leaching can increase the pollution of both surface and groundwater. If facing excess water, which could be caused by heavy rainfall, heavy irrigation, or inefficient drainage, the soil moisture will change. The variation of soil moisture may initiate second growth, which results in bottle-neck-like or knobby tuber shapes.

Apart from stomatal opening, the transpiration of water from a plant into the atmosphere depends on the maximum evapotranspiration rate of the crop. Evapotranspiration can be measured with an evaporation pan of any size and shape in millimetres. Water absorption depends on plant conditions and soil conditions as well. Overall, irrigation management has to decide when water is in short supply, when to start irrigation, and also when to stop irrigation. This could be decided by a manual water balance sheet and irrigation schedule.

Other than trickle irrigation, furrow irrigation is the most widely used irrigation method in corn production. Water is supplied from the main channel by way of siphons or auxiliary supply channels into the cultivation furrows. Drainage channels are needed at the end of the furrows to drain excess water off the field. This helps provide a constant height of water throughout the furrow length and to avoid flooding at the field end. The most important factors for furrow irrigation are furrow distance, length and slope, and ridge uniformity [25].

Optimizing the use of water for both crops and the environment depends on someone recording rainfall, checking equipment, and scheduling irrigation applications. It is important that the responsibilities concerning irrigation management on the farm are clearly defined. A range of sophisticated techniques and tools is available to measure soil water contact and schedule irrigation and to assist in optimizing water use, crop yield and quality, and environmental care. Direct methods: neuron probes (installed, calibrated, and used correctly, can provide a good measure of the quality and distribution of water in the soil profile), tensiometers (useful to run them alongside another system of scheduling as a check), capacitance probes. Indirect method: the manual water balance sheet. Monitoring soil moisture under trickle irrigation systems: applied in frequent small doses [26].

2.3 Models of Corn Growth

Accurate estimations of crop yields are important for many agronomic issues, including agricultural management, national food policies, and international crop trade. Crop yield forecasts are an important piece of information to many members of the agricultural industry. These forecasts help industry members make decisions about production, influence future market prices, and can even affect international trade. Therefore, a simulation model that studies crop growth is necessary in the research of yield increase.

This thesis was inspired by previous works on corn growth model study, which introduced several techniques for plant yield prediction and simulation. This section will introduce two of the most important papers that provided the ideas of calculating the yield and nitrogen accumulation based on temperature and solar radiation and nitrogen effect, respectively.

2.3.1 Previous Work on Temperature and Solar Radiation

Muchow and Sinclair worked out a model that discussed the maize growth in several valid locations from 14°S to 40°N in the northern hemisphere without constraints in 1990 [3]. Their study focused on analyzing the unstressed maize crop's yield responses to variation in temperature and solar radiation among diverse locations, since these two weather variables have a direct and significant impact on maize yield. Besides, it is proven that temperature affects the duration of crop growth. The duration of grain filling actually decreases with the increasing temperature, and the shorter grain-filling periods usually lead to lower grain yield. Although the higher temperature has an influence on the grain filling duration, which may lead to lower yield, Muchow observed that grain yield was unvaried due to coincidentally higher incident radiation at the higher temperature. The significance is obvious when discussing the effect of temperature and solar radiation on potential maize yield simultaneously.

This simple mechanistic growth model aims to simulate the major quantitative impacts of temperature and solar radiation on maize growth, development, and yield. The flow chart expressing the logical process can be seen in Figure 2.3. In order to control other elements, it is assumed that plants were well-watered, ample nutrients were provided, and there were no diseases or pests to be concerned about. Since the model considers situations that minimize the other factors, it will be treated as Scenario 1, the first step of the eventual model.

Scenario 1 Simulation Model

As the basic step of simulation model in this thesis, the corn growth process is simulated under an ideal condition. From the perspective of corn growth, this scenario consists of

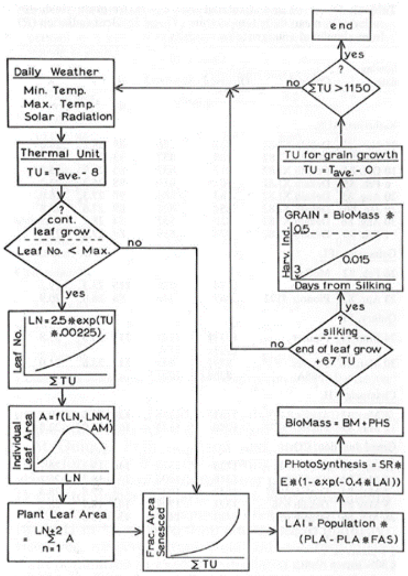


Figure 2.3: A flow chart showing the operation of a maize growth model influenced by temperature and solar radiation on a daily time step [3]

vegetative stages and reproductive stages. From the perspective of model simulating, three parts of calculation should be considered: thermal units, leaf growth and grain growth.

Thermal Units Daily temperature and solar radiation are basic inputs for the model. To obtain the Thermal Units on a daily basis (TU), averaging the daily maximum and minimum temperatures and subtracting a base temperature of 8 is required [3].

$$TU_i = Tave_i - 8 \tag{2.1}$$

The difference equation of calculating the Accumulated Thermal Units (ATU) is shown below.

$$ATU_i = TU_i + ATU_{i-1} \tag{2.2}$$

Leaf Growth In the vegetative stages, the leaf number of a corn plant determines the final yield of this crop. Other basic variables dominating the yield of the corn fruit include the Leaf Number (LN), the fully expanded area of each leaf (A), and the Fraction of total leaf Area was Senesced (FAS). The LN is calculated as an exponential function of ATU.

$$LN_i = 2.5 \times \exp(ATU_i \times 0.00225) \tag{2.3}$$

The A is calculated from LN and the Area of the largest leaf (AM).

$$A = AM \times \exp\big\{(-0.0344 \times [(LN_i - LNM)^2] + 0.000731 \times [(LN_i - LNM)^3]\big\} \tag{2.4}$$

where AM was the area of the largest leaf, LN was the daily leaf number, and Leaf Number Maximum (LNM) was the leaf number that had the largest area.

The FAS is calculated depending on the ATU from emergence according to the exponential relationship.

$$FAS_i = 0.00161 \times \exp(0.00328 \times ATU_i) \tag{2.5}$$

As an important parameter of vegetation structure in the fields of agriculture, forestry, and ecology, the Leaf Area Index (LAI) describes the plant canopies quantitatively, which is defined, as it expresses the one-sided green leaf area per unit ground surface area in broad-leaf canopies.

LAI performs as a key vegetation parameter for modeling mass (water and carbon) and energy (radiation and heat) exchange between the biosphere and the atmosphere [27]. This parameter is generally used as an indicator of the growth rate of a plant pertaining to biological processes. To clarify LAI on a sloping surface, the ground surface area is specifically defined as the horizontal ground surface area. The ambient temperature is the key component that influences leaf canopy development, which determines the LAI of the crop. Since Scenario 1 was developed without other constraints, the function describing the phenological development during the corn cultivation season depends on the daily thermal units and the total leaf number only in this model.

The FAS is one of the core parameters when calculating the LAI. The LAI is determined by plant population (Popu), known as the number of plants per square metre, Plant Leaf Area (PLA), and FAS depending on the ATU.

$$PLA_i = PLA_{i-1} + A_i \tag{2.6}$$

$$LAI_i = Popu \times (PLA_i - PLA_i \times FAS_i) \tag{2.7}$$

Grain Growth The flow chart 2.3 explains the structure of the corn growth based on Scenario 1 limitation on a daily time step. Temperature and thermal units are the main factors influencing this growth mode. Daily thermal units for this development model are calculated as the average of daily maximum and minimum temperatures and subtracting a base temperature of 8. Only if the leaf number approaches the maximum value can the plant proceed to the next step. Otherwise, the plant will continue to grow the leaf and expand the leaf area, where formulas are available to calculate the relationship between total thermal units versus leaf number, and leaf number versus individual leaf area.

The total number of developed leaves was taken seriously, since it was an indicator of the maturity rating of a hybrid [28]. The area of the individual leaf was calculated by defining the total number of leaves to be produced on each plant and the area of the largest leaf. Next, the fully expanded area of each leaf was calculated from the leaf number and the area of the largest leaf. When the plant stops growing new leaves, the factor that area senesced is calculated, considering the effect of solar radiation.

Only with the LAI ready, it can proceed to photosynthesis, a necessary process happening in most plants. Although the exact process would be performed differently by different species, photosynthesis follows a similar theory that converts light energy into chemical energy through cellular respiration. The chemical energy is stored in carbohydrate molecules, including sugars and starches, which are synthesized from carbon dioxide and water. Car-

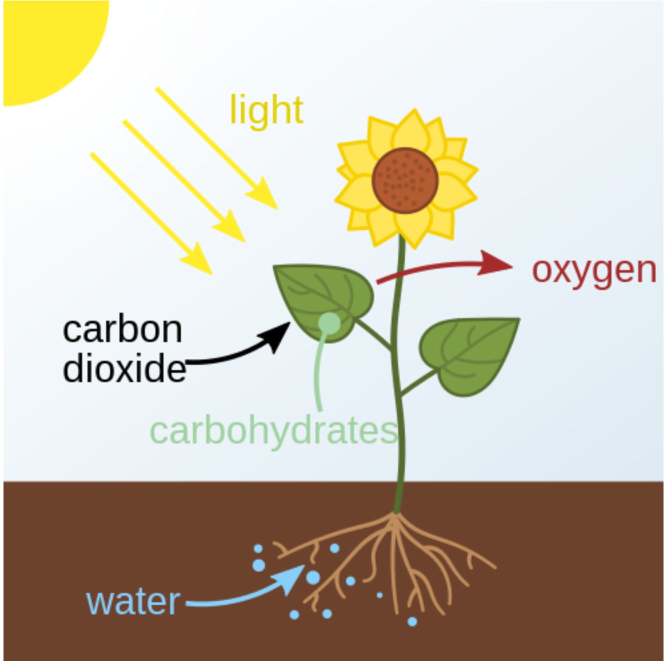


Figure 2.4: The scheme explains the process of photosynthesis in plants [4].

bohydrates such as sugars and starches provide energy to human bodies when consumed as a staple food.

Photosynthesis as a basic process is performed in most plants, including corn for sure, starting from light absorption by a typical protein called chlorophyll. Figure 2.4 indicates how the carbohydrates produced are stored in or used by the plant. The diagram shows the process of transferring light energy to chemical energy through chlorophyll.

During a process called carbon fixation, carbon dioxide is absorbed and converted into sugars. Carbon fixation is an endothermic reaction, which means that heat is absorbing during the reaction from the surroundings. In brief, the core reaction of photosynthesis is capturing sunlight into chemical energy, splitting water to liberate oxygen, and fixing carbon dioxide into sugar.

The equation for photosynthesis is:

$$\text{Carbon dioxide} + \text{water} + \text{photons (light energy)} \rightarrow \text{carbohydrate} + \text{oxygen}$$

+ water

From the theoretical formula shown above, it is obvious that carbohydrates and oxygen are products after the reaction appears on the right-hand side. Both carbohydrates and oxygen are necessary for creatures' survival; therefore, photosynthesis is paid much attention in biological research. With the help of photosynthesis, biomass is accumulated, and silking occurs. Especially, the silking stage is defined as silk emerging from the ear to receive pollen and beginning the fertilization process. It was found that silking will occur in 67 thermal units after the flag leaf is fully expanded [29]. Eventually, the corn reaches maturity and is ready to be harvested.

In Scenario 1, Photosynthesis (PHS) is computed as the result of the daily incident Solar Radiation (SR), the proportion of radiation intercepted by the canopy, and the Radiation Use Efficiency (RUE) of the crop, which is constant under Scenario 1.

$$PHS_i = SR_i \times RUE \times (1 - \exp(-0.4 \times LAI_i)) \tag{2.8}$$

Biomass (BM) is accumulated during the photosynthesis, and grain growth is assumed to begin 3 days after silking.

$$BM_i = BM_{i-1} + PHS_i \tag{2.9}$$

Silking was found to occur 67 thermal units after the flag leaf had fully expanded, and grain growth was assumed to begin 3 days after silking. The grain yield was described as the function of biomass accumulated and a linear increase in Harvest Index (HI). Since harvest index is the ratio of grain mass to BM, an incremental increase in the HI defines the required increase in grain mass. The maximum HI was set to 0.5 to reflect the genetic potential of most current commercial maize hybrids. Consequently, the yield of the plant (Grain) was calculated as the product of accumulated BM and the HI through grain filling.

Grain yield accumulation was computed as a function of BM accumulation and a linear increase HI. It was observed that the harvest index of maize increased linearly with time during grain filing and was relatively stable across environments at 0.015 per day. Only when silking occurs, would the corn start to accumulate grains.

$$HI_i = HI_{i-1} + 0.015 \tag{2.10}$$

So the HI value should be noticed with limitations, where HI was zero at the planting stage, and achieved at 0.5 as the maximum value 33 days after the planting stages. This maximum value reflects the genetic potential of most current commercial maize hybrids.

Consequently, the Grain was calculated as the product of accumulated BM and the HI.

$$Grain_i = HI_i \times BM_i \tag{2.11}$$

TU from silking to maturity were computed with a base temperature of 0°C and no maximum temperature. And as discussed before, the duration of grain filling decreases with increasing temperature, which means a shorter grain-filling period is often associated with lower grain yield. With the previous working results, thermal units from silking to physiological maturity were fixed at 1,150 as an indicator. If the sum of thermal units has proceeded to 1,150, the maize growth process has arrived at the end. The process of Scenario 1 operated as described above.

2.3.2 Previous Work on the Nitrogen Effect

In Scenario 1 discussed above, nitrogen was assumed not to be a constraint on any process. It was imagined that enough nutrients were provided in the soil directly. However, it could be such an ideal state. In the following chapters, the paper promotes the model into the next two levels. Firstly, enough nitrogen was provided from fertilizers with no budget to be concerned about. Secondly, limited fertilizers were provided economically. To increase fertilizer N use efficiency, maximize profit, and reduce the negative impacts on the environment, the N nutrient supply should match plant demand during the growing season [30]. Finding the optimum fertilizers applied to the plants was the ultimate target of this research.

It is necessary to develop quantitative functions to describe the responses of physiological processes to variation in the tissue N level. From previous research, experiments have shown the large effects of nitrogen budget in maize on leaf development and growth, biomass accumulation, and seed growth. These results have clear outcomes, but the constraints are obvious simultaneously. The nitrogen demand is limited by the soil nitrogen availability and the plant nitrogen uptake function. To solve the problem, nitrogen supply should be calculated based on the nitrogen availability in the soil and on a plant uptake function dependent on cumulative thermal units. The factors influencing plant growth have been discussed before, and the previous related works have shown the quantitative relationship between temperature, solar radiation, and nitrogen to the plant.

Scenario 2 Simulation Model

Scenario 2 of the thesis work is explored based on the soil nitrogen budget model developed by Sinclair and Muchow in 1995 for maize [3], considering the situations of enough sunshine, enough water, no pests or diseases, and the application of nitrogen fertilizer ahead of the growing season. It means that effective nutrients are available in the soil to be absorbed by the plant, and no more fertilizers are applied during the growing season.

This nitrogen model was a mechanistic model, which separated the soil into two layers, the top layer and the second layer, to discuss different functions. The top layer received fertilizer and had the process of mineralization of organic nitrogen, denitrification under flooded conditions, and leached nitrogen to the second layer. In the second layer, leached nitrogen was received from the top layer, and organic nitrogen was mineralized. The mineralization process was the core factor to be discussed. It is the process by which chemicals present in organic matter are decomposed or oxidized into easily available forms to plants. According to Dr. Jeff Schoenau, a soil scientist at the University of Saskatchewan, there are two contributors of nitrogen to crop growth. The first is the residual inorganic forms of mineral nitrogen, ammonium, and nitrate, and they are fairly easy to measure. The other important contribution that is not so easy to measure and predict is nitrogen mineralization. The figure below explains the process of nitrogen transfer to the plant.

From the perspective of model simulating, six parts of calculation for Scenario 2 should

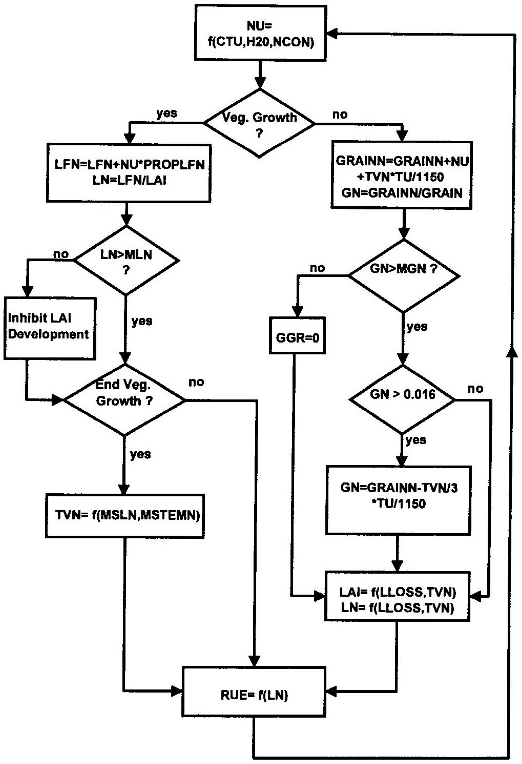


Figure 2.5: A flow chart showing the calculation of plant nitrogen budget in the maize model [3]

be considered: thermal units, leaf growth, nitrogen uptake, soil nitrogen, corn nitrogen, and grain growth. The calculation of thermal units and leaf grows are the same as in Scenario 1, so it will start from nitrogen uptake as follows.

Nitrogen Uptake Mineralization takes such high priority because plant roots can absorb inorganic forms of nitrogen only. For instance, ammonium and nitrate are suitable forms of nutrients. These forms of nitrogen are either available from applied nitrogen fertilizers directly or obtained through the mineralization of the organic nitrogen process. The conversion from organically bound nitrogen in soil matter, crop residues, manure, and other organic amendments into inorganic forms of ammonium and nitrate is mainly practiced by soil microbes. Therefore, the nitrogen mineralization process is highly dependent on growing season weather, which is one of the reasons to prepare the model discussing the temperature and solar radiation at first.

