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Climate change and its effects on Norwegian potato production:

How to counteract the negative impacts of soil compaction by implementing a predictive simulation model

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Abstract

In a world where the population is immersed in the negative effects of climate change, and the extreme weather conditions that emerge, several papers discuss its effect on agricultural practices, and which innovations are crucial. One of the paramount factors in agricultural practices, that is heavily affected by excessive precipitation as a result of extreme weather, is soil compaction.

We want to assess whether climate forecasts can help farmers reduce the impacts of soil compaction, and by doing so, create a higher sense of predictability in future production. Hence, we create a model simulating how extreme weather conditions impact the soil moisture levels throughout potato production.

In the simulation model, we use historical precipitation data from the driest year (2018), and the wettest year (2005) in Norway since 1993. Our model is simplified, but, taking into account the complexity of the hydrologic cycle and its effects on soil moisture levels, we are able to provide a basic framework of the moisture levels throughout the potato production process. We implement optimal and critical moisture levels in the simulation, in order to see whether we are able to limit the amount of operations relying on heavy machinery, when the soil is too wet.

Overall, the results show that heavy precipitation does have a substantial impact on soil moisture levels, and how they effect soil compression. With future extreme weather conditions causing heavy rainfall, precipitation is one of the largest moments of insecurity for farmers, and their agricultural practices. A model with focus on soil moisture levels, and how to combat soil compression, could decrease the sense of uncertainty for farmers around the globe.

An assessment of the literature shows that the negative effects of soil compaction in agricultural processes are prevalent. However, as there is a limited amount of studies that model soil compaction, we suggest that further research is necessary to counteract the extreme weather conditions caused by climate change, and the negative effects originating from soil compaction.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

World Health

The worlds' population is currently growing at a rate of 81 million people per year, and it is expected to reach 8 billion in 2023, and 10 billion by the year 2055 (Worldometer, 2021). This exponential growth, coupled with increasing levels of income in developing countries are driving factors behind the growth in global food demand. By 2050 it is expected that food demand will increase anywhere between 59% to 98% (Valin et al., 2013). Agricultural markets will have to be reshaped in ways not seen before. Farmers all around the globe will need to increase crop production, either by augmenting productivity on existing agricultural lands through fertilizer and irrigation, adopting new methods like precision farming or by increasing the amount of agricultural land (Elferink and Schierhorn, 2016). The potato is a versatile vegetable that contains a lot of valuable nutrients, and it is a natural source of vitamin C and B, minerals such as potassium and iron, and dietary fiber. A meta-analysis from 2013 also claims that potatoes lower the blood pressure, and by that contributes in a positive manner to the health of your heart (Norsk Landbrukssamvirke, 2019).

Another notable benefit of the potato is that it contains only half as many calories as rice and pasta (Fagforum Potet, 2020). This is an attribute that could come in handy in the battle against the increasing rate of overweight and obesity on a global scale. A study conducted by the World Health Organization in 2016 concluded that more than 1.9 billion adults were overweight, and of those more than 650 million were obese. Since 1975 the worldwide incidence of obesity has almost tripled (World Health Organization, 2021). Should this trend continue, an estimate done by World Obesity Federation show that 2.7 billion adults will be overweight by 2025, while over 1 billion will be affected by obesity.

An interesting estimation show that the majority of the world's population lives in countries where overweight and obesity has a higher mortality rate than underweight (World Obesity Federation, 2021). If we look at overweight in Norway, the Norwegian Institute of Public Health has conducted research in both the Tromsø-area and Northern Trøndelag that shows a mere 25% of adult males and 40% of women are considered to be of normal weight, which implies that a large portion of men and women are either overweight or obese (Norwegian Institute of Public Health, 2017). One of the three actions an individual can take in order to prevent overweight and obesity, is to increase consumption of fruit and vegetables, and also legumes, whole grains and nuts. Given that potatoes are rich in important nutrients, as well as being low in calories; it should have an important place on the food platter in both wealthy and developing countries.

Climate Change

Climate change is a phenomenon that will affect agriculture worldwide, with changes in factors such as precipitation and temperature. Since the industrial revolution at the end of the 18th century, human emission of CO2 has increased drastically, leading to a greenhouse-effect in the atmosphere. In order to halt the temperature increase on the planet, it is essential to reduce carbon-emission. It is therefore a good trait that potatoes have an average climate footprint of 0,31 kg CO2-equivalents per kg produced, while rice has a footprint of 2,3 kg and pasta's CO2-equivalents amount to 1,6kg (Hess et al., 2015).

As climate change may lead to a higher frequency of extreme weather conditions (Mirza, 2003); larger amounts of precipitation may cause a higher level of insecurity in agricultural production, and farmers could feel a reduced sense of security as climate change progresses.

In order to preempt the negative impacts of the changing weather conditions, it is important to breed and develop potato varieties with favorable attributes. Qualities such as resistance to illness, how suited the potato is for storage and the quality of the peelings. This kind potato breeding has been present in Norway in the later years. Due to several years of diminishing sales of Norwegian potatoes, the potato-industry made several adjustments to the appearance and quality of the potatoes in order to turn the negative trend around. The research regarding the attributes of different breeds of potatoes is moving rapidly, and it is therefore important to continuously test new species; as the process of developing new species and mapping the suitability of those could take up to a decade (Norsk Landbrukssamvirke, 2021).

2 Background

2.1 NORCE – Seasonal Forecasting Engine

The main purpose of the Seasonal Forecast Engine, run by NORCE Research, is to predict the weather beyond the foreseeable future by using various models. Statistical methods are also applied to minimize the systematical errors of the models. Despite a quite recent start to the project, it has already produced forecasts in different formats, as well as peer-reviewed articles. Reviewing topics such as; how the sea currents affect the Norwegian climate, and how sea temperatures could be utilized in predicting seasonal forecasts. The group of users are companies who operate in insurance, electricity production and suppliers of digital services.

In our thesis we will elaborate on whether this engine could be applied to agriculture. Due to the chaotic nature of weather, forecasts are seldom valid for a time span exceeding ten days. Although it is not possible to predict with certainty how the weather will be in a few weeks' time, it is often possible to say something about the probability of certain weather types (Norce Research, 2021).

2.2 NORCE - Climate Futures

Climate Futures is a center for research-based innovation who aim to create a long-lasting cooperation between corporations, public organizations and research groups across different sectors and disciplines. This is a necessity in order to handle one of the greatest challenges of our time.

An increase in extreme weather phenomena as a result of climate change presents a serious threat towards the economy and the society as a unity. The society is becoming increasingly more vulnerable to extreme weather and climate incidents. Both human lives, important infrastructure, food access, transport and a plethora of other sectors are exposed to these dangers.

So far the possibilities to successfully handle climate risk have been hampered by a lack of engagement and exchange of knowledge between companies, authorities and scientists.

A large amount of information that would have been relevant for decision makers have unfortunately been ignored. A weather forecast spanning a couple of days into the future will no longer suffice to make viable plans. There is no doubt that information about the climate for multiple decades is a necessity, not just the approaching ten days.

There are several examples of how a really long-term forecast could prove useful. Power companies need to be able to make important decisions based on predictions of future precipitation, amounts of snow and power usage. This makes them dependent on good weather forecasts. Insurance companies could vastly decrease costs if they gain more information on future cold periods, floods, storms, and droughts.

Finally, farmers could draw tremendous benefits from knowing when the growth season starts, how much rainfall they can expect, how warm or cold the weather will be, as well as when they should harvest their crops (Norce Research, 2020).

2.3 Gartnerhallen SA

Gartnerhallen SA is Norway's largest supplier of Norwegian fruits, berries, vegetables, and potatoes. They work daily to deliver products of high quality, to promote Norwegian green production (fruits, vegetables, etc.) and to secure a good interaction between the producers and the market.

Gartnerhallen is organized as a cooperatives, where the objective is to maintain the economical and industrial interests of the producers of greens. They describe themselves as driven, on the front foot, proud and innovative. The producers associated with Gartnerhallen are constantly looking for new opportunities to improve their own business, streamline and develop their production. As a company for the greens producers, it is Gartnerhallen's job to be a facilitator for the producers in their effort to improve themselves.

The market for greens is a dynamic one, and Gartnerhallen is close to both the market itself and its participants. Through market based production-planning and coordinated effort, they balance the wishes and needs from respectively producers, customers, and consumers. By delivering what the market demands, they create growth and increased value creation from Norwegian agriculture.

A good condition of nature and soil, as well as a climate in balance, is essential for a well functioning business and production of Norwegian greens. A sustainable and long-term management of the natural resources is of the utmost importance. It lies in their modus operandi that the farm and soil being managed should be handed over in improved condition to the next generation, as has been the case over several previous generations.

Gartnerhallen secures predictable and long-term access to the market for their owners. Among Gartnerhallen's most important tasks, is planning production. The target is to achieve a sustainable economy and predictability for the producers, capability for delivery to the customers, and a balanced market (Gartnerhallen, 2021).

3 Literature review

As there is a limited amount of studies on the impact of soil compaction, we have focused our literature review on how weather effects potato yield and their response.

3.1 Simulating weather effects on potato yield

In our research we have found two previous conducted studies who have utilized simulation of weather effects in order to predict the impact on potato tuber yield. The first study, called "Simulating weather effects on potato yield, nitrate leaching, and profit margin in the US pacific northwest", was conducted using a systems analysis and modelling approach (Woli and Hoogenboom, 2018). Potato yield and the associated nitrate leaching were simulated for various irrigation, soil, and weather scenarios using a widely tested and used potato model called Simulation of Underground Bulking Organs (SUBSTOR). The model uses weather data, soil properties, genotype parameters, and crop management information as inputs in order simulate the daily dynamics of water, nitrogen, biomass, phenology, and tuber yield accumulation. The simulation of potato growth and development is based on the accumulation and partitioning of biomass in relation to intercepted radiation, photoperiodicity and temperature. The control factors for tuber growth are the potential tuber growth rate, and the balance of water and nitrogen in the soil. One of the basic objectives of the study was to compare different locations in the USA in terms of climate difference.

A potato plant has five different growth phases: sprout development (1-30 days after planting), plant establishment (31-50 days after planting), tuber initiation (51-70 days after planting), tuber bulking (71-120), and tuber maturation (121-150 days after planting). The simulation considered five types of weather: *severe cold*, *mild cold*, *average*, *mild hot* and *severe hot*.

Tuber yield improved with an increase in the amount of irrigation water until it peaked at 400mm and declined thereafter, implying that 400mm is the optimum amount of irrigation of potatoes in this specific area.

Among the five weather types, the only significantly influential on tuber yield, was *severe hot*. Its influence was greatest during tuber bulking, and least influential during sprout development and tuber initiation. Among the five growth phases, tuber bulking was associated with the largest yield reductions, while sprout development did not have any yield reduction. When severe hot weather was prolonged through several phases the reduction in tuber yield was significant, with the most vulnerable being severe hot weather from plant establishment throughout tuber maturation. The other weather conditions were not found to have any significant influence over tuber yield (Woli and Hoogenboom, 2018).

3.2 Assessment of potato response to climate change

"Assessment of potato response to climate change and adaption strategies" was a study conducted in the Isfahan province in Iran by using the Long Ashton Research Station-Weather Generator (LARS-WG) for generating daily climatic parameters. The SUBSTOR-potato model was used to simulate baseline and future potato growth and development (Adavi et al., 2018).

The study was conducted with the aims of quantifying the potential impacts of climate change on phenology, growth and tuber yield of potato. Further they seek to evaluate the effectiveness of planting date and variety management strategies for minimizing the impact climate change has on potato production in Iran. The potatoes studied were in the Fereydoon-Shahr region in the Isfahan province during the spring-summer season (May to October) under irrigated conditions with a fairly intensive use of chemical fertilizers. The recorded temperatures were in the interval of 3.6 degrees Celsius and 34.6 degrees Celsius, the cumulative annual solar radiation and annual precipitation during the growing season was 4076 MJ m-2 and 34.8mm, respectively.

LARS-WG, a stochastic weather generator based on the time series approach, was used to generate climatic parameters on a daily basis as one stochastic growing season for each projection period. This included solar radiation, maximum and minimum air temperature and precipitation for four different projection periods. 1982-2012 was used as the baseline for the generator, which then projected data for the periods 2015-2045, 2046-2075 and 2076-2105.

The SUBSTOR-Potato model simulates the growth and development of the potato crop on a daily basis by utilizing information on climate, soil, management and cultivar. First the model needed to be calibrated to accurately predict observed variations in historical yield, before it was modelled to predict climate impact on future potato crop yield. In this case an experiment was performed over three separate years (2011, 2012 and 2013), where the two first years were used to calibrate and the final year was used for validation of the model. Nine pairs of data were used to assess any differences between the simulated and observed data. The data were measured and simulated for three different potato species (Arinda, Sante and Agria) at three different planting dates (30. April, 15. May and 31. May). The different planting dates were used in order to determine the ideal planting date under the effects of future climate change. The specific dates in this study were chosen in order to measure the relationship between the maximum temperature in the area and the tuber initiation stage.

The three potato species were selected to test the adverse effects of climate change on potatoes. Agria is a long season variety while Sante is a medium season variety, and finally Arinda is a short season variety. The study finds two main adaptation techniques in regards to counteract the effects of climate change. The first is to change the planting date. The authors refer to other studies who also have concluded that altering the planting date is one of the simplest and most low cost adaptation strategies. The simulations conducted in this study indicated that delaying the planting until 31. May will ease the harmful effects of climate change by improving tuber yield.

The other approach to challenge the negative effects of climate change, is to apply various varieties of potatoes. As they will show different reactions to the new conditions, due to different growth properties. A comparison between early, medium and late maturing varieties in different studies will ensure that choosing the varieties with higher adaptability is a viable adaptation strategy (Adavi et al., 2018).

3.3 European potato production

The subject of how climate change will affect agriculture has been studied to extent over the globe. From a Norwegian perspective, we have gained a lot of insight from our e-mail correspondence with Eldrid Lein Molteberg, a scientist at the Norwegian Institute of Bioeconomy Research (NIBIO). An unpublished fact sheet, which is being processed from a NIBIO environmental report, highlights many of the opportunities, as well as the needs for adaptation when it comes to growing vegetables and potatoes in an altered climate.

The coming years bring an expectation of an increased average temperature. This will lead to an expansion of the growth season, but it will also lead to more frequent droughts and a greater intensity in rainfalls. These changes have the possibility to provide new opportunities for the production of potatoes and other vegetables. Nonetheless, it could present new challenges and need for adaptation, requiring preventive measures associated with the soil's future production ability, plant material and cultivation technique (Molteberg and Vågen, 2021). An increase in temperature with an implied longer growth season would be beneficial to several species of vegetables and potatoes, while for species better suited to moderate temperatures an increase would be detrimental. However, an expansion of the number of days where the average temperature is high enough for growth would be of limited use if the temperature is unstable and the probability of frost increases.

Norwegian agricultural production could potentially reap positive effects from the climate changes, and would be one of few areas in Europe who could benefit from warmer temperatures and more rainfall. If the soil dries up at an earlier stage, the farmers would subsequently be able to start the sowing process before the current schedule. In general, a longer growth season would lead to increased opportunities for production. These opportunities can, with a certain degree of predictability, give possibility for an expansion of the areas used for growing existing species and new species which require a longer growth period. The expansion could also include higher yielding species, or better quality of existing species as they are reaped under better conditions. An increase in the general quality of the products as they experience a longer production and sales season for fresh vegetables, would result in a decreased need for storage (Molteberg and Vågen, 2021).

Haverkort and Verhagen (2008) also emphasize the repercussions greenhouse gas induced climate change will have on the potato supply chain. Since the start of weather recording thirteen of the warmest years have occurred in the previous fourteen years. In the southern parts of Europe, the major effects of climate change will be reduced water availability and a shorter suitable time slot in the winter months for potato production. For northern Europe, the climate change will decrease the number of days with frost and lengthen the growing season. It will also bring more rain during winter, and a decrease of precipitation during summer, with more erratic but heavier rain storms. Potato yields in temperate climates might increase, provided that water for irrigation remains available, due to a longer growing season and more carbon dioxide in the air (Haverkort and Verhagen, 2008).

In their sixth assessment report, the Intergovernmental Panel on Climate Change have provided an updated evaluation of the scientific basis of climate change. In the section for Northern Europe they ascertain that observations of pluvial flooding, i.e. flooding caused by torrential rain, have intensified. This increase is attributed to human influence on the climate. The Panel finds that these types of floods are projected to increase if the temperature continues to rise. A temperature increase of 1,5 degrees Celsius will with medium certainty result in more pluvial flooding, while a 2 degrees increase will do the same with a high degree of certainty. Interestingly, they find with medium confidence that a global warming of 2 degrees or more will decrease river floods. However, a similar increase will with the same amount of certainty result in severe wind storms in Northern Europe (Intergovernmental Panel on Climate Change, 2021).

It could however be challenging to utilize the possibilities brought by a warmer climate, as it brings an expectation of more drought, more extreme rainfall and/or floods, and coherent periods of high moisture both during spring and autumn. An increased amount and intensity of rainfall would generally have several negative implications. There would be a shorter period of time where the soil is in a sufficiently dry state for sowing, battling weeds and illness, as well as reaping the yield at the right time and during good conditions. For potatoes and other row cultures with a high amount of bare soil, surface runoff and erosion would increase. It could further lead to an increased washing down of nutrients, with an associated environmental risk and loss of nutrition for the crops (Molteberg and Vågen, 2021). Increased precipitation would also shorten the time window in which the reaping conditions are good. This raises the risk of postponing the harvest and/or that the harvest is conducted in wet conditions. Such conditions could make the usage of harvesting machines problematic, as operating heavy machinery on wet ground inflict damage to the structure of the soil. Difficulties with weeds and plant pathogens would also increase in strength with more rainfall. Simultaneously the wet conditions would make it more difficult to counteract such problems (Molteberg and Vågen, 2021).

A consequence of a higher amount of rain would be that the humidity in the air increases. Humidity can affect crop growth in two different ways. In a direct manner by altering the water content of the plant, and indirectly by influencing leaf growth, photosynthesis, pollination, and the likelihood of diseases, see Zhang et al (2017). The article also points to possible joint effects between humidity and high temperature, as humidity could aid crops in retaining water content through decelerating transpiration during warm days. This process might however not sustain if there is a large increase in the number of hot days. In their fact sheet, Molteberg and Vågen points out that a lower degree of transpiration would result in inferior transport of nutrients internally in the plant (Molteberg and Vågen, 2021).

Other effects that could be induced by climate change is droughts and extended periods with warm weather. Potatoes and other vegetables who are best suited for moderate temperature can experience stagnation in the growth process. 16 to 20 degrees Celsius is the optimal interval for photosynthesis. If the temperature exceeds 30 degrees Celsius the biomass production can be hampered. A change in the growth rhythm and altered duration of different stages of the plants development could occur (Molteberg and Vågen, 2021).

