Utrecht University
IMAU

Climate Physics

Development of a Comprehensive Local Climate-Responsive Agricultural Model

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July 11, 2023

Abstract

This study introduces a simple comprehensive local agricultural model to explore the dynamics of population, food production, and land use. The model incorporates diverse scenarios and policies to provide insights into the interactions between population growth, food availability, and climate-related factors. The importance of finding a balance between food production and land preservation is emphasized, as agriculture can both contribute to and detract from Green Growth. The model demonstrates the impact of different policies on population size and the effects of climate damage and land degradation. Comparisons between different policymakers reveal the trade-offs between sustainability and productivity. The application of a Malthusian framework highlights the consequences of unrestricted food production on population dynamics. The models results underlines the need for sustainable land management and provide a foundation for further research on policies that promote Green Growth while ensuring food security and environmental sustainability.

Contents

1 Introduction

Green Growth is the policy that strives to ensures that natural assets continue to provide resources, and environmental services whilst fostering economic growth and development upon which well-being relies (OECD). In the Green Growth debate, agriculture stands out as it can both detract from and contribute to Green Growth (*Stevens*). The cultivation of agricultural lands affects natural resource availability including soil, water, and the environmental quality manifesting through processes such as resource depletion, pollution, and loss of biodiversity. At the same time, agriculture is a vital component of the global food system and plays a crucial role in meeting the needs of a rapidly growing global population, which is projected to reach 9.7 billion by 2050 (*FAO*, 2021). To meet this increasing demand, food production must rise by 70% (*FAO*, 2018).

On the other hand agriculture can also be considered as an economic sector as it contributes to economical growth (*Johnston and Mellor*, 1961),(*Mundlak*, 2000). Global competition in the agricultural sector has led to a focus on maximizing production and reducing costs, often at the expense of environmental sustainability (*Benton and Bailey*, 2019). However, the short-term profitability of intensive agriculture is likely to come at the expense of long-term soil health and viability (*EEA*, 2019), and is the primary reason for soil degradation and consequently reduced agricultural output (*IPES*, 2016). In Europe alone, an average of 2.5 tonnes per hectare of soil is lost every year, which is considerably more than the average annual rate of soil formation (around 1.4 tones per hectare) (*Panagos et al.*, 2015). These high levels of soil loss lead to a loss of agricultural productivity and come with significant economic costs (*Panagos et al.*, 2018)).

Additionally, approximately 10% of Europe's total greenhouse gas emissions originates from agriculture (*Eurostat*, 2018). Affecting meteorological conditions, which changes temperature and precipitation patterns and increases occurrence of extreme weather events leading to increased crop failure. These factors pose a threat to food and nutritional security affecting the health of people and the sustainability of the food system (*EEA*, 2019),(*EEA*, 2021). Consequently, the importance of land management decisions have increased significantly in order to sustain sufficient food production. The Dystopian Schumpeter meeting Keynes model (DSK model) is an integrated assessment model that incorporates agent-based modeling to analyze the dynamic interaction between the economy and the climate system especially for the industrial sector (*Lamperti et al.*, 2018). With the help of the DSK model, policymakers are able to formulate policies and strategies towards a Green Growth transitions. However, the DSK model does not feature the agricultural sector.

In this study, a novel simple local agricultural model is introduced, which can be employed to perform scenario analysis, land-management practices and policy settings as in e.g. the AGRILOVE model by *Coronese et al.* (2021). This model is specifically designed to examine the dynamics of a population (both constant and variable) in relation to agricultural production. The model highlights the population as a key factor driving food demand, leading to land-use transition to meet the required needs. By examine different policies for a population, this model can help policymakers understand the level at which they can sustain their population in terms of food availability. The model provides insights into the dynamics of agricultural production, land-use transitions, and the interplay between population growth, food availability, and climate-related factors. These insights are crucial for formulating effective policies and strategies to address the challenges of food security and sustainable land use in a changing climate.

This study begins with a theoretical explanation of the concepts of land degradation, how crops (specifically the potato) are influence by climate change and the Malthusian framework. Followed by a general description of the workings of the model and tuning of the damage function. Next, the results of the model are discussed presenting the outcomes and insights obtained through various simulations and analyses. Finally the discussion and conclusion follow, where limitations and shortcomings of the model are being discussed along with possible future research avenues.

2 Theoretical background

In this particular agricultural model, food production is considered, which is amongst others hampered by climate damage. To make the function of climate damage in the model more realistic, the climate damage function has been tuned to potato crop yield data from the Netherlands. In order to get a better understand of the processes, first land degradation and how it affects the agricultural system is discussed. Subsequently, the effects of climate change affecting potato harvest is studied. Thereafter, the Malthusian framework, which explores how resource shortages can impact a population. Providing for a better understanding in the relationship between population growth, recourse constraints, and the potential for societal collapse.

2.1 Land degradation

The lasting effects of intensive agriculture during the Roman Empire's occupation of French territories serve as an example of irreversible land degradation (*Dupouey et al.*, 2002). Land degradation is characterized by the long-term deterioration of soil quality, resulting from processes that undermines the capacity of land that provides ecosystem goods (*IPBES*, 2018). Land degradation involves physical disruption caused by erosion, which refers to the removal of soil by water, wind, or by farming activities such as tillage (*Ginoux et al.*, 2012). Negligence towards sustainable soil management, excessive use of pesticides, fertilizers, and a lack of consideration for environmental have contributed to soil degradation leading to loss of essential nutrients and minerals necessary for plant growth (*Nabhan et al.*, 1999).

Climate change acts as an accelerator of land degradation by altering and intensifying rainfall patterns and temperatures (*(Program)*, 2005). Soil erosion is exacerbated by increased intensity of rainfall, while long-term droughts diminish vegetation cover, rendering the soil more susceptible to erosion and nutrient depletion. Leading to significant consequences regarding crop production and their nutritional quality (*Osborne and Wheeler*, 2013), (*Tigchelaar et al.*, 2018), (*Iizumi and Ramankutty*, 2015), (*Loladze*, 2014) , (*Myers et al.*, 2014), (*Ziska et al.*, 2016), (*Medek et al.*, 2017). Furthermore, this degradation contributes to the soil's natural capacity to hold water, which increases the the risk of flooding (*Daniel*, 2015), and hence additional land degradation. The consequences of land degradation extends beyond reduced crop production including food insecurity, increased food prices, climate change, environmental hazard, loss of biodiversity and diminished ecosystem services (*Franchini and Mannucci*, 2015), (*Raiten and Aimone*, 2017).

Intensification of land cultivation has caused increased land degradation, posing challenges for food security (*Gupta*, 2019). As land degradation reduces crop yields, farmers resort to more intensive cultivation practices to keep up with the demands. However, widespread land degradation can feed back into the climate system, reinforcing climate change as soil carbon dioxide (CO_2) and nitrous oxide (N_2O) are released into the atmosphere, becoming significant contributors to climate change (*Khan et al.*, 2022),(*Stocker*, 2014). Whilst agriculture and land clearance have historically been the main drivers of land degradation (*Intergovernmental Panel on Climate Change*, 2022), it is important to note that agriculture does not always have to result in land degradation. Sustainable land practices are possible but not always practised due to social and economical pressure. Nevertheless, sustainable land management is essential for mitigating the adverse effects of agriculture on land and is crucial for long-term environmental and socio-economic sustainability.

Scenarios of climate change in combination with land degradation models can provide useful knowledge on what kind and extent of land management will be necessary to avoid, reduce and reverse land degradation.