Leaching from the total root zone was not calculated in the previous research of Sinclair and Amir [31], since it was assumed that no leaching was done in the arid environment in which the test crop of wheat was grown. The growth process of wheat and maize is similar, so the growth model of wheat was used as a reference for maize growth. And in this research, nitrogen leaching from maize crops is similar. Since the leaching process is very unpredictable, the nitrogen leaching process was ignored in the following discussion. The following part discusses the model in two parts, sufficient fertilizer containing enough nitrogen as resources are provided, and controlled fertilizer provided following economical principles. The model with sufficient nutrients supplied is discussed primarily.

The mineralization of nitrogen in each layer is abbreviated as daily Nitrogen mineralization for the top layer of soil (NMIN1) for top layer soil and NMIN2 for second layer soil (g N $m^{-3}d^{-1}$). The mineralization process was a function of soil organic nitrogen, content, temperature, soil water content, and soluble nitrogen content.

$$NMIN1_i = FM \times NORG1 \times RS \times (1 - \exp(-KS)) \times (200 - NCON1_i)/200 \quad (2.12)$$

where Fraction of soil organic nitrogen available for Mineralization (FM), soil organic Nitrogen content (NORG), soil water response coefficient for N mineralization (RS), temperature response coefficient for Nitrogen mineralization (KS), and solvable soil mineral Nitrogen concentration for the top layer of soil (NCON1) (mg N $L^{-}1H_2O$) determined the NMIN1.

The value of FM was set to 0.15 as done by Sinclair and Amir in 1992. The value of RS was calculated based on the Fraction Transpirable Soil Water (FTSW) using the equations developed by Watts and Hanks in 1978. The value of KS was calculated from the exponential equation for temperature responses used by Watts and Hanks in 1978. The inhibition of mineralization as NCON approached the very high concentration of 200 mg N $L^{-}1$ was reported by Hada et al. 1986. Therefore, the maximum value for NCON would be 200 mg N $L^{-}1$. Since it was mentioned that denitrification was sensitive to soil water content, no temperature responses were included. So, the denitrification process was ignored in this research to simplify the model.

Crop nitrogen uptake is the next step for crop absorption with nutrients provided in the soil. The function of dependence of Nitrogen Uptake (NU) and ATU was sought and developed by Bennett et al. [3] under high soil nitrogen conditions. The plants were well irrigated to obtain a hyperbolic expression of cumulative nitrogen accumulation under unstressed conditions as a function of ATU. From this regression, the asymptote was defined as the total Potential Nitrogen Uptake (PNU) with the value of 26.4 g N m^{-2}. The daily Nitrogen Uptake Potential rate (NUP) (g N $m^{-2}d^{-1}$) was obtained by multiplying the derivative by the TU each day.

$$NUP_i = TU_i \times (PNU \times 5.24 \times 10^{-8}) \times (ATU_i^{1.58}) \times \exp\left[-(ATU_i/958)^{2.58}\right] \tag{2.13}$$

If there was insufficient mineral nitrogen in the soil to meet the NUP requirement calculated in this equation, the NU (g N $m^{-2}d^{-1}$) was set equal to the amount of nitrogen available in the soil for crop uptake. It was defined by Sinclair and Amir [31] that all nitrogen above a concentration of 1.0 mg N L^{-1} water in the soil solution was assumed to be available to the crop. That means if the Nitrogen available in the Soil (SN) is less than 1.0, extra nutrition should be applied from fertilizers. Expressed in formulas, if $SN_i > NUP_i, NU_i = NUP_i$; if $SN_i <= NUP_i, NU_i = 0.001$.

Besides, NU was decreased at low soil water levels as a function of the FTSW mentioned above. The FTSW was assumed as 0.5 in this study.

Soil Nitrogen The nitrogen content in the soil is a key factor to see the process of fertilizer being absorbed by the plant. The soil nitrogen was accumulated by the fertilizer releasing to the soil, determined by the nitrogen mineralization and the depth of the soil. The SN at the initial state was set as SN_0, which was calculated from the fertilizer applied to the soil at the start of growing season.

$$SN_0 = NMIN1_i \times topdepth + fertilizer \tag{2.14}$$

where amount of fertilizer applied to the plant (fertilizer) and the soil depth of the top layer (topdepth) determined SN. The nutrition as N form was absorbed and consumed from the root zone to the stem and leaf of the plant, so the SN was determined by the SN of the last day and the NU of the current day.

$$SN_{i+1} = SN_i - NU_i \tag{2.15}$$

Corn Nitrogen Nitrogen uptake is a core variable that calculates the daily increase in the amount of Leaf Nitrogen (LFN) (g N $m^{-3}d^{-1}$ on a ground area basis) directly. Nitrogen uptake goes to the leaves or stems, and it was found in 1994 by Muchow that 60% of the Percentage of the accumulated Nitrogen during vegetative development went to the leaves (PROPLFN), and 40% of the accumulated nitrogen went to the stems. LFN could be computed by NU multiplied by PROPLFN during leaf development. And the Nitrogen per unit Leaf area (LNT) was calculated as the ratio of cumulative LFN to LAI, as explained previously.

Since corn emergence occurred when the ATU were greater than 87, the leaf number was calculated after the ATU arrived at 87. The LFN was calculated by NU multiplied by the PROPLFN, and the percentage of the accumulated nitrogen during vegetative development went to the leaves. The amount of Stem Nitrogen (STEMN) was calculated based on similar logic. The appearance of successive fully expanded leaves was calculated as an exponential function of accumulative thermal units.

$$LFN_i = NU_i \times PROPLFN + LFN_{i-1} \tag{2.16}$$

$$STEMN_i = NU_i \times (1 - PROPLFN) + STEMN_{i-1} \tag{2.17}$$

Considering the growth stages in reproductive development, the total amount of vegetative Nitrogen available for Translocation to seed (TVN) was the amount of nitrogen in these vegetative tissues at the start of seed growth in excess of the minimum nitrogen contents of senesced leaves and nature stems. The TVN performed as the core parameter, which was calculated at the beginning of grain growth. The ratio between the daily thermal units and the total thermal units for seed development, which is 1,150 thermal units, as explained above, determined the TVN transferred each day to the grain.

$$TVN_i = (LFN_i - 0.4) + (STEMN_i - 2.5) \tag{2.18}$$

Vegetative development, as explained above is the physiological process where leaves mainly grow. It was researched by Muchow in 1998 that inadequate nitrogen results in substantially depressed leaf area development (Muchow, 1988). Besides, observations were consistent in the modeling developed by Sinclair and Amir, where the leaf area was inhibited if the nitrogen supply was inadequate to maintain the LNT. The minimum LNT for maize canopies with developing leaves is about 0.55 g N $m^{-2}d^{-1}$. If the nitrogen per unit leaf area is less than the minimum LNT, which is usually 0.55, then the leaf area would not change. Hence, the maize leaf area was inhibited in the model if the LNT projected for a daily time step was less than the minimum LNT.

$$LNT_i = LFN_i / LAI_i \times 1000 \tag{2.19}$$

The RUE linearly depended on the LNT. If it was not the stage of grain, N loss in leaves resulted in decreased in RUE in the reproductive development stage.

$$RUE_i = 0.12 + 1.5 \times LNT_i \tag{2.20}$$

If it achieved the stage of grain, then the formula would alter and consider the Daily Nitrogen Translocation (DVTN).

$$DVTN_i = TVN_i \times TU_i/1150 \tag{2.21}$$

Then, the RUE that achieved the stage of grain was calculated as follows:

$$RUE_i = 0.12 + 1.5 \times (LNT_i - DTVN \times 0.6) \tag{2.22}$$

During the process of corn growth, reproductive development follows after vegetative development. The nitrogen requirement of seed growth is substantial, since the translocation of nitrogen from leaves to support grain growth results in a self-destruction phenomenon leading to a loss in crop productivity. The equation of RUE expressed above describes the decreases in RUE during grain growth as LNT decreases. Nitrogen plays a significant role in leaf growth as well as in radiation use. The RUE has a maximum value of 1.6 g MJ^{-1}. It requires well-watered conditions and ample nutrition, in the absence of pests and diseases.

Grain Growth The calculations of PHS and BM are the same as Equation 2.8 and Equation 2.9. The calculation of Grain is same as Equation 2.11.

The daily total amount of Nitrogen Accumulated in the Grain (GRAINN) was calculated as equation listed below:

$$GRAINN_i = GRAINN_{i-1} + NU_i + DVTN_i \tag{2.23}$$

The total Grain Nitrogen concentration (GN) was calculated by the total amount of N accumulated in the grain divided by the grain yield:

$$GN_i = GRAINN_i/Grain_i \tag{2.24}$$

The GRAINN was the sum of nitrogen uptake transferred from the TVN. The grain biomass and the grain nitrogen accumulation were calculated separately, and the Grain N concentration was calculated by the division between the two parameters. With the daily accumulation of nitrogen transfer and corn fruit growth, the yield was calculated at the end of the growing season, where the accumulated thermal units achieved 1150. The process of Scenario 2 was performed as explained above. The improvement from Scenario 2 to Scenario 3 will be discussed in Chapter 4.

Chapter 3

Fertilizers

Generally, fertilizer is a uniform description of any material or substance that is distributed to the soil or plants to supply nutrients that are essential to the growth of plant tissues. Both natural and synthetic are counted with the classification of organic fertilizer or inorganic fertilizer, respectively. Organic fertilizers usually originate from organic substances, such as plants, animals, compost, and manure.Unprocessed minerals such as rock phosphate could be classified as organic fertilizers as well. This chapter would discuss about fertilizer properties, the benefits to the plant, and how to choose the fertilizer for the project.

3.1 Fertilizer Properties

As opposed to organic fertilizers, chemical fertilizers are usually artificial products derived from a chemical manufacturing or synthesizing process. Inorganic fertilizers, more commonly called chemical fertilizers, mainly provide three essential macronutrients: nitrogen (N), phosphorus (P), and potassium (K), also known as the “Big 3” nutrients. The selection of varieties of fertilizer usually depends on the requirements of different plants for growth promotion. Besides, other nutrients such as calcium, sulfur, and magnesium may also be necessary and are added to the soil or the plant as secondary nutrients. Chemical fertilizers are made with artificial or synthetic ingredients. [32]

With the aim of providing necessary nutrients for plants, chemical fertilizers contain one or more of the “Big 3” nutrients mentioned above, sometimes along with varying amounts of calcium and sulfur for nutrient varieties. It is possible that plants that are growing lack micronutrients, so additional micronutrients are applied as separate fertilizers apart from ordinary chemical fertilizers when necessary.

Commercial fertilizers have commonly known names that are easier for customers to select. “Straight fertilizers” usually denote those fertilizers containing only one of the “Big 3” components. In contrast, the name “complete fertilizers” means those fertilizers containing nitrogen, phosphorus, and potassium. Some mixed fertilizers are simple mechanical mixes of two or more fertilizers to supply nitrogen, phosphorus, and potassium. In the meantime, other fertilizers are chemical combinations with every individual granule having the same nutrient content. However, some commercial fertilizers may contain some secondary and micronutrients together with main components. So it is quite necessary to read the chemical fertilizer labels clearly before applying them.

Colour identification can be a likely nutrient indicator because of the different physical characteristics of chemical elements. The colour of a fertilizer’s granules is quite useful in indicating the general composition. Grey granules usually contain NP, NPK, or straight P fertilizer. White granules usually indicate a straight N fertilizer, such as urea, ammonium nitrate, or ammonium sulfate. Although the colour recognition can be visually straightforward, it is worth noting that most forms of potassium compounds are also white. And some forms of potassium chloride are reddish because of impurities.

In order to provide nutrition to plants after being applied to the soil, fertilizers are mostly made as granules, which are easily absorbed and transported. Ammonium nitrate and urea on behalf of soluble fertilizers can also readily dissolve in water and be sprayed on plant foliage in diluted form. Talking about soluble form, some chemical fertilizers are also available in liquid formulations. Some of them usually contain NPK and micronutrients for spray application to the leaves, which is called foliar applications. Because of the nutrient content, these fertilizers are rather costly. Besides, chemical fertilizers in powder forms that contain NPK (and micronutrients sometimes) are made for foliar application as well.

It is noticeable that almost every nitrogen fertilizer containing the effective nitrogen forms ammonium (NH_4^+) or nitrate (NO_3^-). The nitrate form acts quickly because of the properties of being immediately leachable, so it can reach plant roots sooner after applying to a growing crop. Also, ammonium would quickly convert to mobile nitrate in warm conditions.

3.2 Nitrogen Benefits the Corn

As discussed above, nitrogen (N), phosphorus (P), and potassium (K) are the "Big 3" primary nutrients in plant nutrition. As one of the most important elements in commercial fertilizers, nitrogen (N) is an essential macronutrient for corn growing, since plants usually absorb more nitrogen during the growing season than any other element [5]. Many experiments have proven that nitrogen influences the growth of leaf development, biomass accumulation, and seed growth [3]. The reason why nitrogen affects the health and nutritional condition of plants is that nitrogen is a major component of amino acids. It functions as a building block of protein, which supports many of the tissues of living things. Chlorophyll, a significant green component in plants, is necessary for photosynthesis. Adequate nitrogen undoubtedly could promote the formation of chlorophyll and the process of photosynthesis. Theoretically, the plant can reach its genetic yield potential with adequate nitrogen availability [33].

Nitrogen deficiency could be the most common nutrient issue farmers ever face. If the plant is deficient in nitrogen during its rapid vegetative growth phase, yield losses are inevitable. However, the risk of nitrogen loss and crop deficiency can be reduced if applying nitrogen multiple times, including the time of maximum crop uptake [34]. Figure 3.1 shows an ear of growing corn is lack nitrogen.

There are three forms that nitrogen exists in the soil, organic N, ammonium ions (NH_4^+), and nitrate ions (NO_3^-). Organic nitrogen is the most common form because it is contained in organic matter in the soil, in the crop residues, as well as in the microbial community within the soil. Although the organic N makes up most of the N in the soil, it cannot be absorbed or used from the soil to the plant until it is converted to ammonium or nitrate ions. The process is known as mineralization by microorganisms where organic

Figure 3.1: A picture of a corn leaf showing symptoms of nitrogen deficiency [5]

N is converted to ion forms that plants can take up [33]. After mineralization, the process referred to as nitrification occurs, which is the conversion of ammonium to nitrate. Eventually, nitrate is the main form that plants can absorb.

No matter which fertilizer is used, the effective ingredient is nitrogen. Figure 3.2 shows a schematic diagram of the conversion of nitrogen forms in the soil. The urea transfers to ammonia after hydrolysis and ammonification. With the hydrogen ion in the soil, ammonia transfers to ammonium ions. After nitrification, the active nitrate ions are now available for the plant.

Nitrogen reactions in the soil are closely linked to two factors, temperature and moisture conditions [34]. As discussed above, nitrogen influences the process of photosynthesis. More specifically, nitrogen supply results in an increase in leaf area, biomass accumulation, and grain yield. Applying fertilizer aims to achieve the target of yield improvement. Nitrogen use is fundamental in agriculture, no matter which plants growing. Optimizing its efficiency is the key to environmentally safe and economical grain production systems.

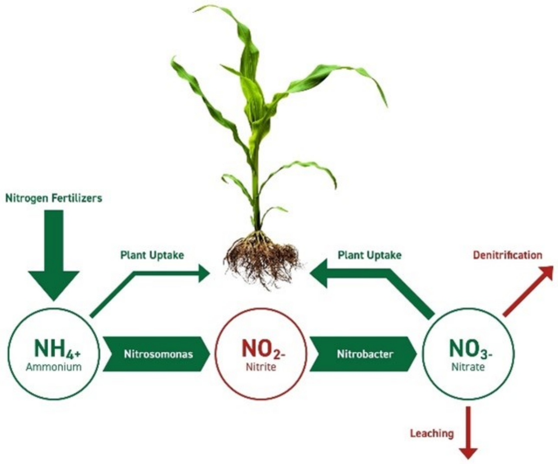


Figure 3.2: A schematic diagram of the conversion of nitrogen forms in the soil [6]

3.3 Advantages and Disadvantages of Chemical Fertilizers

Synthetic fertilizers are usually chosen instead of organic fertilizers in the agriculture field. One of the most significant reasons is the price. Chemical fertilizers can be produced in bulk and have a longer shelf life, which means the product costs are reduced, resulting in savings to the customers. Besides, most farmers and companies select chemical fertilizers because they can show quicker results. Organic solutions need time and moisture to break down, and meanwhile, most synthesis fertilizers are refined, pure minerals that produce near-immediate effects, that is, in a matter of days instead of weeks [35]. There are various forms of chemical fertilizers, many of which come in liquid form and can be spared rather than laid. Dry fertilizers are set on top of the soil, and liquids can be applied to treetops and directly onto high foliage for an extra boost. What's more, many chemical fertilizers can easily be blended with weed and insect control, which saves time and labour and nourishes the landscape.

Inorganic fertilizers usually contain the big 3 minerals (N, P, and K), as mentioned above, but they often lack diverse micronutrients. These micronutrients usually can be received from naturally decomposing materials, including calcium, magnesium, iron, zinc, and so on. It should be of concern that the manufacturing process of agricultural fertilizer may lead to ecological or human health risks. The soil amendments and crop damage after applying fertilizer to farmlands are worrisome as well. In order to protect plants and soil from hazardous damage caused by fertilizer application, EPA has ruled specified limits on the levels of heavy metals and other toxic compounds to reduce the toxicity and mobility of the unsafe constituents, whose concentration limits are based on the "best demonstrated available technology".

Pollution caused by chemical contamination from synthetic fertilizers can lead to nearby waterways turning green or clouded with algae blooms, taking on an unusual odour and depleting oxygen for fish and other species, suffocating them [35]. So the manufacturing process of synthetic fertilizers is often not considered environmentally friendly. In addition, these inorganic fertilizers usually present as highly concentrated solutions, so over-spraying or over-application can overwhelm the landscape easily. High mineral levels can undoubtedly lead to instant damage such as root burn. From a long-term point of view, chemical use can alter the pH balance of the soil. The high value of pH is harmful to most of the crops growing. The agricultural process would be affected negatively.

In past times, the use of chemical fertilizer was easily out of control, and then the excess fertilizers might destroy the soil properties and fertilities, such as osmolarity and water-holding capacity, which led to soil erosion. Soil microorganisms can also be adversely affected by the excess usage of chemical fertilizers. Sometimes several varieties of weed plants with high nitrogen proportions can act as fertilizers to replace the chemical products, such as chickweed, yellow dock, and so on. The decomposed organic matter also acts as a natural fertilizer. Organic compost or well-aged herbivore manure creates nutrient-rich organic material capable of improving soil quality and texture. Chemical fertilizers usually have a higher cost than natural fertilizers and may contain certain toxic materials that cause allergies, but they are still crucial to modern agriculture development.

