Modeling Crop Yields and Water Balances for the Netherlands with WOFOST

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1 Introduction

The world population is growing, the climate is changing, and big parts of the world are entering a new level of welfare. This increase in welfare leads to different requirements for the diet. Overall, it can be said that an increase in welfare leads to an increase in protein requirement as it is also known that when all the increase of protein mainly origin from animal proteins, resources could be depleted faster than using plant proteins. Also, different health impacts could be reached by using plant proteins. That is why other sources of protein could be favorable in terms of environment or health. One of the potential crops could be soy. Much of the current products available to meat protein are based on soy. However, it is relatively unknown what type of impact soy has on the environment and health. That is why this study looks at the potential of using soy for food to support a sustainable protein transition in the Netherlands.

In the Netherlands, conscious food consumption patterns are growing. As part of this general trend, there is a decrease in milk consumption due to the perception that milk negatively impacts the environment and potentially health. Next to reducing milk, vegetal alternatives, such as soy drinks, have been on the rise as replacements for milk. These alternatives have a lower impact on the environment, but the question remains: What are the consequences of shifting to an alternative protein source on health and the environment? As soy is one of the first alternatives for animal proteins, we have chosen soy drink produced from Dutch soya bean production as a case study. However, the methodology in this analysis can also be used for calculating the impact of other alternatives. For this protein transition, we investigated the consequences of replacing 10% of the current protein intake with milk products by protein intake from soya drink on a number of selected indicators: diet, production, land use, water use, and GHG emissions, and Nutrient loss (Figure 1).

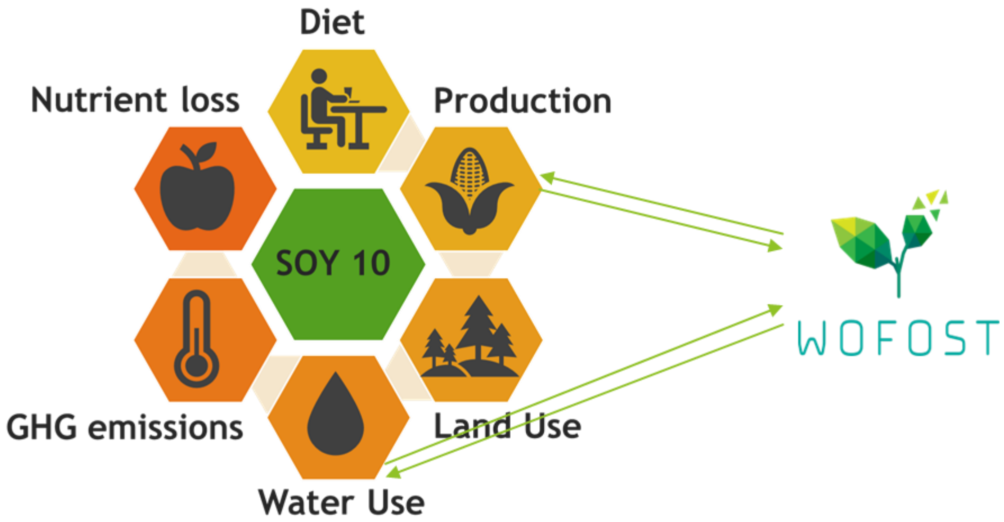

Figure 1: A pictorial representation of the core of the study and the role of the crop modeling approach.

To analyze the impacts of protein transition in the sectors mentioned above, we have used various data sets from FAO, CBS, and NZO. In this study, we analyzed the impacts of protein transition in the current as well as future. To estimate the impacts of protein transition in the future, we have used the crop modeling approach for various agronomic scenarios (Irrigated and Rainfed). This technical report thoroughly discusses the modeling approach and its role in the protein transition study mainly focused on the production and water use (Figure 1).