2.2 Climate change and potato crops

The potato is the most important non-grain crop worldwide (*FAO*, 2019), with its viable climate smart nature and relative high nutrient content the potato is considered a crop that can potentially combat food insecurity (*Lutaladio and Castaldi*, 2009),(*Devaux et al.*, 2014), (*Jennings et al.*, 2020). However, with increasing temperatures, prolonged droughts, intensified precipitation and inconsistent rain patterns, agriculture faces significant challenges (*FAO*, 2015).

Various studies have been conducted on the impact of climate change on potato crops, yielding inconsistent results. Studies of *Adekanmbi et al.* (2023), *Brassard and Singh* (2007), *Vashisht et al.* (2015) project future decrease in potato yields due to increased temperature and CO_2 concentrations, particularly under changing precipitation patterns. However, *Tooley et al.* (2021) and *Tubiello et al.* (2002) suggest that climate change might lead to increased potato yields . The observed variations in the projected future potato yields, contribute to differences in geographical area, management practices, and differences in General Circulation Models (GCM) used during for the research (*Adekanmbi et al.*, 2023).

Temperature plays a crucial role in potato growth, with the crop thriving between $16°C$ and $25°C$. However, temperatures above the optimum range leads to a decline in development rate (*Nasir and Toth*, 2022). Where tuber growth of the potato is inhibited above a temperature of $33°C$ (*Ingram and McCloud*, 1984), (*Wolf et al.*, 1990), (*Timlin et al.*, 2006). Frost events during potato development can also be detrimental for the growth of the potato and cause damage, resulting in soft and blackened parts (*Chang et al.*, 2014).

Precipitation is another critical factor for potato growth, with an ideal range of 500mm to 700mm during the growth period (*FAO*, 2019). Studies have shown that changes in potato yield correlate with changes in precipitation, indicating a future decrease under rainfed conditions (*Adekanmbi et al.*, 2023). Water shortage beyond 60% due to drought reduces the growth rate, while excessive water leads to leaching and tissue decay known as blackheart (*Nasir and Toth*, 2022).

CO_2 can have both positive and negative effects on potatoes. Increased CO_2 levels can enhance photosynthesis rates and accelerate bulking, leading to faster potato growth(*Wheeler et al.*, 1991). However, elevated CO_2 increases the susceptibility of potatoes to pests and diseases, and interferes with natural biological processes (*Finnan et al.*, 2005). Nonetheless, the overall impact of rising CO_2 levels on potato yields is projected to be positive, with expected global increases by 2050 due to CO_2 fertilization and adaptation benefits (*Finnan et al.*, 2005), (*Fleisher et al.*, 2008).

It is worth mentioning that the crop yields determinant is not only limited to temperature, precipitation and CO_2, but also depends on other factors, such as soil quality (e.g., nutrients and salinity), soil moisture, seed quality, leaf development, temperature sensitivity, fertilization, pests, soil management, and other parameters play an essential role in crop growth process and the harvested yields, but are not included in the scope of this study.

2.3 Malthusianism

In 1798, Thomas Malthus introduced his hypothesis on population growth and resource limitation in his work "An Essay on the Principle of Population" (*Malthus et al.*, 1992) as a rebuttal on the believe of the perfectibility of humanity. Malthus argued that with an increasing population the happiness and well-being of society requires a corresponding increase in food production. However, this capability of exploitation cannot be infinite due to the planetary boundaries. Hence, when the population growth exceeds the capacity of available resources a Malthusian catastrophe occurs, which has the effect of restoring balance by reducing a population due to famine, war or poverty. Nevertheless, modern society seems not capable to recognise its limits and will therefore often overshoots them provoking irreversible damages such as climate damage.

Malthus's theory can be represented by a differential equation describing population change over time ($\frac{dP}{dt}$), which is influenced by the growth rate ($\frac{dG}{dt}$) and the mortality rate ($\frac{dM}{dt}$):

$$\frac{dP(t)}{dt} = -MP(t) + GP(t) \tag{1}$$

where P represents the population, G represents the growth rate, and M represents the mortality rate. The mortality rate is influenced by a shortfall in food supply compared to the actual required demand. In reality, the situation would be significantly more nuanced due to the cultural shifts and complex regional and individual disparities around access to food, water and other resources (FAO, 2009)

Since the publication of Malthus's work, there have been divergent views on the validity of his theory. The debate over Malthusianism often centers around the relationship between population growth and resource availability. However, scholars hold contrasting views on the Earth's carrying capacity (i.e. resource availability). Some argue for limitless potential due to human ingenuity (*Simon*, 1996), while other stress the need for responsible resource management and population control (*Bartlett*, 1994). A more modern formulation of the Malthusian theory states that while technological progress may temporarily increase per capita income through resource abundance, the finite nature of land as a limiting factor eventually brings per capita income back to its long-run level (*Ashraf and Galor*, 2011).

Still, the Malthusian perspective on population growth and resource constraints continues to be a significant discussion, influencing national and international environmental policies. Some economists argue that technological advancements and agricultural improvements since the Industrial Revolution have enabled societies to overcome the Malthesian trap (Malthusian catastrophe) [BRON]. Additionally, proponents of sustainable development and ecological economics emphasize that potential ecological collapse resulting from overpopulation and overconsumption (*Catton and Dunlap*, 1980), (*Club van Rome*, 1972). However, others contend that extreme poverty and persistent challenges in developing countries suggest the Malthusian trap continues to operate (*Rostow*, 1982), (*Bremmer*, 2010). Evidence supporting Malthusianism can be observed in poorer countries with booming populations, particularly in regions like East Africa, which have yet to escape the Malthusian trap (*Korotayev and Zinkina*, 2015).

3 General structure and timeline events

The model is constructed with a bottom-up structure where individual parts are specified in detail and linked to form a larger system. This approach enables a separate investigation of the driving forces behind land degradation and the impacts of climate change on potato crops within the model. The model has finite resources consisting of 100 plots of land, which all have an initial productivity of 100% (i.e. no land degradation has occurred yet). Every plot of land is designed as an object, which all have the same set of rules. The land is either nature or agriculture, the inital state of the land is randomly assigned based on the initial population of the model. Each plot of land has a standardized size based on the average surface of a Dutch agricultural field, which is approximately 5.5 hectares (*CBS*, 2022). The average potato production per hectare in Netherlands in 2021 is 40,000 kg (*Koen van Gelder*, 2022), where one kilogram of potato accounts for 800 kilocalories.

The interactions between the different objects in the model are shown in figure 1. The population, which is fed with crops originating from the land, is the leading factor in the amount of land used for crop production. When there is an abundance of food, the excess is stored for future use. Conversely, if the harvested food is insufficient to feed the population, food can be withdrawn from storage to compensate for the shortage. The yield on the agricultural lands depends on various factors such as land cultivation practices, land degradation and climate influences. All these factors, including the population and storage, influence the policy for the next year. The new policy, in turn, affects all other factors. It is important to note that transportation of food is not considered in this model, since it is a local model.

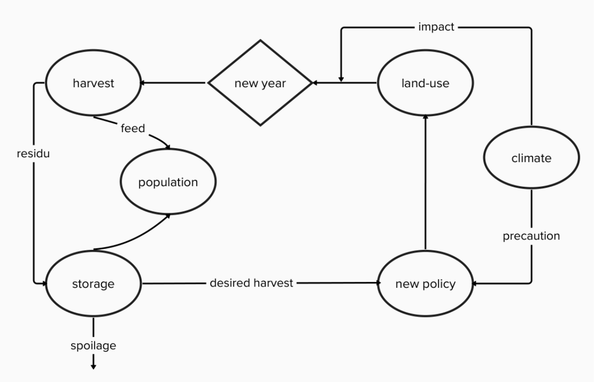


Figure 1: General structure of the agricultural policy model.