3.4 Reduce Pollution Caused by Chemical Fertilizers

As discussed above, by applying chemical fertilizers and animal manure on fields, the nutrients provided, such as nitrogen and phosphorus, are necessary to promote plant growth and increase the yield. But it is also possible that nutrients are not fully utilized by the plants during the growing season and can be lost from the fields and impact the air and downstream water quality negatively. These excess nutrients like nitrogen and phosphorus can be washed or leached from the farm fields into groundwater during rainfalls and snow melting over time. If the concentration of nitrogen and phosphorus in groundwater achieves a high level, it can cause the eutrophication of water bodies. Eutrophication is a process by which an entire body of water, or parts of it, becomes progressively enriched with minerals and nutrients [36]. It can lead to hypoxia, which causes a decrease in aquatic life. Moreover, excess nutrients can cause harmful algal blooms in freshwater systems. These harmful algal blooms can not only disrupt wildlife development, but can also produce toxins that are harmful to human bodies. The process is also harmful to the ecological environment starting from the marine biosphere. Besides, nitrogen can easily escape in gaseous form from fertilized soils to the air. Nitrogen-based compounds such as ammonia and nitrogen oxides are typical of the nutrient-losing phenomena. Also, nitrogen oxide is one of the most concerning greenhouse gases, which brings environmental protection to the front.

As excess fertilizers can cause so much harm, agriculture fields are responsible for reducing nutrient losses from operations. Therefore, both economical and environment-friendly targets can be achieved. The optimum amount of fertilizer should be applied to the plant during the growing season, where “optimum” leads to the right amount of nutrients being applied at the appropriate time of the year, with the correct method being used and applied at the right placement. Moreover, EPA recommends that farmers emphasize the use of conservation drainage practices. Typically, in the Midwest of the USA, sub-surface tile drainage is crucial to managing water movement passing through soils. Usually, soluble forms of nitrogen and phosphorus can be carried by drainage water. Strategies should be developed to reduce nutrient loads and maintain adequate irrigation for plant production at the same time. And the conservation drainage describes applications including changes in drainage system design and operation, bioreactor logging, saturation buffers, and drainage system changes.

Other than that, agricultural workers need to pay attention to annual land cover security. Farmers can use cover crops 7 or perennial 8 to prevent periods of bare land on farmland, which can increase the operation using the rate of arable land and prevent waterway erosion and loss. Plants that are not economical crops can also be planted along the edges of the fields, such as trees, shrubs, and grass. It has been proven that these plants can help prevent the loss of soil and nutrients from the field by absorbing or filtering the nutrients as a planted buffer.

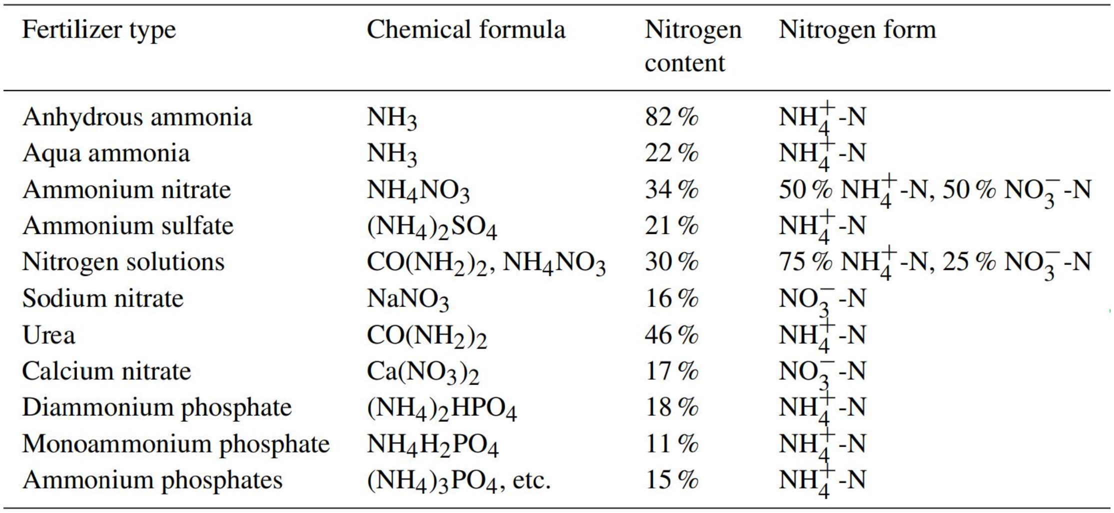
What's more, farmers can reduce the frequency and concentration of cultivated fields, which is called the implementation of the conservation tillage. This process promotes improved soil health, reduced soil erosion, and diminished soil runoff and compression. Therefore, the likelihood of nutrients reaching waterways through runoff can be diminished.

Except for solving the soil problem with regard to plants, the access of livestock to streams should also be controlled. Ranchers are more likely to face a situation where crops and livestock are managed simultaneously. It is recommended that fences be installed by the side of water sources, such as streams, rivers, and lakes, to block animals from entering.

The corporation would be a future trend in agricultural development, since people work for the same purposes of improving crop yield, decreasing excess charges, and protecting the environment for sustainability, where unified standards can be discussed and followed. Therefore, working with stakeholders and organizations can be effective in reducing nutrient pollution in water and air. Farmers and ranchers can engage with organizations such as state governments, agricultural organizations, conservation groups, educational institutions, non-profit organizations, and community groups [37].

3.5 Frequently Used Fertilizers Comparison

The market for N fertilizer is various and popular. Among all the widely used N fertilizers in agriculture, urea is the most common and popular one not only because urea contains a



Fertilizer type	Chemical formula	Nitrogen content	Nitrogen form
Anhydrous ammonia	NH_3	82 %	NH_4^+-N
Aqua ammonia	NH_3	22 %	NH_4^+-N
Ammonium nitrate	NH_4NO_3	34 %	50 % NH_4^+-N, 50 % NO_3^--N
Ammonium sulfate	$(NH_4)_2SO_4$	21 %	NH_4^+-N
Nitrogen solutions	$CO(NH_2)_2$, NH_4NO_3	30 %	75 % NH_4^+-N, 25 % NO_3^--N
Sodium nitrate	$NaNO_3$	16 %	NO_3^--N
Urea	$CO(NH_2)_2$	46 %	NH_4^+-N
Calcium nitrate	$Ca(NO_3)_2$	17 %	NO_3^--N
Diammonium phosphate	$(NH_4)_2HPO_4$	18 %	NH_4^+-N
Monoammonium phosphate	$NH_4H_2PO_4$	11 %	NH_4^+-N
Ammonium phosphates	$(NH_4)_3PO_4$, etc.	15 %	NH_4^+-N

Figure 3.3: A list of frequently used fertilizer types with the chemical formula, nitrogen content, and nitrogen form [7]

high N content at 45%, but also because it can convert to nitrate rapidly. Another common form of N fertilizer, urea ammonium nitrate, contains an N content of 28% to 32%, which is popular in side-dressing applications as well as in starter fertilizers. As a soluble form of N, ammonium sulfate provides both N (21%) and sulfur (24%). Ammonium nitrate contains both ammonium and nitrate forms of N providing 33% of N. Anhydrous ammonia has the highest N content of any of the available products [33]. Figure 3.3 was developed in [7] that studied the 11 nitrogen fertilizer types and their effective content in nitrogen form. Several frequently used fertilizers will be introduced in detail below.

It seems like a wide variety of nitrogen fertilizers could be selected. However, farmers usually have limited time to apply fertilizers at spring planting. Generally, it is because they have a high workload, large production areas, and wet fields. A nitrification inhibitor is popularly applied with fertilizers to deal with the problems mentioned above. Farmers usually apply nitrification inhibitors with anhydrous ammonia for corn production. However, anhydrous ammonia requires a piece of specialized equipment for storage, handling, and application, which causes many producers to choose other nitrogen fertilizers.

No matter which fertilizer is used, the effective ingredient is nitrogen. Figure 3.4 is

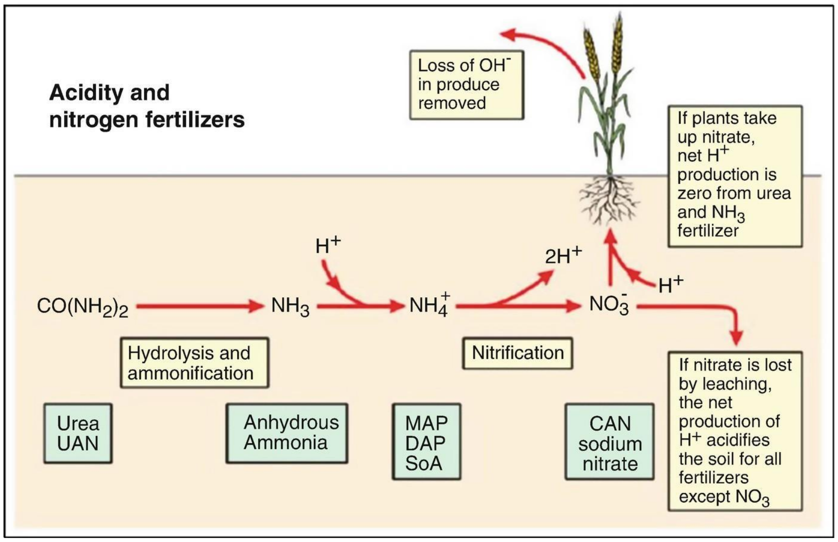


Figure 3.4: The process of nitrogen fertilizer transformation [8]

a schematic diagram of the conversion of nitrogen forms in the soil. As one of the most applied fertilizers in agriculture, urea has been used as an example to show the process. The nitrogen fertilizer transfers to ammonia after hydrolysis and ammonification. With the hydrogen ion in the soil, ammonia transfers to cation ammonium. After nitrification, the active anion nitrate is available for the plant to absorb.

Fertilizer - Anhydrous ammonia [32]

Anhydrous ammonia is one of the most popular commercial nitrogen fertilizers in gaseous form, which is usually compressed and stored as a liquid (nurse tanks rated for above 250 psi). It is colourless at room temperature and is under pressure as a gaseous form. When required to apply fertilizer, the container releases pressure, and liquid anhydrous ammonia vaporizes, then escapes as an invisible and highly hydrophilic gas. The pungent odour can be detected during the vaporization process. The operation should be undertaken carefully with less human exposure, since the hazardous process can result in alkali burns; frostbite; inhalation damage to the mouth, throat, lungs, and eyes; and even death. So personal protective equipment should be worn all the time when working with large tanks.

Nitrogen acquired from the air reacts with hydrogen from natural gas at high temperatures and high pressure. A catalyst is presented in order to promote the yield of anhydrous ammonia in a manufacturing process. More than the source of nitrogen and other commercial fertilizers, anhydrous ammonia can also be directly applied on its own. Because of the gaseous property, the loss from vaporization can be prevented by injecting it into the soil directly. Ammonia is effective as the source of nitrogen for crops if soil conditions are favorable for injection and the closure of the injection channel. Besides, anhydrous ammonia is more resistant to loss from the soil by leaching or denitrification because of the necessity to go through the nitrification process. The reason is that anhydrous ammonia is converted by bacterial action, not the nitrate, more slowly than other nitrogen sources. N-Serve slows the conversion of NH3 to the nitrate form as an anti-bacterial agent.

After anhydrous ammonia is injected into the soil, the pH of the injection sites increases to a high value and high ammonium concentration, which is lethal to most microorganisms. And the process of nitrogen conversion can be influenced. The affluent protein source for microbes on the fringes of the band enhances reproduction as well. There are research results that show that after a few months of application, the recolonization is complete.

One of the most typical forms of anhydrous ammonia is aqua ammonia, which dissolves in water in a low-pressure solution full of free ammonia, usually stored in closed, low-pressure tanks and injected into the soil much like anhydrous ammonia. It is found that the amount of free ammonia increases as the air temperature increases. When applying aqua ammonia to the soil, it does not need to be as deep as with anhydrous ammonia because of the properties of the low-pressure solution and the small amount of free ammonia. Although the merits of aqua ammonia are obvious, it is not commonly used nowadays in agriculture because of the cost of handling the water in the product.

Fertilizer - Ammonium Nitrate [32]

Another well-known product of nitrogen fertilizers is ammonium nitrate, which is manufactured by reacting nitric acid with anhydrous ammonia and is produced as a dry granular material. In order to prevent caking, the product is concentrated, prilled, and coated.

Ammonium nitrate usually separates into two forms. Half of the nitrogen exists in the nitrate form, and the other half is in the ammonium form. The latter one is preferred when applied to the soil surface and not incorporated. It is because ammonium nitrate usually does not volatilize as free ammonia, but high pH soils are the exception. Urea is more popular and has been replacing ammonium nitrate in recent years because it is more valuable and convenient to maintain and transport. In contrast, ammonium nitrate can be easily explosive and is not easy to store and transport.

Fertilizer - Ammonium Sulfate [32]

Ammonium sulfate as a typical crystalline nitrogen fertilizer is produced by anhydrous ammonia reacting with sulfuric acid. It is an outstanding source for plants requiring both nitrogen and sulfur because it consists of 21% of nitrogen and 24% sulfur. Unlike other sources, such as ammonium nitrate, ammonium sulfate exists in crystalline form with low nitrogen content, which makes it easy to store and transport. Primarily, ammonium sulfate would be used commonly in sandy soil areas where sulfur is highly required as well.

Another new dry nitrogen fertilizer is ammonium nitrate-sulfate, which is manufactured by reacting anhydrous ammonia with a mixture of sulfuric acid and nitric acid. It has the properties of easy storage and handling. Besides, ammonium nitrate-sulfate is commonly used in blended fertilizers and is easy to apply directly. All these merits make it a good replacement for ammonium nitrate.

Fertilizer – Urea [32]

Unlike other nitrogen fertilizers, urea contains the highest percentage of nitrogen, which is produced by reacting ammonia with carbon dioxide in the manufacturing process. Urea is highly solvable and has a large potential for nitrogen loss through leaching in sandy soil or sub-surface tile drainage in poorly drained soils. As a dry nitrogen material that is easily applied, urea is more competitive than other fertilizers and rapidly replaces ammonium nitrate nowadays. The process of urea decomposing to absorbable nitrogen form is called hydrolyzation, which is driven by the enzyme urease. After urea is applied to the soil, enzyme urease presented in the soil and on crop residues will promote the reaction, and urea will combine with water and form ammonium carbonate.

It is worth noticing that urea is commonly applied to the surface of the soil, but it is the most readily volatilized dry nitrogen fertilizer among all varieties. Moreover, the effective nitrogen form of the reaction, ammonium nitrate, is also unstable and easily decomposes into water, ammonia, and carbon dioxide. Similar to ammonia, the product of urea hydrolyzation is easy to lose. Urea has a major disadvantage in that considerable amounts of N can be lost through volatilization if it is not incorporated into the soil soon after application.

However, urea is still widely used in agriculture because the risk of loss can be minimized through different methods. After incorporating urea into the soil, farmers can apply tillage, injection, or a half inch or more of water from rainfall or pivot irrigation. The technique of urease inhibitor is popularly applied with urea, which retards the hydrolysis process of urea for a couple of weeks under most field conditions. Urea can also be coated with inert materials or with N stabilizers to delay N release, which may increase the N use efficiency and reduce the potential for N losses. These chemical fertilizers are called controlled-release fertilizers and are introduced in the following sessions. In addition, the properties of simple, cost-effective, easy to handle, and consistently profitable make urea very attractive to farmers [30]. Overall, urea has a high nitrogen percentage and is easy to apply, but the risk of potential loss without protection should be a concern.

Fertilizer - Urea-Ammonium Nitrate [32]

The non-pressure solution of ammonium nitrate, urea, and water is called urea-ammonium nitrate (UAN), another popular nitrogen fertilizer be widely applied. Since the material contains more water, it can be stored at a lower temperature while maintaining its effectiveness. It will stay in the form of salt crystals at about -18°C for 28% solution and 0°C for 32% solution. Besides, UAN solutions can be easily handled because they can be pumped, mixed with chemicals, and sprayed through techniques. Because of the easily corrosive properties, UAN solutions will destroy metal fittings quickly, such as brass, bronze, and zinc. Suitable materials chosen as containers are aluminum alloys, stainless steel, rubber, polyethylene, vinyl resins, neoprene, and glass.

Although urea provides plenty of available nitrogen to the crop, the nitrogen uptake efficiency can be quite low because nitrogen can be lost to the atmosphere through urease hydrolysis. After application to the soil surface, the hydrolysis process promotes the volatilization of ammonia to the surroundings and increases the soil pH in the vicinity of urea granules. Farmers usually decide to apply extra nitrogen fertilizer to ensure that sufficient nitrogen can be provided to the crop. Controlled-release fertilizers have proven that they have the potential to reduce denitrification losses, improve the synchronization of nitrogen release and uptake, and minimize nitrogen leaching based on crop necessity.

3.6 Controlled-Release Fertilizer

Currently, there are a variety of brands available with differing nitrogen release characteristics. These fertilizers are contained controlled-release fertilizers.

The varieties of controlled-release fertilizers (CRFs) are created for improving nutrient use efficiency and minimizing environmental hazards. This term refers to fertilizing granules that intercalate within carrier molecules and thereby improve the efficiency of nutrient release to the crops and reduce the ecological, environmental, and health hazards. Because of these characteristics, controlled-release fertilizers make a significant difference in the efficiency improvement of nutrient availability and environmental degradation reduction. Polymers was chosen as the coat around the fertilizer for control purposes.

In detail, CRFs are designed in a capsulated form with a coating of organic or inorganic material. Both natural and synthetic are appropriate options as the coated polymer. Some of the coated polymers are biodegradable, which helps improve the biological activity with a lack of toxicity. Polyvinyl chloride, polyacrylamide, and rubber are popular options as synthetic biodegradable polymers. The release rate and duration of plant nutrients can be controlled to increase the availability of nutrients for a longer period compared with quick-release fertilizers. The process can be controlled based on the nutrients released into the fixing medium during the fixation process in the soil.

Controlled-release fertilizers are widely used these days based on the merits explained as follows. Firstly, compared with conventional fertilizers that are soluble in water, CRFs can improve agronomic safety, because they reduce the toxicity caused by high soil ionic concentration from the application of old-fashioned fertilizers, such as ammonia and urea. Therefore, CRFs allow the application of substantially larger amounts of fertilizer compared with conventional fertilizers.