This is also underlined by Haverkort & Verhagen (2008), who state that the potato crop grows best in cool, but frost-free seasons and does not perform well in heat. In their article they also refer to the first simulation model-based global study of the effect of climate change on potato production, a study conducted by Hijmans et al in 2003. Under the assumptions of a current global climate (1960-1990), and a future climate (2040-2069) with an increase in average temperature of 2.1 and 3.2 degrees Celsius depending on the climate scenario. With unaltered planting time and varieties, the total global yield in areas currently cropped with potato were calculated to decline by respectively 18% and 32%. When adapting planting time and varieties to the new situation, the decrease in yield was between 9% and 18%. The simulation did however show strong yield increases in higher latitudes (50 degrees to 60 degrees north and south) where potatoes might be grown where it hitherto was too cold.

On a general basis, there is uncertainty regarding which amount the temperature will increase in this century, but it can be stated with high amount of certainty that both the amount and intensity of precipitation will increase. It is also assumed that the increase in temperature will be larger in the northern parts of Norway than in the southern parts. The growth season, which is defined as the number of days with an average temperature over 5 degrees Celsius, is expected to increase with between one and two months in most parts of Norway, and up to three months in northern Norway (Molteberg and Vågen, 2021).

3.3.1 Heavy machinery and soil compaction

Heavy machinery is utilized in agriculture both to prepare soil for cultivation, and during the growth and harvesting processes. Use of such machines apply high pressure to the soil, which ultimately can lead to compaction. When the density of the soil is high, it will become more difficult for the roots to develop, and it will prevent the roots from growing beneath the plough pan. As a consequence, the root system can be reduced which also limit the area the plant can obtain nutrients and water from, leading to reduced growth and stressed plants. The potato crop's ideal soil condition for production is well-drained, deep, and loose. Sandy soils are often used for potato production, but this type of soil seems to be particularly susceptible to subsoil compaction. This has a negative effect on potato roots as they are unable to penetrate dense soil. Tubers might also be affected, as the soil compaction can physically restrain developing tubers, leading to reduced yield and quality (Holmkvist, 2008).

A way to counteract this problem is sub-soiling. This method loosens up the plough pan by deeper tillage. It is possible to break the soil compaction by using vertically fixed blades to cut the soil. This decreases soil strength and bulk density, which makes it possible for the roots to burrow further down in the soil. Ultimately, this can reduce stress caused by insufficient supply of water and nutrients (Holmkvist, 2008).

3.3.2 The Hydrologic Cycle

Percolation and infiltration rate

As precipitation falls on to the ground, most of it sinks into shallow layers of soil near the surface, where it is utilized by plants, animals and people. Water infiltrates the soil by moving through the surface. If the rainfalls are too heavy for the water to easily infiltrate the soil, some of it will "run off". Occasionally the runoff will drastically exceed infiltration, culminating in floods ((National Weather Service, 2021).

The infiltration rate is the velocity at which water enters the soil, and it is dependent on the type of soil. The rate is usually measured by how fast water can progress through the different soil levels. The measurement is millimeter per hour. When the soil is dry, water will infiltrate at a swift rate. This is known as the initial infiltration rate (Brouwer et al., 1990). When water replaces air in the pores, the water from the soil surface will infiltrate at a slower pace before it eventually reaches a steady rate. This is called the basic infiltration rate (Brouwer et al., 1990), and it is the rate we will use in our model. The soil type which is best suited for growing potatoes is sandy loam (Westerfield and Anderson, 2014), which has a basic infiltration rate of 20-30 mm/hour (Brouwer et al., 1990).

The movement of water through the soil itself is called percolation. The water percolates through the different levels of the soil until it reaches the ground water, which is water below the surface (National Weather Service, 2021). The speed of the percolation is greatly dependent on the soil type. Loamy soils have a moderate percolation speed, in the range of 2.54 mm to 25.4 mm per hour. This is an ideal situation as the soil holds water and nutrients for a sufficient time, in order for the plant roots to absorb them, but the soil does not easily become waterlogged (Kerby, 2021).

Evapotranspiration

Any typical plant absorbs water from the soil through its roots, utilizing it in physiologic and metabolic functions. Eventually the water is released back into the atmosphere through the plants leaves as vapor. The entire process from water uptake through the roots, the transport through plant tissue and finally release of vapor by the leaves, is known as transpiration. Water will also evaporate directly into the atmosphere from the soil in the surrounding area of the plant. This is also true for dew and droplets of water on stems and leaves of the plant. The combination of evaporation and transpiration is referred to as evapotranspiration (Water Science School, 2018).

The rate at which transpiration occurs is dependent on several weather conditions, such as temperature, humidity, precipitation, the availability and intensity of sunlight, soil type and saturation, wind, and land slope. Higher temperatures are associated with greater transpiration rates. When the relative humidity in the air around the plant rises, the evaporation rate slows down and it becomes harder for water to evaporate into saturated air. Wind moves the air around the plant, which replaces the more saturated air around the plant with drier air, thus increasing transpiration. If the soil is lacking moisture plants can begin to senesce, which may result in leaf loss and less transpiration of water. Also, different plants transpire water at various rates (Water Science School, 2018).

4 Scope of the thesis

A crucial impact of climate change, is that the frequency of extreme weather events may increase (Mirza, 2003). Extreme weather conditions will progressively disrupt agricultural productivity, and can create a larger source of insecurity for farmers all around the globe. Extreme weather, including high levels of precipitation, can flood fields and create problems for agricultural production.

As previously mentioned, the soil's moisture levels can have a severe impact on soil compaction rates and soil structure. If the frequency of extreme precipitation become more prevalent, it is likely that the insecurity in agricultural production will grow.

Gartnerhallen and NORCE has provided the basis of this thesis, where they question whether it is possible to apply the data from the weather forecasting engine in agricultural production planning.

Hence, our research question is: *How can climate forecasts help farmers reduce the impacts of soil compaction, and further create a larger sense of security in future production?*

In this thesis we simulate how precipitation impacts the soil moisture levels in the potato growth process. Because the moisture level impact how much soil compaction occurs when using heavy machinery in agricultural processes. Thus, we want to see whether possible future advancement of daily precipitation forecasts can be used to give potato farmers better predictability regarding damage is inflicted on the soil structure throughout the growing season. The model will establish a framework for when future climate prediction models become more accurate.

Hence, we have created a simulation model that begins with the planting process and ends at harvest. When conferring with Molteberg at NIBIO, she mentioned that the main issue regarding precipitation is that heavy rainfall makes the ground undrivable. This is due to faster compaction of the soil, which ruins the soil structure and can cause water logging. Heavy machinery is used in operations such as planting, weed control, sub soiling, dry rot control and harvesting. This increases the likelihood that the farmer either does not perform these tasks, causing damage to the tubers, or carry them out anyway, and impairing the soil structure of the potato beds. We therefore want to simulate the soil moisture levels throughout the production process, where we input historical data, and see if we can give the farmers a more secure foresight of the occurring soil structure damage caused by the potato production.

We use historical data, because climate prediction models are still unable to provide an accurate representation of daily precipitation for a longer time span than the foreseeable future.

As the variables and parameters of the simulation model are fitted to a smaller production scale than any farm, and the variables and parameters are quite generalized, it is likely that larger scale operations require adjusted parameters. However, we believe that the model give a general overview of what the soil moisture levels might look like throughout the potato production process, and thus provide valuable input for farmers planning their upcoming production season.

Because potato production go through multiple stages, where individual choices are made by each farmer, we have made some assumptions on what methods the farmers in the simulation will use. For example, some farmers use drip tape to water their crops, whilst others use tractors with sprinklers and large water reservoirs. The input data, assumptions and model are discussed in depth in the following sections.

5 Data

In this section, we present and describe our data sources and how we processed the data. The main data being used in the simulation is historical precipitation data provided by NORCE. The data set contains historical data from 1993 to 2020.

5.1 Data selection

5.1.1 Climate futures data

The historical precipitation data from NORCE, give us an overview of aggregated daily precipitation since 1993. We use this data as variable inputs in our simulation to represent how the weather have behaved previously, in a dry and wet year. Because the data set contains input from multiple locations, we choose weather data from the location of one of the largest potato production farms in Norway.

Precipitation

Water supply is an essential ingredient when it comes to growing any type of crop. While potatoes require less water in the growing process than rice, wheat, and maize, the amount of precipitation will still have an effect on potato production. A simple laboratory experiment indicates that potatoes are able to survive for up to two days under water, before there is a risk of developing soft rot. If the harvest is subject to heavy rainfall it could result in damage to the tubers (Glorvigen, 2021).

The variation in the Norwegian potato harvest volumes will likely be affected by the amount of precipitation shown during the setting and growth period of the potato production process. More importantly in the soil moisture simulation, the precipitation is the only source of water other than the irrigation system. The precipitation might increase the soil moisture level above a critical level, and it is therefore important to look at the precipitation as an input.

With future advancements of the NORCE climate futures model, farmers might be able to obtain climate forecasts that can be used in the model. The data from the climate futures model is specific to different areas. From the data, based on postal codes, the farmers can use their postal address to extract the climate data for their area. After extracting the data, they can apply the precipitation data to the model.

The model investigates how the precipitation impacts the moisture level of the soil, which again impacts soil compaction. The climate predictions are able to give the farmers more predictability in their upcoming production, and how soil compaction impacts the soil structure.

5.1.2 Pre-processing data

The code used in processing the data can be viewed in the appendix section A1, we have used R as it is efficient when managing large amounts of data, which is preferable as the historical precipitation data has over 300 million observations.

The precipitation data from NORCE show the longitude, latitude, date and the amount of precipitation in meters. The columns are called *long*, *lat*, *date* and *prec* respectively.

In order to process the data to make it available as input data in our model, we load the data in R Studio. The data set is very large, and we have to subset the data set into multiple data frames.

With climate change, the occurrences of extreme weather conditions become more prevalent. Hence, we want to look at the two most extreme scenarios available. 2018 has been recorded as the driest summer in Norwegian history since the beginning of the data set (Manglerød, 2021), and one of the wettest was in the year 2005 (Schage, 2006). We first format the date column to a workable date format, then we create a column called year, where we extract the years from the dates and finally subset the years we want to use in the simulation.

One of the largest potato production farms in Norway is Silkebækken Gård in Heradsbygd. We find the longitude and latitude for the area in question, and subset the precipitation data based on the specific position.

The typical growing season for the potato starts in the spring. Thus, we subset 120 days from the first of March. In order to subset the correct data, we create a day of year column. Thereafter, we subset the days we want based on the day of year column. The first of March is the 60th day of the year, 120 days later we find the 28th of June at day 179.

The precipitation of the periods in question can be found in figure 5.1, and figure 5.2. It can be noted that the precipitation in 2018 is far less than in 2005, which coincides with the fact that 2005 was considerably wetter than in 2018.

Finally, we export the data frames as excel sheets to easily use them in the simulation.

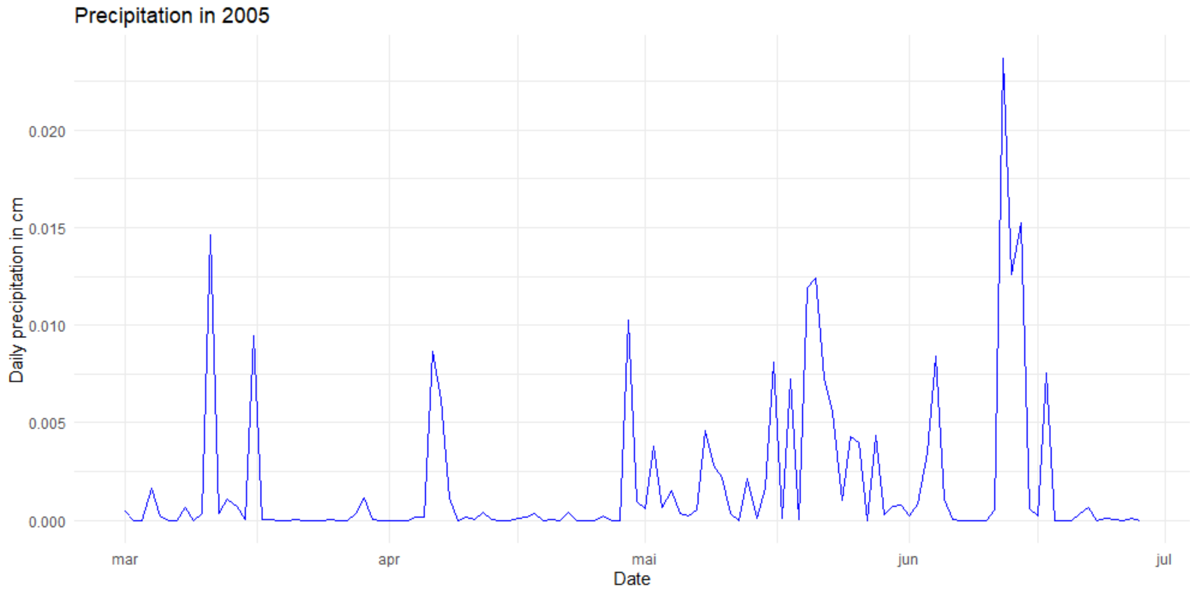

Figure 5.1: Historic precipitation in 2005

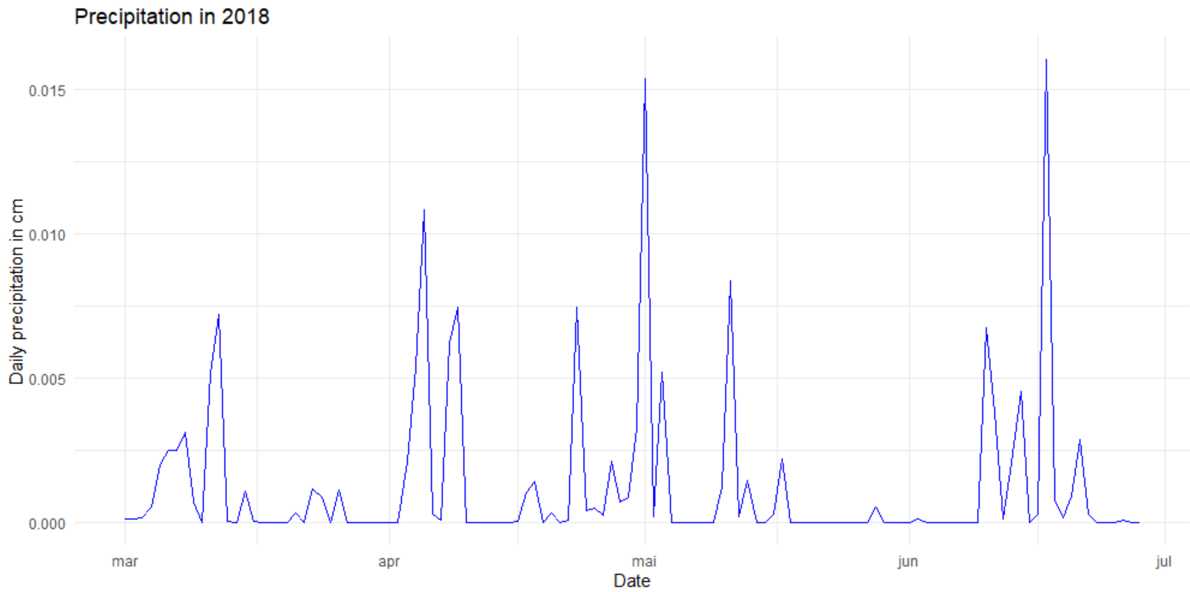

Figure 5.2: Historic precipitation in 2018

6 Methodology

In the following section, we first present the potato production processes. Thereafter, we explain the assumptions we have made in the variables of the model. Finally, the simulation set up and the model is presented and explained.

6.1 Process overview

The potato production process might be more complex than it seems. This section will give an in-depth description of the processes that will further be implemented in the simulation model. Figure 6.1 show a simplified flowchart overview of the process, which show the stages of the production that will be used in the methodology section of this paper. We start the process with planting and conclude when the harvest enters storage, as our focus is on the growth production and not the storage of the potatoes.

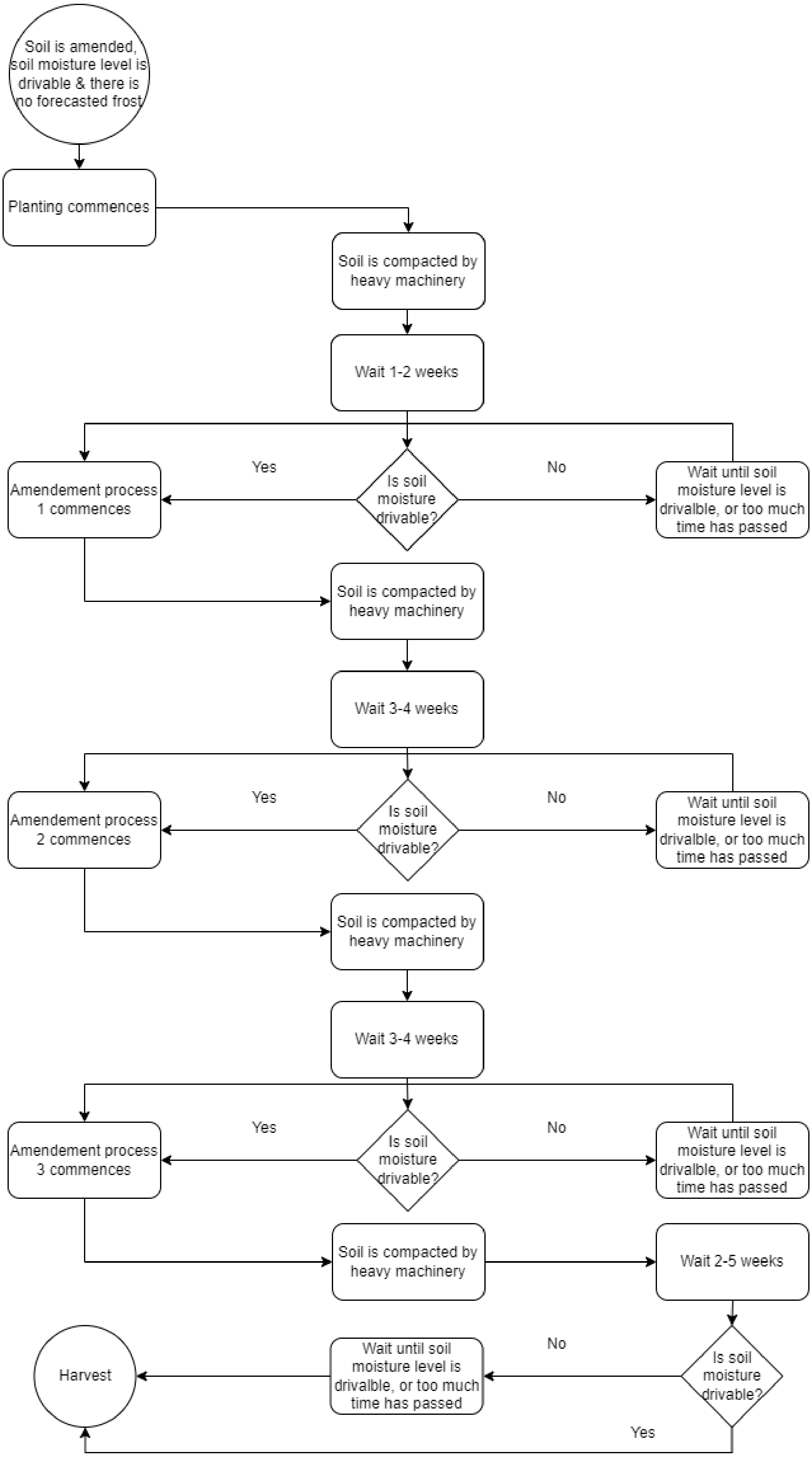

Figure 6.1: Simplified flowchart of potato production process

6.1.1 Potato planting

When planting potatoes, the weather has an impact on when it is preferable to plant. Firstly, when planting potatoes early in the year the temperature of the soil is essential to whether the farmer is able to plant or not. If the soil is frozen and has not been able to thaw, it is not possible to plant. If planting prior to an upcoming frost, the seed potatoes may get damaged, and they might not be viable for crop production (Pavlista, 1995). In the simulation, we will begin planting after the first of March. This ensures that there are no temperature levels below freezing in the simulation.