2 WOFOST crop model

We used WOFOST (WOrld FOod STudies) crop model in this study. WOFOST is a simulation model for the quantitative analysis of the growth and production of annual field crops. The WOFOST, cropping systems model, has been applied operationally over the last 25 years as part of the MARS crop yield forecasting system (Wit et al., 2019). With WOFOST, you can calculate attainable crop yield, total biomass, water use, etc., for a location given knowledge about soil, crop, weather, and crop management. The WOFOST crop simulation model, implemented in the Monitoring Agricultural ResourceS (MARS) system, has played a key role in crop monitoring and yield prediction in Europe (Velde et al., 2015).

It is a mechanistic, dynamic model that explains daily crop growth based on the underlying processes, such as photosynthesis, respiration, and how environmental conditions influence these processes. Crop growth is calculated with time steps of one day, based on knowledge of processes at a lower level of integration (such as the instantaneous photosynthesis-light response curve of a single leaf). Next, the low-level processes are integrated and combined with other processes (phenology, respiration) to explain system behavior at a higher level of integration. Nevertheless, some parts of the model are descriptive and/or static. This is mainly because some of the processes involved are yet not adequately understood. In WOFOST, crop growth is simulated on the basis of eco-physiological processes such as growth and phenological development with a fixed time step of 1 day. The model follows the classical distinction between production levels:

- Potential production is only limited by radiation, temperature, atmospheric CO2 concentration, and crop features
- Water and nutrient-limited production where growth limitations due to water and/or nutrient shortage play a role
- Actual production where growth reducing factors like weeds, pests, diseases, or pollutants reduce production to the field level's actual yield.

There are multiple implementations of WOFOST are available from Wageningen University and Research (http://wageningenur.nl/wofost). However, for this study, we have used the C version of WOFOST, which is available as open access and found here (https://github.com/isupit/wofost_copernicus). The model was simulated on Wageningen University and Research's High-Performance Computing (HPC), Annuna.

2.1 Modeling approach

The WOFOST can be used to simulate different levels of the yields (potential, water-limited, and actual). However, we used the model to simulate crop yields at this study's water-limited and potential levels. The hierarchy of the model simulation is shown in Figure 2. To estimate the impacts of proteins transition by replacing soybean, we have chosen major cereal (Wheat) and fodder crops (Silage maize, grassland), which contributes indirectly to milk protein contribution. We used various (climate and crop files) publically available data sets to simulate crop yields in WOFOST.

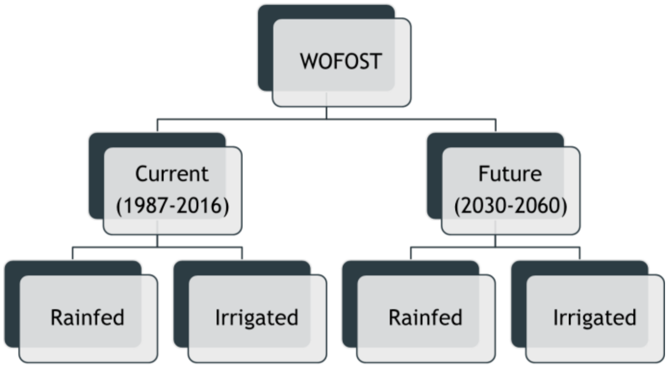

Figure 2: WOFOST model simulation hierarchy

2.1.1 Water-limited Production

The water-limited production is determined by the water availability as well as water use during the growth of the crop period. Water use is mainly determined by crop transpiration and soil evaporation. The initial water availability determines the crop water requirement during the crop growth period, the maximum soil-water holding capacity dependent on rooting depth and the available soil moisture fraction, and the balance of water inputs (mainly precipitation) and use during the growth period. The initial soil water availability in the maximum rooting depth should be based on the measurement of soil moisture content at crop emergence or should be based on the water balance calculation during the months before crop emergence. Often only a rough estimate for the initial soil water availability is available for the WOFOST simulation. However, the sensitivity of water-limited production to this initial soil water availability is often quite substantial. The maximum soil-water holding capacity is determined by the maximum rooting depth (of a full-grown crop) and the available soil moisture fraction (moisture content at field capacity minus that at the wilting point). For these three variables, reliable values are available for each soil type for which WOFOST simulations are done to achieve precise water-limited crop production analyses.