Due to the reduction of toxicity and salt content of the substrates, CRFs may help farmers reduce costs, decrease labour requirements, and save energy. Moreover, controlled-release fertilizers help decrease the risk of environmental pollution, because the release rate of nitrogen is controlled, so the evaporation losses of ammonia can be reduced. Meanwhile, the losses of nutrients can be reduced as well, especially the nitrate-nitrogen by the uptake of nutrients by the plants through gradual nutrient release. The consumption of controlled-release fertilizers in the US agricultural market has increased rapidly in the past decade, especially the usage of polymer-coated fertilizers. An average annual rate of 21% has been achieved and shows the popularity [30].

However, controlled-release fertilizers cannot replace conventional fertilizers anywhere. First of all, the manufacturing process of producing CRF is more expensive than conventional ones, making the prices rise as well. Besides, sulfur-coated urea, one of the most popular CRFs, always decreases the pH in the soil, which can lead to soil acidification and create nutrient disorders resulting in calcium and magnesium deficiencies. In addition, the release rate of CRFs is usually impacted by the factors of fertilizer type, thickener type and concentration, soil temperature and moisture, and so on. Other than the properties of CRF on its own, the released nutrients may be inadequate from CRF in situations with low soil temperature and moisture.

Generally, controlled-release fertilizers are proposed in four types of release modes: diffusion, chemical reaction or decomposition, swelling, and osmosis. The diffusion process happens according to the biodegradable polymer encapsulated in the fertilizer in which water is diffused, making nutrients soluble. The penetration of the microorganisms and the degradation of the insoluble part of the fertilizer follows as the next step. The release rates of slow-release nitrogen fertilizers after application are based on various factors, such as specific fertilizers' characteristics, weather conditions, and soil properties.

In detail, fertilizer morphology, molecular weight distribution, and chemical and physiochemical factors (such as pH, mechanical strength, and temperature) can affect the decomposition of biodegradable polymers. The biodegradable polymer releases nutrients in the process called hydrolysis and releases the polymeric chain into nontoxic smaller molecules that are easier for plants to absorb.

Controlling the nutrient release to match the crop demand is the objective to develop controlled-release fertilizers. Besides, they are expected to promote use efficiency compared to conventional fertilizer products while protecting the environment by reducing toxin release. To achieve the goal, the release rates in different soils and environmental conditions should be predicted to monitor the proper release amount of nutrients and use efficiency. The release curve of chemical fertilizers is quite different from the pattern of plant uptake of the nutrients, which is a sigmoidal form. The initial release of conventional fertilizers is described as a "burst" because of the high rate, and the last to the third quarter of the nitrogen release is described as a "tailing effect" because of its much lower release rate. The CRF that performs better on release control is coated with hydrophobic materials [38].

In order to meet the demand of the population increase and food shortage, the agricultural field is facing pressure to increase nitrogen use efficiency by 10% by 2050. Meanwhile, limited arable land and water sources restrict the development of yield. Optimizing the use efficiency of fertilizers to maximize the crop yield would be achievable if nitrogen management practices increase such as adopting appropriate application timing and nitrogen fertilizer forms.

Besides, nitrogen losses could be increased with the inappropriate configuration of fertilizer use such as application timing and rate and a fraction of ammonium-nitrogen and nitrate-nitrogen. Both ammonium-nitrogen and nitrate-nitrogen can increase the nitrous oxide emission through nitrification and denitrification under different soil temperature and moisture conditions. The ammonium-form fertilizers promote rapid volatilization, while the nitrate-form fertilizers contribute to nitrogen leaching. It has been researched that excess nitrogen input can significantly increase the nitrate-nitrogen leaching to the aquatic system through drainage and raise the emission of nitrous oxide.

3.7 Selection of Polymer-Coated Urea

There are a bunch of fertilizers classified as Controlled-Release Fertilizer (CRF), where the valid ingredients would be slowly released at a controlled rate compared with regular fertilizers. The technique implemented by the coat surrounds the soluble fertilizers. The development of CRF has been extensively studied to provide an efficient way of administering nutrients. Besides, the process is carried out safer and more economically because the CRF are made available to the target at the desired rate or concentration level. So nutrients can be sustained in the soil for a longer time [39].

Controlled-release fertilizers are beneficial to environmental protection, since they have shown the potential to reduce NO_3^- leaching from the soil through the root zone and improve nitrogen use efficiency. With the control of nitrogen release, the rate of nitrogen use efficiency is improved. The nutrient loss is reduced, on the other hand, primarily due to nitrate leaching, and the volatilization of ammonia and nitrous oxides, which contributes to minimizing the environmental pollution.

The outside layer is made mostly from polymer materials, which play a significant role in controlling the permeability of irrigation water to fertilizer nitrogen granules and therefore release urea-nitrogen via a diffusion process slowly through the swelling polymer membrane [40]. The thickness of the coating determines whether the nutrient nitrogen is released over a specified time period, but this also reduces elemental nitrogen concentration in the fertilizer granule [39]. Most CRF sold on the market using polymer coatings are mostly made of a thermoplastic resin such as polyolefin, polyvinylidene chloride, and copolymers. These materials cannot degrade easily in soil, so the release is slow and controlled, and the materials accumulate over time [41].

Polymer-Coated Urea (PCU) is well-known for its controlled-release nutrients that could reduce nitrate-nitrogen NO_3^- leaching into groundwater, which reduces the harm to the local environment. A 2-year field experiment detected the four nitrogen fertilizer treatments and how nitrogen concentration affects groundwater [41]. It is because relying on measurements of nitrogen uptake and nitrogen use efficiency can be one of the clearest ways to assess the impacts of nitrogen fertilizer on groundwater quality. The benefit of nitrogen-efficiency improvement reflects in the yield increase, and reports with convincing data have shown the results [42].

Enhanced-efficiency fertilizers and, more specifically, controlled-release N fertilizers such as PCU, have the potential to increase crop N use and reduce N loss. In polymer-coated urea, each urea prill is individually coated with a polymer (or plastic) coating. Unlike the unprotected urea, which rapidly dissolves in water and then converts to ammonium and nitrate, the urea in the PCU dissolves inside the coating and slowly diffuses into the soil over time.

The effects of applying PCU or uncoated dry urea have been studied and compared at different N rates on corn grain yield and quality. Plant nitrogen accumulation and anion nitrate as the factors detecting the plant nutrient absorption and grain yield were calculated to determine the N use efficiency of the coated urea across N rates [30]. Polymer-coated urea is commonly used, which provides nitrogen to the soil and the plant in the corn-planting industry, which controls the release of nitrogen over time. There are a variety of types and brands of PCU available to crop producers.

In general, PCU works similarly to nitrogen inhibitors. The dissolution of urea in PCU is determined from a static test in which PCU is dissolved in water, and the refractive index of the solution is determined as a function of time [43]. Besides, urea and PCU were found to have a higher usage efficiency that broadcast-applied approximately 1 week before corn planting and were incorporated into the upper 5 cm of soil [30].

One of the best-performing commercial fertilizers is polymer-coated urea, which is efficiency-enhanced to potentially increase nitrogen use efficiency and reduce nitrogen losses to the environment. Over the past several decades, the nitrogen use efficiency in the US has increased by around 30%, but nearly half of the nitrogen fertilizer input failed to be absorbed by crops. Researched shows that all of the PCU products tested released above 80% of their N within 35 days of the application when the surface was applied under field conditions during the summer heat [35]. A significant amount of nitrogen was released into the environment via reactions such as nitrification, denitrification, leaching, and volatilization. Nitrogen excess release can cause numerous environmental and ecological problems, such as greenhouse gas emissions, eutrophication, soil acidification, and a reduction in biodiversity.

Because of the advantages mentioned above, polymer-coated urea was selected as the fertilizer applied in the simulation model of corn growth in this thesis.

Chapter 4

Model Design in Fertilizer Application

As discussed above, four factors influence the plant growth. Nitrogen supply is one of the key points. Sinclair and Muchow discussed the effect of nitrogen supply in 1995. The growth of maize yield has been demonstrated as being closely associated with the increase of nitrogen fertilizer application. However, excessive fertilizer application may lead to counterproductivity because of nitrogen leaching, which can be harmful to both the crop yield and the environment. Crops absorb nutrition from the soil, including nitrogen and other micronutrients. Therefore, the relevancy of nitrogen absorption from the soil to the plant is important to discuss. This chapter would mainly discuss Scenario 3 model design and the improvement from Scenario 2 to Scenario 3.

4.1 Improvement from Scenario 2 to Scenario 3

Sinclair and Muchow developed a mechanistic model of maize growth and development to account for the influence of soil and crop nitrogen yield. Their attributions were generated based on a mechanistic model describing the soil nitrogen budget for maize crops that effectively accounts for nitrogen movement and transformations in the soil, published in 1978 by Watts and Hanks. Two layers of soil were simulated to simplify the process of nitrogen transformation. In each soil layer, the soil nitrogen budget incorporated fertilization, mineralization, denitrification, and leaching, respectively. The crop uptake rate of nitrogen determines the growing condition. And the crop uptake rate of nitrogen is determined by the daily thermal units, soil water content, and soil nitrogen availability.

N reactions in the soil are closely linked to both temperature and moisture conditions. If corn is deficient in N during its rapid vegetative growth phase, yield losses are inevitable. Meanwhile, applying N at multiple times, including the time of maximum crop uptake, can spread the risk of N loss and crop deficiency, improve profitability by reducing N rates, and benefit the environment.

The properties and characteristics of commercial chemical fertilizers have been discussed in Chapter 3 in detail. Polymer-coated urea is selected in the simulation model of this thesis analysis process. Scenario 3 is now realized based on the basic model, Scenario 1, and the apply-once fertilizer model, Scenario 2, introduced in Chapter 2. The difference between Scenario 2 and Scenario 3 is the separate application of fertilizers.

As introduced in Scenario 2, chemical fertilizer is considered during the growing process of corn. However, considering the factor of operation complications, labour, and money, most farmers apply the fertilizers only once, which is at the beginning of the sowing season. In this way, the nutrition required from plants will not be of concern during the following process in the growing season, and the farmers can focus on other factors determining the plant yield, such as irrigation and pesticide application.

The nutrition contained in the fertilizer can undoubtedly promote the flourishing process of the plant; however, the disadvantages and challenges caused by chemical fertilizer are clarified in Chapter 3 as well. Besides, the improvement of chemical fertilizer usage efficiency should be emphasized. The consumption of chemical fertilizer is necessary and inevitable in the agricultural field.

To contemplate the pros and cons of fertilizer application, the problem should be thought through seriously in consideration of both farmers and the environment. Farmers as individual elements, no matter whether the farms are small- to medium-scale privately owned farms or are administrated by big companies, the short-term income and benefits are deliberated as the primary goal to support the operation. The enhancement of crop yield and quality takes the leading role as the dominant factor that determines the financial returns.

On the other hand, environmental protection has become one of the most significant problems that influences the entire society. Human activities, including agricultural and manufacturing operations, can produce harmful by-products, which may disturb and upset the ecosystem. In the end, humans may eat their own bitter fruit if they take seriously only the high productivity rate and outcomes, but ignore all the negative impacts of modern technology. Modern agriculture performs in a similar way. Chemical fertilizers are still applied widely and are beneficial to the plants, but the application should be controlled, and the nutrition use efficiency should be increased to meet the target of environmental protection.

Therefore, instead of applying the fertilizers only once at the beginning of the growing season, a better choice is to apply them one more time in the middle of the growing season. From the operation results of the Scenario 2 simulation model, the NUP on a daily basis dropped approximately between Day 160 and Day 190. The visualized figures are shown in Chapter 5. The exact time may vary depending on different regions and weather data, but the range stays the same from the data obtained from the Scenario 2 model. NUP aims to calculate the soil N conditions according to TU. Meanwhile, the amount of soil nitrogen almost ran out during a similar period. This would be the period when insufficient nutrition may affect the corn fruit and yield in the process. So the approximate time to apply the fertilizer twice can be decided.

It is obvious that if applying the whole amount of fertilizer at the beginning of the growing season, although a slow-release fertilizer is used, the amount of nitrogen available in the soil may still be lost and cannot support the crop development at a later period. As discussed above, this is significant, because if there is insufficient nutrition, the corn fruit may shrink the size of loseth plump granular because of the nitrogen deficiency.

Eventually, the yield and quality of the plant drop severely, and the farmers do not gain profits. Meanwhile, the nitrogen leaking into the environment is harmful. To deal with the issues here, fertilizer application separation can be a better solution. Because during the middle of the growing season, the remaining fertilizers can be applied to the plant freshly to support the growth of the corn. The loss of effective ingredients would be much less than the situation in Scenario 2.

4.2 Scenario 3 Simulation Model

Forecasting crop yield is a valuable piece of information to collect in the agricultural industry, since it helps industry members with farming management such as making decisions about production and influencing market prices. The agricultural process is complicated and intricate. A complete model considering every single aspect during the process can be a big issue. In this thesis, a bunch of assumptions are made to simplify the problem and figure out the optimum problem in a simple way.

Among these three scenarios, the common assumption factors are that enough sunshine and water are provided. No pets or diseases disturbing the crop is ideal. Scenario 1 assumes there is unlimited nitrogen available in the soil for plant consumption, which makes this scenario an ideal model. Scenario 2 assumes that a fixed amount of nitrogen-fertilizer is provided, and all of them are applied at the beginning of the growing season. Scenario 3 has a fixed amount of nitrogen fertilizer as well, and part of them is applied at the start of the sowing season. Meanwhile, the rest of them are applied in the middle of the growing season. Since the advantages of polymer-coated urea have been discussed in Chapter 3, both scenarios 2 and 3 have selected polymer-coated urea as the nitrogen fertilizer applied to the plant.

4.2.1 Goal of the Scenario 3 Simulation Model

In order to simplify the problem, the assumption of fixed amounts of fertilizers applied in the Scenario 2 model is made. It is similar to the problem of Scenario 3 in that the total amounts of chemical fertilizers are fixed for the whole growing process. Part of the fertilizers are applied at the beginning of the growing season, and the rest of them are applied during Day 160 and Day 190. The goal of Scenario 3 is to figure out the optimal time to apply the fertilizers twice during the growing season, which means the exact day to meet the requirements of different regions based on the given data.

Meanwhile, the fixed amount of fertilizer is split to apply twice, and the exact amounts of fertilizer to be applied the first and second times should be determined as well. Last but not least, good crop yield is the ultimate goal of any growth simulation model. The optimal yield that satisfies an exact time to apply an exact amount of remained fertilizers the second time should be worked out. Scenario 3 would solve the problems outlined above.

4.2.2 Scenario 3 Operating Process

This thesis was undertaken to develop a mechanistic growth model for corn to simulate the major effects of fertilizer application on corn growth, development, and yield. Temperature and solar radiation are considered weather inputs as well. The effect of solar radiation and temperature on corn yield was studied by examining observed and simulated yields among locations. Daily minimum temperature, maximum temperature, and solar radiation were inputs for the model. In other words, the objective of this part was to use the model to analyze for unstressed maize crops the yield responses to variation in fertilizer application time and amount and temperature and solar radiation impacts among diverse locations.

The simulation model worked as a loop. The flow chart of Scenario 3 is presented in Figure 4.1. The local temperature and weather data were imported to calculate the TU. When starting the operation of this simulating model, the initial state of soil nitrogen, daily temperature, and solar radiation were input on Day 120. At the start of the process, part of the polymer-coated urea was applied to the plant, and the nitrogen available in the soil was calculated as the initially applied fertilizer multiplied by variable X, the percentage of fertilizers applied for the first time. In reality, the polymer-coated urea would release into the soil slowly and in a controlled manner. The exact release rate function influenced by placement and temperature was developed by Curtis J. Ransom in 2020 [44].

On the next day, the thermal units were calculated one more time. The ATU and the day of the year would be the indicator as to whether to end the loop or not. If the ATU was greater than 1,150 and the day was 300 of the year, then the process was finished and the loop was broken.

From the perspective of model simulating, six parts of calculation for Scenario 3 should be considered: thermal units, leaf growth, nitrogen uptake, soil nitrogen, corn nitrogen, and grain growth. The calculation of thermal units and leaf growth are the same as in Scenario 1, so it will start from nitrogen uptake as follows.

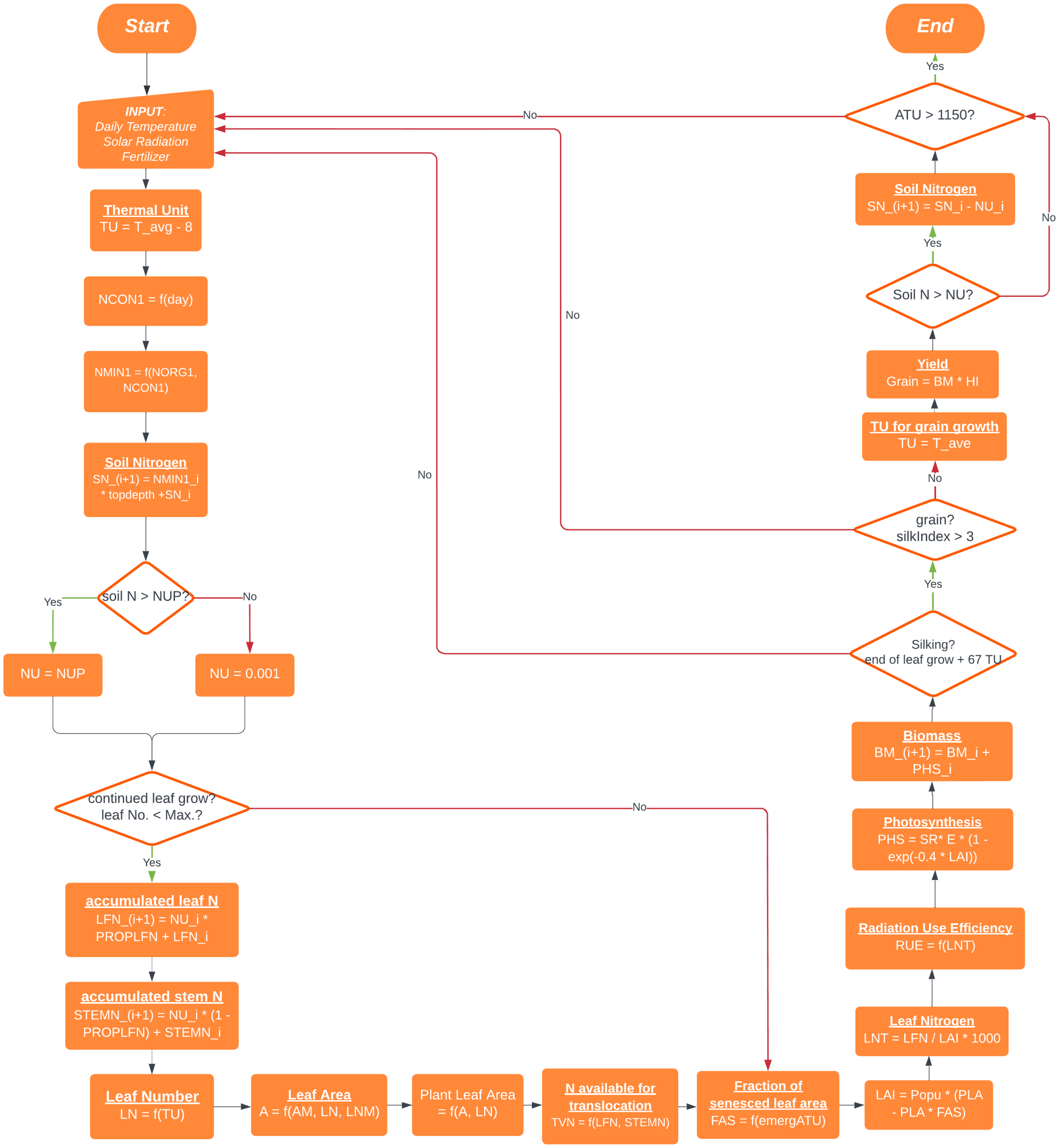


Figure 4.1: The flow chart of the corn growth simulation model operation in Scenario 3.