After the soil is sufficiently thawed, the farmers will mound the soil up into ridges, this is usually done by heavy machinery like a tractor with the correct aggregate. Thereafter, the seed potatoes are taken from storage and cut into pieces according to where the potatoes' eyes are located. The eyes of the potato is the growing point of the potato tuber. The cut seed potatoes are then loaded into the planting machine. The planting aggregate then places the tubers in the ridges and cover them with soil. In the time periods when the potato beds receive heavy rainfall, the precipitation could be detrimental to the process. This is because heavy machinery running on wet soil cause damage to the soil structure and compact the soil, which then could hamper the growing process of the potato, as well as the soil's suitability for future crop production. In the simulation, the soil moisture level at the time of planting will be essential to predict how the soil structure is impacted by heavy machinery.

6.1.2 Amending

The potato seedlings begin to grow roots, and the new shoots emerge from the soil. The potatoes grow on the roots of the plant, and it is important that the soil once again is mounded up on the stem of the plant, as direct sunlight can cause damage to the potatoes (Pavlista, 1995).

For the production to yield good quality potatoes, access to water, sunlight and nutrients need to be consistent. This means that the farmers need to water their potato crops and add nutrients to the soil in order to prevent nutrient leeching. The irrigation system for potato crops could be set up using drip tape next to the trenches, or by farming equipment and heavy machinery. If potatoes sit in pools of water for an elongated period, it could cause rot or disease. However, as potatoes need water, it is important that the soil has proper drainage which can be provided by pulling up soil around the growing stems, a process called subsoiling (Pavlista, 1995).

During the growth process of the potato, the plants need leaf fertilizer to add sufficient amounts of nutrients to the growing plant. There is a special focus on the addition of phosphorus, nitrogen, and potassium. This can be sprayed with other additives to the soil, again by using heavy machinery such as tractors (Pavlista, 1995).

As well as relying on the addition of nutrients, the potato beds need to be amended to have proficient weed control. There are different methods of weed control, where some spray with chemicals that do not affect the plant, whilst others till the soil more often to pull out weeds and their roots (Pavlista, 1995).

The amendment process require multiple runs of heavy machinery. Similarly to the planting process, the impact of the amendment period on the soil structure depends on the moisture content of the soil. The negative impact from the amendment period therefore depends on the precipitation in the area before, and at the time of amending. In the simulation, the moisture levels at the day of the amendment processes is vital to create an image of how the soil structure is affected by the heavy machinery used in these processes.

6.1.3 Harvesting

When harvesting the potatoes, the farmers usually wait until the vines wither back. This indicates that the tubers have reached maturity. Whilst some farmers choose to burn back their vines to prevent disease, others do not (Pavlista, 1995).

Harvesting is accomplished by use of specialised heavy machinery, that again tills up the soil and pulls the potatoes out of the ground. The machine sorts the potatoes from the soil and place the harvest into containers that are driven to storage.

As the harvesting process is dependant on heavy machinery yet again, the precipitation play a role in how the process impacts the soil structure. The moisture level simulated in our model will again be pertinent to fathom how the soil structure is impacted by the heavy machinery used in the harvesting process.

6.2 Assumptions and constraints

Temperature and Frost

Temperature is an important part of the potato growth process. Yara writes that root growth is optimal with soil temperatures between 10 and 35 degrees Celsius, root development is best between 15 and 20 degrees Celsius and leaf growth best occurs between 20 to 25 degrees Celsius (Yara, 2021).

While the growth process of the potato plant is optimal in these temperature ranges, they are nonetheless able to be grown outside of these temperatures. However, as frost is harmful to the potato tubers, there should not occur any days with forecasted temperatures below 0 degrees Celsius during the growth period. Because temperature is not used as an input in our model, we assume that the simulation does not have any occurrences of temperatures below freezing. We also assume that the soil temperature remain within the optimal temperature ranges throughout the process.

Irrigation and moisture

When growing potatoes, it is important not to water too often in the first fortnight. After this period, the potatoes should receive 5 to 7,5 cm of water on average per week (Pavlista, 1995). It is important that the potatoes do not dry out, and the simulation will apply irrigation to the soil every day to keep it moist. Progressing past the ten week mark, the potato plants will senesce. When the crops turn yellow during the senescence stage, it is important to stop the watering to ensure that the potatoes do not rot. At this stage in the model, the irrigation will subside.

In order to simplify the simulation, we will assume that the farmer use drip tape or some other in stationary irrigation system to water the potato crops. The irrigation from the stationary watering system will be changed to keep the moisture content within the optimal moisture levels during each stage of the simulation. It will adapt itself to the current stage in the growth process.

Checkup amending processes

Two weeks after setting the potatoes, the farmer should mound the soil around the potatoes in order for the new tubers to avoid sunlight exposure. This process will be executed simultaneous with the other amendment processes, such as fertilization and weed control. The potato plants will be mounded at each checkup amending stage.

During the first fortnight after setting the tubers, the potatoes should not receive any fertilizer. After passing two week mark, the simulation will fertilize every fourth week, unless the moisture level is not within the optimal range. As a result of heavy rainfall there could be nutrient leeching, and the fertilization routine should be sped up to counteract the effects. After plant senescence, the application of fertilizer should cease, as it needs water in order to reach the tubers. As the simulation has stopped watering at this point, there would be no point in further fertilizing.

As weeds grow at a different rate in various climates, the simulation will apply weed control substances at the same time as fertilization. Thus, the damage to the soil structure is minimized because the use of heavy machinery is limited to a bare minimum.

The checkup amendment process completes the above tasks, and takes one day.

Potato type

Because different types of potato grow at individual rates, we will simulate based on the Yukon Gold that reach maturity approximately 14 weeks after setting (Cropwatch, 2021).

Precipitation

The accuracy of forecasted daily meteorological data depends on how far in the future the forecasts are. At this stage, we do not have very accurate daily forecasts for more than approximately two weeks into the future. Forecast engines can only predict whether a period will be generally warm or cold and whether there will be drought or wet. However, research and progress is being made in order to expand the horizon of accurate meteorological data. In order for the simulation to produce the desired results, we assume that the model has a futuristic approach, where when daily meteorological data is accurate enough to be utilized.

Percolation, runoff and evapotranspiration

Because there are immensely many factors that effect the percolation rate of soil, water runoff rate and evapotranspiration rate, we assume that the farmer adds water retention amendments to the soil at the first and last stage of the simulation which give a daily percolation and runoff rate at 2% and 3% respectively. The remaining stages have no water retention amendments added, and the percolation and runoff will be considerably larger at 30%. The evapotranspiration rates are estimated from the 2010 study on the study named "The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems" (Lin, 2010).

General assumptions

Because the growth process of the potato crop contain so many factors, we rely heavily on assumptions and general inputs that can be viewed as inaccurate.

6.3 Simulation Model

In this section, we explain how the simulation is built in order to provide output that could help farmers' predictability in the potato production process. The first section explains the simulation environment SimPy, and how it works. The following sections are more specific to the python programming language used in the model, thus explaining how the simulation is built, what variables are used and how the model allows for user input.

6.3.1 SimPy

"SimPy is a process-based discrete-event simulation framework based on standard Python" (Team SimPy, 2020a). The framework is efficient at simulating and visualizing real-life events and provide a good structure for the simulation process we are undertaking. The processes in the simulation are defined with generator functions, where in this instance vehicles, farmers and potato plants are perceived as the active components of the simulation. SimPy also provides types of shared resources, in order to model points in the simulation that are viewed as model limited capacity congestion points (Team SimPy, 2020a). We will use these resources to model weather constraints that congest the growing process of the potato plants.

Further, SimPy provides possibilities to perform the simulation in real time, as fast as possible or by manually preceding through the different events of the simulation. In our simulation, we will be using the manual progression of events with different time allotments for each point of the process.

We have chosen to use SimPy for our simulation, as the different processes interact with each other and also depend on the completion of previous processes. The Discrete Event Simulation is based on using statistical functions, where queuing and resource usage within logistics can be used with ease. Because SimPy is released under the MIT licence, and model developers are encouraged to share their techniques with each other, there are multiple resources available for free online. It is a free tool published by the Massachusetts Institute of Technology, that can be used by everyone and has an ease of access for anyone who wants to use it.

6.4 Simulation Set Up

The whole simulation is performed in SimPy. The following sections decompose all the steps of the model, and explain the simulation set up. The code for the simulation model can be found in appendix A2.

6.4.1 Libraries

A physical library is normally a space where books are collected and held. The libraries in python are very similar; they are a collection of precompiled code that can be accessed and used after the library has been called, and compiled in the program for some specific well-defined operations (Chanda, 2021). As well as precompiled code, the library can contain e.g. documentation, configuration, message templates, classes and values. A library is in other words a collection of related modules. Libraries contain bundles of code that can be used repeatedly in different processes in the python program. The perk of libraries is that they make it easier and more convenient for programmers, as it is not necessary to write the same bundle of code multiple times for similar programs (Chanda, 2021).

The libraries imported in our simulation are seen in table 6.1, where the name of the library, its prefix in the program and it's intended use, is presented.

Library name	Name in program	Used for
simpy	simpy	Used to generate the simulation environment
matplotlib.pyplot	plt	Used for graph visualization
pandas	pd	Used for importing the historical precipitation data

Table 6.1

6.4.2 Variables

In python, a variable is a reserved memory location to store values where it further in the program gives the value data to the computer for processing when the variable is called (Sturtz, 2021). All the variables in python have a datatype, in subsection 6.4.3 we describe our list variables, those being described in this subsection are all numerical. The numerical input variables can be found in table 6.2, and the equation based can be found in 6.3.

Numeric variables

Variable	**Value**	**Explanation**
soil_potato_capacity	4	Soil potato capacity
transiratopn_h	0.000467	Water lost by transpiration daily with high shade
transpiration_m	0.0005	Water lost by transpiration daily with medium shade
transpiration_l	0.00093	Water lost by transpiration daily with low shade
evaporation	1	Daily evaporation of water
absorption_rate1	0.00033	Water absorbed by potato tuber at pre emergence and senecsence
absorption_rate2	0.0041	Water absorbed by potato tuber at initiation and full bloom
tubers	7	Amount of tubers that grow from one potato crop
pre_min	65	Minimum optimal moisture level at pre emergence
pre_max	80	Maximum optimal moisture level at pre emergence
pre_mid	72	Middle of the optimal moisture level range at pre emergence
initiation_min	70	Minimum optimal moisture level at initiation
initiation_max	80	Maximum optimal moisture level at inititation
initiation_mid	75	Middle of the optimal moisture level range at initiation
bloom_min	80	Minimum optimal moisture level at full bloom
bloom_max	90	Maximum optimal moisture level at full blom
bloom_mid	85	Middle of the optimal moisture level range at full bloom
senescence_min	80	Minimum optimal moisture level at plant senescence
senescence_max	90	Maximum optimal moisture level at plant senescence
senescence_mid	85	Middle og the optimal moisture level range at plant senescence
harvest_min	60	Minimum optimal moisture level at harvest
harvest_max	65	Maximum optimal moisture level at harvest
harvest_mid	62	Middle of the optimal moisture level range at harvest
dry_soil_weight	1450	Weight of dry soil kg/ m^3
initial_moisture_level	75	Initial moisture level of the soil
max_moisture_level	90	Critical moisture level for using heavy machinery

Table 6.2: Numeric variables in the simulation

In order to simulate in a smaller environment, we limit the size of the patch and look at a square meter of land. The amount of potato seedlings in a square meter, where the potatoes are spaced 38 cm apart and the mounds are spaced 98 cm apart, is 4.

In a study published in the Agricultural and forest meteorology (Lin, 2010), a layout of transpiration rate of water for high shade, medium shade and low shade were presented. In the beginning the shade level will be low, as the plants are small and do not throw a very large shadow, after the plants have grown larger, the medium transpiration rate will be applied. Further, when the plants have grown larger, they will cast more shade and therefore, towards the end of the simulation, the high shade transpiration rate will be used. We use the figures closest to the precipitation and temperature profile in Norway, which give us the transpiration rates as seen in the numeric variable table.

During the different stages of the growth process, tubers absorb a certain amount of moisture. Converting the numbers to kg, it gives us the absorption rates as seen in table 6.2. The first absorption rate will be used in the beginning of the process, where the plants are in a pre emergence stage. Further on, after the tubers have sprouted, the second absorption rate will be used.

Research show that daily water evaporation from soil rarely exceed 0.01 mm (Shellito et al., 2018). We convert it to the area used in the model. The evaporation rate of water will therefore be set to a constant 1kg pr day.

One potato plant usually give between 5 and 10 tubers, the mean is 7,5 and we round down to 7. The amount of tubers in the ground will therefore be set to 7 tubers per potato plant.

In order to look at how the moisture levels change throughout the growth process, the potato producer will try to keep the soil moisture levels within an optimal range throughout the process. The optimal soil moisture levels for each process are seen in the table 6.2, and were collected from the book "EC95-1249 Potato Production Stages: Scheduling Key Practices", written by Alexander Pavlista (1995). The moisture level will be added to the soil in to keep it in the middle of the optimal range. If, at some point throughout the process, the moisture levels are outside of the optimal range, the farmer will allow the crops more time in the ground so that they get at a certain amount of days within the optimal moisture limit. The variables, seen in table 6.2, are the minimum, middle and maximum moisture levels that are optimal in each stage of the process.

In order to keep track of the soil moisture levels, we calculate the soil moisture using the dry soil weight and the weight of water in the ground at each day. We assume that the dry soil weight in our simulation is equal to what could be considered the average. As dry soil usually weighs between 1200 and 1700kg, we assume the dry soil weighs 1450kg. We begin our simulation at a 75% moisture level, which is within the optimal range for the pre emergence stage.

With wet soil comes additional soil compaction and soil structure damage when performing tasks using heavy machinery. In order to prevent the potato farmer from creating excessive soil structure damage, we set a maximum moisture level where the farmer has to either wait until the soil is dry enough to use heavy machinery, or has to wait a maximum number of days until the process can not be put on hold any further. Because the maximum optimal moisture level for the soil is 90%, we state that the farmer has to put the process on hold if the soil moisture levels exceed 90%.

Variables based on equations

The variables based on equations are presented in table 6.3.

Variable	Equation	Explanation
loss1	(transpiration_l)+ soil_potato_capacity*(absorption_rate1*tubers)+ evaporation	Amount of water lost by transpiration, evaporation and absorption from the crop during pre emergence
loss2	(transpiration_m)+ soil_potato_capacity*(absorbation_rate2*tubers)+ evaporation	Amount of water lost by transpiration, evaporation and absorption from the crop during initation and full bloom
loss3	(transpiration_h)+ soil_potato_capacity*(absorbation_rate2*tubers)+ evaporation	Amount of water lost by transpiration, evaporation and absorption from the crop during pant senescence and harvest
initital_soil_weight	((initial_moisture_level*dry_soil_weight)/100)+dry_soil_weight	Calculation of initial soil moisture level

Table 6.3: Equation variables in the simulation

In order to calculate the amount of moisture loss from the soil at the different stages of the process, not including water percolation and runoff, the following variables give an estimate based on the transpiration rate, the amount of plants, the absorption rate, the amount of tubers in the ground and evaporation. The *loss1* variable will be applied in the pre emergence stage, the *loss2* will further be used until the plant senescence stage where the *loss3* variable will be applied.

Loss1 is based on the transpiration rate with low shade, where the crops are below ground at pre emergence. The absorption rate from the tubers is low, as the crop is small and absorb a limited amount of water. The evaporation rate is constant.

Loss2 is based on the transpiration rate with medium shade, where the crops have emerged and grow above ground at initiation and full bloom stage. The absorption rate from the tubers at these stages are larger, as the plant require more water to grow, and the potatoes to size up. The evaporation rate is constant.

Loss3 is based on the transpiration rate with high shade, where the crops are in the senescence stage. The crops die back, and the potatoes absorb a lot of water to further grow in size. The evaporation rate is constant.

The initial soil weight variable, calculate the soil weight at the planting stage where the moisture level of the soil is at 75%.

6.4.3 Lists

Lists in python are used to store multiple items in a single variable. As one of four built-in data types to store data collections, the items in the list are ordered, changeable and allow for duplicate values (Zakir et al., 2021). The items in the lists are indexed, where the index starts at [0] and ends with an index of [number of entries - 1].

Because of its properties, it is an ideal data collection storage when running through a simulation process. Each entry is stored at their respective time position. The potato production process contains multiple lists to store Container levels, and they can be found described in table 6.4.

In addition to the lists seen in the lists table, there is a *day_list*. The *day_list* give a frame of reference for the the simulations resulting graphs. The list is only used to create a time frame for the x axis of the graphs, and the day list have been generated with sequential numbers from 1 to 120.

The historical precipitation data is stored as two lists named *list_2005* and *list_2018*. We import the excel file to the python environment using the pandas library. First we import the precipitation excel files and make the precipitation column into a data frame.

Thereafter we convert the data frames into lists, and convert the precipitation from meter to the amount of water added to our simulated soil.

When running the simulation, the list being used containing historical precipitation will be called *precipitation*.

List name	Entries	Length	Description
time_list	Num	Days in simulation	Stores each day in the simulation
weight_list	Num	Days in simulation	Stores the soil's weight levels
moisture_list	Num	Days in simulation	Stores the soil's moisture levels

Table 6.4: Lists

6.4.4 Environment processes

A virtual environment in python is a tool for dependency management and project isolation. (Sarmiento, 2019) In SimPy, the environment manages the simulation time as well as the scheduling and processing of events. The environment also provide methods to step through or execute the simulation (Team SimPy, 2020a).

In the simulation we store the SimPy environment in a variable called "env". In order to specify which process should be simulated in the simpy environment, we include the potato production def in the environment process.

In the SimPy environment, the best method for simulation control is the time frame of the simulation. The most important method for time frame simulation control is "Environment.run()", which decide how long the simulation runs (Team SimPy, 2020a). In the Environment section of our code, we set a maximum limit of days starting at 0 and ending at 120.

6.4.5 Resources

In the SimPy environment, shared resources are one way of modeling process interaction. SimPy has three resource categories, which are described below.

"**Resources** -Resources that can be used by a limited number of processes at a time" (Team SimPy, 2020b).

"**Containers** -Resources that model the production and consumption of a homogeneous, undifferentiated bulk". It may either be continuous or discrete (Team SimPy, 2020b).

"**Stores** -Resources that allow the production and consumption of Python objects" (Team SimPy, 2020b).