The yearly sequence of events in the model is as follows:

I Harvest of all potato crops and storing them into the storage. This typically occurs between late August and October.

II The food is evenly distributed amongst the population. Any leftover crops are are stored such that they can be used to feed the people when there is not enough harvest to feed the population due to land degradation or climate damage.

III In case of a variable population, growth and mortality occurs and the new population for the next year is established.

IV The decisionmaker assesses the storage, population, and the state of the land to estimate the required yield for the next year and formulates a new policy accordingly.

V The new crop is cultivated based on the policy.

VI Climate damage occurs, affecting potato growth and influencing the yield for the following year. Additionally, land used for conventional agriculture degrades, reducing its effectiveness and yielding lower outputs in subsequent year.

Two models have been developed to account for the population dynamics in the agricultural model. In the first model, the population is treated as a constant, where the amount of food required is determined solely by the fixed population size. The second approach, inspired by Malthus' principle of population, considers a variable population that adjusts based on the availability of food.

Farmers in the agricultural model are categorized into two types: the conventional farmer and the sustainable farmer.

1. Conventional farmers:
   The conventional farmer utilizes the latest techniques to maximize the productivity of the land, resulting in harvesting the maximum capacity of the respective plot of land. These intensive farming practices exploit the land and lead to land degradation of 1% per year of conventional farming

2. Sustainable farmers:
   The sustainable farmer adopts environmentally-friendly methods to cultivate the land, which only yields a harvest of 70% of the maximum capacity of the land. These practices however, ensure that no land degradation will occur.

With these two types of farmers, examination of the trade-off between intensive farming and sustainable practices in terms of land productivity and land degradation can be examined.

Land degradation refers to the decline in productive capacity of the land due to various factors, including intensive farming practices. Therefore, it is assumed that 1% of the agricultural land degrades per year of conventional farming (i.e., reduction of land productivity). When the land is left fallow (i.e., made nature again) for an entire year, it has the ability to restore itself at a rate of 1%, effectively regaining its lost productivity. This implies that the land can restore itself at the same rate at which it degrades, providing a natural mechanism for recovery. In case there is no land degradation it automatically entails that there is no land restoration, since land productivity is not able to go beyond 100%.

Climate damage is represented by a lognormal probability density function (PDF) that is used to determine the impact of weather conditions on the harvest. By selecting a random number from this PDF each year, the model can simulate the occurrence of favorable or unfavorable weather conditions that affect potato growth. Where a negative selected number implies a better than average year, and a positive selected number implies a worse than average year.

To establish the parameters of the lognormal PDF, a correlation study has been conducted to analyze the relationship between potato yield and various meteorological factors in the Netherlands. The results of this study are displayed in section 4. It is important to note that the policymaker in the model has the ability to account for some level of anticipated climate damage.

To ensure statistical reliability, the model output is averaged over 10 Monte Carlo simulation. By employing the Monte Carlo iteration technique and exploring various scenarios, providing a robust and comprehensive insights into the dynamics of the agricultural system under different conditions.

Storage is used to store the surplus of food from the harvest, with a maximum of one years worth of food for the population. Because this model does not account for international trading (explicitly), the storage acts to a certain extent as a buffer for climate variability or damage. However, due to rotting processes, 10% of food is lost in the storage each year. Note that this is an optional function which can be turned on and off in the model. The policymaker is able to account for such losses, and hence will use more land in order to keep the storage stocked.

Policymakers: Three distinct policy approaches have been examined in the model, each with its own distinct strategy and objectives: the nature lover, the switcher, and the bio farmer.

1. Nature lover:
   The nature lover prioritizes returning land to its natural state and minimizing agricultural land usage. This policy focuses on conventional farming techniques and uses only the minimum amount of land necessary for food production such that it can maximize nature.

2. Switcher:
   The switcher aims to optimize agricultural productivity by constantly switching to the most productive land available. This policy selects the highest yielding land each year, often leading to a reduced presence of natural areas as agricultural land takes precedence.

3. Bio farmer:
   The bio farmer emphasizes on sustainable farming practices, striving to strike a balance between agricultural productivity and environmental conservation. While the Bio Farmer recognizes the importance of nature, there is a willingness to allocate some natural areas for agricultural use in order to promote sustainability.

A more in dept description of how the policymakers establish their policy is described in appendix A.

4 Tuning of the damage function

The agricultural model presented in this study focuses on the impact of climate damage on potato crop yield. To establish the relationship between climate factors and potato yield, a linear multi-variable analysis has been conducted using data on temperature, precipitation, and crop yield in the Netherlands. Temperature and yield data were obtained from the Food and Agricultural Organization of the United Nations (*FAO*, 2023), (*FAO*, 2022), precipitation data was collected from the Copernicus data-bank (*Copernicus Climate Change Service*, 2019). All data-sets represent data of the Netherlands covering the years from 1961 up to 2021 for the months of April to September (i.e., growing season).

To analyze the yearly variability in the data, all raw data-sets is detrended. From the temperature anomaly data and precipitation data a first-order function was removed. From the crop yield data a second-order function was removed. It is worth noting that the influence of changing CO_2 levels on potato crop growth, although important, falls outside the scope of this multi-variable correlations as it represents a long-term trend rather than yearly variability.

Location	R	R^2
The Netherlands	-0.02	0.08

Table 1: Correlation coefficient (R) and coefficient of determination (R^2) for a multi-variable analyses comparing potato yield with temperature and precipitation in the Netherlands.

Table 1 displays the results of the linear multi-variable correlation. The correlation coefficient is just negative with a corresponding coefficient of determination of nearly null. Because of the low coefficient of determination, the linear multi-variable regression model turns out not to be able to explain the potato yield with temperature and precipitation.

To have a better indication of how potato harvest varies in the Netherlands, data of the gross consumption potato harvest per hectare from the year 1994 up to 2022 was gathered from the CBS (*CBS*, 2023). In this data-set, the mean concerns 48800 kg potatoes per hectare with a standard deviation of 3100 kg potatoes per hectare, which gives a percentile difference of approximately 6%. Based on these statistics the lognormal PDF is tuned to the order of magnitude of these results, as can be seen in figure 2.

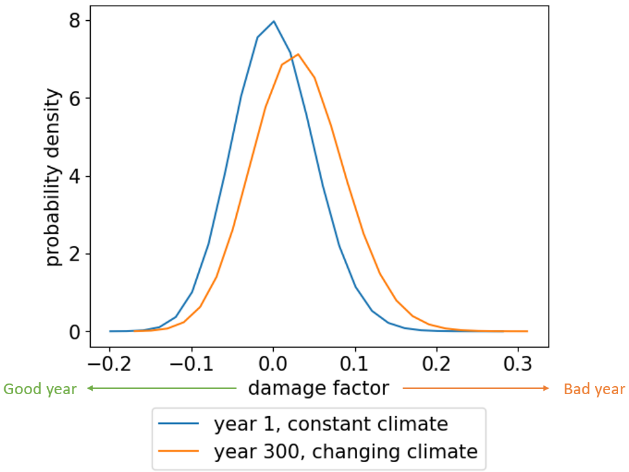


Figure 2: The damage function represented by a lognormal probability density function. The blue line represents a constant climate and/or the first year when there is climate change. The orange line represents the PDF after 300 years if there would be climate change.

The lognormal PDF that presents the first year and remains the same if climate does not change, has a mean of 0.0 and a 90 percentile of 0.06. Hence, if the policymaker wants to account for a 90 percentile climate damage it will increase its desired harvest by 6%. When a changing climate is regarded, the mean of the lognormal shifts to 0.03 with a percentile of 0.11 after 300 years.