Nitrogen Uptake Based on the condition of this model, the formula that fits the situation best was chosen. The major factors influencing crop response to soil nitrogen fertility were the total amount of nitrogen obtained from the soil, the nitrogen constraint on leaf area development, and adjustments in the accumulation of crop biomass [3]. Ideally, the fertilizer is applied on the first day of the growing season, and nitrogen releases into the soil immediately for use. In reality, the first part of fertilization was applied 1 week before sowing, as the effective ingredients need time to release from the granular state to the soil. The soluble mineral nitrogen concentration for the top layer of the soil (NCON1) was calculated based on the development of Ransom (2020) [44].

$$NCON1_i = 9 + 0.71 \times (day - 7) \tag{4.1}$$

Since the soil N budget part was calculated based on the model developed by Watts and Hanks (1978), the two layers of soil had different functionalities as discussed in Chapter 2.3.2. The soil top layer received fertilizer, and then the mineralization of organic N occurred. The mineralization process of nitrogen in the soil was a function of soil organic N content, temperature, soil water content, and soluble N content. The NMIN1 was calculated from Equation 2.12.

The phenological development of corn was described as a function of the daily thermal units, total leaf number, and nitrogen available in the soil. Since the thermal units had a different value before and after the silking stage, the calculation was considered separately. Daily TU before silking were calculated by averaging the maximum and minimum temperatures and subtracting a base temperature of 8°C. The daily thermal units after silking were calculated by averaging the maximum and minimum temperatures directly.

The corn nitrogen uptake was calculated based on the daily weather data. The daily NUP was calculated by multiplying the derivative by the TU of each day. The equation was introduced in Chapter 2 as Equation 2.13. The relationship between SN and NUP is the same in Scenario 2 and Scenario 3. If the SN is less than 1.0, extra nutrition should be applied from the fertilizers: if $SN_i > NUP_i, NU_i = NUP_i$; if $SN_i <= NUP_i, NU_i = 0.001$.

Soil Nitrogen The nitrogen content in the soil is a key factor to see the process of the fertilizer being absorbed by the plant. The soil nitrogen accumulated by the fertilizer releasing into the soil, determined by the nitrogen mineralization and the depth of the soil. The SN at the initial state was set as SN_0, which was calculated from the fertilizer applied to the soil at the start of growing season.

$$SN_0 = NMIN1_i \times topdepth + fertilizer \times X\% \tag{4.2}$$

where the fertilizer was the amount of PCU applied to the plant, the top depth was the soil depth of the top layer, and X was the percentage of fertilizers applied for the first time. The nutrition as N form was absorbed and consumed from the root zone to the stem and leaf of the plant, so the SN was determined by the SN and NU of the last day.

The most significant improvement from Scenario 2 to Scenario 3 was the second-time fertilizer application. The day applying fertilizer the second time was assumed as L, which impacted the fluctuation of soil nitrogen. In this thesis, it is assumed that when the sowing season begins, the fertilizers applied the first time are fully released in the soil, and the nitrogen contents are available to be absorbed in scenarios 2 and 3. From the work by Ransom in 2020 [44], PCU usually releases over 80% of their N 9 days after their stated timing. So when applying the remaining fertilizers in Scenario 3 on Day L, it was assumed that 80% of the remaining fertilizers were released evenly in 9 days when it approached day L. After day = (L+9), 20% of the remaining fertilizers were released evenly during the following days.

The actual amount of fertilizer being applied may vary depending on the locations, soil conditions, weather, and operation of farming. In this work, 250 kg ha^{-1} PCU was used for the simulation process. The amount of the PCU was recommended by the government in Ottawa, and it fits the requirement, because this thesis discusses the corn-planting conditions in Ottawa eventually.

$$SN_{i+1} = (fertilizer \times (100 - X)/100 \times 80\%/9) + SN_i - NU_i \tag{4.3}$$

Corn Nitrogen The calculations of variables in corn nitrogen part are same in Scenario 2 and Scenario 3. The formulas are the same. See Corn Nitrogen in Scenario 2: 2.3.2.

Grain Growth The calculations of variables in the grain growth part are same in Scenario 2 and Scenario 3. The formulas are the same. See Grain Growth in Scenario 2: 2.3.2.

With the formulas discussed above, the process of the simulation model was clearly explained. However, the process cannot be analyzed under perfect conditions, so assumptions were made to promote the process.

4.3 Scenario 3 Model Initialization and Assumptions

For the purpose of operating the model smoothly, a bunch of assumptions and model initializations were made following the previous research results. In order to comprehend the model clearly, the abbreviation of the variables and parameters that appeared in the model are introduced here as well. In order to explain the assumptions clearly, it will be introduced according to the calculation distribution.

Thermal Units First of all, the time is determined from January 1 as Day 1, and each day follows that order. Therefore, the corn is usually planted around May 1, which is Day 120. In this thesis, the plant process starts on Day 120.

The TU and ATU was initialized starting from crop planting. The accumulated thermal units after the emergence stage were set at emergATU as 0. The accumulated thermal units after the silking stage were set at silkATU as 0. Both emergATU and silkATU only appear in the model for simulation.

Leaf Growth The total number of leaves initialized as an input set to the model was defined as 5. Also, the plant population was set to 7 m^{-2} in the experimental crops. A total leaf number of 18.3 was used in all simulations. The plant leaf area was initialized as

0. The LAI was initialized as 0 as well. The largest leaf area was assumed as 750 square centimetres. This data was assumed based on the research published by Muchow in 1990.

Crop emergence occurred 87 thermal units after sowing. And silking was found to occur 67 thermal units after the flag leaf was fully expanded. Since grain usually starts to grow 3 days after reaching the silking stage, a parameter called silkIndex was initialized at 0. When the silkIndex is greater than 3, grain starts to accumulate. The thermal units required from silking to maturity are 1,150, so an indicator was set to recognize whether the grow process had finished or not.

Nitrogen Uptake The NMIN1 was initialized at 0 g N $m^{-3}d^{-1}$, and the mineralization of N of the second soil layer (NMIN2) was initialized at 0 g N $m^{-3}d^{-1}$. The FM was set as equal to 0.15, as done by Sinclair and Amir in 1992. The soil organic nitrogen content of the top layer was set to 0.5 g N kg^{-1} (Wetselaar, 1967), and the second layer was set to 0.1 g N kg^{-1}. The RS was calculated based on the fraction of FTSW using the equation developed by Watts and Hanks 1978, assumed as 1 to simplify the equation. The KS was calculated from the exponential equation for temp response used by Watts and Hanks 1978, assumed as 1 to simplify the problem.

The soluble mineral nitrogen concentration at the start of the experiment was measured at 3.5 mg N L^{-1} for the top layer and 1.0 mg N L^{-1} for the remaining soil profile. Other related variables were set in the soil nitrogen budget to describe conditions in simulated environments. The depth of the topsoil layer was set to 0.25 m, and the second layer for nitrogen mineralization was set from 0.25 m to 0.4 m, which aims to account for the observed distribution of soil organic nitrogen. To simplify the process, it is assumed that all effective ingredients go to the top layer of the soil (to do the mineralization) after applying the fertilizers. The NMIN1 NMIN1 formulas was used to calculate the N mineralization process.

Soil Nitrogen The SN is assumed as 0.1 g N m^{-2} at the start of the simulation. In the following steps, it is assumed that the extra SN was provided by fertilizers only. If there were more than 1 g N L^{-1} water in the soil, it was considered as “enough nitrogen in the soil", which means no extra chemical fertilizers are required during the growing process of the plant. This condition fits the assumption of Scenario 1; however, for Scenario 2 and 3, the fertilizer application is required because usually there is not enough nutrition provided in the soil. Therefore, it is assumed that initially, the soil nitrogen was 0.1 g N m^{-3}. And the amount increased when applying nitrogen fertilizers and continue to decrease because of the consumption of the plant. The parameter NUP was calculated using the formula with variables such as thermal units, the total potential nitrogen uptake and accumulated thermal units. The formula is introduced in next session. If there were insufficient nitrogen in the soil, then NUP itself would be equal to the nitrogen available in the soil.

The day applying fertilizers the second time was set as Parameter L, which ranges from Day 160 to Day 190. The percentage of fertilizers applied for the first time was set as parameter X, which ranges from 39% to 90%. Therefore, the percentage of fertilizer applied in the middle of the growing season was easily calculated as (1-X). One of the objectives of this model is to arrange the parameters L and X to achieve the highest grain yield.

Corn Nitrogen The FTSW was assumed at 0.5. The PNU was assumed to have a value of 26.4 g N m^{-2}. The accumulated amount of leaf nitrogen and set nitrogen were initialized as LFN equals 0 and STEMN equals 0. Muchow (1994) found that 60% of the accumulated nitrogen during vegetative development went to the leaves, while 40% went to the stems. Therefore, the parameter PROPLFN was set to 0.6. The accumulated amount of grain N was initialized at 0. The minimum nitrogen per leaf area for maize canopies with developing leaves was about 0.55 g N m^{-2} by Muchow in 1994. So the LNT was initialized at 0.55. The daily N translocation was initialized at 0.

Grain Growth The accumulated biomass was initialized at 0 as well as the harvest index and the grain. The maximum harvest index was set as 0.5 to reflect the genetic potential of most current commercial maize hybrids. A radiation extinction coefficient of 0.4 was used. The maximum radiation use efficiency for maize during vegetative and early grain growth was 1.6 g MJ^{-1} under fully irrigated, high N conditions.

Since nitrogen plays a significant role in leaf growth, the N concentration is performed in a range to promote the growth. If the N concentration is too low, which is lower than 11 g N kg^{-1}, then grain growth may stop. If the N concentration is too high, which is higher than 16 g N kg^{-1}, then the N translocation from leaves and stems decreases [3].

Chapter 5

Experiments and Results

Since the theories of the thesis in three scenarios have been discussed above, this chapter will introduce the experiments of Scenario 2 and 3 for comparison. The performance of the model presenting Scenario 3 will be emphasized for discussion and analysis. The visualization results will be performed with original data presented in tables as well.

The input data was collected from Daymet and USDA-NASS. The weather data was downloaded from Daymet. Reliable long-term, continuous, and gridded estimates of daily weather and climatology variables are collected by ground-based observation through statistical modeling techniques and shared with users on Daymet. The corn yield data was downloaded from the United States Department of Agriculture, National Agricultural Statistics Service, as known as USDA-NASS. Input weather data of Ottawa were collected using IoT-based sensors planted in the field. The mechanism and methodology of IoT sensors were introduced in Chapter 2.1. The simulation models were developed based on real-life data.

Considering the similarity between the United States and Canada and the outstanding development of agriculture in the US, the simulation chose several agricultural provinces as the virtual locations for planting corn. Oklahoma was selected as the representative in US to simulate the yield. Data from Oklahoma in 1982 was selected for model accuracy detection. Besides, the weather data collected in Ottawa was provided by local farmers in 2021. In this thesis, Oklahoma and Ottawa were selected to see the experiment results.

Python was used as the simulation tool to generate and optimize the corn growth model. Each scenario was simulated as a specific model for results comparison. The code is attached in the appendices.

5.1 Experiment Design

The goal of this fertilizer optimization experiment is to see when is the best time to apply fertilizer in order to achieve a higher nitrogen absorption rate. The simulation model aims to work out the best fermentation time of PCU applied to the plant in order to obtain the highest yield. As the primary conditions for plant growing, the weather patterns are presented for both selected regions, including the daily average temperature, daily solar radiation, daily precipitation, and daily vapour pressure.

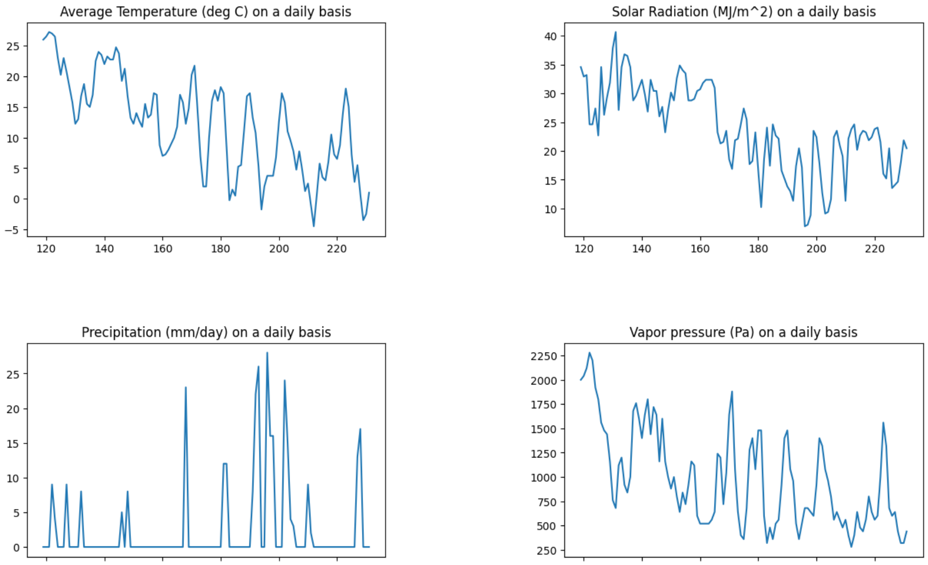


Figure 5.1: The weather patterns of Oklahoma in Scenario 2 and 3 simulations.

As discussed before, Scenario 2 reveals the plant growing with fixed fertilizer applied

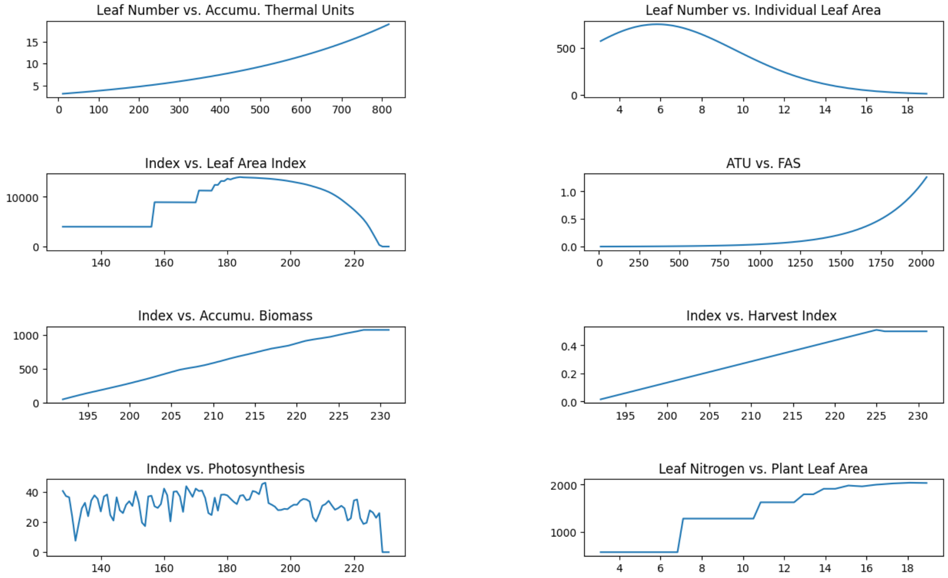


Figure 5.2: The crop growth situation of Oklahoma in Scenario 2 simulation

primarily at the sowing season, and Scenario 3 separates the fixed amount into two parts to improve the plant growth: part one applied at the sowing season and the remaining part at the middle of the growing season. The Scenario 2 simulation model was operated prior to Scenario 3, because the range of parameters X and L should be estimated based on the results of Scenario 3. The optimization of fertilizer application amounts is the highlight of Scenario 3 beating Scenario 2. In both scenarios, the fixed amount of fertilizer, PCU, is provided at the start of the experiment. However, in Scenario 3, only X% of the PCU is applied at the beginning, and the rest of fertilizers are applied on Day L, where both variables X and L are unknown. Eventually, the growth model aims to simulate the highest yield of the crop in various locations. Therefore, the target is to find the optimal pair of X and L as well as the highest yield. The rough range of L was decided based on past real-life experience. The parameter X was set as an outer loop with parameter L in the code. The range of X varied between 1% and 99% to see the performance of corn nitrogen uptake and soil nitrogen. After testing in a bunch of trials, the rough range of X was determined

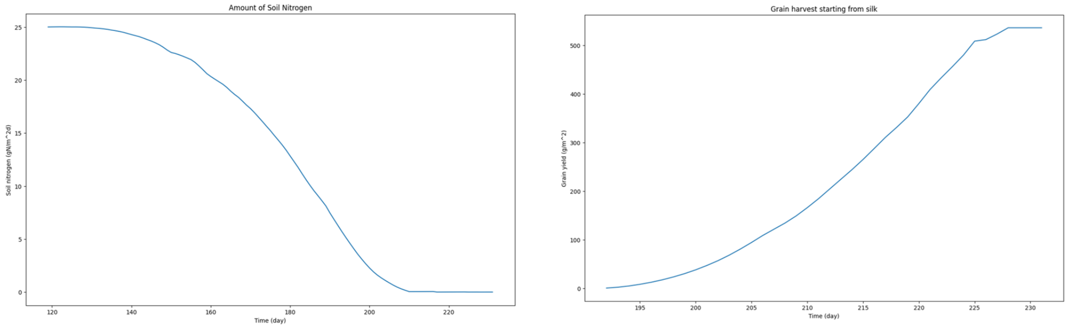


Figure 5.3: The amount of soil nitrogen and the grain harvest starting from the silking stage on a daily basis in Oklahoma in Scenario 2 simulation

as 1% to 60%.