2.1.2 Potential Production

Crop growth is determined only by CO2 concentration, irradiation, temperature, plant characteristics, and planting date. Potential production represents the absolute production ceiling for a given crop when grown in a given area under specific weather conditions. It is determined by the crop's response to the temperature and solar radiation regimes during the growing season. Atmospheric CO2- concentration is assumed to be constant. All other factors are assumed to be optimal (e.g., pest and weed control, no losses caused by traffic or grazing) and in ample supply (nutrients and water). Because crop properties also determine potential yield, yield potential varies over crop varieties and can be increased by breeding. Near to potential yield, levels are realized in field experiments by research institutes, seed companies, and some front-runner farmers.

2.2 Model inputs

We used crop-specific, soil, and weather data at the grid level from various data sources and literature for the model simulation. Simulation grids (Figure 3) were selected based on climate data (approximately 50km X 50km). We simulated yields mainly for cereals (wheat) and fodder crops for livestock feed (silage maize and grassland) and soybean to contribute to protein transition for the current and future scenarios.

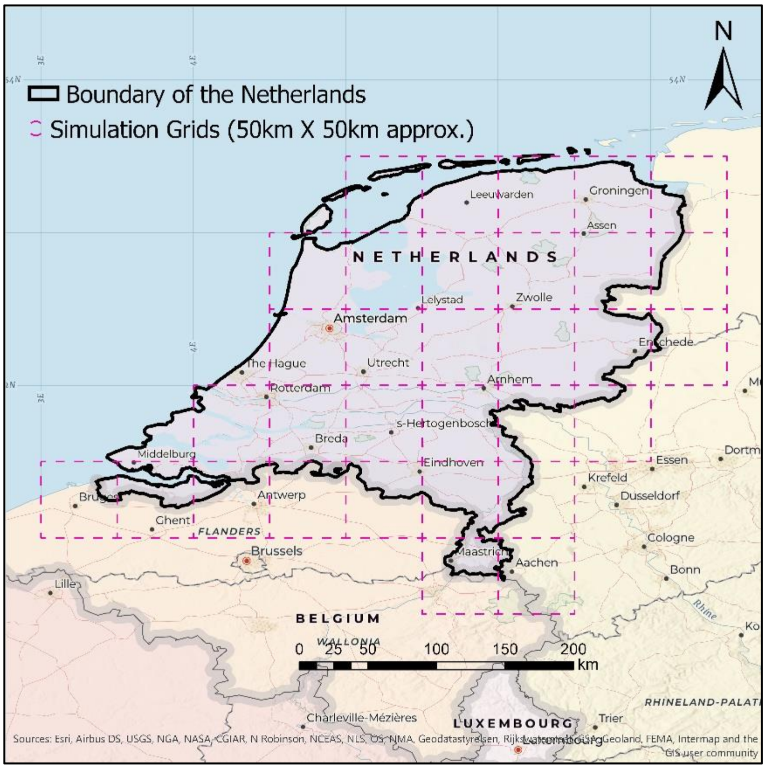

Figure 3: National boundary of the Netherlands and simulation grids

2.2.1 Crop files

For each crop, which is needed to be simulated, providing a WOFOST crop file with a specific set of parameters is mandatory. These parameters refer to, amongst other things, phenology, assimilation and respiration characteristics, and partitioning of assimilates to plant organs. Therefore, we used specific crop files for each crop (A sample for wheat in Table 4). Most of the crop files included in WOFOST have been developed for simulation of crop growth in the European Communities (EC) (Boons-Prins et al., 1993). The differences among the different files of one species are usually minimal. The regions of the EC to which the data sets pertain are indicated in the comment in the files. The calibration of WOFOST crop parameters is already performed before bringing the files into use.