The basic concept of the different resource types are the same. All the resources are some kind of container that has a limited capacity. The processes in the simulation can either try to put something into the resource, or try to get something out of the container. If, for some reason, the resource is full or empty, the process has to wait for it to be either emptied or filled (Team SimPy, 2020b).

In the potato production simulation process, our main type of resource is Container. The Container allows for the retrieval of their current level, which makes the storage of the resource level at each day of the process simple. The Container resource variable's capacity and initial level must be specified in the simulation.

In the potato production simulation there are three Container resources, the different containers can be found described in table 6.5. In order to use the container resources, the *yield* statement is used to call the Container and the container name in use is thereafter specified. In order to remove a unit from the Container, the *get* statement is used. If the process wants to add something to the Container resource, we use the *put* statement. After yielding the specific container, and stating whether to remove or add to the container, we specify the amount we want to remove or add.

Container name	Capacity	Initial value	Description
soil_moisture	100	75	The container for soil moisture level, in %
soil_weight	2900	1450	The container for soil weight, in kg
complete_cap	1	0	The container that allows the production process to only be completed once in the simulation

Table 6.5: The Container resources in the simulation

6.4.6 Model

Each stage of the model will be based on the hydrologic cycle seen in figure 6.2. Precipitation and irrigation will add moisture to the soil. There is water loss by percolation, evaporation, surface runoff, transpiration and the crop's water absorption.

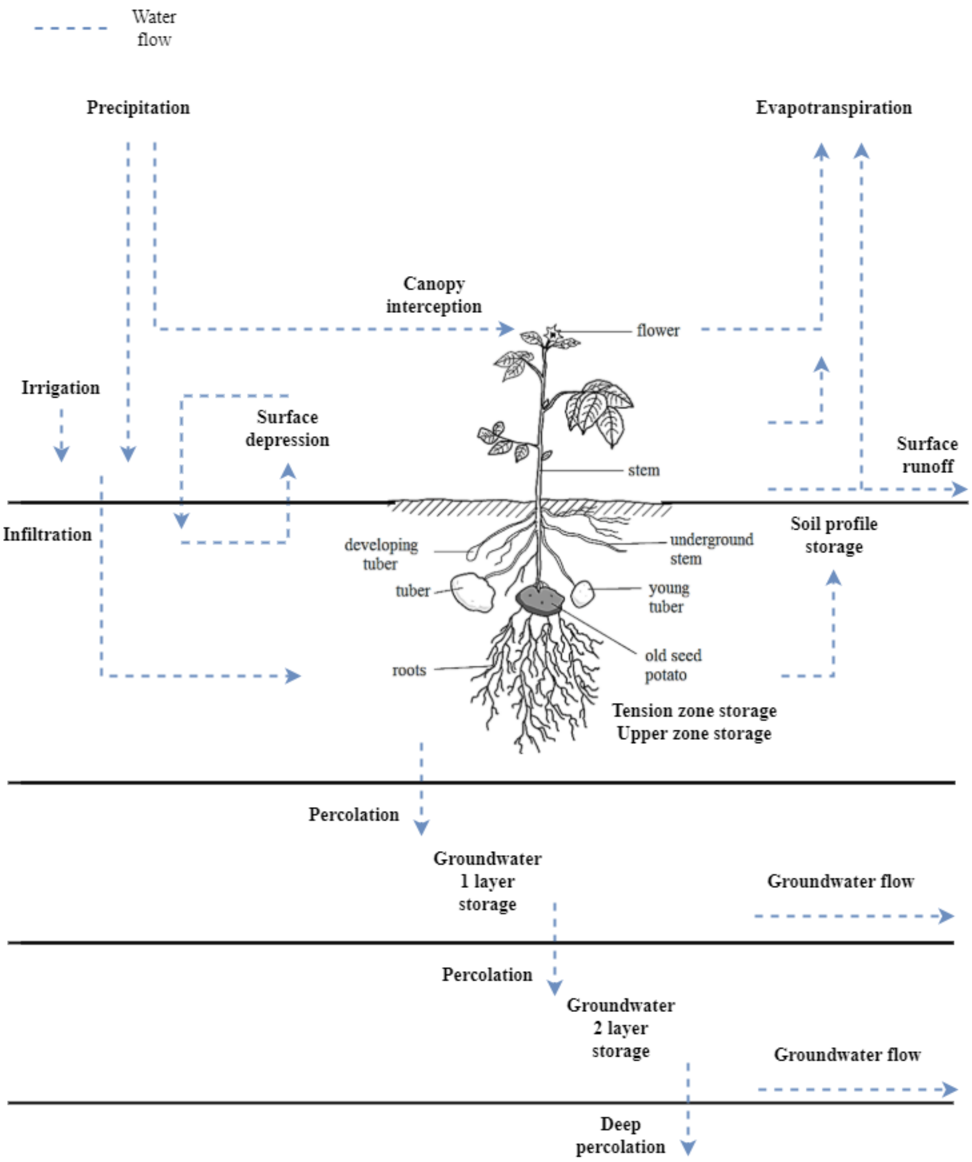

Figure 6.2: The hydrological cycle, adapted from (Gurram, 2013)

The stippled lines in figure 6.2 show the movement of water. Precipitation either infiltrate the soil directly, or after canopy interception. The irrigation infiltrate the surface level of the soil directly. The infiltration rate depends on the surface depression at the time of impact.

If there is more water than the soil moisture storage allows, there is moisture loss caused by surface runoff. There is also water loss caused by evaporation and plant transpiration, where moisture leaves the upper zone storage.

After the water infiltrate the soil, it enters the soil profile storage, tension zone storage and upper zone storage. By percolation, the water moves from the upper zone to the first groundwater layer storage.

From the first groundwater layer storage, some water move away with groundwater flow. Whilst some water proceed downwards toward the second groundwater layer storage by percolation. The water from the second groundwater layer storage also move along with groundwater flow, as well as downwards by deep percolation.

The rate at which the water moves depend on a multitude of factors, e.g. soil moisture level, surface depression, soil and air temperate, air moisture level and soil composition. These are factors we have simplified in the model, as we have had to make a number of assumptions due to limited previous research and time.

Main def

The main def runs all the processes in the simulation. The def is called *potato_production* and encapsulates the variables *env*, *soil_weight*, *soil_moisture* and the *complete_cap*.

The simulation runs for as long as the statements in the simulation are true, which is completed by using a *while True* loop. The simulation prints what day it is starting and the initial moisture level, using the *print*() function.

The first statement in the potato production simulation is *yield complete_cap.put*(1). This statement puts 1 completion into the *complete_cap* container, which stops the simulation from repeating the process multiple times.

Thereafter, the initial levels of all containers are appended into their respective lists. The day in the simulation is also appended into the *time_list*. Throughout the model, the container levels and simulation days will be appended, so that we can keep track of the soil moisture levels, the amount of precipitation and the time frame.

Planting process

Process flowchart

In order to begin the planting at day 1, we timeout the environment by 1. This process is completed by the *yield env.timeout* statement, which tells the environment to timeout for a certain amount of time.

A simplified version of the simulated planting process can be seen in the flowchart in figure 6.3. The day of the planting process begins with the precipitation segment. If there is precipitation, the precipitation and water evaporation from the soil adjust the soil moisture level. If there is no precipitation, only the evaporation adjust the moisture levels of the soil. Afterwards, the day of the simulation and the new Container levels are appended into their respective lists and the environment times out for one day, as the planting process only takes one day.

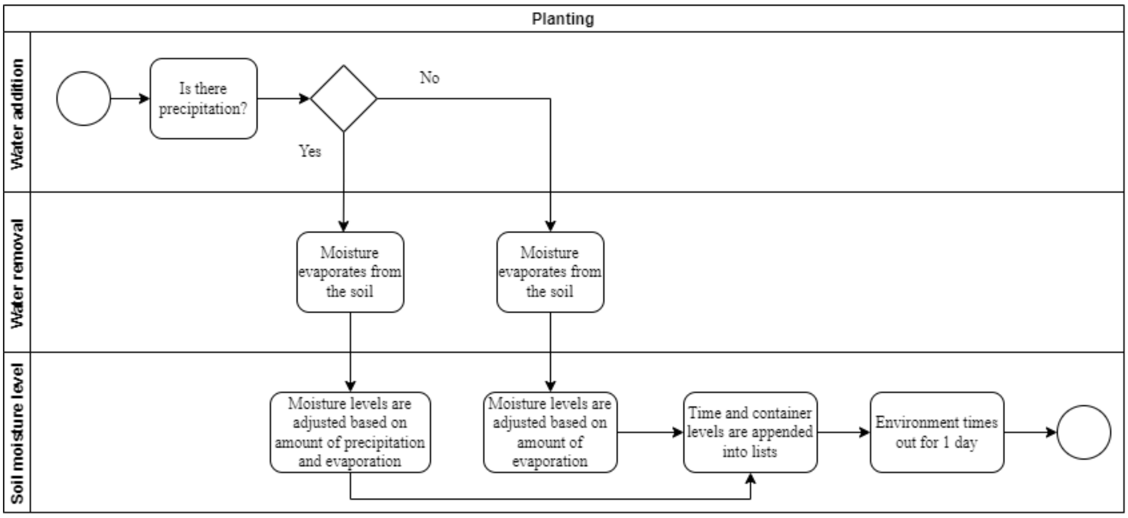

Figure 6.3: Flowchart of the simulated planting stage

Code and variables

In the planting process, we have not started irrigating the soil as this is not recommended straight after planting. The moisture level at the beginning of the simulation is 75%, which is in the optimal moisture level range for pre emergence.

We calculate the moisture level by using the weight of the soil. For the soil weight fluctuation of the planting process, we use an *if* statement. Hence, if the precipitation at the current day in the simulation is larger than 0, the precipitation weight gets added to the *soil_weight* Container. Whilst the rate at which the soil moisture evaporates from the soil, gets removed from the *soil_weight* container. The *else* statement ensures that if there is no precipitation on the current day, the evaporation amount is removed from the *soil_weight* Container.

Thereafter, the current *soil_moisture* level is removed from the soil moisture container, and replaced by the newly calculated soil moisture. The equation for the soil moisture level calculation is seen in equation 6.1, where the moisture level is calculated based on how much of the soil weight is water, as a percentage.

$$\frac{soil\_weight.level - dry\_soil\_weight}{dry\_soil\_weight} * 100 \tag{6.1}$$

The time of planting, as well as the resource Container levels are appended to their respective lists and the planting process ends with the printing of which day of completion.

First wait process

Process flowchart

The first wait process commences, and last between 7 to 14 days depending on the moisture levels of the soil. A simplified version of the simulated first wait process can be seen in figure 6.4. The first segment is seven days long, and second segment can be seven days long depending on the moisture level of the soil. The crops have been planted and are in the pre emerging stage.

Firstly, water percolation and surface runoff occur and remove moisture from the soil. Secondly, if there is precipitation, the precipitation amount, evaporation and absorption by the crop adjust the soil moisture level. If there is no precipitation, only the evaporation and the absorption by the crop adjust the moisture levels. Thereafter, the time and moisture level is appended into their respective lists and the environment times out for one day. If the simulation is in the first seven day segment, the process will be repeated seven times, one for each day.

When the simulation is in the second segment, the soil moisture level decides how many times the process will be repeated. Should the soil moisture level not be in the optimal range for pre emergence, the process will repeat until it has either reached optimal moisture level, or seven days pass. This gives the crop more time to develop and emerge, if the moisture level conditions are sub optimal.

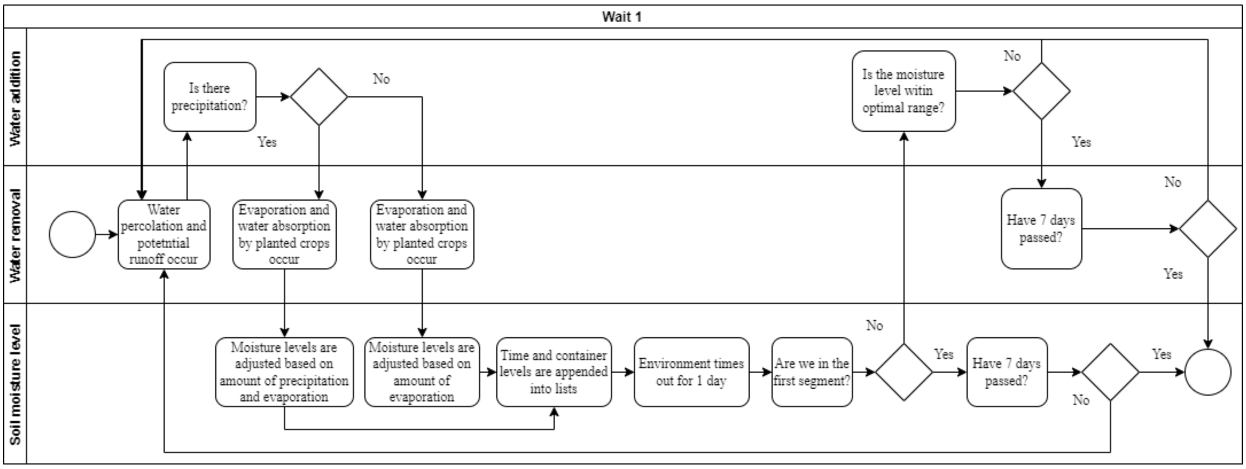

Figure 6.4: Flowchart of the simulated wait1 stage

Code and variables

The first seven days of the waiting process are looped in a for loop. Where after seven days, the first part of the process is completed.

Posterior to planting, the potatoes are not supposed to be watered for 7-14 days. This means that the soil dries out quickly. In order to not lose too much moisture at this stage, we assume that the farmer adds water retention amendments at planting so that the percolation rate for the next period subsides. Hence, at the wait 1 stage of the simulation, we assume that the percolation and surface run off rate is 2% on a daily basis.

The 2% percolation and surface runoff are removed from the weight of the soil. If there is precipitation, the precipitation, evaporation and crop absorption adjust the weight of the soil. Else, if there is no precipitation, only the evaporation and crop absorption adjust the soil weight. The amount of soil moisture lost by evaporation and crop's absorption is called $loss1$. This variable is calculated based on the rate absorbed and transpiration by the crops at the pre emergence stage.

Thereafter, the mew soil moisture is calculated using the equation 6.1, and becomes updated in the $soil\_moisture$ Container.

The time and Container levels are appended to their respective lists, and the environment times out for a day. This process is looped for seven days.

Further, if the soil moisture level is not in the preferred moisture range after the seven days, the process is looped until the moisture level is in range, or seven more days have passed.

The first checkup amending process

Process flowchart

The first check up amending process commences the day following the wait process. A simplified flowchart of the checkup amending process can be seen in figure 6.5.

The process starts as the previous wait 1, where percolation and surface runoff occur and remove moisture from the soil. Then, if there is rain, the precipitation, evaporation and water absorption adjust the soil moisture levels. With no precipitation, the water absorption by the crop and the water evaporation adjust the moisture level. Thereafter, the time and Container levels are appended to their respective lists and the environment times out one day.

The important moment in the checkup amendment process, is whether the soil moisture level is above the critical level for using heavy machinery. If the soil moisture is above the critical level, the process will loop through until it either has decreased below the critical level, or eight days have passed. The day at which the soil moisture level is below critical, the amendment process occurs. If the soil moisture level is above critical level for all eight days, the amendment process occurs at day eight.

The general framework of the checkup amendment processes and the harvest are the same, however the variables in the simulation change.

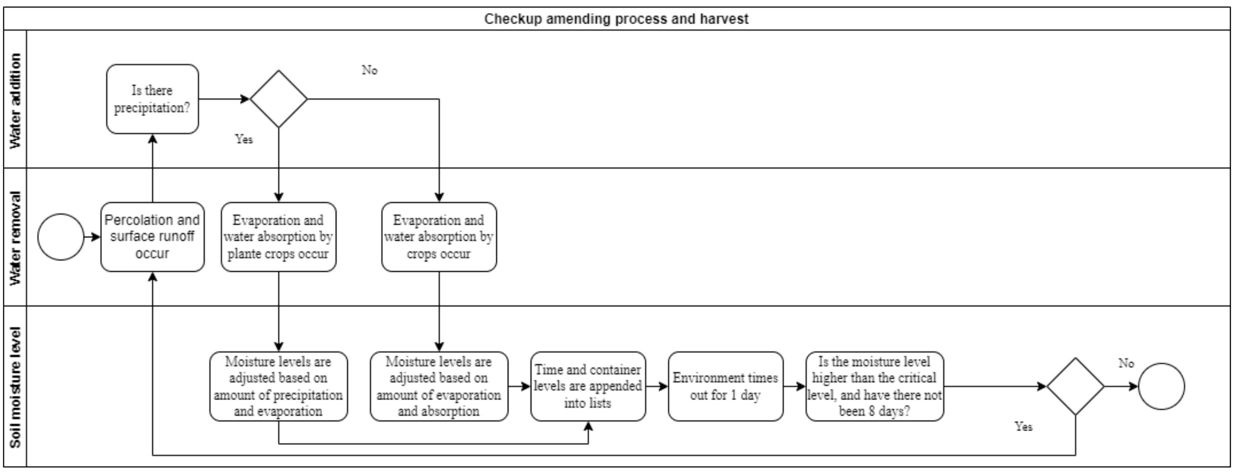

Figure 6.5: Flowchart of the simulated checkup and harvest stages

Code and variables

The checkup amendment process is divided into two segments. Where the first segment only runs if the soil moisture level is above critical, and the second segment is the amendment process.

The variables for the days in the first segment are similar to the first wait process. However, as the crops are now at a stage where they acquire more moisture, the irrigation system will add moisture to keep the water content of the soil within the optimal level at each day. The drainage at the stages after pre emergence is also critical, and there are no water retention amendments in the soil. Hence, the rate of water percolation and runoff will increase to 30%.

The new moisture content will thereafter replace the old, and the Container levels and time will be appended to their respective lists. The environment will time out for one day.

If the moisture level is not below the maximum soil moisture level until seven days have passed, the second segment will continue. The amendment process contain the same calculations as the above segment, where moisture depart the soil at the same rate and irrigation is added to the soil in order to keep the crops at the optimal moisture level for its part of the growth process.

The environment times out for one day, and the time and Container levels are appended to their lists. The segment concludes with printing out the day of the amendment process.

Second wait process

Process flowchart

The second wait process looks similar to the first wait process. The main difference is that the second wait is longer than the first, and that the irrigation has been switched on. The first part of the process lasts for 21 days, and the second is still seven days long. This is because the second wait process is between three and four weeks.

The flowchart for the second wait process can be seen in figure 6.6.