Urea as a frequently used fertilizer in corn planting is often applied to the crop using the 2-step technique. Based on the farmer's experience in real life, the second time of fertilizer application usually happens as the sprouts grow, when the plant has reached 4 inches and before reaching 8 inches tall [45], that would be around the V6 growth stages to replenish, also known as 6 - 8 weeks after sowing. Using that information as a reference, the starting day of the planting process is assumed as Day 120 of the year. The second fertilizer application time can be approximately days 160 to 180 in this thesis. To analyze the results precisely, the figures of soil nitrogen in Scenario 2 show a decreasing curve below, and the time range where the drop occurred is the reference for the parameter L range selection in Scenario 3. Therefore, the L range was adjusted for each region on the basis of the farmers' experience and the Scenario 2 simulation results. A 3D plot was presented from the Scenario 3 model based on parameters X, L, and yield, to visualize the optimal results, which is the highest yield occurring at (1-X%) PCU applied the second time at L day of the year.

In order to see the improvement from Scenario 2 to Scenario 3, the crop growth conditions for both scenarios need to be figured out to explore how the simulated crops are coming along. When comparing the two scenarios, Scenario 3 presents the optimal results of X and L, which were figured out from the 3D plot explained above. Parameters X and L are determined from the 3D plot, so they perform as the given value in an optimal

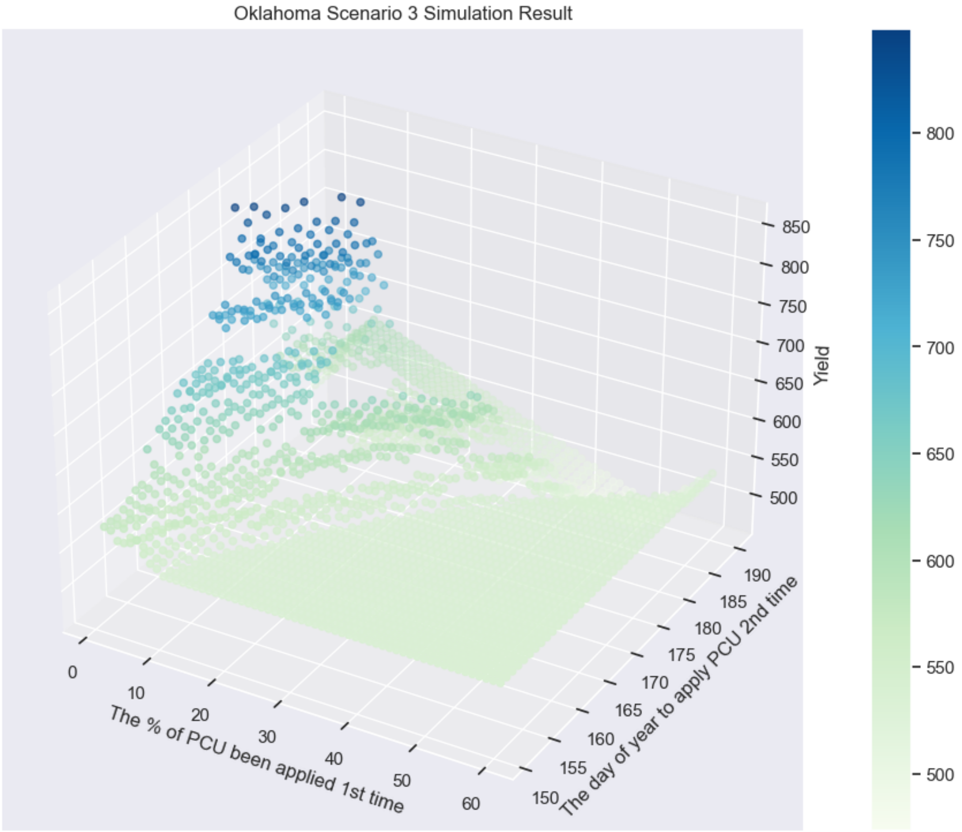


Figure 5.4: Oklahoma Scenario 3 simulation results in 3D

situation. The changing process of soil nitrogen on a daily basis in a Scenario 3 optimal situation is also shown to see the variation. The grain harvest condition is visualized on a daily basis to see the yield.

In the code operating process of Scenario 3, Parameter X (varying from 1% to 60%) works as an inner loop, while Parameter L (determined according to different regions) works as an outer loop. The simulation model of corn growth in Scenario 3 aims to predict the yield operated within the nested loops. Therefore, each pair of X and L corresponds to a specific value of corn yield. After finding the highest yield in the list of the results of crop yield, the corresponding pair of X and L is found according to various locations. The impact of fertilizer application can be seen from the experiment.

5.2 Simulation Results of Oklahoma

This section introduces the simulation results of the scenarios 2 and 3 model performed in Oklahoma. Weather conditions is the primary factor that impacts crop growth. Figure 5.1 explains four aspects of the weather patterns: the average temperature (calculating from the minimal and maximal temperature), solar radiation, precipitation, and vapour pressure. All of the variables are expressed on a daily basis.

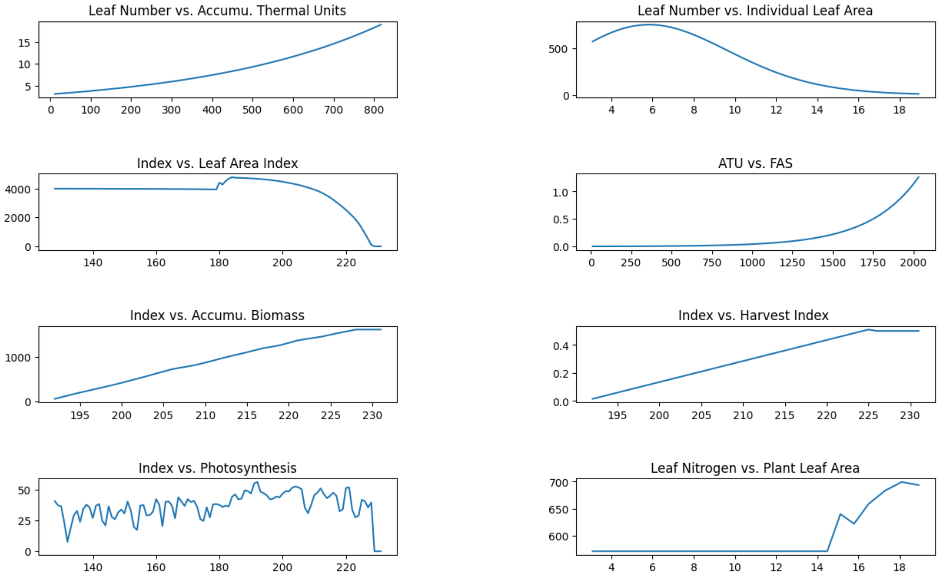


Figure 5.5: The crop growth situation of Oklahoma in Scenario 3 simulation when applying 88% of the given PCU on Day 179

5.2.1 Scenario 2 Simulation Results of Oklahoma

The crop growth situation in Scenario 2 is introduced in 8 subplots in Figure 5.2, which are ATU versus leaf number, leaf number versus individual leaf area, leaf area index on a daily basis, ATU versus FAS, accumulated biomass, HI, and PHS on a daily basis, and leaf

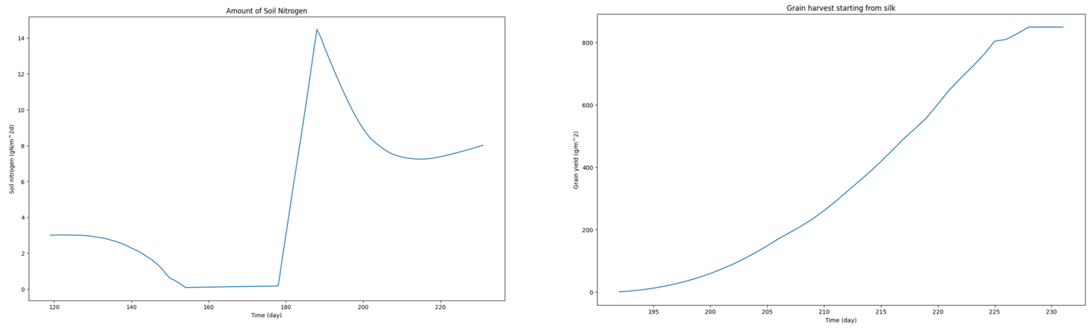


Figure 5.6: The amount of soil nitrogen and the grain harvest starting from the silking stage on a daily basis in Oklahoma in Scenario 3 simulation when applying 88% of given PCU on Day 179

number versus PLA. These figures mostly visualize the relationships among the variables from formulas explained in Chapter 2, Scenario 1, 2.3.1. Besides, cross-contrasting with Figure 2.3, the plots have similar trends, especially ATU versus leaf number, leaf number versus individual leaf area, and HI on a daily basis. This proves the precision of the Scenario 2 simulation model.

After contrasting with the experimental results of nitrogen available in the soil on a daily basis in Scenario 2, the obvious drop of the SN curve occurred between Day 160 and Day 180 in Figure 5.3 (the left subplot). Considering the separation of fertilizer application in Scenario 3, the range of parameter L is set to be Day 150 to Day 190. The range is wider than the results showing from the figures in order to avoid calculation mistakes in the following steps. The exact day is optimized in the following process, according to the inputs of different regions.

The yield of Oklahoma in Scenario 2 can be obtained from the right subplot in Figure 5.3, which shows the grain harvest from the silking stage. The yield is the grain accumulated at the plateau at the end of the curve. From the figure, it can be ascertained that the yield of Oklahoma in Scenario 2 is 53.59 g m^{-2}, taking the last two decimal places.

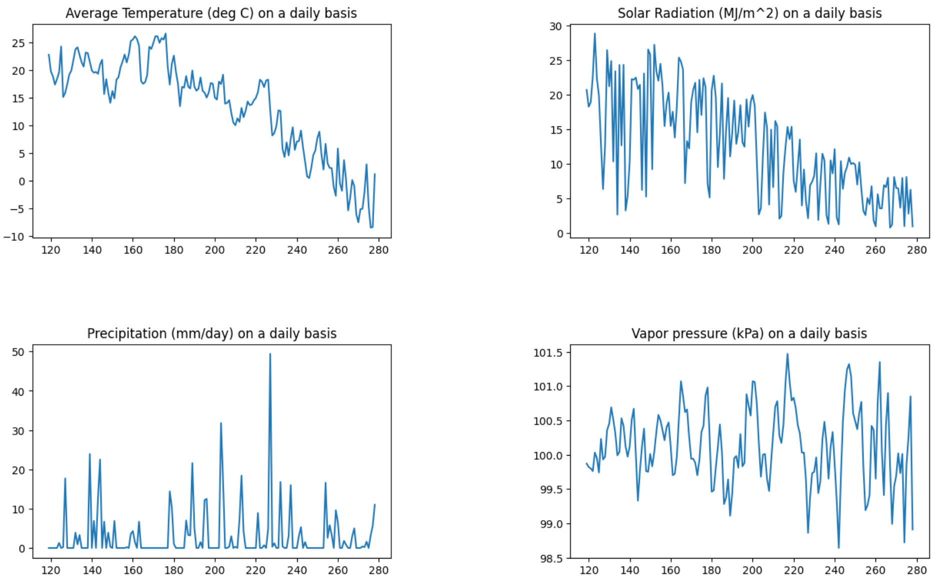


Figure 5.7: The weather patterns in Ottawa in Scenario 2 and 3 simulations

5.2.2 Scenario 3 Simulation Results of Oklahoma

As discussed above, the range of X is determined as 1% to 60%, and the range of L is determined as Day 150 to Day 190 based on Figure 5.3. The simulation results of Scenario 3 are shown in Figure 5.4, and the optimal yield is obtained. The trend of scattered points shows the yield of each pair of X and L. The darker points represent the higher yield on the plot. It is obvious that the higher yield usually occurs at the lower value of X. In Oklahoma, the optimal yield is 84.89 g m^{-2} at X=12, L=179. In other words, the highest yield occurs when applying 88% of the given PCU on Day 179 of the year, at approximately the end of June.

It can be seen from the 3D figure that the timing of fertilizer application has a distinct impact on the crop yield. The trend of the scattered points in the plot is explains with varied colours. In Oklahoma, the high yield usually occurs on Day 175 to Day 185, because the dark blue points appear at the range. Instead of applying more fertilizers the first time,

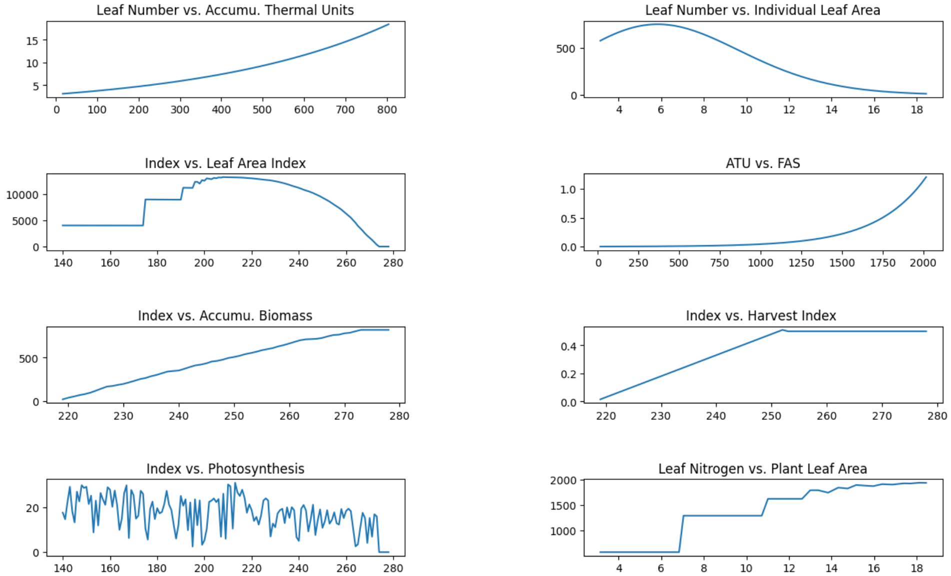


Figure 5.8: The crop growth situation of Ottawa in Scenario 2

more dark points appear before X achieving 20. The coloured 3D figure shows the obvious impact of PCU based on the timing and the percentage of first-time application.

After figuring out the optimal results in Scenario 3, Figure 5.5 shows the crop growth situation when applying 88% of the given PCU on Day 179. Compared with Figure 5.3, LAI, PHS on a daily basis and leaf number versus PLA are influenced by the later nutrition supply. Other than that, the subplots in Figure 5.5 show a similar trend to Scenario 2, meaning that the crop grows well in Scenario 3.

The amount of soil nitrogen varying on a daily basis in Scenario 3 is shown in Figure 5.6 in the left subplot. The slope of SN in Scenario 3 sharply increases at approximately Day 180. It is because the remaining fertilizer was applied to the crop, and 80% of the remaining fertilizers were released evenly after 9 days when it approached Day L. After day = (L+9), 20% of the remaining fertilizers were released evenly during the following days. The slow release of PCU is reflected in the figures, where the curve of SN fluctuates slightly

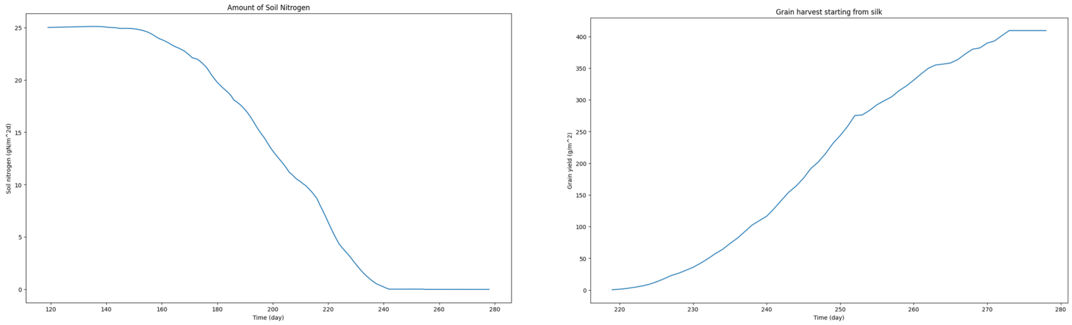


Figure 5.9: The amount of soil nitrogen and the grain harvest starting from the silking stage on a daily basis in Ottawa in Scenario 2

after the second-time fertilizer application. The situation is similar in Ottawa. Compared with Figure 5.3 in Scenario 2, the supplementary fertilizer can extend and promote the growth of corn by adding the available nutrition to the soil. Meanwhile, Figure 5.6 right subplot shows the grain harvest from the silking stage on a daily basis, and the yield can be found as well.

5.3 Simulation Results of Ottawa

The input data of Oklahoma in the US aims to operate in the simulation model and observe the performance. If the model works well, it can be used to predict the yield in Ottawa with the available input data. Different from other regions, input data from Ottawa was collected by IoT sensors planted in the field. The real-life data helped simulate the growth model, and the simulation model and results can help the development of corn farming in Ottawa.

This section shows the simulation results of the Scenario 2 and 3 models performed in Ottawa. With weather conditions as the primary factor, Figure 5.7 shows the average temperature, solar radiation, precipitation, and vapour pressure on a daily time step in 2021. These weather parameters input as known data to operate the simulation models of scenarios 2 and 3.