2.2.2 Soil file

A soil file contains information on physical soil characteristics. This comprises data on water retention, hydraulic conductivity, and workability. These soil data are used to calculate the daily water balance of the soil needed to simulate water-limited growth and determine the optimal sowing date. Chemical soil properties are not included in this file. The default values of chemical properties are included in the site file (section 2.2.3). The soil types delivered with WOFOST consist of two groups: EC (European Community) / SR('Staringreeks') – group 1 and the texture/AWC (available water capacity per meter soil depth)-group 2. Soil types starting with EC and SR (files with extension *.NEW) can be used to simulate water-limited crop growth with free drainage and groundwater influence. Soil types indicated by AWC values (files with the extension *.AWC) can only be used for simulation with free drainage, as information on hydraulic conductivity is not available. The files starting with 'EC' have been developed in connection to the soil map of the EC (Balz, 1986; Reinds, 1992). The files starting with 'SR' are connected to the 'Staringreeks' (Heinen et al., 2020). The collection of soil data is described WUR database (PM Driessen, 1986). The syntax is identical to that of the crop files. However, in this study, we used the EC group soil file, EC3(medium-fine). This is because, in the Netherlands, we see EC3 as a majority in the soil group. In annexure (Table 5), we provided a soil file (EC3).

2.2.3 Site file

The site file concerns the default values for soil characteristics that are not given in the soil file. Site files are available in WOFOST for specific regions. The site file used for the Netherlands is provided in the annexure (Table 6).

2.2.4 Weather files

Weather files contain the meteorological data used in the simulation model. This concerns radiation (sunshine), air temperature, rainfall (precipitation), air humidity, and wind speed. In this study, we used various climate data sources for the current and the future to assess yields and water balances in WOFOST (section 2.3).

2.3 Climate data

WOFOST simulation had been done with two different climate datasets for historical (1981-2014) and future (2015-2050, until mid future), each described below:

2.3.1 W5E5 (Current)

The W5E5 climate dataset (Lange, 2019b) was used to simulate the current scenario in the WOFOST. The dataset was selected because it is the dataset with which the ISIMIP3b climate scenarios were bias-corrected and is, therefore, the historic climate assumed by our climate scenario before its starting point. The W5E5 data was retrieved from the PIK ESGF node; all units are stated in Table 1. W5E5 (Cucchi et al., 2020; Lange, 2019b), a dataset based on a combination of simulations from global weather models, satellite data, and weather station observations. The dataset covers the period 1979-2016 at daily temporal resolution and the entire globe at 0.5°x0.5° grid spacing (approximately 56km x 56km). As mentioned earlier, W5E5 was compiled to support climate bias adjustment of those models used in phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b; (Lange, 2019b, 2019a)), which we also used in this study.

Table 1: Specs of climate variables bias-adjusted and statistically downscaled for ISIMIP3b and W5E5. Note that the upper limits of pr and prsn correspond to 600mmday^{-1} and 300mmday^{-1}, respectively, while the lower and upper limits of tas, tasmax and tasmin correspond to -90 °C and +70 °C, respectively.

Variable	Short name	Unit	Limits
Near-Surface Relative Humidity	hurs	%	[1, 100]
Near-Surface Specific Humidity	huss	kg kg-1	[0.0000001, 0.1]
Precipitation	pr	kgm-2 s-1	[0, 0.0069444444]
Snowfall Flux	prsn	kgm-2 s-1	[0, 0.0034722222]
Surface Air Pressure	ps	Pa	[480, 110000]
Surface Downwelling Longwave Radiation	rlds	Wm-2	[40, 600]
Surface Downwelling Shortwave Radiation	rsds	Wm-2	[0, 500]
Near-Surface Wind Speed	sfcWind	ms-1	[0.1, 50]
Near-Surface Air Temperature	tas	K	[183.15, 343.15]
Daily Maximum Near-Surface Air Temperature	tasmax	K	[183.15, 343.15]
Daily Minimum Near-Surface Air Temperature	tasmin	K	[183.15, 343.15]