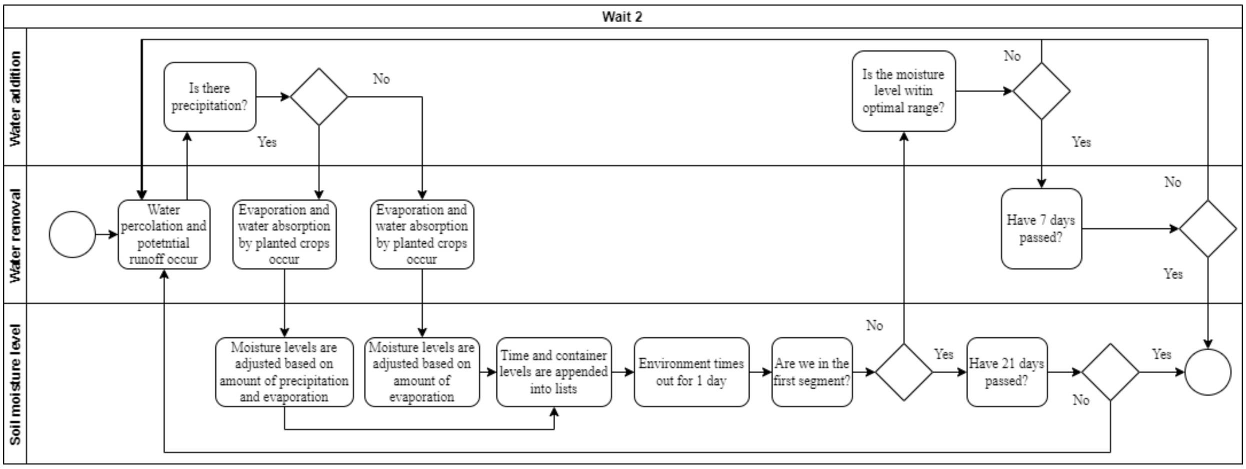

Figure 6.6: Flowchart of the simulated wait 2 stage

Code and variables

With the irrigation system now activated, the soil moisture calculations are based on both the absorption rate and the evaporation rate, as well as the water added by the irrigation system. The $loss1$ variable has been exchanged with $loss2$, and the pre emergence stage variables have been replaced with the initiation stage variables.

Other than this, the process of the second wait process is the same as the first wait process. Again the time and container levels are appended into their respective lists, and the simulation prints which day the wait process has ended.

Second checkup amending process

Code and variables

The second checkup amending process has the same structure as the first. The main difference is that the transpiration and absorption rate is different at this stage, and $loss1$ has been replaced with $loss2$. We are also at the initiation stage of the growth process, and the pre_mid variable has been replaced with $initiation\_mid$.

Because the optimal moisture levels are different at this stage in the growth process, the optimal range has also been changed to $initiation\_min$ and $initiation\_max$.

Again, the time and Container levels are appended into their respective lists, and the simulation prints what day the amendment process have ended on.

Third wait process

Code and variables

At the third wait process, the growth process has gone into the full bloom stage. This means that the optimal moisture levels are changed from *initiation_mid* to *bloom_mid*. The range has also been updated from *initiation_min* and *initiation_max*, to *bloom_min* and *bloom_max*.

Other than these minor changes, the third wait process stays the same as the second wait process.

Third checkup amending process

Code and variables

The third checkup amending process is the same as the second one, but the optimal moisture levels have changed as the plant is in full bloom. Therefore, the *pre_mid* has been replaced with *initiation_mid*.

Fourth wait process

Process flowchart

The fourth wait process is similar to the previous wait processes. However,the duration is only two weeks. The fourth wait process flowchart can be seen in figure 6.7.

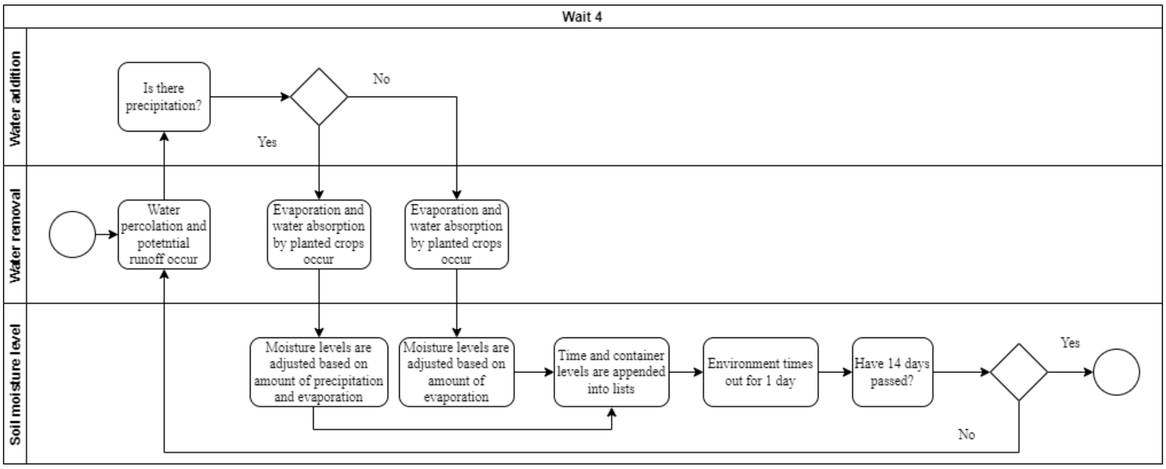

Figure 6.7: Flowchart of the simulated wait 4 stage

Code and variables

The *for i in range* is now fourteen days. Similarly to the first wait process, there is no irrigation, and there has been added water retention amendments to the soil. The moisture loss rate at this stage is set to 3%, and the irrigation system has been turned off. The only moisture being added to the soil at this stage, is precipitation.

The rate at which water is lost from the soil is also changed, and $loss2$ has been replaced with $loss3$.

Other than the change in the moisture variables and the time frame difference, the process is the same.

Harvesting

Code and variables

The harvesting process is similar to the amendment processes. If the soil moisture level is above the critical moisture level, the process is put on hold up to seven days, or until the moisture level once again below the critical value. The water percolation loss is now at 2% daily, and the other moisture loss is equivalent to $loss3$.

The harvesting process is the final one in the simulation, and it ends with a print out of the what day the simulation ends on, as well as graphs containing the container levels throughout the simulation.

7 Analysis

In this section we analyse the model output, and in which manner the model show how the precipitation impacts the soil moisture levels. The analysis will consist of two parts. We will first simulate using the historical data from 2005, in order to see how the model is impacted by a high level of precipitation. Secondly, we simulate using the historical data from 2018, in order to show how a dry year impacts soil moisture levels. Further, in the next section we will discuss the moisture levels' impact on soil compaction, and its effects toward agricultural practices.

7.1 Simulating with 2005 precipitation

The following subsection give an analysis of the results from our simulation using the historical precipitation from 2005.

When looking at the amount of precipitation throughout the simulation period, we find that most days receive very little precipitation. The precipitation levels are presented in figure 7.1. Almost 100 days are recorded with precipitation between 0 and 2,5mm, whilst only one day is recorded with precipitation above 20mm. However, there is a large number of days with more than over 10mm precipitation. For the purpose of our simulation, our main concern is when the large amounts of precipitation occur, as all the processes do not require heavy machinery.

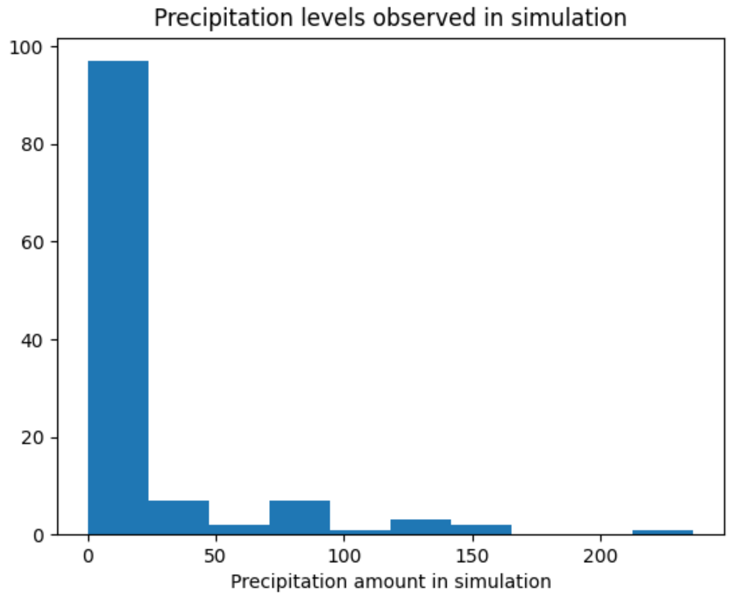

Figure 7.1: Historical 2005 precipitation levels

As there are multiple occurrences with a high level of precipitation in the 2005 data set, the most important factor is at what time in the growth period the different levels of precipitation occur. Figure 7.2 show how much precipitation occurs during the simulated time period. The first ten days show low levels of precipitation, but there is an occurrence of almost 15mm before 20 days have passed. The next 50 days also have quite low amounts of precipitation, but receive more than 5mm at four separate occasions. If these instances with a high amount of precipitation occur at days when heavy machinery is required, the precipitation may delay the processes and thus have a negative impact on the crop. After 60 days have passed, there are higher levels of precipitation, where approximately half of the days have above 5mm precipitation. This is problematic, as the optimal moisture levels are lowest at the harvesting stage. As harvest ends after approximately 90 days, and the surrounding days show some of the highest amounts of precipitation in the data, there is a high chance that the soil structure will be compacted substantially.

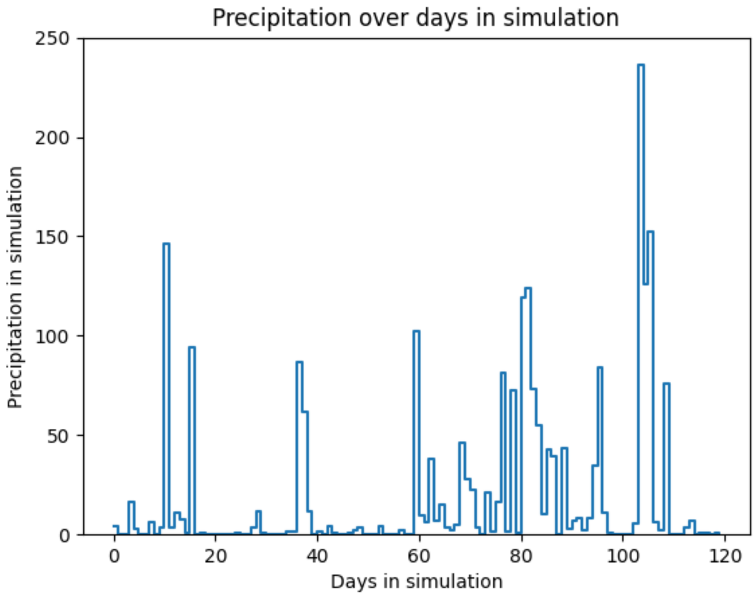

Figure 7.2: Historical 2005 precipitation over time, in the simulation

The output from the simulation tells us what days the different processes occur and what the moisture levels are at that point in time. In 2005, the time frame could look as in figure 7.3. From start to finish, the simulation takes 96 days. The first checkup happens on day 16, the second checkup occurs on day 45, the third checkup is on day 74 and the harvest takes place on day 96.

```
The simulation starts at day 0
The moisture level is now 75.00 %
The planting starts at day 1
The moisture level is now 74.93 %
The wait process ends at day 15
The moisture level is now 68.02 %
The checkup ends at day 16
The moisture level is now 78.50 %
The wait process ends at day 44
The moisture level is now 75.05 %
The checkup ends at day 45
The moisture level is now 75.01 %
The wait process ends at day 73
The moisture level is now 85.00 %
The checkup ends at day 74
The moisture level is now 86.46 %
The process is extended to day 89
The moisture level is now 92.93 %
The process is extended to day 90
The moisture level is now 91.17 %
The process is extended to day 91
The moisture level is now 89.76 %
The process is extended to day 92
The moisture level is now 88.44 %
The process is extended to day 93
The moisture level is now 86.74 %
The process is extended to day 94
The moisture level is now 85.50 %
The process is extended to day 95
The moisture level is now 86.11 %
The harvest ends at day 96
The moisture level is now 90.11 %
The amount of days in the simulation is 97
```

Figure 7.3: Simulation output, showing time frame with 2005 data

When running the simulation, we want to look at the soil moisture levels in order to find how compacted the soil might become throughout the potato production process. Figure 7.4 show the different soil moisture levels throughout the simulation. The two levels that represent most days in the simulation are the days where the precipitation is insignificantly small, and the moisture level is within the optimal moisture range. The histogram show quite a few days at and above the critical level of 90%.

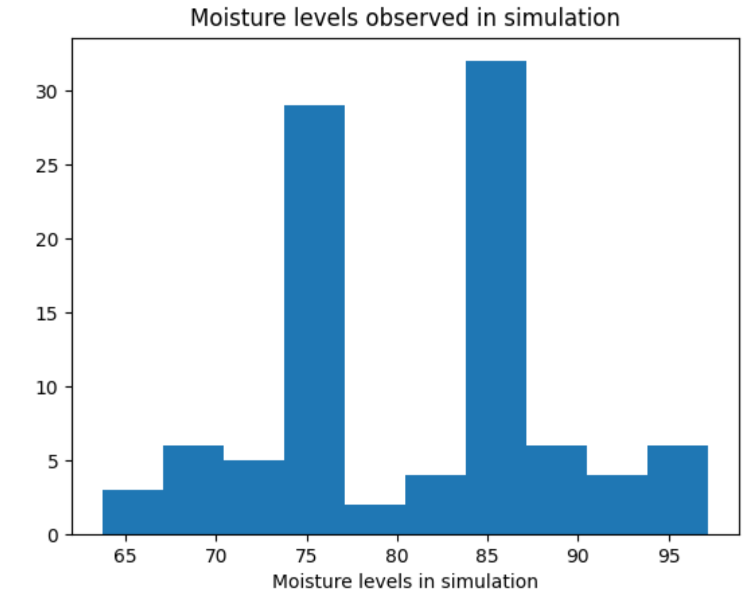

Figure 7.4: Simulated soil moisture levels, 2005

There are several days where the soil moisture level is above the optimal range, which could lead to crop damage. It is important to note when the moisture levels are the highest, as this enable us to see when processes that require heavy machinery should be postponed.

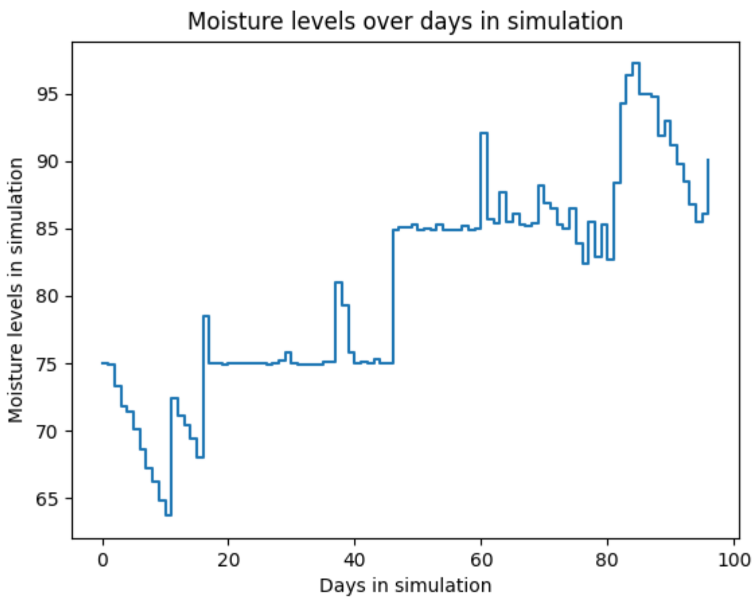

Figure 7.5: Simulated soil moisture levels over time, 2005

The soil moisture levels over time are shown in figure 7.5. At day 16, the moisture levels are quite low and there will not be a large compaction impact. At day 45 the optimal moisture level is higher, implying that the compaction impact may be more severe. At day 74 the moisture level is almost equal to the level at day 45.

Whilst the harvest is supposed to occur at a drier state, we should expect a lower rate of soil compaction. However, the moisture level is far beyond the critical value for several days. As there is a lot of precipitation at the harvest time, the moisture level of the soil never dries enough to reach the optimal moisture level at harvest. Both at harvest and after senescence, the soil moisture is above the optimal level, which could impact the crop yield. It is worth noting that the harvest has been put on hold for multiple days, and the harvest process ends up occurring at a time where the moisture level is higher than some of the previous days.

7.2 Simulating using 2018 precipitation

The following subsection give an in depth analysis of the results from our simulation using the historical precipitation from 2018.

The precipitation levels from 2018 are presented in figure 7.6. When looking at the precipitation in 2018, most days in the 120 day period have almost no rainfall. The largest amount of precipitation is between 14 and 16mm, and occurs very seldom. Generally, in comparison to the 2005 simulation, we expect that the precipitation in the simulation will impact the soil moisture levels a lot less. This is further illustrated in figure 7.7, where the precipitation over the 120 day time period is presented.

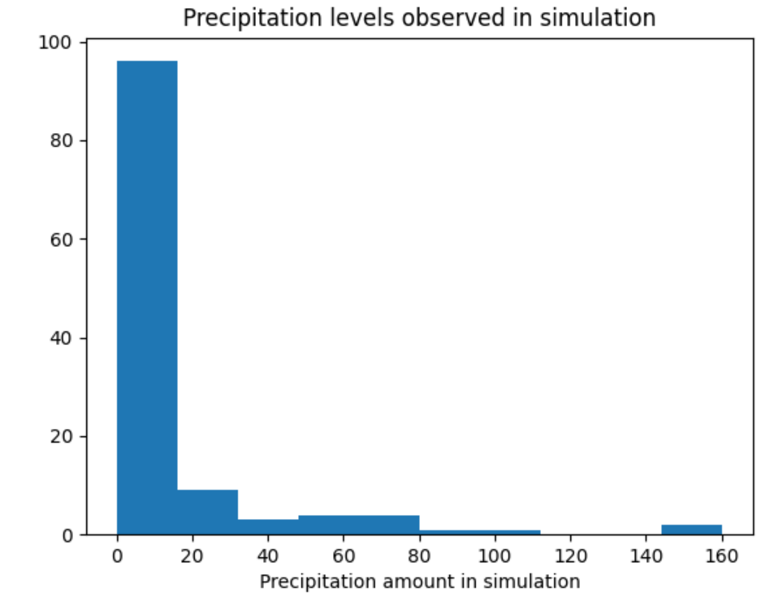

Figure 7.6: Historical 2018 precipitation levels

Figure 7.7 show precipitation over the 120 day time period. In comparison to 2005, the precipitation amounts are quite low. The largest amounts of precipitation take place at day 61 and 110, where levels above 15mm of precipitation occurs. The first two weeks display a frequent number of days with precipitation. The proceeding period is dry at first, but there is a larger amount of precipitation nearer to the 40 day mark. The amount of precipitation stays below 10mm with the exception of three times.