5 Model results

The model considers two population scenarios: a constant population and a population that varies with food availability based on the Malthusian framework. By examining these scenarios, the model provides insights into the implications of different population dynamics on agricultural production and food security.

To provide a clear overview of the available scenarios and their corresponding abbreviations, Table 2 displays the various variables and their states:

Variable	Abbr.	State	Comment
Farmer	NL	-	Natuer lover
	SW	-	Switcher
	BF	-	Bio farmer
Climate damage	C	0	No climate damage.
		1	Climate damage under a constant climate.
		2	Climate damage under a changing climate.
Land degradation	D	0	No land degradation.
		1	Land degradation of 1% per conventional harvest. Automatically also implying that there is also land restoration of 1% per year of the land being nature.
Precaution	P	0	Policymaker does not account for potential climate damage.
		1	Policymaker accounts for potential climate damage by taking the percentile 90 of the current log-normal PDF.
Spoiled food	S	0	No food spoilage in the storage.
		1	Every year 10% of the food spoils in the storage.

Table 2: Summary of Model Options, Scenarios, and Abbreviations

5.1 Baseline

The establishment of this baseline case serves as a reference point that allows for comparisons of results from other scenarios. Allowing assessment of the impact of different factors, such as land degradation, climate damage, and policy interventions on agricultural production and food security.

The baseline scenario represents the maximum potential yield that the model can achieve under ideal conditions; all plots of land are farmed conventionally, yielding maximum capacity. Additionally, there is no spoilage in storage, no land degradation, and no climate damage allowing for an optimal agricultural production. The baseline production is specifically designed to meet the food requirements of the baseline population. This implies that the maximum yield obtained in the baseline scenario is sufficient to feed 100% of the population within the model.

5.2 Constant population

Figure 3 presents a time-lapse simulation displaying the various processes occurring in scenario NL_C1_P1_S1. In this scenario, the population size is set at 33% compared to the baseline population. The figure provides valuable insights into the dynamic interactions within the simulation, showcasing the changes in land use, agricultural productivity, and the preservation of natural areas over time.

The beginning of the simulation shows a relatively steady harvest supply. Due to climate damage there is variability in the supply, but on average there are more crops cultivated than are needed to provide the entire population of food. This surplus of yield is stocked in the storage, which is able to function as a buffer for potential climate damage. However, due to an increasing land degradation, over time the harvest supply declines. Because of this, the nature lover is forced to convert nature plots into agricultural plots to match demand. It will do so until the maximum capacity is reached and no more plots can be employed for agricultural purposes. All agricultural plots used, produce to their maximum harvest potential based on the current productivity of the land. However, the trade-off is that the land degrades by 1% per year. Consequently, each year, the policymaker accepts a gradual decline in land productivity as a compromise for the preservation of nature. Once the storage and harvest combined do not have enough provision to maintain the entire population, technically the policymaker has failed to provide enough food and is forced to import food from others to prevent a famine.

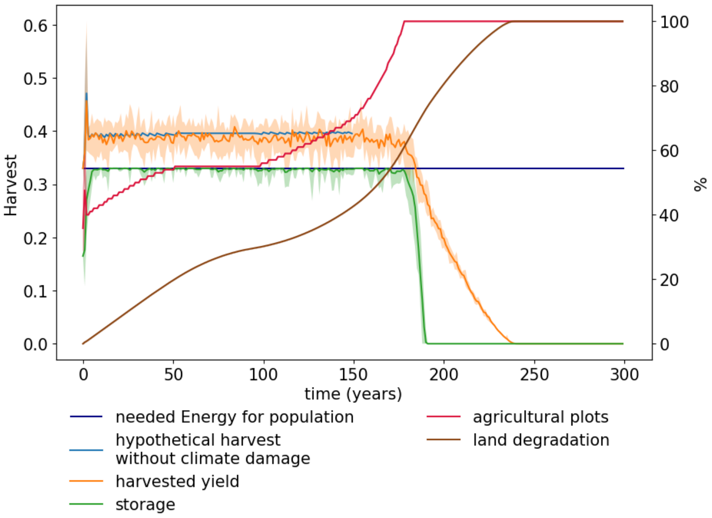


Figure 3: Time-laps visualization of scenario NL_C1_P1_S1 for a population of 33%, where harvest relative to the baseline is displayed on the left y-axis, and the percentage of resources is used or degraded is depicted on the left y-axis. Both are plotted against simulation time.

If scarcity of food occurs it could manifest itself in many different ways depending on how food is divided amongst the population. In the event of a food shortage, the increased prices make food unaffordable for a part of the population, particularly those with limited financial resources. As a result, access to food becomes restricted, which increases the mortality rate. But in the case where food is divided equally amongst the population, this could result in a population that gradually declines in health. The population does not perish right away in the instance of a food shortage, but for example becomes less effective in cultivating the fields. This would mean that there would be another factor that is able to limit the harvest other than climate damages and land degradation. However, these cases fall outside the scope of the research.

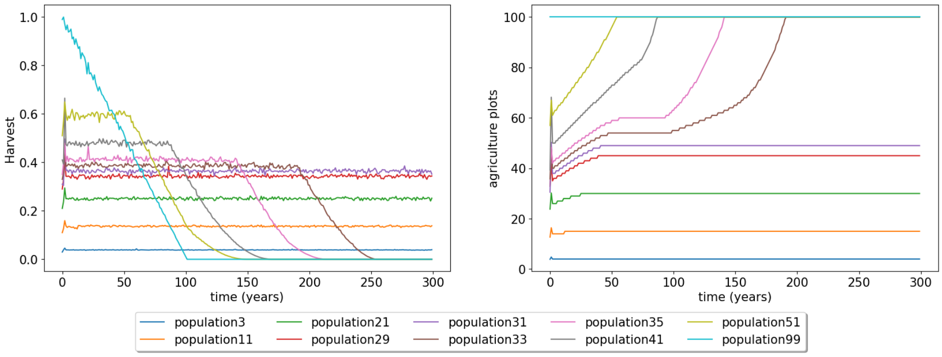


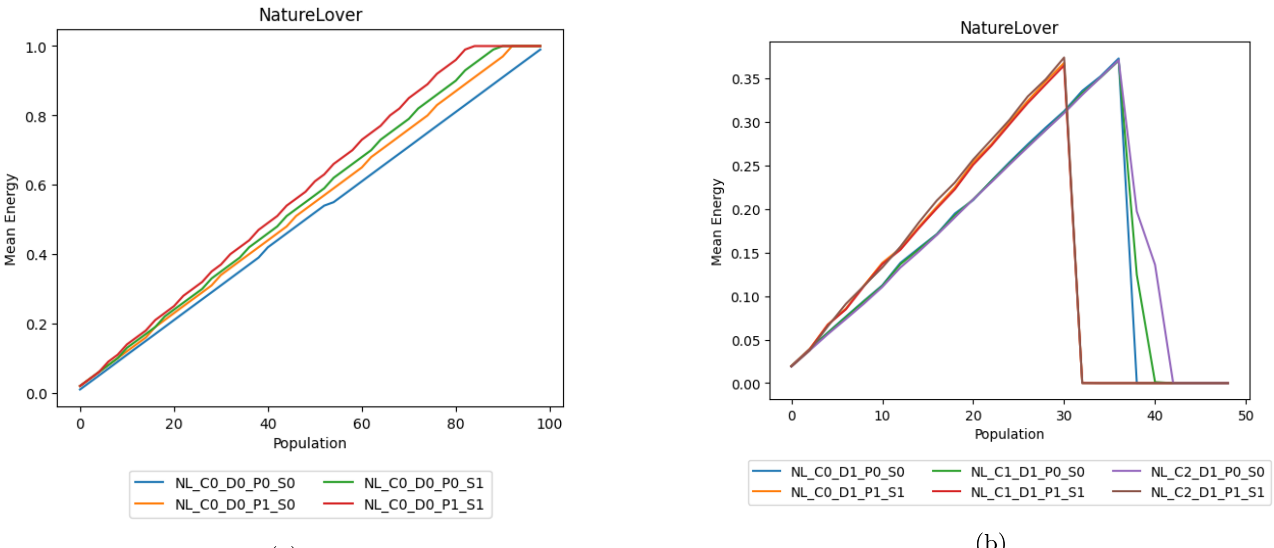
Figure 4: Scenario NL_C1_D1_P1_S1, for multiple populations per unit land. In the left figure the mean energy respective to the baseline is displayed against the simulation time of 300 years. The right graph displays the amount of agricultural plots used for the cultivation of crops against simulation time.