2.3.2 ISIMIP 3b (Future)

The climate scenario for the future was selected from the scenarios provided by the Intersectoral Impact Model Intercomparison Project (ISIMIP). ISIMIP collaborates with over 100 research institutions worldwide, evaluating the impact of climate change scenarios on different economic sectors through modeling. The project works provide bias-corrected CMIP6 climate scenario datasets for each new simulation round. All participating modeling institutions run their models with the same climate forcing data, thus making their results more inter-comparable (Lange, 2019a). The latest climate data provided by ISIMIP is the ISIMIP3b climate forcing dataset. This dataset was selected to run the WOFOST future scenario mainly because (a) it belongs to the CMIP6 dataset, which is the most recent climate scenario data available, (b) the data has a relatively high resolution, although it is a global dataset (30 arcminutes, 0.5°), and (c) the data is already bias-corrected.

For the simulation round ISIMIP3b, three climate scenarios were available, each a specific combination of a shared socio-economic pathway (SSP) and a representative concentration pathway (RCP). The three scenarios available are SSP1-RCP2.6, SSP3-RCP7.0, and SSP5-RCP8.5, with respectively an increasingly drastic level of climate change (World Bank, 2021). Ideally, all three scenarios would have been modeled with the WOFOST. However, as the analysis was restricted by time availability to a single scenario, it was decided to use the high emission scenario SSP3-RCP 7.0. This was considered the most likely scenario since it was the closest to the 'middle of the road'.

Each scenario was available as simulated by five different global circulation models (GCMs): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL. Again, ideally, all five datasets would have been run with the WOFOST, but this was not possible in practice, so a single GCM was selected. GCM selection was performed based on their rainfall predictions. This is the climatic variable where GCMs tend to disagree most, both in terms of geographic distribution and in absolute values (Müller et al., 2010). As this study intends to determine whether water availability might become a problem for food production, the scenario was selected that was the most limiting in terms of reducing rainfall and increasing temperature. The time-series annual rainfall and annual temperature parameters for the simulated region were plotted over all five GCMs (Figure 12). Their slopes were estimated with a linear trendline (Table 2). The scenario with the combined lower trendline in rainfall and higher trendline in temperature was selected, which was UKESM1-0-LL.

Table 2: Slope values of annual rainfall and temperature parameters from 2015-2100 for the Netherlands

Models	Rainfall	Maximum Temperature	Minimum Temperature
GFDL-ESM4	0.25	0.03	0.03
IPSL-CM6A-LR	1.65	0.05	0.05
MPI-ESM1-2-HR	-1.13	0.03	0.03
MRI-ESM2-0	0.19	0.02	0.01
UKESM1-0-LL	-0.45	0.07	0.06

Time series (2015-2050) plot for annual rainfall, maximum temperature, and minimum temperature for the model UKESM1-0-LL, considered for this study shown in Figure 4. Overall, the maximum and minimum temperature has projected to have a drastically (up to 3°C) increasing trend from the current. In terms of rainfall, the model has projected decreasing trend over time. The annual rainfall has projected a decrease of around 100mm from the current.