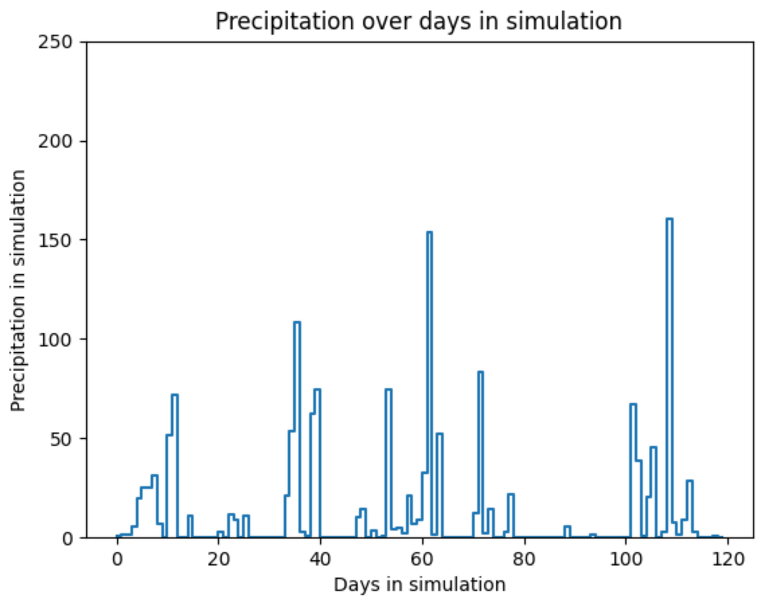

Figure 7.7: Historical 2018 precipitation over time in the simulation

The model output, illustrated in figure 7.8, shows what the time frame of the potato process might have looked like in 2018. The first checkup is at day 16, the second occurs at day 45 and the third at day 74. The harvest ends at day 89.

```
The simulation starts at day 0
The moisture level is now 75.00 %
The planting starts at day 1
The moisture level is now 75.02 %
The wait process ends at day 15
The moisture level is now 71.15 %
The checkup ends at day 16
The moisture level is now 72.01 %
The wait process ends at day 44
The moisture level is now 74.92 %
The checkup ends at day 45
The moisture level is now 74.92 %
The wait process ends at day 73
The moisture level is now 85.13 %
The checkup ends at day 74
The moisture level is now 86.00 %
The harvest ends at day 89
The moisture level is now 55.68 %
The amount of days in the simulation is 90
```

Figure 7.8: Simulation output, showing time frame with 2018 data

The moisture levels in the simulation are shown in figure 7.9. The amount of precipitation is much lower in 2018 than 2005, and the moisture levels rarely exceed the critical value. They mostly stay within the optimal range, which may predict an advantageous production yield.

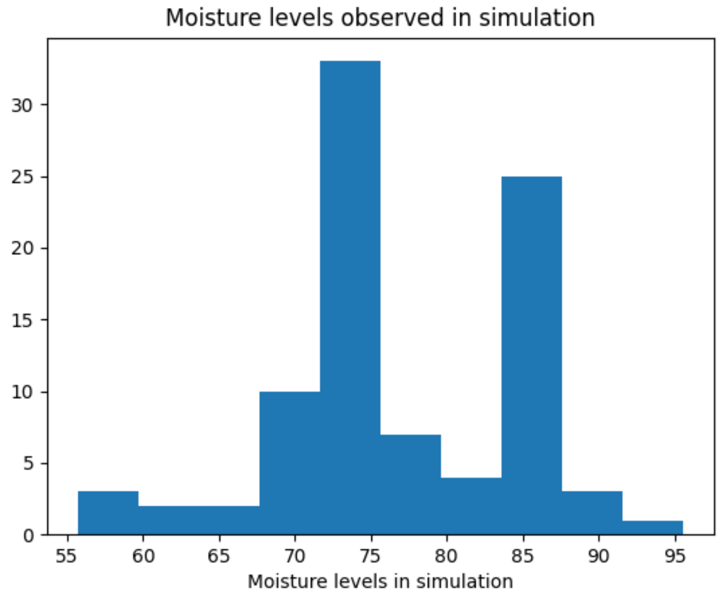

Figure 7.9: Simulated soil moisture levels, 2018

The 2018 moisture levels over time shown in figure 7.10. Compared to 2005, the soil moisture levels never exceed above the critical value when processes in need of heavy machinery occur. At day 16, the moisture level is just above 70%. At day 45 there is only an insignificant amount of precipitation, and the moisture level is in the middle of the optimal range.The 74th day show a higher moisture level, as the optimal range has increased, and the observed level is approximately 86%. The moisture level at harvest is approximately 56%, which is a little below optimal at this stage. However, the significant drop in the moisture level could have positive effects on the soil compaction as the harvest process involve heavy machinery.

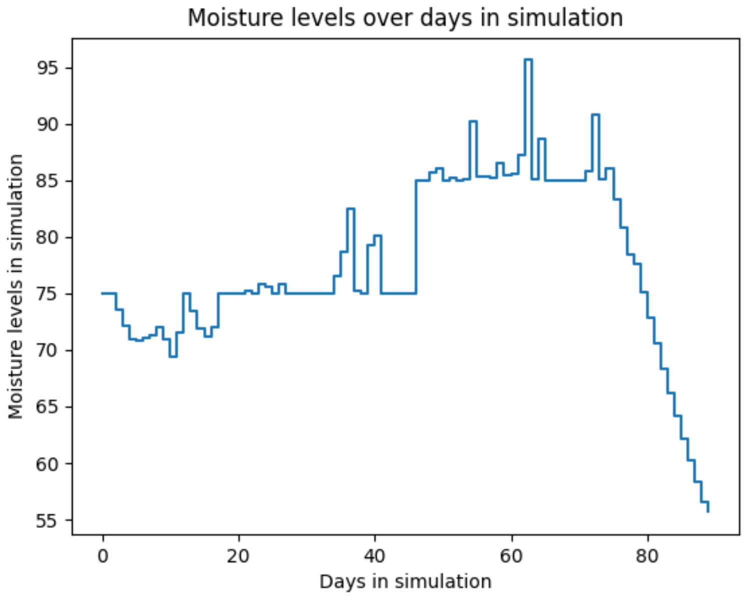

Figure 7.10: Simulated soil moisture levels over time, 2018

7.3 Analysis conclusion

By simulating two years with very different precipitation levels, the results are quite contrasting. In 2005, where the precipitation levels were abundant, the model tried to limit the effects of soil compaction by delaying the harvest process which require heavy machinery. However, an interesting finding is that the moisture levels did not decrease, thus the harvest took place at a time with a critically high soil moisture level. On the other hand, as the model gave an idea of when the moisture levels around the time of harvest would be lowest, the farmer could have proceeded to harvest at that time. This would limit the negative soil compaction impacts.

If the farmer had, for example, planted the crops before the first of March, and used the predicted precipitation for the shifted time period as input. This could have made the precipitation levels and the agricultural processes and operations better matched, resulting in a lower rate of compaction. The effects of alternating planting dates have been pointed out in (Adavi et al., 2018).

The model could provide better foresight for farmers by visualising the risk of postponing production processes. With future advances within climate prediction models, weather probability distributions could further improve their insight. A prediction based model also allows for new iterations as the production process progress to the next stage, hence offering the farmers a tool in both planning and execution. In this sense, the model give the farmers better security regarding what to expect when planning the production, and thereby decreasing the amount of soil compaction and its coherent negative effects.

In 2018, the precipitation amounts were substantially lower than in 2005. The effects of the model do not assert themselves as extensively. Because the precipitation levels were mostly insignificant, and the moisture levels only exceeded the critical moisture level once, the soil moisture stayed within the wanted ranges with the help of irrigation.

As we look at how the moisture levels impact soil compaction, and the model focuses on how the precipitation effect the moisture level, the 2018 simulation will not prove interesting to discuss in depth. Hence, we will focus our discussion on the 2005 simulation.

8 Discussion

The process of creating a simulation model for potato growth has established itself as a very complex one. The sheer amount of factors that exert an impact, have by far exceeded our expectations, and the challenge to implement them all has proven to be complicated due to the restricted time frame of our thesis as well as our limited previous knowledge of agricultural processes. In addition to being an extensive and complicated process, there has also proved to be a lack of information and research about essential parameters, especially regarding soil compaction.

Furthermore, there is a lack of available data regarding the trade off between early planting and soil compaction. As the effects of soil compaction are greatly dependent on weather events and less so on other management practices, it proves a difficult problem to treat (Franzmeier and Steinhardt, 2009). Our contact at NIBIO, Molteberg, stated that soil compaction provides one of the greatest challenges for Norwegian farmers. Franzmeier and Steinhardt (2009) mentions slower germination, lower plant population and nutrient deficiency symptoms as possible results of soil compaction. A specific example of the problem with compacted soils is that corn growing in compacted plots show symptoms of nitrogen deficiency, even though more than ample nitrogen has been applied.

8.1 Soil compaction impacts

"Soil compaction occurs when soil particles are pressed together, reducing pore space between them" (DeJong-Hughes, 2018). Figure 8.1 show how the space of the soil particles are effected, where the illustration on the left show the soil structure when it is not compressed, and the right illustration show how the soil structure is in a compressed state. When compaction takes place, the pores in the soil are fewer and smaller, which thereupon create a greater soil density.

When soil is compacted, it reduces the rate of water infiltration and drainage, because soil moisture is more effectively drained with a larger amount of space to move through. The exchange of gases in compacted soils are also slowed down, which can increase the occurrence of aeration related issues. With soil compaction, the soil strength increases and it will be more difficult to compact the soil further. (DeJong-Hughes, 2018)

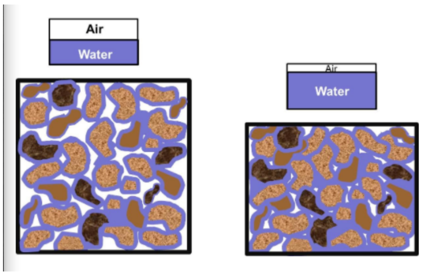

Figure 8.1: Illustration of soil compaction, (DeJong-Hughes, 2018)

DeJong-Hughes also state that wheel traffic, without a doubt, is the major cause of soil compaction. He claims that with increasing farm size, there is often a limited window of time to get operations done in a timely manner (DeJong-Hughes, 2018). This points to what Molteberg at NIBIO expressed, that farmers often are not able to put certain processes on hold and drive on wet soil with heavy machinery.

Figure 8.2 illustrate how tire pressure and moisture levels impact soil compaction. The figure is specific to a certain type of soil, and a given size and type of tires where the machinery have a specific wheel load. The rates at which compaction appear is very individual, however the fact that an increase in soil moisture levels cause increased compaction is prevalent in all soil types (DeJong-Hughes, 2018).

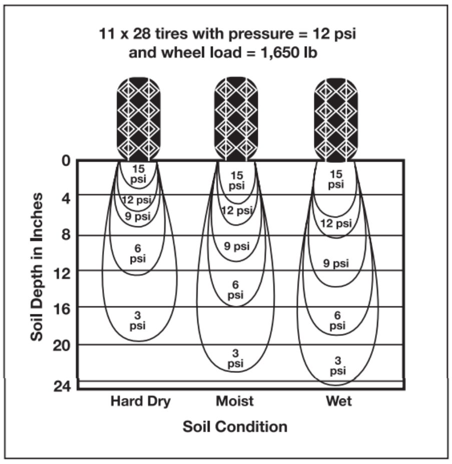

Figure 8.2: Soil compaction from wheel traffic, (Idowu, 2013)

Soil compaction can have both desirable and undesirable effects on plant growth. Figure 8.3 show how crops respond to soil compaction. In dry weather, at low bulk densities, yields improve with a slight increase in soil compaction. This is because low rates of soil compaction speed up the rates of germination, by the fact that soil compaction cause a greater contact between seed and soil. However, with an increased rate of compaction than the optimum, the crop yield subsides and thereafter declines. A high rate of compaction in a year with dry weather, can lead to stunted growth where the plants get drought stressed because of of the minimal root growth (DeJong-Hughes, 2018).

In wet weather, crop yields will only reduce with soil compaction. This is caused by a decrease in soil aeration and a higher risk of root disease, which stress the crops and result in a lower crop yield (DeJong-Hughes, 2018).

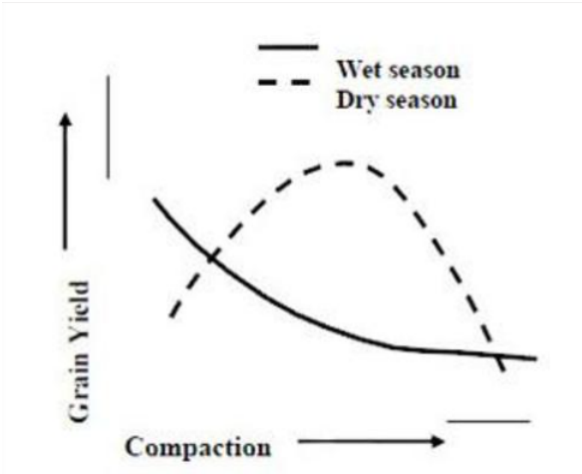

Figure 8.3: Compaction impact on crop yield in dry and wet weather, (DeJong-Hughes, 2018)

With an increase in the soil density, caused by soil compaction, the roots of a crop are less able to penetrate the soil, and generally become shallow and malformed. Because of the restriction of root growth, the crops have a decreased ability nutrients and moisture. Soil compaction therefore lead to a heavier fertilizer dependency, thus increasing production costs (DeJong-Hughes, 2018).

Increased traffic with heavy machinery delay seedling emergence, which cause a higher risk of disease, predation and moisture shortage. It affects the plant height and reduce the root mass, which can lead to moisture stress, nutrient deficiencies and lodging. Some estimate that soil compaction can reduce the crop yield as much as 60%. However, as factors that impact compaction are so broad, the effects on yield are variable (DeJong-Hughes, 2018).

DeJong-Hughes provide a lot of information on how soil compaction negatively impact crops, however Franzmeier and Steinhardt claim that there are not any consistent symptoms for plants who grow in compacted soil. They further state that the variety of effects can spark cause for confusion with other problems (Franzmeier and Steinhardt, 2009).

Our simulation model finds that an increase in precipitation is followed by a rise in soil's moisture levels. Franzmeier and Steinhardt (2009) states that the effects of soil compaction depends on weather conditions, while DeJong-Hughes (2018) proclaims that wheel-based machinery is the primary cause of soil compaction. Both articles do, however, agree that the combination of compacted soil and large amounts of water is problematic for crop growth, thus providing further basis for the necessity of planning the production cycle to accommodate the changing climate. This has implications for the end of the production cycle, as harvesting under wet conditions can cause soil compaction. Starting the next potato production cycle with compacted soil could be damaging to the yield, either by reducing the size of the harvest itself, or by limiting the availability of nutrients. By using a prediction model, the farmer would be able to plan the harvesting process in such a way that the negative ramifications for the next season are minimized.

As seen in our analysis, the significant amounts of precipitation in 2005 slow the harvest by a multitude of days. Even though the harvesting process was delayed, the conditions did not improve, and the farmers would have to run heavy machinery over critically wet soil. This could lead to a significant amount of soil compression, which could have negative impacts on the following season if precautionary measures are not implemented.

The soil compaction could lead to a reduction of crop yield, slower germination, different symptoms of nutrient deficiency, increased rate of root disease and restricted root growth. All of the previously mentioned negative impacts of soil compaction amplify precipitation as a driver of uncertainty. As climate change increase occurrences of extreme weather conditions, the precipitation levels in 2005 may serve as a guideline for what we can expect in the future.

8.2 Precipitation as a moment of uncertainty

By affecting how farmers will have to conduct their line of work, there is no doubt that climate change will have economical ramifications for the agricultural sector.

Brita Aasprang (2013) separates direct and indirect effects when discussing how farmers are affected by changes in the climate. The former includes the effect's changes in climatic relationships can impose on the production of agricultural goods, and they can be difficult to separate from the yearly variations in the growth conditions. Agriculture is one of the lines of work that are most affected by changes in the climate. Alterations in weather conditions are however not a new phenomenon for farmers, and uncertainty regarding these are something all types of farmers have had to relate to. The unpredictable weather is something farmers have developed strategies for over several generations. As discussed previously in our thesis, climate change will bring higher temperatures, increased amount of precipitation during autumn, less precipitation during the winter months and summer for certain places, and generally a more unstable weather with increased variation from year to year. A changing climate will, however, produce opportunities for the agricultural sector, by for example making it possible to introduce new species or by allowing several harvests per season.

Weather is not the only aspect of uncertainty that farmers must cope with. Indirect effects that are not related to the weather conditions' direct impact on agriculture, but by how they affect other factors, that in turn imposes changes on Norwegian agriculture. Norwegian agricultural policy can serve as an example (Aasprang, 2013). United Nations' climate panel and international climate cooperation affects how this policy is formed. This in turn, results in regulations and measures that are put in motion to adapt to global climate change and reduce climate gasses. Another indirect effect on Norwegian agriculture could be how the climate changes affects the agriculture in other countries; floods or droughts abroad can have an impact on the prices of input factors such as fertilizer, feed concentrate/grain feed and pesticides.

There are also other factors that have an impact on farmers and their economic situation, such as investment decision and the market prices for agricultural commodities. In regard to the market, Norwegian farmers experience a certain safety as they negotiate with the state on a yearly basis through their organizations in order to get an agricultural deal on prices and subsidies. There are two ways to handle the uncertainty regarding climate according to Faures et al. (quoted in Aasprang, 2013). One is to reduce the sources of the uncertainty factors and the other is to lessen the consequences. The latter is to some extent tended to by attaining the safety through negotiations with the authorities. The uncertain factors and their effects are highlighted in a master thesis by Nybø (2020), where she points to the economic and mental hardships experienced by the farmers around Randaberg in Norway in the aftermath of a drought in the summer of 2018. The drought caused several crops to perish, leading to an acute crisis for farmers in Southern-Norway.

The Norwegian agricultural cooperative is well-functioning under normal conditions, providing good advice and negotiating favorable prices for its members. They also took measures and gave advice concerning how the farmers best could navigate themselves through the crisis. Both the authorities and agricultural sector acknowledged that the crisis was a reality, but still faced criticism for how they handled it. The farmers were advised to order large amounts of straw and other forms of feed, but this was easier said than done as the farmers do not receive their economic grants until February. The prospect of acquiring debt of several tens of thousands NOK were not appealing for the farmers, and this insight seemed to be lost on the governing bodies, sparking frustration and anxiety among farmers (Nybø, 2020).

A survey conducted by Sentio on behalf of the insurance company Frende Forsikring finds that damages caused by torrential rain represents the greatest climate induced fear among Norwegian farmers, regardless of the part of the country they reside (Bondebladet, 2021). The head of the Norwegian farmers guild, Astrid Solberg, explains that torrential rain can cause floods which can destroy the crops. Several areas in Norway are also exposed to landslides that can rinse away topsoil, or even bring buildings and infrastructure along. Elongated periods of precipitation also lead to erosion and leaching of nutrients, which is unfavorable to the quality of the soil. Extended periods of drought is also a factor that the farmers worry about, as this can result in failing crops. Solberg states that the dry summer of 2018 in southern Norway have left lasting impressions, as there still are farmers who struggle with the economic aftermath (Bondebladet, 2021).

Further in her report, Aasprang refers to one of the conclusions found in a British examination, conducted by Lorraine Whitmarsh containing both interviews and a survey which stated that the attendees did not put floods in direct context with climate change. There was not found any significant difference between those who had personal experience with floods and those who had not. It is pointed out that we do not experience climate change directly, just the effects of it. The phenomenon of climate change is made evident to us by the use of mathematical models, says Kollmus and Agyeman (2002, quoted in Aasprang, 2013). They further state that we can experience a flood, but the only way we can perceive that the flood was caused by climate change is through secondhand information from sources like the media.