As the population per unit of land increases, the nature lover faces challenges in sustaining the entire population with an adequate food supply. As can be seen in figure 4, where the policymaker is able to provide sufficient crop production up to a population of 31%. However, as the population continues to increase beyond 31%, the harvest starts to decline over time due to land degradation. This decline reflects that the policymaker is using all of its available land in a non-sustainable manner. Implying that the policymaker is unable to sustain the entire population with an adequate food supply, indicating potential food shortages and challenges in maintaining population well-being.

The steady amount of crop production observed in the mean energy yield is corroborated by the amount of land plots used for agriculture, which is depicted in the right graph of figure 4. When the nature lover is able to produce enough food for the entire population, the number of land plots used for agriculture remains stable. This indicates an efficient use of available land to meet the populations food demands without needing to expand agricultural activities. However, when there is not enough food produced to maintain the population, the policymaker is compelled to eventually maximize the utilization of land plots for agriculture. This means that all available land suitable for farming is employed in an effort to increase crop production and meet the populations food requirements.

This dynamic relationship between food production, land utilization, and population sustainability highlights the interconnections of these factors within the agricultural model. It underlines the significance of efficient land management, sustainable farming practices, and proactive measures to ensure food security and the well-being of the population. It is important to note that the simulations presented only cover a 300-year period, and it is possible that land degradation may continue beyond this time-frame.

To explore the carrying capacity of the policymaker nature lover under different policies and scenarios, a series of simulations have been conducted with increasing population sizes. The simulations were performed for 50 different populations, starting from a factor of 1 with increments of 2 for each scenario.



(a)

(b)

Figure 5: Mean energy against population per unit of land for various scenarios under a nature lover policy. Mean energy yield is averaged the last 50 years of the simulation (i.e. year 250 up to 300).

In the baseline scenario where there is no factor hampering the harvest (i.e., no land degradation and no climate damage), the policymaker is able support a population equal to the maximum capacity of the land. When there is no variability for the policymaker to account for (i.e., no spoilage, and no potential climate damage, as represented by the blue line in figure 5a), the amount of cultivated agricultural plots grows linearly with the increasing size of population per unit of land. Consequently, the harvested mean energy yield grows linearly with its population.

In the scenario where the policymaker accounts for climate damage, but the climate damage always happens to be zero (i.e. the orange line in figure 5a), the policymaker increases its harvest with 6% (According to the 90 percentile from the lognormal PDF, explained in section 4). This entails that the policymaker will employ more land earlier on to compensate for possible climate damage. As a result, the maximum capacity is reached at an earlier stage. This proactive strategy aims to ensure an adequate food supply and maximize the capacity to support its population. In the scenario where 10% of the food in storage spoils every year due to rotting processes (i.e. the green line in figure 5a), the policymaker chooses to compensate for this in the same way it accounts for potential climate damage. Therefore, the policymaker will reach the maximum capacity of its land with a population, which is 10% smaller compared to the scenario where no food is lost in storage. Note that when the policymaker accounts for possible climate damage and food loss in storage does not directly hinder the cultivation of crops. The policymakers ability to provide for the population at a 100% level, as defined in the baseline scenario, remains intact.

Introducing scenarios where land degradation and climate damage impede with the amount of crop harvest from the fields, leads to changes in the policymaker ability to sustain the population. Figure 5b illustrates the combined effects of different scenarios and policies on the performance of the nature lover. The occurrence of land degradation obligates the policymaker to earlier enforce more plots of land for agricultural purposes and is hence not able to uphold as big as a population when there is no land degradation.

The impact of climate damage appears to be relatively minor, even in a changing climate. Employing policies, which enforce earlier employment of agricultural land, have a larger impact on the size of the population that can be maintained. The policies employed have a counterproductive working, because instead of mitigation these policies enhance land degradation, which seems to be the major factor in the loss of crop production. It is worth noting that these findings are specific to the nature lover policymaker and may differ for the switcher and bio farmer policymakers, who employ different strategies and approaches to address these challenges.

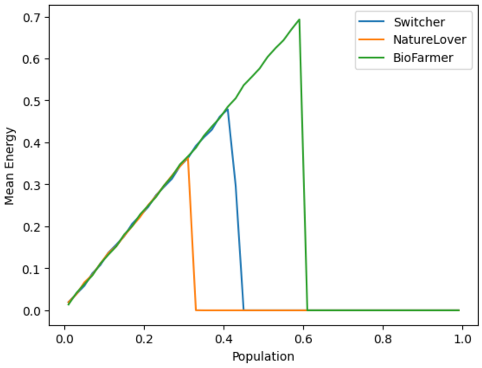


Figure 6: Comparison of the different policymakers under scenario C1_D1_P1_S1, where the mean energy yield is plotted against the population per unit of land.

The results of exploring the different policymaker under scenario C1_D1_P1_S1 are displayed in figure 6, which gives insights into the policymakers respective abilities to sustain the population under these conditions. It can be seen that the general behaviour for all three policymakers is the same. In the beginning, the mean energy yield increases linearly with the people land factor, and eventually the land has degraded because of which crops can no longer be produced. The linear increase in mean energy yield, as long as sufficient resources are available, can be attributed to the relationship between population size and energy demand. In the model, it is assumed that each person consumes the same amount of calories per day. Therefore, a larger population indicates a greater overall energy requirement, leading to a linear growth in mean energy yield for an increasing population. Figure 6 illustrates the performance of different policymakers in terms of providing sufficient food to the population. Among the three policymakers, the bio farmer demonstrates to be the most successful in meeting the food needs for the largest population, followed by the switcher, and finally the nature lover. However, if other factors (e.g., production of wood, CO_2 levels) would have been taken into account the ranking of the best to worst policymaker would not necessary remain the same.

The nature lover always makes a policy where it fully exploits all the agricultural plots of land in order to maintain as much nature as possible, because of which it sustains the smallest population. The policymaker bio farmer is able to maintain the largest population, because the bio farmer would do everything in its power to not let the land degrade. This means that only when strictly necessary the bio farmer would employ conventional farming (in contrary to the other two policymakers), such that it is able to farm for a longer period of time without damaging the land. The switcher on the other hand, does only employ conventional farming, but changes from land every year. This means that with a low enough population, the switcher will use the maximum capacity of a plot of land, degrade the land by 1%, but then makes the land fallow and allowing it to restore itself again. It then proceeds using other plots of land that have a higher productivity for the harvest of next year. The switcher however, comes into trouble when it has to use more than half of the maximum amount of available land plots. At that moment, the switcher is forced to degrade the land more than it is able to give it time to restore itself.