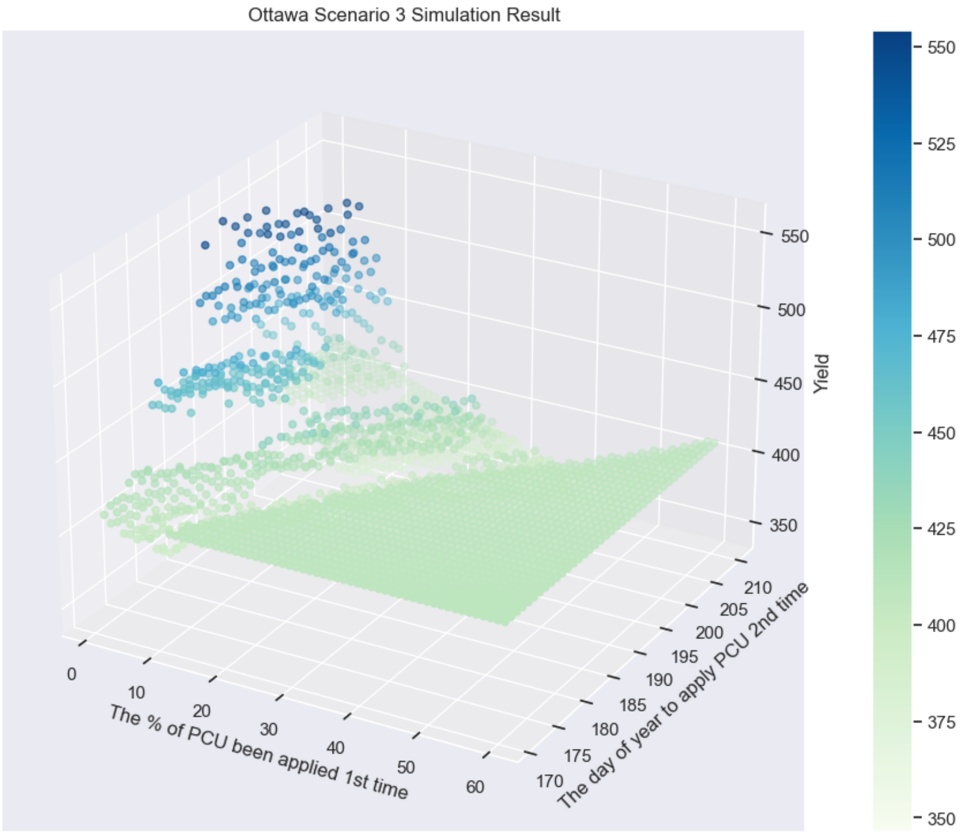


Figure 5.10: Ottawa Scenario 3 simulation results in 3D

5.3.1 Scenario 2 Simulation Results of Ottawa

In order to determine the range of parameter L to operate the Scenario 3 simulation model, the curve of SN is required to see where the drop is. Figure 5.8, in the left subplot, shows that the obvious reduction mainly appears between Day 180 and Day 200. It is the period when the plant greatly needs to absorb the nutrition in the soil. That is why the reduction is much more evident than in other periods. To reduce mistakes when calculating the optimal results, the range of Parameter L for Scenario 3 is selected as days 170 to 210. At the same time, the yield of Scenario 2 simulation can be read from the grain harvest plot in Figure 5.9. The yield of Ottawa in Scenario 2 is 40.94 g m^{-2}, taking the last two

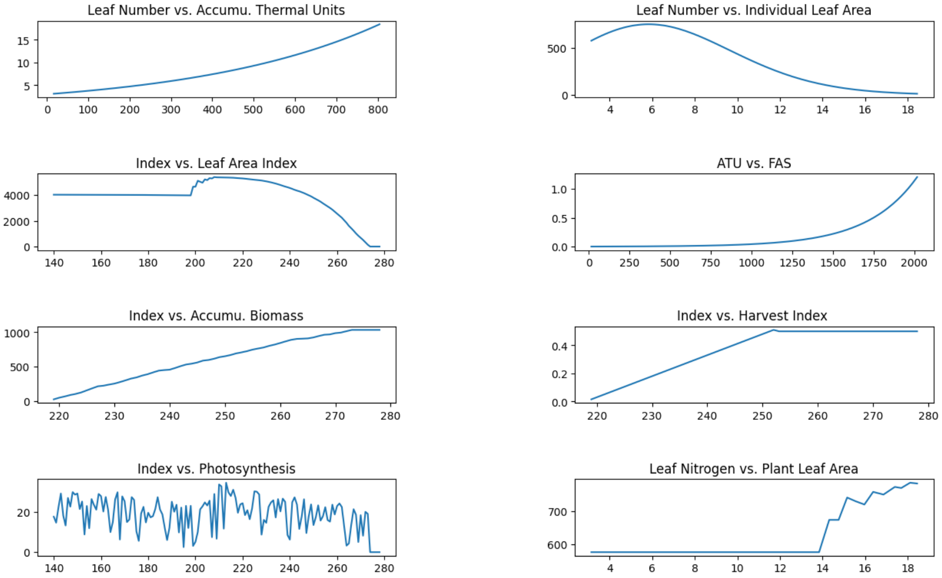


Figure 5.11: The crop growth situation of Ottawa in Scenario 3 simulation when applying 91% of given PCU on day 196.

decimal places.

5.3.2 Scenario 3 Simulation Results of Ottawa

Similarly to the experiments for Oklahoma, a 3D view plot is required to visualize the optimal yield with the corresponding pair of parameters X and L. The range of X is decided as 1% to 60%, and the range of L is determined as days 170 to 210 from the farmers' experience and the analysis in Figure 5.9. With determined ranges of parameters X and L, the Scenario 3 simulation model can be operated, and Figure 5.10 shows the results. The darker points in the plot represent the higher yield. The optimal yield in Ottawa in Scenario 3 is 55.43 g m^{-2} at X=9, L=196. In other words, the highest yield would occur when applying 91% of the given PCU on Day 196 of the year, approximately in the middle of July.

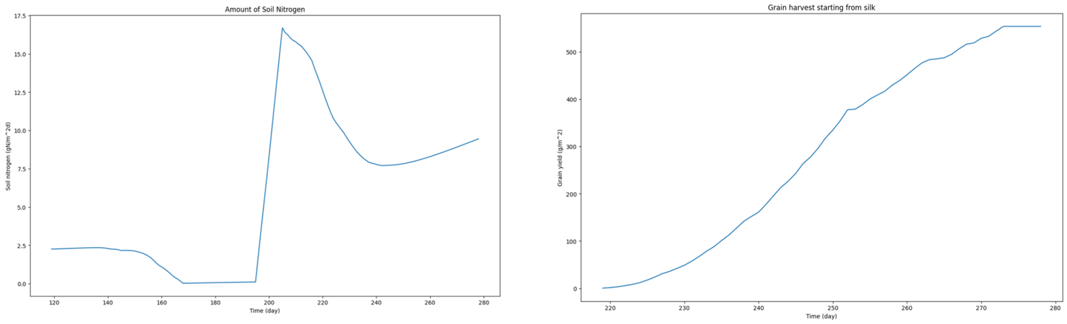


Figure 5.12: The amount of soil nitrogen and the grain harvest starting from the silking stage on a daily basis of Ottawa in Scenario 3 simulation when applying 91% of given PCU on day 196.

The timing and percentage of PCU application influences the yield. Each pair of X and L generate a specific yield, and the points scatter in the plot and show the trend. The legend on the right explains the relation of colour trend and the yield. The darker points representing the higher yield mainly distributed over Day 175 to Day 200 before X achieves 20. This 3D view of the scattered plot shows how the PCU impacts the yield based on the timing and the percentage of first-time application.

With the optimal parameters X and L simulated from the model, the crop growth condition is shown in Figure 5.11. The trends are similar in Scenario 2, which means the plant is growing well, as expected in simulation. From the left subplot in Figure 5.12, the soil nitrogen in Scenario 3 rises sharply after fertilizer application during the middle stage. As explained before, the PCU releases based on the specific rate according to different brands of products. The increasing trend starts approximately at Day 200, which shows the second-time application of PCU. After 9 days of release, the PCU in the soil is available for the plant to absorb, so the dropping trend occurs. 20% of the remaining fertilizer in the soil is released slowly after Day 240, which explains the slight improvement in the figure. With enough nutrition in the soil, the plant can replenish and grow and prepare for the accumulation of grain. And the right subplot of Figure 5.12 shows the harvest process of grain from the silking stage.

5.4 Simulation Results Comparison

The optimal results of Oklahoma and Ottawa are explained and visualized above. Table 5.1 shows the results briefly. The yields cannot be compared among different regions, because the weather varies a lot, and the temperature may drop and increase sharply even in two provinces close to each other.

Location	% of PCU applied 1st time	% of PCU applied 2nd time	Parameter L (day)
Oklahoma	12%	88%	179
Ottawa	9%	91%	189

Table 5.1: Experimental results of parameters X and L in Scenario 3 in Oklahoma and Ottawa

As discussed in Chapter 4, each pair of parameters X and L has a corresponding value of yield. The optimized yield is calculated from the model and listed below in Table 5.2. The increasing rate is calculated by subtracting the Scenario 2 yield from the Scenario 3 yield and then dividing by the Scenario 2 yield in order to notice the increasing or decreasing rate from Scenario 2 to Scenario 3 in each region. It is obvious from Table 5.2 that all of the regions show an outstanding rising trend from Scenario 2 to Scenario 3 in corn yield performance.

Location	Scenario 2 Yield (g/m^2)	Scenario 3 Yield (g/m^2)	Increasing Rate
Oklahoma	53.59	84.89	58.40%
Ottawa	40.94	55.43	35.38%

Table 5.2: The experimental results of corn yield in each region performing Scenario 2 and Scenario 3

Although the exact rate may differ from location to location, the simulation model performed a much higher yield when applying fertilizer separately compared with the operation in Scenario 2. It means more effective nutrients from fertilizers can be absorbed by the crop. Then the grain is increased with more nitrogen available in the plant. The

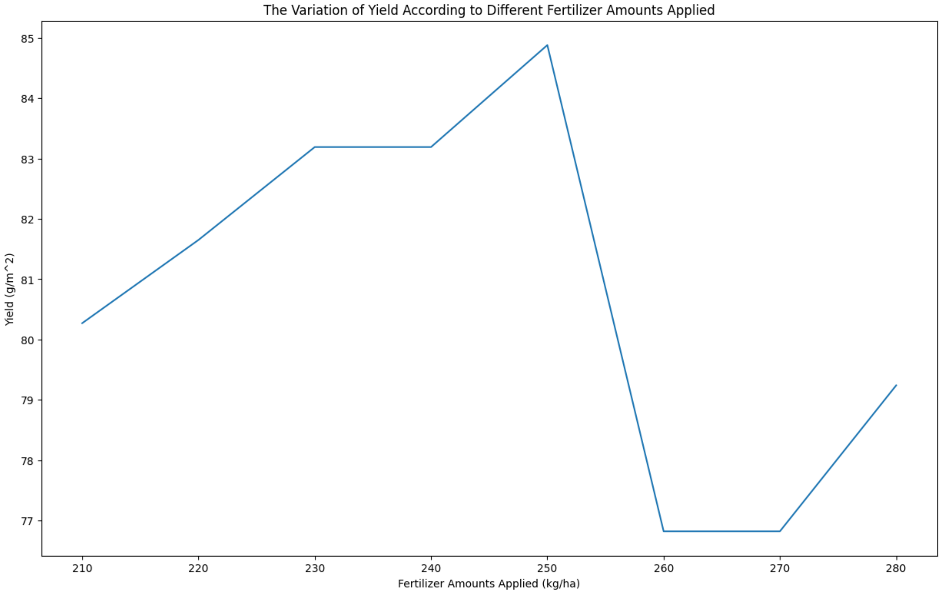


Figure 5.13: Variation of yield according to different amounts of PCU provided in Oklahoma.

Scenario 3 techniques, which apply PCU in two steps, can significantly improve the corn yield regardless of the location factors.

As long as other factors remain the same, applying fertilizers one more time during the growing season can feed the plant with fresh nutrients, especially during the process of silking and maturing, even if the total amount of the fertilizer does not change. The impact of applying fertilizer separately affects the yield remarkably with the increasing rate reaching at least 35% on the yield from Scenario 2 to Scenario 3. What's more, from the results shown in Table 5.1, the percentage of fertilizers applied firstly at the start of the sowing season is usually around 10% of the total amount. It could be inferred that nutrients such as nitrogen are usually required in higher quantities during the latter part of the growing season instead of the start of the growing season.

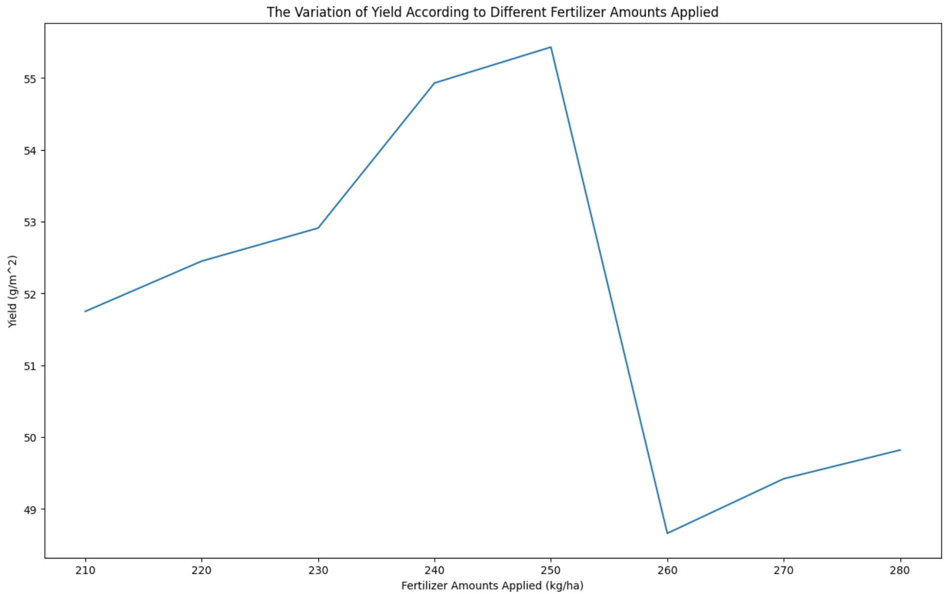


Figure 5.14: Variation of yield according to different amounts of PCU provided in Ottawa.

5.5 Scenario 3 with Changing Amounts of Fertilizer

The amounts of PCU applied prior to the simulation model are provided as known input from the government: 250 kg N ha^{-1}. It should be considered whether the variation of the given fertilizer impacts the yield. Therefore, the fixed amount of fertilizer changes from 210 to 290 in increments of 10 to see the optimal yield difference in Oklahoma and Ottawa. Both figures 5.13 and 5.14 show a distinct peak at amount 250. Other than that, the yield varies depending on the changing amounts of fertilizer, but none of the values in the range can exceed the performance of 250 kg N ha^{-1}.

The value of 250 kg N fertilizer ha^{-1} is recommended by the government. It can be seen from the figure that the value was selected reasonably. This conclusion can also reflect the statements discussed in Chapter 3. If too much fertilizer is applied to the soil, most fertilizers may leach or lose from the plant, which is harmful to the soil and the surroundings. But too little fertilizer will not support the growth of the crop. An appropriate value is calculated to ensure that the effective plant is growing and that the environmental impact is negative. Therefore, this given amount from the government, 250 kg N ha^{-1}, is scientific and can be used as reference in future research.

Chapter 6

Conclusion and Future Work

As explained above, the thesis has developed a mathematical model with 3 scenarios to simulate the corn yield according to climate data in Oklahoma and Ottawa. This chapter would conclude from the theories and experiments above, and discuss potential future work.

6.1 Conclusion

Fertilizers play an important role in agriculture in promoting crop yield and improving the quality of the grain. The improved yield is helpful in feeding human beings around the world and provides economic benefits at the same time. Although the application of fertilizers assists with the growth process of plants, the negative effect of fertilizers on the environment, such as nitrogen leaching and water pollution, should be given serious attention,. Therefore, the usage efficiency and the amount of fertilizers used need to be optimized to meet the requirements of agricultural purposes while simultaneously reducing the impact on the surroundings. This thesis aims to develop a mathematical model that simulates and predicts the corn yield with additional amounts of fertilizer. Python was used as the tool to generate and develop the simulation model. The technique used to achieve the goal was to separate the total amount of available fertilizers into two parts and apply them at the start of the sowing season and in the middle of the growing stages, respectively.

As discussed in Chapter 4 and Chapter 5, the 3-step scenario logic worked well in the performance of the simulation model. From the experiment results, the technique of separating fertilizers performed the highest yield in Scenario 3, because more fresh fertilizers released into the soil can be absorbed by the plant immediately, compared with Scenario 2, where the total amount of fertilizers were applied together at the start of the planting season.

With the real-life weather data collected from IoT sensors, the simulation model showed well performance in figuring out the optimal results and met the expectation. Specifically in this work, simulation experiments from Oklahoma and Ottawa are presented. If applying 12% of 250 kg N $ha^{-}1$ PCU to the plant at the start and the remaining fertilizer on Day 179 of the year, the corn yield in Oklahoma would achieve 84.88 (g $m^{-}2$), 58.40% higher than applying 100% fertilizer at the beginning of the sowing season. And in Ottawa, the corn yield would increase from Scenario 2, 40.94 (g $m^{-}2$), to Scenario 3, 55.42 (g $m^{-}2$), if using the technique of applying 9% of the PCU the first time and the remaining part on Day 189 of the year. Since temperature and solar radiation are key factors affecting the plant growth and the climate conditions are similar in Oklahoma and Ottawa, the similar results are justified.

Generally speaking, the optimal time to apply the rest of the PCU in the middle of the growing season varied among different regions. The SN curve in Scenario 2 needs to be taken seriously as an important reference factor. If a new region or location is asked for yield prediction and fertilizer application day optimization, Scenario 2 should be performed at first, because the range of applying fertilizer the second time needs to be calculated based on the figure showing when available nitrogen in the soil was dropped from results of Scenario 2. After that, Scenario 3 can perform and determine the best time to apply the exact percentage of the remaining PCU on which day of the year, and the optimal yield can be calculated as well.

6.2 Limitations

This thesis was performed with assumptions to simplify the problem. Therefore, the limitations of the model should be noticed before applying it to other situations. Firstly, all three scenarios were assumed based on conditions of enough sunshine and enough water being provided. Besides, the effects of pests or diseases on the crop were not considered in this work. However, the impact of irrigation and insects play significant roles in real life. Especially in the growing stage of a plant, insufficient water can lead to the severe result of grain loss. Both of the parameters of KS (the temperature sensitivity coefficient) and RS (the soil water content coefficient) explained in Chapter 4 should be calculated following the condition of the water supply. Since the factor of water is neglected, both of them were assumed as 1 to simplify the equation. The parameters may vary depending on location changes and water supply, and this is one of the limitations of the work. Since the project emphasizes the impact of fertilizer, water is assumed as unlimited at this time and can be considered in the model at the next step.