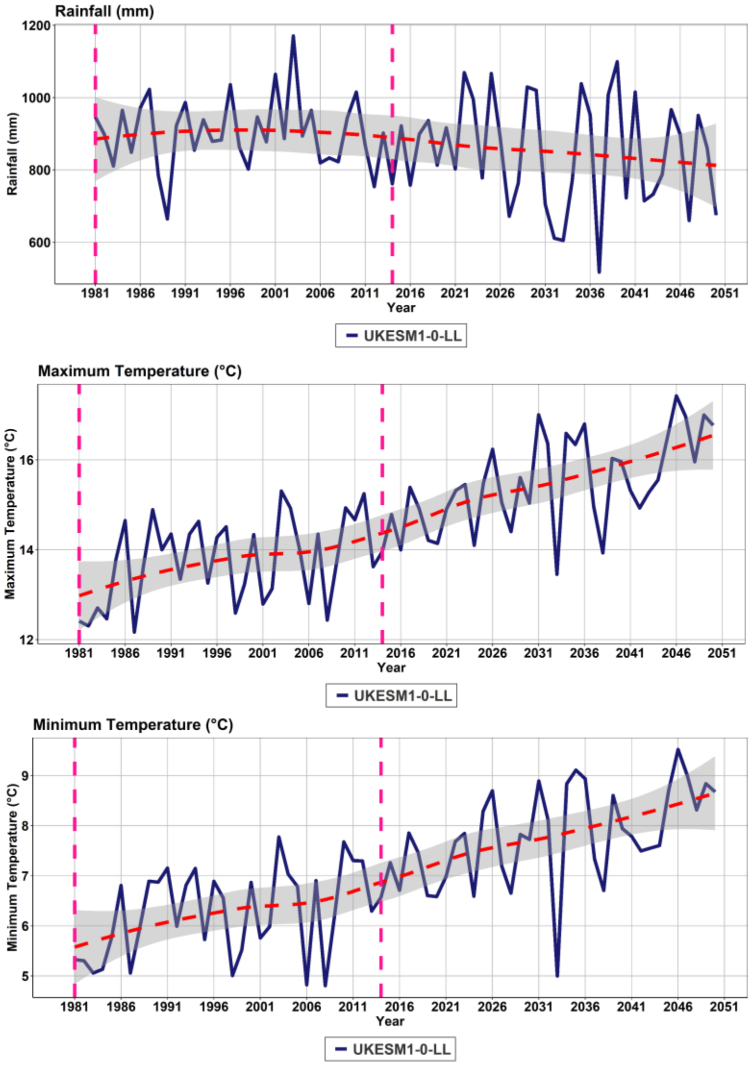

Figure 4: Time series (1981-2050) plot for annual rainfall, maximum temperature, and minimum temperature for various model UKESM1-0-LL. The red dashed line indicates the trend over time (1981 to 2050). The pink lines represent the current period (1981-2014)

The climate data of the climate scenario SSP370 and model UKESM1-0-LL was retrieved from the PIK ESGF node, spanning from 2016 to 2050. All units were transformed to the units stated in Table 1. The downloaded variables were temperature, precipitation, and long and short wave downwelling radiation. As precipitation data was available as daily values, it was not necessary to provide data on the number of wet days per month. Cloudiness was also not required when using radiation data. Compared with current (1981-2014), the annual mean maximum & minimum temperature and annual precipitation in the Netherlands for the UKESM1-0-LL model and SSP3 RCP 7.0 scenario are shown in Figure 5.