5.3 Variable population

In the Malthus model, the population is no longer considered a constant variable. Instead, it experiences annual growth of 1%. This growth rate reflects the natural increase in population over time. In the Malthusian framework, the population's well-being and survival depend on the availability of adequate food resources. When there is insufficient food to meet the populations needs, mortality rates increase due to malnutrition and other related factors. The populations food requirements are directly linked to its size, as a larger population necessitates a greater food supply to sustain its members. By incorporating the dynamics of population growth, food availability, and mortality, the Malthus model seeks to explore the relationship between population growth and resource constraints. This model can provide insights into the potential consequences of population increases on food security and the need for sustainable resource management.

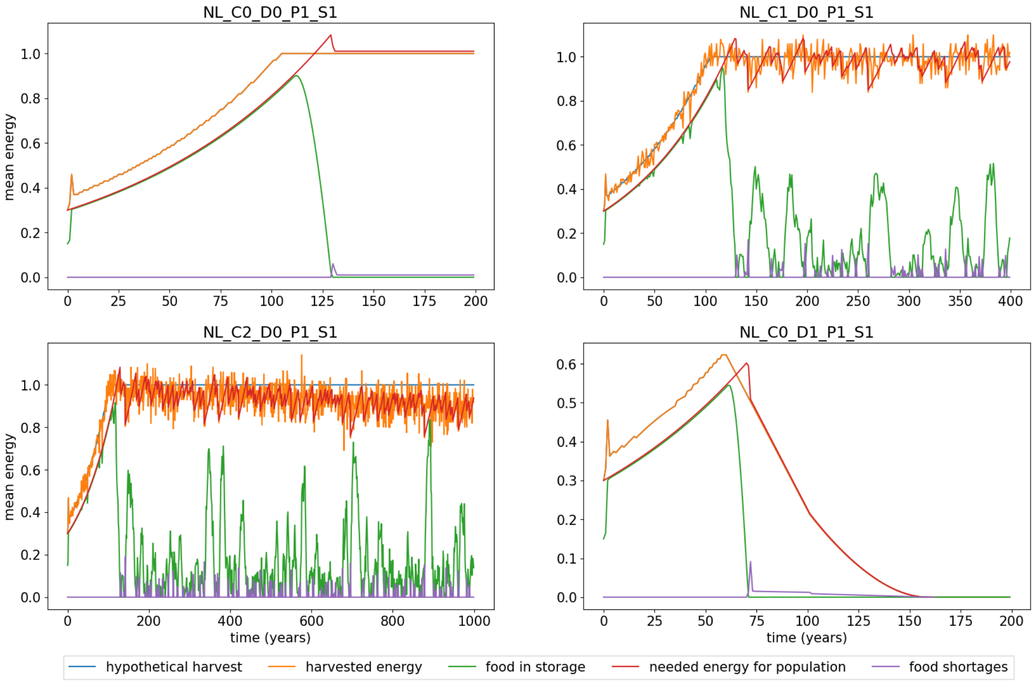


Figure 7: Various scenarios with a variable population, where in all figures the mean energy is plotted against the simulation time. Note that simulations times are different in the graphs.

In scenarios where there are no direct limitations on land productivity (i.e., scenario NL_C0_D0_P1_S1 as can be seen in figure 7), the population initially experiences steady growth at a rate of 1% per year. This growth continues even after the maximum harvest capacity of the land is reached, resulting in a population that exceeds the lands ability to sustain it. As long as there is food in storage, the population can sustain itself, allowing it to grow even when the lands maximum capacity is reached. However, once the food in storage is depleted, mortality rises, and population is forced to decline. Resulting in an equilibrium scenario where the population reaches a level that can be sustained by the lands maximum production capacity. In this state, the population continues to grow at a rate of 1% per year, which is offset by a 1% mortality rate due to food shortages. Overall, this dynamic equilibrium allows the population to persist at a level slightly higher than what the land can naturally provide. It showcases the intricate balance between population growth, food availability, and the utilization of stored resources.

In the scenario NL_C1_D0_P1_S1 as can be seen in figure 7, the variability in the harvest increases. This increased variability in the harvest directly affects the population. Once the maximum capacity of employed agricultural land is reached, a quasi steady state is reached where the population fluctuates around the maximum capacity of the land depending on the storage and harvest. When the harvest is sufficient and storage levels are high, the population can exceed the maximum capacity of the land temporarily. However, this situation is not sustainable in the long run, as the lands maximum capacity remains unchanged. On the other hand, if the harvest experiences lower yields or if storage levels are depleted, the population will face increased mortality levels. Without adequate food resources, the population cannot be sustained above the maximum capacity, leading to a decline in population size. Therefore, in a scenario with climate damage but no land degradation, the population will show more variability around the maximum capacity. It can temporarily exceed this capacity if storage and harvest conditions are favorable, but without sustainable production, the population will face increased mortality levels.

In a scenario NL_C2_D0_P1_S1 (see figure 7), the model initially allows the harvest and population to grow to the maximum capacity of the land. However, as the impact of climate damage gradually increases over time, the harvest, and therefore also the population starts to decline. It is important to note that the effects of climate damage on the population in this scenario are relatively slow and may not be immediately visible. This gradual increase in climate damage eventually leads to food shortages, which in turn result in increased mortality rates and a decline in population size. It is worth mentioning that with a gradually changing climate, no tipping points or other major impacts have been taken into account. Therefore, in a scenario with climate damage in a changing climate, the population initially reaches its maximum capacity but eventually starts to decline due to the worsening effects of climate damage.

Because the policymakers primary focus will be to meet the food needs of the population. The policymaker is inclined to adopt short-term solutions to address immediate food shortages and ensure the survival of the population. However, in scenarios where land degradation is present,there is a long-term process that hampers the supply of crops and reduces the energy yield from the land. As land degradation continues to worsen over time, it gradually diminishes the lands capacity to support agricultural productivity. This decline in energy yield ultimately impacts the food availability and, consequently, the population. As the land degradation intensifies, the energy yield and food supply will gradually decrease, leading to a downward spiral in population growth. The diminishing energy yield from the land is insufficient to support the needs of the population, resulting in a continues food shortages. This downward trend in population will continue as long as land degradation persists. Therefore, in scenarios where land degradation is a long-term process that hampers crop production, the energy yield from the land will eventually decline, leading to a downward spiral in population growth.

6 Discussion

The development of a new model inherently involves making several assumptions to simplify the complexity of the real-world system. While the model presented in this study is simplified and does not capture the full complexity of real-world dynamics, it serves as a starting point for further exploration and refinement. Some potential suggestions for future research and development include:

Refine parameterization

In section 4, a linear multi-variable analysis was performed to tune the climate damage function to the variability in temperature and precipitation. However, the coefficient of determination showed that temperature and precipitation were not able to explain the variability in the harvest data of the potato. Meaning that there are other factors playing a role in the variability of harvested potatoes.

Determination of climate damage is challenging due to its complex nature. Additionally, this factor is highly localized, which makes it difficult to generalize the behaviour across different regions. The same problems holds for the parameters of land degradation and land restoration. Furthermore, some of these factors may exhibit tipping points or threshold effects, where a small change in one factor can lead to a significant and nonlinear response in the system. Understanding and quantifying these tipping points can be challenging, as they often arise from complex interactions and feedback loops within the agricultural system. Local data, expert knowledge, and sensitivity analyses can help refine and validate the model to improve its accuracy and reliability.