6.3 Future Work

This project presented the importance of discipline-crossing from my bachelor's program, chemical engineering, to my current graduate program, Systems Science and Engineering. With the knowledge gained from my undergraduate study, I understood the working process of chemical fertilizers for plants to grow deeply and thoroughly. The nitrogen-transferring process from the fertilizer to the soil and the plant is the basic theory of the simulation model. The systematic learning and knowledge of the Python operation that I acquired during my graduate studies were useful tools to write and optimize the simulation model. The combination of knowledge learned from chemical engineering and systems science prepared my research for this fertilizer optimization study.

The simulation model of this thesis has shown the positive results of fertilizer application on corn growth, and the limitations were discussed in the previous section. In the next step, the impact of water on the nitrogen uptake of corn should be taken into consideration in the simulation model. With the impact of temperature, solar radiation, water (also considered as irrigation), and nitrogen supply (fertilizer application), this simulation model can fit a real situation much better. Moreover, the smart farming project was developed and established by the research group of the Department of Systems Science and Engineering at the University of Ottawa to promote the corn growth project in Ottawa. This simulation model was developed based on the theories and ideas generated in the group. In the future, this simulation model can be optimized to fit the requirements of the project in order to improve the yield and quality of corn planting in Ottawa.

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APPENDICES

Appendix A

Scenario 1 Simulation Model in Python

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
# Initialization
'''
TLN: Total Number of leaves initiated
tMax: Daily max temp. (C)
AM: Area of largest leaf (cm2)
ATU: Accumulated thermal units
Popu: Population was used as number of plants per squared meter
SR: Solar Radiation
E: Radiation use efficiency
BM: Biomass
TLN:
'''
# Assume the planting date is May 1st(aka 120 from Jan. 1)
startDay = 120
# Assume the max leaf number is 18.3
leafMax = 18.3
```

```
# Initiate the leaf number LN
LN = 0
# Assume the total number of initiated leaves TLN is 5
TLN = 5
# LNM = Leaf number having the largest area
LNM = 3.53 + 0.46*TLN
# Assume that the largest leaf area AM is 750(cm^2)
AM = 750
# Initiate the accumulated thermal units
ATU = 0
# Accumulated thermal units after emergence
emergATU = 0
# Accumulated thermal units after silking
silkATU = 0
# Assume the plant population is 7 (plants/m^2)
Popu = 7
# Initiate the accumulated biomass
BM = 0
# Initiate the silking state
silk = False
# Thermal units needed from silking to maturity
finish = 1150
# Initiate harvest index
HI = 0
# Initiate grain
Grain = 0
# When silk index is greater than 3, grain starts to grow
silkIndex = 0
# Initiate plant leaf area
PLA = 0
# Define a helper dic Leaf number/individual leaf area
```

```
dic = {}

# List of emergATU, LN, Area, FAS, LAI, PHS, HI, ls = list
lsEATU = []
lsLN = []
lsA = []
lsFAS = []
lsLAI = []
lsPHS = []
lsHI = []
lsIndex = []
lsBM = []
lsPLA = []
lsGrain = []

# load weather data
def loadWeather(f):
    df = pd.read_csv(f, skiprows=[0,1,2,3,4,5,6])
    # Convert the solar radiation from watt to MJ
    df['srad␣(MJ/m^2)'] = df['srad␣(W/m^2)'].multiply(86400/1000000)
    # Obtain the daily average temperature
    df['tave␣(deg␣c)'] = (df['tmin␣(deg␣c)'] +
    df['tmax␣(deg␣c)']).divide(2)
    data = df[['tmin␣(deg␣c)', 'tmax␣(deg␣c)', 'tave␣(deg␣c)',
    'srad␣(W/m^2)', 'srad␣(MJ/m^2)']]
    return data

# A new leaf emerges then
# adding the individual leaf area into the plant leaf area.
def helper(dic, LN, A):
    if np.floor(LN) not in dic:
```

```
        dic[np.floor(LN)] = A
    else:
        A = 0
    return dic, A

def accumuPla(PLA, dic, LN, A):
    # If the current leaf is growing and no new leaf emerge,
    replace the previous leaf area with the current leaf area.
    if np.floor(LN) in dic:
        PLA = PLA - dic[np.floor(LN)] + A
    else:
        PLA = PLA + A
    dic[np.floor(LN)] = A
    return dic, PLA

weatherData = loadWeather(OK)

# Load weather data
# tAve: daily average temperature (C)
# sRad: solar radiation (MJ/m^2)
tAve = weatherData['tave (deg c)'];
sRad = weatherData['srad (MJ/m^2)']

# Since dataframe is zero-index. Index starts from startDay - 1
index = startDay - 1

while silkATU <= finish and index < 300:
    # Thermal unit is in different value before and after silking
    TU = tAve[index] - 8 if not silk else tAve[index]
    # Thermal unit cannot be negative
    TU = 0 if TU < 0 else TU
```

```
ATU += TU
lsIndex.append(index)

if ATU > 87:
    emergATU += TU
    lsEATU.append(emergATU)

    if LN < leafMax:
        LN = 2.5 * np.exp(ATU*0.00225)
        lsLN.append(LN)
        A = AM * np.exp(-0.0344*((LN-LNM)**2)+0.000731*((LN-LNM)**3))
        # Append individual leaf area at each index step
        lsA.append(A)
        # Everytime a new leaf emerges,
        add the individual leaf area into the plant leaf area.
        dic, A = helper(dic, LN, A)
        PLA += A
        dic, PLA = accumuPla(PLA, dic, LN, A)
        lsPLA.append(PLA)
        # Mark the day that leaves stop growing
        flagLeafDay = index
        # Mark the ATU that leaves stop growing
        flagLeafATU = ATU
    FAS = 0.00161*np.exp(0.00328*emergATU)
    lsFAS.append(FAS)
    # Green leaf area index
    LAI = Popu * (PLA-PLA*FAS)
    # Add a condition to determine the leaf area index
    so that it cannot be negative number
    LAI = LAI if LAI > 0 else 0
    lsLAI.append(LAI)
```

```
    # The radiation use efficiency is 1.6 from emergence
    until 500 thermal units after silking, thereafter 1.2
    E = 0.4 if silkATU < 500 else 0.3
    # Daily photoSynthesis depends on daily solar radiation
    PHS = sRad[index] * E * (1-np.exp(-0.4*LAI))
    lsPHS.append(PHS)
    # Keep updating the accumulated biomass
    BM += PHS
    lsBM.append(BM)

    if ATU >= flagLeafATU+67:
        silk = True
        silkATU += TU
        silkIndex += 1

    # Grain growth was assumed to begin 3 days after silking
    if silkIndex > 3:
        if HI < 0.5:
            HI += 0.015
        else:
            HI = 0.5
        lsHI.append(HI)
        # Keep updating the grain yield (g/m^2)
        Grain = BM * HI
        lsGrain.append(Grain)
# Increment the index for the next iteration.
index += 1
```

Appendix B

Scenario 2 Simulation Model in Python

```
import pandas as pd
import numpy as np

# Initialization is same as Scenario 1
'''Apply the Fertilizer'''
# Since dataframe is zero-index.
# Index starts from startDay - 1
index = startDay - 1
# Initial fertilizer in  kg N/ha
N_fer_per_hectare = 250
# N_fer in g N/m2
N_fer = N_fer_per_hectare * 0.1
SN = N_fer

# load weather data
def loadWeather(f):
    df = pd.read_csv(f, skiprows=[0,1,2,3,4,5,6])
    # Convert the solar radiation from watt to MJ
    df['srad␣(MJ/m^2)'] = df['srad␣(W/m^2)'].multiply(86400/1000000)
```

```
    # Obtain the daily average temperature
    df['tave␣(deg␣c)'] = (df['tmin␣(deg␣c)'] +
    df['tmax␣(deg␣c)']).divide(2)
    data = df[['tmin␣(deg␣c)', 'tmax␣(deg␣c)', 'tave␣(deg␣c)',
    'srad␣(W/m^2)', 'srad␣(MJ/m^2)']]
    return data

# A new leaf emerges then
# adding the individual leaf area into the plant leaf area.
def helper(dic, LN, A):
    if np.floor(LN) not in dic:
         dic[np.floor(LN)] = A
    else:
        A = 0
    return dic, A

def accumuPla(PLA, dic, LN, A):
    # If the current leaf is growing and no new leaf emerge,
    replace the previous leaf area with the current leaf area.
    if np.floor(LN) in dic:
        PLA = PLA - dic[np.floor(LN)] + A
    else:
        PLA = PLA + A
    dic[np.floor(LN)] = A
    return dic, PLA

weatherData = loadWeather(OK)

'''Load Weather Data'''
# tAve: daily average temperature (C)
tAve = weatherData['tave␣(deg␣c)']
```

```
lsTemp = pd.Series(tAve).values.tolist()
# sRad: solar radiation (MJ/m^2)
sRad = weatherData['srad␣(MJ/m^2)']
lsSR = pd.Series(sRad).values.tolist()
# prcp: precipitation (mm/day)
Prcp = weatherData['prcp␣(mm/day)']
lsPrcp = pd.Series(Prcp).values.tolist()
# vp: vapor pressure (Pa)
Vp = weatherData['vp␣(Pa)']
lsVp = pd.Series(Vp).values.tolist()

while silkATU <= finish and index < 300:
    NCON1 = 9 + 0.71 * (index - 7)
    NMIN1 = FM * NORG1 * RS * (1 - np.exp(-KS)) * (200 - NCON1) / 200
    SN += NMIN1 * topdepth

    if not silk:
        TU = tAve[index] - 8
    else:
        TU = tAve[index]
    # Thermal unit cannot be negative
    if TU < 0:
        TU = 0
    else:
        TU = TU
    ATU += TU

    '''considering fertilizer application'''
    NUP = TU * (PNU * 5.24 * (10 ** (-8)) * (ATU ** 1.58)
    * np.exp(-(ATU / 958) ** 2.58))
    if SN > NUP:
```

```
    NU = NUP
else:
    NU = 0.001

lsNU.append(NU)

if ATU > 87:
    emergATU += TU
    lsEATU.append(emergATU)

    if LN < leafMax:
        # Calculate the accumulated leaf N
        LFN += NU * PROPLFN
        # Calculate the accumulated stem N
        STEMN += NU * (1 - PROPLFN)
        if LAI != 0:
            LNT = LFN / LAI * 1000
            lsLNT.append(LNT)
        if LNT < 0.55:
            inhibit = True
        else:
            inhibit = False

        LN = 2.5 * np.exp(ATU * 0.00225)
        lsLN.append(LN)
        A = AM * np.exp(-0.0344 * ((LN - LNM) ** 2)
        + 0.000731 * ((LN - LNM) ** 3))
        lsA.append(A)
        dic, PLA = accumuPla(PLA, dic, LN, A, inhibit)
        lsPLA.append(PLA)
        flagLeafDay = index
```

```
    flagLeafATU = ATU
    TVN = (LFN - 0.4) + (STEMN - 2.5)

FAS = 0.00161 * np.exp(0.00328 * emergATU)
lsFAS.append(FAS)
LAI = Popu * (PLA - PLA * FAS)
if LAI > 0:
    LAI = LAI
else:
    LAI = 0
lsLAI.append(LAI)
if LNT > 0.55:
    LNT = LNT
else:
    LNT = 0.55
if not grain:
    E = 0.12 + 1.5 * LNT
else:
    E = 0.12 + 1.5 * (LNT - DTVN * 0.6)
if E > 1.6:
    E = 1.6
else:
    E = E
lsE.append(E)
PHS = sRad[index] * E * (1 - np.exp(-0.4 * LAI))
lsPHS.append(PHS)

if ATU >= flagLeafATU + 67:
    silk = True
    silkATU += TU
    silkIndex += 1
```

```
if silkIndex > 3:
    grain = True
    if HI < 0.5:
        HI += 0.015
    else:
        HI = 0.5
    lsHI.append(HI)

    if not GInhibit:
        BM += PHS
        lsBM.append(BM)
        Grain = BM * HI
    lsGrain.append(Grain)

    '''grain nitrogen accumulation'''
    DTVN = TVN * TU / 1150

    # Calculate the accumulated grain N
    GRAINN += NU + DTVN

    # Grain N concentration
    GN = GRAINN / Grain
    if GN < 0.011:
        GInhibit = True
    elif GN > 0.016:
        GN = (GRAINN - (TVN / 3) * TU / 1150) / Grain
    else:
        GInhibit = False
    lsGN.append(GN)
```

```
    if SN > NU:
        SN -= NU

    lsIndex.append(index)
    lsSN.append(SN)

    # Increment the index for the next iteration.
    index += 1

'''Plot the Results'''
```

Appendix C

Scenario 3 Simulation Model in Python

```
import pandas as pd
import numpy as np
import array as arr
import matplotlib.pyplot as plt

# Initialization is same as Scenario 1
'''Apply the Fertilizer'''
# Since dataframe is zero-index.
# Index starts from startDay - 1
index = startDay - 1
# Initial fertilizer in  kg N/ha
N_fer_per_hectare = 250
# N_fer in g N/m2
N_fer = N_fer_per_hectare * 0.1
SN = N_fer

# load weather data
def loadWeather(f):
    df = pd.read_csv(f, skiprows=[0,1,2,3,4,5,6])
```

```
    # Convert the solar radiation from watt to MJ
    df['srad␣(MJ/m^2)'] = df['srad␣(W/m^2)'].multiply(86400/1000000)
    # Obtain the daily average temperature
    df['tave␣(deg␣c)'] = (df['tmin␣(deg␣c)'] +
    df['tmax␣(deg␣c)']).divide(2)
    data = df[['tmin␣(deg␣c)', 'tmax␣(deg␣c)', 'tave␣(deg␣c)',
    'srad␣(W/m^2)', 'srad␣(MJ/m^2)']]
    return data

# A new leaf emerges then
# adding the individual leaf area into the plant leaf area.
def helper(dic, LN, A):
    if np.floor(LN) not in dic:
        dic[np.floor(LN)] = A
    else:
        A = 0
    return dic, A

def accumuPla(PLA, dic, LN, A):
    # If the current leaf is growing and no new leaf emerge,
    replace the previous leaf area with the current leaf area.
    if np.floor(LN) in dic:
        PLA = PLA - dic[np.floor(LN)] + A
    else:
        PLA = PLA + A
    dic[np.floor(LN)] = A
    return dic, PLA

weatherData = loadWeather(OK)

'''Define variable X, L and their ranges'''
```

```
lsX_percent = np.arange(1, 61).tolist()
lsReapply_day = np.arange(171, 211).tolist()

for L in lsReapply_day:
    for X in lsX_percent:
        while silkATU <= finish and index < 300:
    NCON1 = 9 + 0.71 * (index - 7)
    NMIN1 = FM * NORG1 * RS * (1 - np.exp(-KS)) * (200 - NCON1) / 200
    SN += NMIN1 * topdepth

    if not silk:
        TU = tAve[index] - 8
    else:
        TU = tAve[index]
    # Thermal unit cannot be negative
    if TU < 0:
        TU = 0
    else:
        TU = TU
    ATU += TU

    '''considering fertilizer application'''
    NUP = TU * (PNU * 5.24 * (10 ** (-8)) * (ATU ** 1.58)
    * np.exp(-(ATU / 958) ** 2.58))
    if SN > NUP:
        NU = NUP
    else:
        NU = 0.001

    lsNU.append(NU)
```

```
if ATU > 87:
    emergATU += TU
    lsEATU.append(emergATU)

    if LN < leafMax:
        # Calculate the accumulated leaf N
        LFN += NU * PROPLFN
        # Calculate the accumulated stem N
        STEMN += NU * (1 - PROPLFN)
        if LAI != 0:
            LNT = LFN / LAI * 1000
            lsLNT.append(LNT)
        if LNT < 0.55:
            inhibit = True
        else:
            inhibit = False

        LN = 2.5 * np.exp(ATU * 0.00225)
        lsLN.append(LN)
        A = AM * np.exp(-0.0344 * ((LN - LNM) ** 2)
        + 0.000731 * ((LN - LNM) ** 3))
        lsA.append(A)
        dic, PLA = accumuPla(PLA, dic, LN, A, inhibit)
        lsPLA.append(PLA)
        flagLeafDay = index
        flagLeafATU = ATU
        TVN = (LFN - 0.4) + (STEMN - 2.5)

    FAS = 0.00161 * np.exp(0.00328 * emergATU)
    lsFAS.append(FAS)
    LAI = Popu * (PLA - PLA * FAS)
```

```
if LAI > 0:
    LAI = LAI
else:
    LAI = 0
lsLAI.append(LAI)
if LNT > 0.55:
    LNT = LNT
else:
    LNT = 0.55
if not grain:
    E = 0.12 + 1.5 * LNT
else:
    E = 0.12 + 1.5 * (LNT - DTVN * 0.6)
if E > 1.6:
    E = 1.6
else:
    E = E
lsE.append(E)
PHS = sRad[index] * E * (1 - np.exp(-0.4 * LAI))
lsPHS.append(PHS)

if ATU >= flagLeafATU + 67:
    silk = True
    silkATU += TU
    silkIndex += 1

if silkIndex > 3:
    grain = True
    if HI < 0.5:
        HI += 0.015
    else:
```

```
            HI = 0.5
        lsHI.append(HI)

        if not GInhibit:
            BM += PHS
            lsBM.append(BM)
            Grain = BM * HI
        lsGrain.append(Grain)

        '''grain nitrogen accumulation'''
        DTVN = TVN * TU / 1150

        # Calculate the accumulated grain N
        GRAINN += NU + DTVN

        # Grain N concentration
        GN = GRAINN / Grain
        if GN < 0.011:
            GInhibit = True
        elif GN > 0.016:
            GN = (GRAINN - (TVN / 3) * TU / 1150) / Grain
        else:
            GInhibit = False
        lsGN.append(GN)

if SN > NU:
    SN -= NU

lsIndex.append(index)
lsSN.append(SN)
```

```
    # Increment the index for the next iteration.
    index += 1

opt = 0
for i in column_yield:
    if i >= opt:
        opt = i

print("The highest yield: ", opt)

'''Plot the results'''
```