Most people find it hard to fathom what climate change entails, and the effects are perceived to be distant in a time perspective. At the same time, they are portrayed as one of the greatest threats in our time. The combination of climate change as a global risk factor, and not being able to visualize the effects in the immediate future can appear frightening for many (Bauman, 2006, quoted in Aasprang, 2013). While climate change is not something we feel on a day-to-day basis, the weather is on the contrary quite prominent in the farmers daily life. In her analysis, Aasprang found that most Norwegian farmers believed that climate change would either have no effect on their farm, or that it would affect the farm negatively to a small extent. Relatively few were of the belief that climate change could have a positive impact on their farm. It would appear that the farmers to a larger degree look at the risks instead of the opportunities regarding climate change. Quite few of the farmers asked were of the opinion that their farms would be severely affected by climate change, indicating that Norwegian farmers in general are not too concerned by local climate effects. This could stem from the fact that Norwegian agriculture is regulated by the state and part-financed, which can lead to a sense of protection for the farmers, as they for example have a scheme for recoupment if the crops are damaged.

The fact that Norwegian farmers to a greater extent focus on the risks of climate change rather than the opportunities could be due to the media coverage, as they most often portray climate change as a threat. Most research does however state, that the agriculture at our latitudes could benefit from the climate changes.

From the perspective of the European mainland, different researchers present contradicting predictions regarding the economic impact climate change will pose. In an article from 2013, Shrestha et al. investigate the medium-term impact of climate change on the agriculture of the European Union (EU). Their overall results provide an indication of increased yields and production level in the EU agricultural sector due to climate change. Stronger impacts are seen in Central and Northern Europe, while they are of a lesser magnitude in Southern Europe.

Further, their simulation predicts that prices of agricultural commodities will be reduced because of climate change. Of the different scenarios they have analyzed prices tended to decrease more in a warm-global scenario than they would in a mild-global scenario, which is consistent with yield changes. Generally, climate change was found to have a positive impact on the agricultural production, as the yields increase.

Climate change is predicted to have a relatively small impact on the EU aggregate land use, with a slight decrease of a maximum -0,5% in total utilized agricultural area relative to the baseline. The area of most arable crops reacts positively to climate change due to improved yields and land productivity. In global scenarios, the utilized agricultural area drop more significantly, up to – 2,3%. This is due to the price effect that hampers agricultural profitability and offsets production gain, leading to a fall in demand for land (Shrestha et al., 2013).

Total welfare will have a small positive impact from climate change, as it will improve slightly due to consumer gain from lower food prices. The agricultural income has a greater reaction, and it is caused by the increase in yields. However, when adjusting for the decreasing price the income change ends up being barely negative. Agricultural products usually have an inelastic demand, and an improvement in productivity usually make farmers see their incomes diminish (Shrestha et al., 2013).

The article by Shresta et al. introduce climate change scenarios for European countries and assume that crop yields in non-EU countries remain unchanged. The authors admit that this can cause bias, either upward or downward, regarding price effects.

Their results contrast with what the European Environment Agency (EEA) find in their projections from 2019. They state that climate impacts have resulted in smaller harvests and increased production costs, affecting the quality, quantity, and price of farmed products in Europe. The conditions for growing crops in Northern Europe are projected to improve, while the opposite is the case for the southern-European crop production. When projecting using a high-end emission scenario, the EEA finds yields of non-irrigated crops are estimated to decrease in southern Europe by up to 50% by 2050. Which in turn could result in a considerable decline in farm income, with large regional variations. When using a similar scenario EEA predicts that farmland values will recline in parts of southern Europe by more than 80% by 2100, which could culminate in land abandonment. This will again have an impact on trade patterns, which will then affect agricultural income. Food security is not under threat in the EU, but a worldwide surge in demand for food could apply pressure on food prices in the approaching decades (European Environment Agency, 2019).

8.3 Climatic uncertainty

Healthy soils and sufficient amounts of water is a necessity for agriculture to be possible, as they provide the basis for production. Alterations in precipitation, temperature and other atmospheric conditions induced by global warming will directly affect soils (Borron, 2006). While predicting specific impacts for particular areas is extraordinarily difficult, expected extreme weather events will with a high degree of certainty accelerate erosion and damage soils (Rounsewell et al., 1999; cited in Borron, 2006).

Farmers all over the globe hold a huge body of information about their farming systems (Borron, 2006). They have witnessed phenomena and modified their farming systems over several generations to better accommodate changing needs. These practices are especially seen in the range of crop varieties and livestock breeds evolved to best suit the local use. Global climate change induces a significant risk, and these changes will occur at an accelerating pace, prompting the farmers to observe, learn and respond more rapidly than before. The changes will be swifter and more drastic than previously, perhaps necessitating new means of sharing information. Farmers who possess a traditional knowledge base, retains an advantage in further developing ecological processes to take action against the effects of climate change (Borron, 2006). The above mentioned locally adapted seeds have been developed for generations of farmers to best suit the regional climate. This could provide a viable approach to global changes, given that certain locally adapted varieties are better suited to cope with difficult climate conditions.

The previous two years have demonstrated the fragility of the food supply chain, whether at the hand of climate change, political disruption, or a global pandemic. Networks that were tried-and-trusted fell afoul of supply chain disruption, lack of workers to conduct the harvest or closure of borders. These factors have all been encountered before, but not at such a magnitude as now. Now more than ever, we live in a society were consumers demand that supplies are available (Shin, 2021).

In 2019 the U.S. Global Change Research Program's Forth National Climate Assessment report showed an expected increase in phenomena such as rising temperatures, extreme heat, drought, wildfire, and heavy downpours (Shin, 2021). These events will progressively disrupt agricultural productivity. The report also warns that an increase in challenges to aspects of food production – such as crop yields – presents a threat to rural livelihoods, sustainable food security and price stability. The Australian wildfires in 2019 to locust swarms in Africa in 2020 and the North American climate pattern "La Niña" in 2021 have caused difficulties for farmers worldwide (Shin, 2021). These phenomena shows that there are many things that are out of our control sphere. Hence, planning for the unknown is as crucial as planning for the ordinary.

In Norway the extreme weather named "Frida" wreaked havoc upon farmers in the Buskerud County in 2012, causing 500 years old topsoil to be washed away in streams, fruit trees worth several hundred of thousand NOK to be blown away, and animal feed to rot. The intensity of the downpour caused the harvest to become jeopardized. For some farmers the weather conditions result in an extra workload lasting several weeks, just to salvage the remains. One of the farmers who were interviewed could inform of an increasing problem with extreme weather conditions in Norway. The father of the interviewee had run the farmstead for four decades and had only experienced harvest-ruining weather conditions once, while the son had faced such conditions three times in the previous ten years (Amundsen et al., 2012).

In order to face the impending changes caused by global warming, adaptability seems to be of the utmost importance. Studies such as the one discussed in the article "Assessment of potato response to climate change and adaptation strategies" (Adavi et al., 2018), will be important in order to map the best possible responses to a transforming climate. Possessing data about which potato species thrive under different conditions, companioned with long-spanning weather forecasts, will make planning for future harvests somewhat more predictable.

An indication of which types of weather can be expected in the years to come could play an essential part in developing new and more sturdy species. The Norwegian agricultural industry does already have some experience in developing new species. After experiencing several years of declining demand for Norwegian potatoes, the industry decided to act by developing more aesthetically pleasing potatoes to accommodate the needs of the consumers. The evolution process focused on improving qualities such as suitability for storage, the quality of the peeling, and reducing food waste. Developing new species does however take a significant amount of time and chartering whether the species are suited for the Norwegian market could lead to the process taking up to a decade (Norsk Landbrukssamvirke, 2021).

Our simulations show that precipitation and the moisture level coincide; persistently high levels of precipitation are associated with elongated periods of high moisture levels as observed in the final stages of the 2005 simulation. An assumption we have relied on in the model that might deviate from reality is that the irrigation system continuously wants to keep the moisture levels within the optimal range. In order to keep the moisture in this interval, the model does not take future precipitation into account when applying more water, thus subsequent rainfall can result in an artificially augmented moisture level. It is also worth noting that our simulation is based on a fairly small patch of soil, 1 m^3. Upscaling the potato production to farm scale would have implications for the soil moisture, as well as the fact that individual farmers have their unique way of approaching the day-to-day framing process.

The model also simplify factors such as evaporation, transpiration, and percolation. However, a key take-away is that a more saturated soil will prolong the hydrologic cycle.

In previous years, periods with heavy rainfall have caused the harvest to be delayed, or in the worst-case scenarios ruining the entire crop. A simulation model with prediction inputs would make the farmers able to plan the growth process, and optimally avoid harvesting under wet conditions. In a nearly optimal scenario, the model would give ample warning of the approaching period with heavy rainfall and thus, hopefully making the farmer able to salvage the harvest.

As climate change is predicted to increase the frequency of extreme weather events, we found it useful to base our prediction on two years with a lot of rain and a small amount of precipitation, respectively. Basing the model on such extreme years could provide a useful base of knowledge for future events, where both periods of drought and increased rainfall are to be expected. By applying a simulation-based prediction model, such as our own, the uncertainty of future weather events can be reduced, which again would allow the farmers to apply their knowledge of farming under different weather conditions. The results from our simulations provide a staple for what type of information could have been passed on to the farmers, had the model been implemented prior to the years 2005 and 2018. Had the farmers been made aware of the probability of the elongated periods of heavy rainfall in the time leading up to the harvest in 2005, uncertainty could have been reduced and the farmers would have been able to make a more informed decision on when to proceed with the harvesting process.

Previously in our discussion we have mentioned negative impacts of soil compaction such as slower germination, different symptoms of nutrient deficiency, reduced plant population, incidents of aeration related problems such as an increased risk of root diseases. The restriction of root growth, can further reduce the absorption of water and nutrients. If these impacts should persist and carry over to the next production period, the price of a lack in planning might come with an economic interest for the farmer. A decrease in the size of the yield combined with heavier reliance on fertilizer could have a serious impact on the individual farmer's profit, especially when we look at a global picture where dependence on fertilizer is expected to increase as a result of more extreme weather. Taking precautionary measures will be essential for farmers in the future in order to run their operation efficiently. By utilizing a prediction model the farmers would be better equipped when facing uncertain weather conditions.

As mentioned earlier, in section 4, climate prediction models are still unable to provide accurate predictions for future precipitation. Hence, we have simulated using historical data. In order for the model to provide security for farmers in the future, climate prediction models will have to improve, and the simulation model needs to be enhanced in order to take probability distribution into account. Furthermore, variables we have previously made assumptions about, should be more grounded in reality. Especially temperature will assert a great effect on the hydrologic cycle and potato growth, as it directly effects evapotranspiration and potatoes' optimal growing conditions. Hence, incorporation of temperature as an input variable will further fortify the model.

9 Conclusion

Climate change asserts itself as one of the main drivers behind uncertainty in global agriculture, especially with the encroaching aspect of increased extreme weather events. We have tried to answer the following:

How can climate forecasts help farmers reduce the impacts of soil compaction, and further create a larger sense of security in future production?

We approached the problem by creating a simulation model, to see if NORCE's climate predictions can be used to simulate future production, and thus create predictability when farmers plan their production season. With the predictability of the soil moisture levels, the farmer knows when to carry out processes that require heavy machinery. Hence, creating a larger sense of security in their future production season, and limiting the repercussions of soil compaction.

Due to the limitations of the current climate prediction models, we utilized historical data to chart how precipitation impacts soil moisture. By using precipitation data from one of the driest, and one of the wettest years recorded since 1993, we were able to see how extreme weather conditions impact soil moisture levels. With this, we discussed how the soil moisture levels simulated in these years affect soil compaction.

As the 2018 precipitation levels proved to have an insignificantly low impact on the moisture levels in the model, we centered our discussion around the 2005 simulation.

When simulating the production using the historical precipitation data from 2005, we found that the high levels of rainfall have a notable impact on the soil moisture levels. The model delayed the harvesting process, in an attempt trying to prevent excessive soil compaction. However, as the moisture levels did not recede, the model completed the harvest on a day with wet soil. On the other hand, the model gave an overview of the moisture levels during the postponing of the harvest, therefore the farmer would be better suited to make a more qualified decision regarding when to proceed.

In order for the simulation model to be operational, climate predictions will have to improve and thus provide daily precipitation data beyond the foreseeable future. Considering the amount of generalizing assumptions regarding the production process, our model is quite simplified. Further development of our simulation, by including other factors such as temperature, would be beneficial for future application. Further studies on subjects such as evapotranspiration, percolation and water infiltration are required in order to certify the accuracy of the model. However, from our results, we can draw the conclusion that a simulation model of similar character could help reduce the impacts of soil compaction.

Thus, creating a higher sense of foresight when the farmer plans the production process.

9.1 Further studies

It is not uncommon that model based studies have to simplify their calculations and focus on the deciding factors. This is also the case in our thesis.

The simulation model we developed as part of our master thesis rely on several assumptions that simplify the natural processes that take place in the real world. Both the hydrologic cycle and asserted tire pressure have been severely simplified due to time restraints and limited previous knowledge on our part.

As there are a multitude of articles regarding the negative impacts of soil compaction on agricultural production, it is inherent that soil compaction is one of the major moments of insecurity within agricultural production. Despite the severity of it, there are only a limited amount of studies regarding the actual variables and parameters that impact soil compaction. Thus, future researchers are encouraged to explore the topic further, in order to halt the negative effects climate change have on agricultural processes, as well as increasing predictability in agricultural production.

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Appendix

A1 R code, used in data processing

```
# Packages and preparations ----------------------------------------

# Clean the environments:
# Clean plots
graphics.off()
# Clean environment
rm(list=ls())
# Clean console output
cat("\014")

#install.packages("ff_4.0.4.tar.gz")
#install.packages("data.table")
#install.packages("doBy")

library(writexl)
library(ff)
library(data.table)
library(ggplot2)
library(doBy)
library(readxl)
library(tidyverse)
library(lubridate)
library(data.table)

#Setting WD ---------------------------------------------------------
setwd(dirname(rstudioapi::getActiveDocumentContext()$path))
getwd()

#Importing Data ----------------------------------------------------

#import precipitation file
precip <- fread(file = "precip1.csv", sep = ",")


#Processing data --------------------------------------------------

precip$date <- format(as.Date(precip$date,
                              format = "%d-%m-%Y"),
                      "%d/%m/%Y") #format the date column

precip$year <- format(as.Date(precip$date,
                              format = "%d/%m/%Y"),
                      "%Y") #extract the year from the date column


precip2005 <- subset(precip, year == "2005",
                     select = c("lon",
                                "lat",
                                "date",
                                "prec")) #subsetting 2005

precip2018 <- subset(precip, year == "2018",
                     select = c("lon",
                                "lat",
                                "date",
                                "prec")) #subsetting 2018
```

```
precip2005 <- subset(precip2005,
                     lon == 11 & lat == 60,
                     c("date", "prec")) #subsetting by lon&lat

precip2018 <- subset(precip2018,
                     lon == 11 & lat == 60,
                     c("date", "prec")) #subsetting by lon&lat

#creating day of year column
precip2005$dayofyear <- seq.int(nrow(precip2005))

#creating day of year column
precip2018$dayofyear <- seq.int(nrow(precip2018))


#getting the precipitation for 120 days
precip2005 <- subset(precip2005,
                     dayofyear > 59 & dayofyear < 180,
                     c("date", "prec", "dayofyear"))

#getting the precipitation for 120 days
precip2018 <- subset(precip2018,
                     dayofyear > 59 & dayofyear < 180,
                     c("date", "prec", "dayofyear"))

#Plotting the data ------------------------------------------

#formatting dates as dates for graphs

precip2005$date <- as.Date(precip2005$date,
                           format = "%d/%m/%Y",
                           tryFormats =c("%Y-%m-%d",
                                         "%Y/%m/%d"))

precip2018$date <- as.Date(precip2018$date,
                           format = "%d/%m/%Y",
                           tryFormats =c("%Y-%m-%d",
                                         "%Y/%m/%d"))

#grap of the precipitation from 2005


ggplot(data=precip2005, aes(x=date, y=prec)) +
  geom_line(color = "blue")+
  ggtitle("Precipitation in 2005")+
  xlab("Date") +
  ylab("Daily precipitation in cm")+
  theme_minimal()


#graph of the precipitation from 2018
ggplot(data=precip2018, aes(x=date, y=prec)) +
  geom_line(color = "blue")+
  theme_minimal()+
  ggtitle("Precipitation in 2018")+
  xlab("Date") +
  ylab("Daily precipitation in cm")


write_xlsx(precip2005,
           "C:/Users/47941/Desktop/Master_Potet//precip2005.xlsx")

write_xlsx(precip2018,
           "C:/Users/47941/Desktop/Master_Potet//precip2018.xlsx")
```