$\mathbf{CO_2}$ emission

The impact of land on CO_2 emissions and climate change is a significant concern in agriculture. Land degradation and land-use change contribute to approximately 35% of human-caused CO_2 emissions since 1850 (*Foley et al.*, 2005). However, it is worth noting that potatoes, as a crop, have relatively low agricultural emissions compared to other crops (*Haile-Mariam et al.*, 2008), (*Clune et al.*, 2017).

Still the agricultural model can account for two CO_2 sources, considering the direct CO_2 release from burning trees during land conversion and the release of stored CO_2 in the soils due to land cultivation. Further research is needed to investigate these aspects and their implications on agricultural sustainability and climate change mitigation.

Variety of food

Currently, the model only considers one type of food. It would be valuable to expand the model to incorporate multiple crops, each reacting differently to climate damage and soil quality. Additionally, the introduction of livestock would offer a new dynamic in the model. A portion of the harvested crops would then be allocated to feed the livestock, which means that certain food production requiring more resources to produce the same amount of calories. Such that in case of a food shortfall the population could potentially compensate by consuming more of the crops themselves rather than allocating them to livestock.

DSK model

Agriculture is of importance in the Green Growth debate as it is able to contribute as detract from sustainability. By integrating the DSK model, which emphasizes the interplay between social, economic, and ecological dynamics, with the agricultural model, a more comprehensive assessment of the social-ecological consequences of different agricultural policies and interventions can be assessed. Providing valuable insights for decision-making towards a Green Growth transition.

Complex scenarios policymakers

Policies have a significant impact on crop production as on the quality of the land and climate.

In the current model, the policymaker primarily focuses on adjusting policies to meet immediate food demand. However, it is crucial to consider the implementation of long-term policies to address broader issues such as sustainability, resilience, and resource management.

In addition to the current policymakers being clairvoyant, they can be trained to consider historical data, which influences their decision-making and impacts existing policies.

Including trade

Increased fluctuations in the world food supply can be attributed to increased climate variability (*Warren et al.*, 2014), (*Challinor et al.*, 2015), (*Seekell et al.*, 2018). By establishing trade partnerships, these local agricultural areas can address gaps or limitations in their respective food production systems and by trading enhance food security. Moreover, trade can lead to specialization, where each area focuses on producing the crops or livestock that they are most efficient in, leading to increased productivity.

Future research and practical implementation should explore the potential of such trade partnerships, taking into account local contexts, and environmental considerations to maximize the benefits for all involved parties.

7 Conclusion

This study has established the groundwork for a simplified agricultural model that encompasses both constant and variable populations. By incorporating diverse scenarios and policies, the model provides valuable insights into the intricate interactions among population dynamics, food production, and their impact on land resources.

The results have demonstrated the influence of different factors such as climate damage, land degradation, and policy choices on food supply and population dynamics. The policymaker nature lover, with its focus on nature conservation, showed the impact of employing different policies, and the effect of climate damage and land degradation. Additionally, policymaker nature lover was compared to two other policymakers. The switcher, who only uses plots of land with the highest productivity and the bio farmer, who values land quality the most. The bio farmer, is the most sustainable farmer of all policymakers and is therefore able to hold off land degradation. Hence, the bio farmer is able to maintain the largest population, followed by the switcher, and lastly the nature lover.

Thereafter, a Malthusian framework was used to simulate a variable population that varies on the availability of food. From which the results give insight on the potential consequences of unrestricted food production. A steady population around the maximum capacity of harvest production was reached in the scenario without climate damage and land degradation. In the addition of climate damage, the population keeps fluctuating around the maximum capacity of harvest production. When land degradation is present, the productivity of the land keeps reducing until the land is fully exploited and no longer able to produce anything. Because the population is dependent upon the food produced, population will follow the trend of the harvest.

The development of the model helps to gain insight in the balance between food production and land preservation and is the first step in scoping pathways towards Green Growth.

Acknowledgement

I like express my sincere appreciation to Dr. Claudia Wiener for valueable help, guidance, and comments during the entire thesis. Dr. Anna von der Heydt, and Msc. Andrea Di Benedetto for the helpfull feedback and always being open to answer questions. Lastly, to my family, my boyfriend, and my roommates for their understanding, encouragement, and support during the course of this study.

Thank you for your invaluable help and support.

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A Workings of the policymaker

In the Agricultural model, the policymakers play a crucial role in ensuring an adequate food supply for a growing population. They employ a general approach to determine the necessary crop yield for the next year, taking into account the food requirements of the population and the desired amount to restock the storage. By comparing the desired yield with the predicted yield under the current policy, policymakers can make informed decisions on land allocation and policy adjustments to meet the population's food needs. This iterative process ensures that the policymaker strategy remains adaptable to changing circumstances.

Firstly, the policymaker assesses the food needs of the population, considering factors such as population size, growth rate, and individual food consumption. This calculation involves estimating the total food requirement for the population to ensure everyone is adequately fed. Secondly, the policymaker considers the desired quantity to restock the storage. This quantity is determined based on factors like storage capacity, desired reserve levels, and considerations for potential food spoilage. It ensures that there is a sufficient buffer of food in storage for contingencies. By assessing the performance of the current policy, the policymaker can estimate the expected yield for the upcoming year. Finally, the policymaker compares the desired yield with the predicted yield under the current policy. If the predicted yield falls short of the desired yield, adjustments to the policy and land allocation are necessary. If the predicted yield is more than necessary, plots of land that are used for cultivation are given back to nature. By iteratively following this approach each year, the policymaker aims to ensure that the necessary yield is achieved to meet the food requirements of the population and maintain an adequate supply in storage. How each policymaker establishes their policy is explained in the following subsequent sections.

Nature lover

The nature lover holds a strong appreciation nature and hence prioritizes its preservation, even if it comes at the expense of land productivity. The decision-making process of the nature lover is depicted in figure 8.

In cases where the predicted crop yield exceeds the desired yield, indicating an excess of food production, the policymaker faces the challenge of managing the surplus of crops. Since there is no option of trading or storing the excess food, the policymaker decides to retire the agricultural plot with the lowest productivity, returning it to its natural state. This action is taken to maintain a balance between food production and storage capacity, such that no food has to be thrown away. After converting a plot of land back to nature, the policymaker recalculates the predicted energy yield to assess if it still surpasses the desired yield. If the predicted yield remains greater, the policymaker continues the cycle of retiring low-productivity plots until the predicted yield is smaller than the desired yield. If predicted yield falls short on the desired yield, indicating a food shortage, the policymaker takes proactive measures to ensure an adequate food supply. The policymaker first converts sustainable agricultural lands into conventional practices to increase productivity. If the shortage persists, the nature lover policymaker, driven by the goal of preserving as much nature as possible, is left with no choice but to convert natural lands into agricultural use. In this case, the policymaker selects the plot of land with the highest productivity, maximizing food production while minimizing the impact on natural areas. Once the predicted yield aligns with the desired yield, a new policy is established for the upcoming year's harvest. This iterative process allows the policymaker to continually adapt and optimize land allocation strategies to meet the changing food needs of the population.

The Nature Lover policymaker, with its emphasis on prioritizing nature conservation, operates under a rigid framework that allows us to examine the impact of solely focusing on food supply without considering land preservation. By disregarding the preservation of land, this policy approach allows us to explore the potential consequences and dynamics of unrestricted food production. Under the Nature Lover policy, agricultural lands are converted back to nature whenever the predicted yield exceeds the desired yield, leading to a reduction in food production. Conversely, when there is a food shortage, the policy involves converting natural lands into agricultural use, potentially impacting the preservation of natural areas. This approach provides insights into how food supply dynamics would unfold if the sole objective were to meet the immediate food demands of the population, disregarding long-term land sustainability and preservation concerns.

Switcher

The switcher always tries to maximize production, by only using conventional farmers and plots of land with the highest productivity. The decision-making process of the switcher is depicted in figure 9.

The switcher adopts a unique approach to land management, focusing solely on utilizing plots of land with the highest productivity and employing conventional farming practices. Each year, the switcher selects the necessary number of plots to meet the desired yield. But after one harvest, the plots no longer have the highest productivity. Consequently, the policymaker takes the decision to retire all the previously cultivated plots and

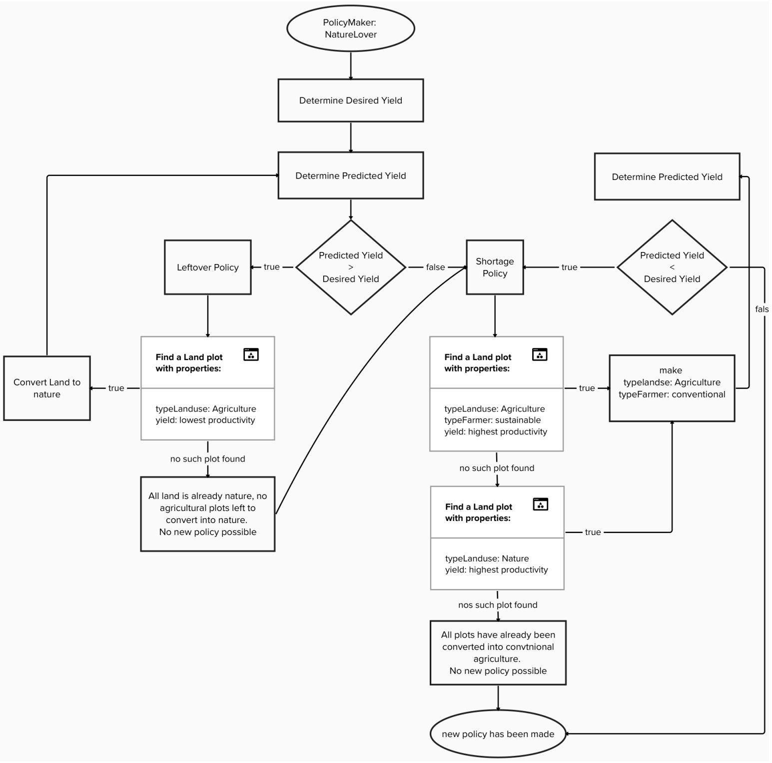

Figure 8: Flowchart policymaker nature lover.

replaces them with new plots that exhibit the highest productivity. By which the retired plots are given an opportunity to restore themselves, allowing for natural recovery processes to take place.

However, a challenge arises as the productivity of these plots diminishes over time and the switcher continues to reuse plots that have not had sufficient time to fully recover. With this a cycle emerges where the need for more plots becomes increasingly necessary. This scenario highlights a potential dilemma for the switcher, as it becomes compelled to employ a growing number of plots due to the insufficient time for complete restoration. This pattern ultimately has implications for land management decisions and the long-term sustainability of the agricultural system employed by the switcher.

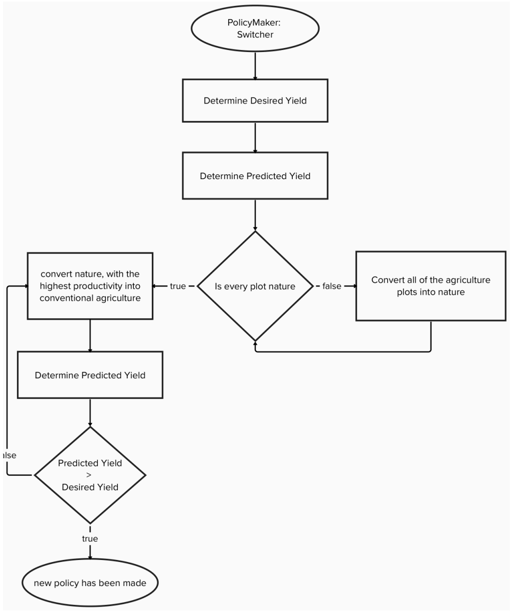

Figure 9: Flowchart policymaker switcher.

Bio farmer

The bio farmer values the quality of the ground above everything. It will therefore only employ sustainable farmers and only resort to conventional farmers if not possible otherwise. The decision-making process of the bio farmer is depicted in figure 10.

In situations where the projected crop yield surpasses the desired yield, indicating an excess of food production, the policymaker is faced with the challenge of managing this surplus. Since trading or storing the excess food is not an option, the policymaker initiates a series of actions. Firstly, the conventional farming practices are transformed into sustainable cultivation methods to minimize any potential waste. If a surplus still remains, agricultural plots are retired and returned to their natural state, allowing nature to reclaim the land. These measures are implemented to prevent the unnecessary disposal of food. After each conversion, the predicted yield is recalculated and compared to the desired yield. If the projected yield remains higher than the desired yield, the policymaker continues the cycle until the predicted yield aligns with or falls below the desired yield.

Conversely, if the projected yield falls short of the desired yield, the policymaker takes steps to increase the harvest. Initially, the bio farmer converts plots of land with the highest productivity from their natural state into sustainable agriculture. If no plots are available for conversion, the bio farmer is compelled to convert existing sustainable agriculture into conventional agriculture. This process is repeated until the projected yield meets the desired yield. At that point, a new policy is formulated based on the current conditions and requirements.

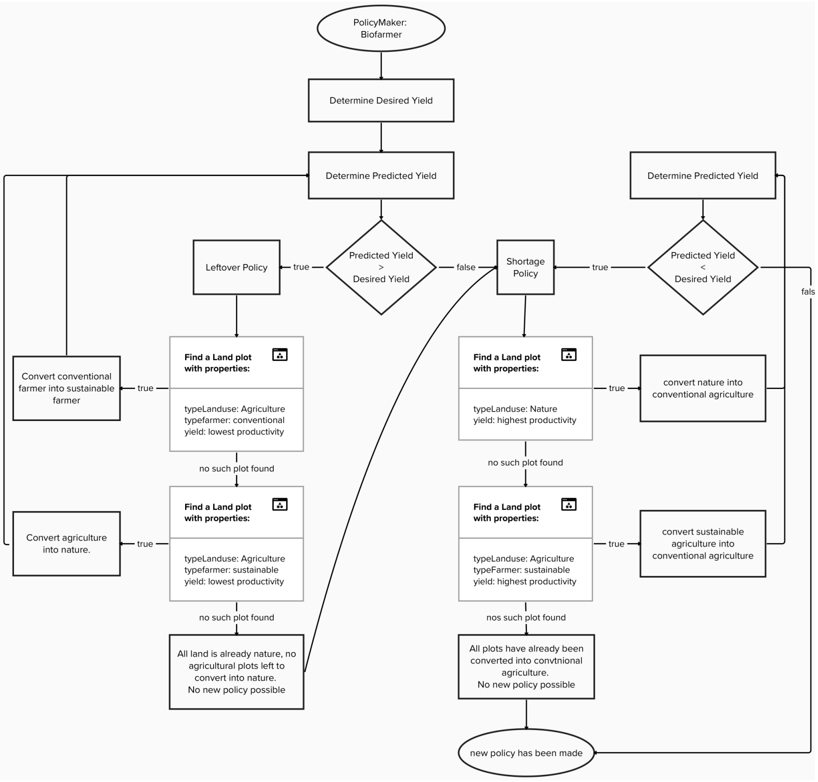

Figure 10: Flowchart policymaker bio farmer.