A2 Simpy python code, The Simulation Model

```
############# LIBRARYS ETC ####################


import simpy
import matplotlib.pyplot as plt
import pandas as pd

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################## LISTS #######################

#list to store days in simulation
time_list = []

#list to store soil weight
weight_list = []

#list to store the moisture content of the
# soil from the simulation
moisture_list = []



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################## VARIABLES AND PARAMETERS ########


#amount of potatoes allowed in 1 square meter
#amount of potatoes in soil, soil capacity
soil_potato_capacity = 4

    #evaporation rate

#kg lost by evaporation daily with high shade
transpiration_h = 0.000467

#kg lost by evaporation daily medium shade
transpiration_m = 0.0005

#kg lost by evaporation daily in low shade
transpiration_l = 0.00093

    #water absorption rate
absorption_rate1 = 0.00033 #kg absorbed by tuber
absorption_rate2 = 0.0041 #kg absorbed by tuber

    #Evaporation rate
evaporation = 1 #kg water evaporated daily

#amount of tubers that grow from one potato plant
tubers = 7




loss1 = ((transpiration_l)+
            soil_potato_capacity*(absorption_rate1*tubers)
            +evaporation) #amount of water absorbed and lost during first and last wait
loss2 = ((transpiration_m)+
            soil_potato_capacity*(absorption_rate2*tubers)+
            evaporation) #amount of water absorbed and lost during middle part of the process
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loss3 = ((transpiration_h)+
            soil_potato_capacity*(absorption_rate2*tubers)+
            evaporation) #amount of water absorbed and lost during last part of process



#Optimal soil moisture levels for each process in %
    #pre emergence
pre_min = 65
pre_max = 80
pre_mid = 72

    #tuber initiation
initiation_min = 70
initiation_max = 80
initiation_mid = 75

    #Full bloom
bloom_min = 80
bloom_max = 90
bloom_mid = 85

    #Plant senescence
senescence_min = 80
senescence_max = 90
senescence_mid = 85

    #Harvesting
harvest_min = 60
harvest_max = 65
harvest_mid = 62

    #Soil moisture calculations
dry_soil_weigth = 1450 #loose earth in kg/m^3
initial_moisture_level = 75 #75%
initial_soil_weight = (((initial_moisture_level*dry_soil_weigth)/100)+dry_soil_weigth)




day_list = [] #creating an empty list
for i in range(120): #for 120 days
    day_list.append(i) #append the days to the list


#creating precipitation list for 2005
precip2005 = pd.read_excel(r"precip2005.xlsx") #getting the data from the excel file
prec_2005 = pd.DataFrame(precip2005, columns= ['prec']) #creating a dataframe with precipitation

list_2005 = prec_2005["prec"].tolist() #converting the dataframe to a list
precipitation = [element * 10000 for element in list_2005] #converting the precipitation to mm

#creating precipitation list for 2018
precip2018 = pd.read_excel(r"precip2018.xlsx") #getting the data from the excel file
prec_2018 = pd.DataFrame(precip2018, columns= ['prec']) #creating a dataframe with precipitation

list_2018 = prec_2018["prec"].tolist() #converting the dataframe to a list
list_2018 = [element * 10000 for element in list_2018] #converting the precipitation to mm



max_moisture_level = 90 #maximum moisture level for driving on soil
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#-----------------------------------------------------------------------------------------

######################## ENVIRONMENT PROCESS (1/2) ########################################

env = simpy.Environment() #setting the environment as simpy


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#################### RESOURCES ####################################################

#resource containers

#soil weight in kg
soil_weight = simpy.Container(env, capacity=2900, init=initial_soil_weight)

#moisture content in the soil in % where saturation at 100% is max
soil_moisture = simpy.Container(env, capacity=100, init=initial_moisture_level)

#process containers, to only allow for the process to be completed once
complete_cap = simpy.Container(env, capacity=1, init=0)





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################## MODEL ####################################################################

#--------------------------------main def------------------------------------
#the main def, that runs all the processes in the potato production
def potato_production(env, soil_weight, soil_moisture, complete_cap):
    while True:
        yield complete_cap.put(1)
        print("The simulation starts at day %s" %env.now)
        print("The moisture level is now %s " %soil_moisture.level)
        time_list.append(env.now) #day 0 is appended to capture initial storage levels
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)


        ############### planting process #####################################################

        yield env.timeout(1) #the planting process takes 1 day
        if precipitation[env.now] > 0:
            #the addition of moisture changes the soil weight
            yield soil_weight.put((precipitation[env.now]))
            yield soil_weight.get(evaporation)
        else:
            yield soil_weight.get(evaporation)
        #the soil moisture level is changed out with a new calculation
        yield soil_moisture.get(soil_moisture.level)
        #the new soil moisture level is calculated
        yield soil_moisture.put(((soil_weight.level-
                                 dry_soil_weigth)/
                                 dry_soil_weigth)*100)

        time_list.append(env.now)
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
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print("The planting starts at day %s" %env.now)
print("The moisture level is now %s " %soil_moisture.level)

#———————————————————————————————————————————————————————————————————————————————

################ first wait process ##################################################

for i in range (7):
    yield soil_weight.get((soil_weight.level -1450)*0.02)
    yield soil_moisture.get(soil_moisture.level) #the absorption the seeds grab from the soil
    if precipitation[env.now] > 0:
        yield soil_weight.get(loss1)
        #the addition of moisture changes the soil weight
        yield soil_weight.put((precipitation[env.now]))
    else:
        yield soil_weight.get(loss1)
     #precipitation gets added to the soil moisture
    yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
    yield env.timeout(1) #each wait lasts for 1 day
    time_list.append(env.now) #second time input to time list
    #appends to correct list  soil weight level at current time
    weight_list.append(soil_weight.level)
    #appends to correct list soil moisture level at current time
    moisture_list.append(soil_moisture.level)
#optimal moisture level for pre emergence
if soil_moisture.level not in range (pre_min, pre_max):
    for i in range (7):
        yield soil_weight.get((soil_weight.level -1450)*0.02)
        #the absorption the seeds grab from the soil
        yield soil_moisture.get(soil_moisture.level)
        if precipitation[env.now] > 0:
            yield soil_weight.get(loss1)
            #the addition of moisture changes the soil weight
            yield soil_weight.put((precipitation[env.now]))
        else:
            yield soil_weight.get(loss1)
        #precipitation gets added to the soil moisture
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #each wait lasts for 1 day
        time_list.append(env.now) #second time input to time list
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
print("The wait process ends at day %s" %env.now)
print("The moisture level is now %s " %soil_moisture.level)

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#################### first checkup amending process ########################################

if soil_moisture.level > max_moisture_level: #critical moisture level of max_moisture_level
    #if the soil level is above drivable safe level, the process can timeout up to a week.
    # After a week, the process has to be completed
    for i in range(7):
        yield soil_weight.get((soil_weight.level -1450)*0.3) # daily moisture loss
        if precipitation[env.now] > 0:
            yield soil_weight.get(loss1)
            #the addition of moisture changes the soil weight
            yield soil_weight.put(((precipitation[env.now])+((((pre_mid-
                                  (((soil_weight.level-
                                      dry_soil_weigth)/dry_soil_weigth)*100)))*14.5))))
        else:
            yield soil_weight.put((((pre_mid-
                                  (((soil_weight.level-dry_soil_weigth)/
                                      dry_soil_weigth)*100)))*14.5))
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                yield soil_weight.get(loss1)
            #the soil moisture level is changed out with a new calculation
            yield soil_moisture.get(soil_moisture.level)
             #the new soil moisture level is calculated
            yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
            yield env.timeout(1) #each waiting day takes one day
            time_list.append(env.now) #the time days are recorded in the time list
            #appends to correct list  soil weight level at current time
            weight_list.append(soil_weight.level)
            #appends to correct list soil moisture level at current time
            moisture_list.append(soil_moisture.level)
            print("The process is extended to day %s" %env.now)
            print("The moisture level is now %s " %soil_moisture.level)
    yield soil_weight.get((soil_weight.level -1450)*0.3)
    if precipitation[env.now] > 0:
        yield soil_weight.get(loss1)
        #the addition of moisture changes the soil weight
        yield soil_weight.put(((precipitation[env.now])+
                                (((pre_mid-(((soil_weight.level-dry_soil_weigth)/
                                                dry_soil_weigth)*100)))*14.5)))
    else:
        yield soil_weight.put((((pre_mid-
                                    (((soil_weight.level-dry_soil_weigth)/
                                        dry_soil_weigth)*100)))*14.5))
        yield soil_weight.get(loss1)
    yield soil_moisture.get(soil_moisture.level)
    #the new soil moisture level is calculated
    yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
    yield env.timeout(1) #the planting process takes 1 day

    time_list.append(env.now) #the time of checkup is added to time list
    #appends to correct list  soil weight level at current time
    weight_list.append(soil_weight.level)
    #appends to correct list soil moisture level at current time
    moisture_list.append(soil_moisture.level)
    print("The checkup ends at day %s" %env.now)
    print("The moisture level is now %s " %soil_moisture.level)

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################ second wait process ############################################################

    for i in range (21):
        yield soil_weight.get((soil_weight.level -1450)*0.3)
        yield soil_moisture.get(soil_moisture.level) #the absorption the seeds grab from the soil
        if precipitation[env.now] > 0:
            yield soil_weight.get(loss2)
            #the addition of moisture changes the soil weight
            yield soil_weight.put(((precipitation[env.now])+
                                    (((initiation_mid -(((soil_weight.level-dry_soil_weigth)/
                                                        dry_soil_weigth)*100)))*14.5)))
        else:
            yield soil_weight.put((((initiation_mid-
                                        (((soil_weight.level-dry_soil_weigth)
                                          /dry_soil_weigth)*100)))*14.5))
            yield soil_weight.get(loss2)
        #precipitation gets added to the soil moisture
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #each wait lasts for 1 day
        time_list.append(env.now) #second time input to time list

        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
    #critical moisture level of max_moisture_level
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if soil_moisture.level not in range(initiation_min, initiation_max):
    for i in range (7):
        yield soil_weight.get((soil_weight.level -1450)*0.3)
        #the absorption the seeds grab from the soil
        yield soil_moisture.get(soil_moisture.level)
        if precipitation[env.now] > 0:
            yield soil_weight.get(loss2)
            #the addition of moisture changes the soil weight
            yield soil_weight.put(((precipitation[env.now])+
                                  (((initiation_mid -(((soil_weight.level-dry_soil_weigth)/
                                                        dry_soil_weigth)*100)))*14.5)))
        else:
            yield soil_weight.put((((initiation_mid-
                                     (((soil_weight.level-dry_soil_weigth)/
                                             dry_soil_weigth)*100)))*14.5))
            yield soil_weight.get(loss2)
        #precipitation gets added to the soil moisture
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #each wait lasts for 1 day
        time_list.append(env.now) #second time input to time list
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
print("The wait process ends at day %s" %env.now)
print("The moisture level is now %s " %soil_moisture.level)

#------------------------------------------------------------------------------

############## second checkup amending process ##################################################

if soil_moisture.level > max_moisture_level: #critical moisture level of max_moisture_level
    #if the soil level is above drivable safe level, the process can timeout up to a week.
    # After a week, the process has to be completed
    for i in range(7):
        yield soil_weight.get((soil_weight.level -1450)*0.3)
        if precipitation[env.now] > 0:
            yield soil_weight.get(loss2)
            #the addition of moisture changes the soil weight
            yield soil_weight.put(((precipitation[env.now])+
                                  (((initiation_mid -(((soil_weight.level-dry_soil_weigth)/
                                                        dry_soil_weigth)*100)))*14.5)))
        else:
            yield soil_weight.put((((initiation_mid-
                                     (((soil_weight.level-dry_soil_weigth)/
                                         dry_soil_weigth)*100)))*14.5))
            yield soil_weight.get(loss2)
        #the soil moisture level is changed out with a new calculation
        yield soil_moisture.get(soil_moisture.level)
        #the new soil moisture level is calculated
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #each waiting day takes one day
        #the time days are recorded in the time list
        time_list.append(env.now)
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
        print("The process is extended to day %s" %env.now)
        print("The moisture level is now %s " %soil_moisture.level)
yield soil_weight.get((soil_weight.level -1450)*0.3)
if precipitation[env.now] > 0:
    yield soil_weight.get(loss2)
    #the addition of moisture changes the soil weight
    yield soil_weight.put(((precipitation[env.now])+
                          (((initiation_mid -(((soil_weight.level-dry_soil_weigth)/
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                                                    dry_soil_weigth)*100)))*14.5)))
        else:
            yield soil_weight.put((((initiation_mid-
                                    (((soil_weight.level-dry_soil_weigth)
                                    /dry_soil_weigth)*100)))*14.5))
            yield soil_weight.get(loss2)
        #the soil moisture level is changed out with a new calculation
        yield soil_moisture.get(soil_moisture.level)
        #the new soil moisture level is calculated
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #the planting process takes 1 day

        time_list.append(env.now) #the time of checkup is added to time list

        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
        print("The checkup ends at day %s" %env.now)
        print("The moisture level is now %s " %soil_moisture.level)

        #------------------------------------------------------------------------------

        ###################### third wait process ################################################

        for i in range (21):
            yield soil_weight.get((soil_weight.level -1450)*0.3)
            yield soil_moisture.get(soil_moisture.level) #the absorption the seeds grab from the soil
            if precipitation[env.now] > 0:
                yield soil_weight.get(loss2)
                #the addition of moisture changes the soil weight
                yield soil_weight.put(((precipitation[env.now])+
                                    (((bloom_mid-(((soil_weight.level-
                                                dry_soil_weigth)/dry_soil_weigth)*100)))*14.5)))
            else:
                yield soil_weight.put((((bloom_mid-
                                        (((soil_weight.level-dry_soil_weigth)/
                                                dry_soil_weigth)*100)))*14.5))
                yield soil_weight.get(loss2)
            #precipitation gets added to the soil moisture
            yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
            yield env.timeout(1) #each wait lasts for 1 day
            time_list.append(env.now) #second time input to time list

            #appends to correct list  soil weight level at current time
            weight_list.append(soil_weight.level)
            #appends to correct list soil moisture level at current time
            moisture_list.append(soil_moisture.level)
        #critical moisture level of max_moisture_level
        if soil_moisture.level not in range(bloom_min, bloom_max):
            for i in range (7):
                yield soil_weight.get((soil_weight.level -1450)*0.3)
                #the absorption the seeds grab from the soil
                yield soil_moisture.get(soil_moisture.level)
                if precipitation[env.now] > 0:
                    yield soil_weight.get(loss2)
                    #the addition of moisture changes the soil weight
                    yield soil_weight.put(((precipitation[env.now])+
                                        (((bloom_mid-(((soil_weight.level-dry_soil_weigth)/
                                                        dry_soil_weigth)*100)))*14.5)))
                else:
                    yield soil_weight.put((((bloom_mid-(((soil_weight.level-dry_soil_weigth)/
                                                    dry_soil_weigth)*100)))*14.5))
                    yield soil_weight.get(loss2)
                #precipitation gets added to the soil moisture
                yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
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        yield env.timeout(1) #each wait lasts for 1 day
        time_list.append(env.now) #second time input to time list
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
print("The wait process ends at day %s" %env.now)
print("The moisture level is now %s " %soil_moisture.level)

#--------------------------------------------------------------------------------------------------------------------

################## third checkup amending ##########################################################

if soil_moisture.level > max_moisture_level: #the critical moisture level is max_moisture_level
    #if the soil level is above drivable safe level, the process can timeout up to a week.
    # After a week, the process has to be completed
    for i in range(7):
        yield soil_weight.get((soil_weight.level -1450)*0.3)
        if precipitation[env.now] > 0:
            yield soil_weight.get(loss2)
            #the addition of moisture changes the soil weight
            yield soil_weight.put(((precipitation[env.now])+
                                        (((bloom_mid-(((soil_weight.level-
                                            dry_soil_weigth)/dry_soil_weigth)*100)))*14.5)))
        else:
            yield soil_weight.put((((bloom_mid-
                                        (((soil_weight.level-dry_soil_weigth)/
                                            dry_soil_weigth)*100)))*14.5))
            yield soil_weight.get(loss2)
        #the soil moisture level is changed out with a new calculation
        yield soil_moisture.get(soil_moisture.level)
        #the new soil moisture level is calculated
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #each waiting day takes one day
        time_list.append(env.now) #the time days are recorded in the time list
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
        print("The process is extended to day %s" %env.now)
        print("The moisture level is now %s " %soil_moisture.level)
yield soil_weight.get((soil_weight.level -1450)*0.3)
if precipitation[env.now] > 0:
    yield soil_weight.get(loss2)
    #the addition of moisture changes the soil weight
    yield soil_weight.put(((precipitation[env.now])+
                            (((bloom_mid-
                                (((soil_weight.level-dry_soil_weigth)
                                /dry_soil_weigth)*100)))*14.5)))
else:
    yield soil_weight.put((((bloom_mid-
                            (((soil_weight.level-dry_soil_weigth)
                            /dry_soil_weigth)*100)))*14.5))
    yield soil_weight.get(loss2)
#the soil moisture level is changed out with a new calculation
yield soil_moisture.get(soil_moisture.level)
#the new soil moisture level is calculated
yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
yield env.timeout(1) #the planting process takes 1 day

time_list.append(env.now) #the time of checkup is added to time list
#appends to correct list  soil weight level at current time
weight_list.append(soil_weight.level)
#appends to correct list soil moisture level at current time
moisture_list.append(soil_moisture.level)
print("The checkup ends at day %s" %env.now)
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print("The moisture level is now %s " %soil_moisture.level)

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######################## fourth wait process ##################################

for i in range (14):
    yield soil_weight.get((soil_weight.level -1450)*0.03)
    yield soil_moisture.get(soil_moisture.level) #the absorption the seeds grab from the soil
    if precipitation[env.now] > 0:
        #the addition of moisture changes the soil weight
        yield soil_weight.put((precipitation[env.now]))
        yield soil_weight.get(loss3)
    else:
        yield soil_weight.get(loss3)
    #precipitation gets added to the soil moisture
    yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
    yield env.timeout(1) #each wait lasts for 1 day
    time_list.append(env.now) #second time input to time list
    #appends to correct list  soil weight level at current time
    weight_list.append(soil_weight.level)
    #appends to correct list soil moisture level at current time
    moisture_list.append(soil_moisture.level)


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######################## harvesting ########################################################

if soil_moisture.level > max_moisture_level: #the critical moisture level is max_moisture_level
    #if the soil level is above drivable safe level, the process can timeout up to a week.
    # After a week, the process has to be completed
    for i in range(7):
        yield soil_weight.get((soil_weight.level -1450)*0.02)
        yield soil_moisture.get(soil_moisture.level) #the absorption the seeds grab from the soil
        if precipitation[env.now] > 0:
            #the addition of moisture changes the soil weight
            yield soil_weight.put((precipitation[env.now]))
            yield soil_weight.get(loss3)
        else:
            yield soil_weight.get(loss3)
        #precipitation gets added to the soil moisture
        yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
        yield env.timeout(1) #each wait lasts for 1 day
        time_list.append(env.now) #second time input to time list
        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)
        print("The process is extended to day %s" %env.now)
        print("The moisture level is now %s " %soil_moisture.level)
yield soil_weight.get((soil_weight.level -1450)*0.02)
if precipitation[env.now] > 0:
    #the addition of moisture changes the soil weight
    yield soil_weight.put((precipitation[env.now]))
    yield soil_weight.get(loss3)
else:
    yield soil_weight.get(loss3)
#the soil moisture level is changed out with a new calculation
yield soil_moisture.get(soil_moisture.level)
#the new soil moisture level is calculated
yield soil_moisture.put(((soil_weight.level-dry_soil_weigth)/dry_soil_weigth)*100)
yield env.timeout(1) #the planting process takes 1 day
print("The harvest ends at day %s" %env.now)
print("The moisture level is now %s " %soil_moisture.level)
time_list.append(env.now) # time input to time list
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        #appends to correct list  soil weight level at current time
        weight_list.append(soil_weight.level)
        #appends to correct list soil moisture level at current time
        moisture_list.append(soil_moisture.level)

        #------------------------------------------------------------------------------


#--------------------



##################### ENVIRONMENT PROCESS (2/2) ####################################################

#setting the process of the environment as the main prosses def
env.process(potato_production(env, soil_weight, soil_moisture, complete_cap))
total_days = 120 #amount of days in the simulation
env.run(until = total_days) #setting the environment time to total amount in the simulation

#-----------------------------------------------------------------------------------------------

####################### PRINT OUTS ##############################################################
print("The amount of days in the simulation is %s" %len(time_list))


plt.figure()
plt.hist(precipitation)
plt.title("Precipitation levels observed in simulation")
plt.xlabel("Precipitation amount in simulation")
plt.savefig("2018 precipitation levels.png")


plt.figure()
plt.step(day_list, precipitation, where="post")
plt.title("Precipitation over days in simulation")
plt.xlabel("Days in simulation")
plt.ylabel("Precipitation in simulation")
x1,x2,y1,y2 = plt.axis()
plt.axis((x1,x2,0,250))
plt.savefig("2018 precipitation levels over time.png")


plt.figure()
plt.hist(moisture_list)
plt.title("Moisture levels observed in simulation")
plt.xlabel("Moisture levels in simulation")
plt.savefig("2018 moisture levels.png")

plt.figure()
plt.step(time_list, moisture_list, where="post")
plt.title("Moisture levels over days in simulation")
plt.xlabel("Days in simulation")
plt.ylabel("Moisture levels in simulation")
plt.savefig("2018 moisture levels over time.png")


#-----------------------------------------------------------------------------------------------
```