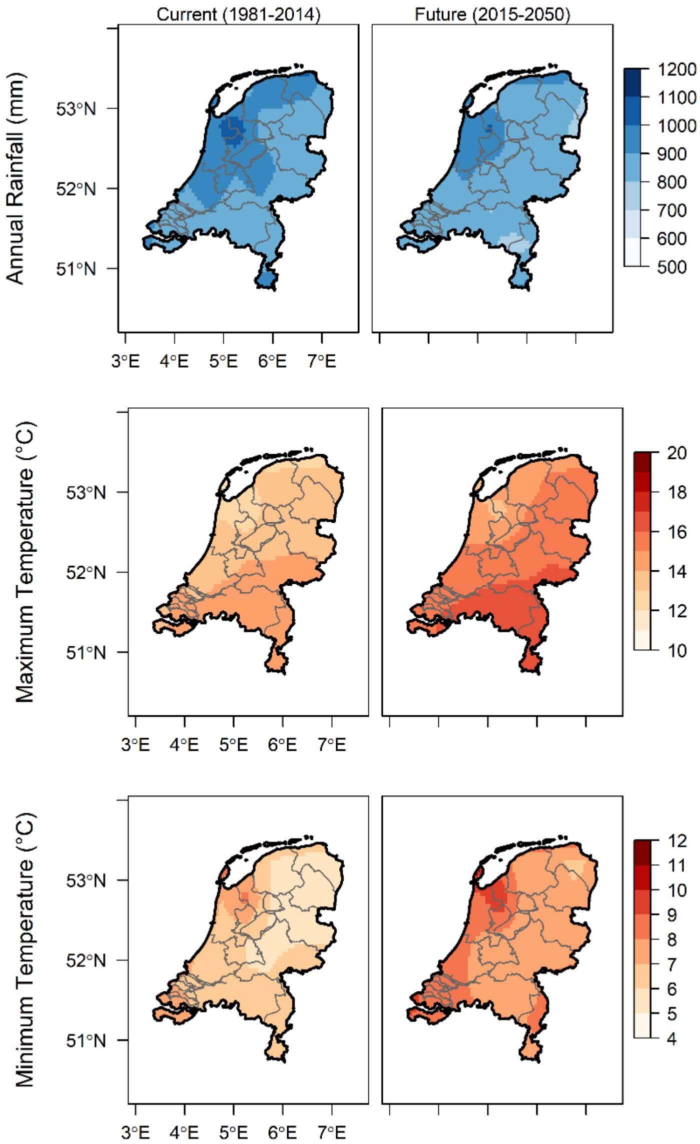

Figure 5: Comparision of annual temperature and rainfall between current future for the Netherlands

Figure 5 explains the spatial pattern of rainfall and temperature changes over the Netherlands. Accounting annual rainfall pattern, future rainfall was projected to be decreased compared to the current, especially in the western region. The maximum and minimum temperature has projected to increase all over regions up to 3°C in the mid future.

3 Results

3.1 Model simulation

The model simulation for different crops has been analyzed to estimate the impacts of protein transition in production and water use. The model has been calibrated to match the current yields based on FAO current yields: Grassland (9.4 t DM/ha), Silage maize (15.6 t DM/ha), Wheat (8.1 t DM/ha), and Soya bean (3.0 t DM/ha). Based on the current (2015) FAO yields, milk production of 13550 ktonnes and food production of 5147 ktonnes are needed to be reduced to 13036 ktonnes (difference of 514 ktonnes from the current) and 4633 ktonnes (difference of 514 ktonnes from the current), respectively (Table 7). Further, an additional soya bean production of 60.3 ktonnes/year was calculated for the supply of soya drinks in the process of 10% protein transition (Table 7).

For the lower milk production, fewer roughages are needed, and this was estimated by using their feed conversion ratios (g feed dry matter per g milk) and dry matter (DM) yields for grass and silage maize in 2015 (Table 8). Milking cows also eat concentrates and by-products (estimated at 30% on a DM basis, where the roughages contribute 70% to the total ratio for producing milk). Part of this 30% contains main crop products (like wheat) while the other part consists of residues (such as from the food industry). It is assumed that 75% of the dry matter intake from concentrates and by-products that are no longer needed in the protein transition scenario will replace crops grown for feed in the Netherlands. To calculate the amount of land involved, we used the simulated yields of wheat, silage maize, and grassland and replaced milk production for the current and future. The following sections will elaborate on the model simulations then subsequently the impacts on production and water use.

3.1.1 Silage maize

Maize silage (*Zea mays L.*) is made out of whole ensiled maize plants. It is one of the most valuable forages for ruminant livestock, and it is used wherever maize can grow, from temperate regions to the tropics. The average yield as per the FAO database of silage maize is 15.6 t/ha in the Netherlands. Figure 6 shows the simulated yields, water use, and water use efficiency from WOFOST for the crop silage maize. Overall, future yields are projected to decrease around 0.5t/ha & 0.25t/ha compared to the current in irrigated and rainfed, respectively. At the same time, water use and water use efficiency have been projected to increase from the current in both irrigated and rainfed.

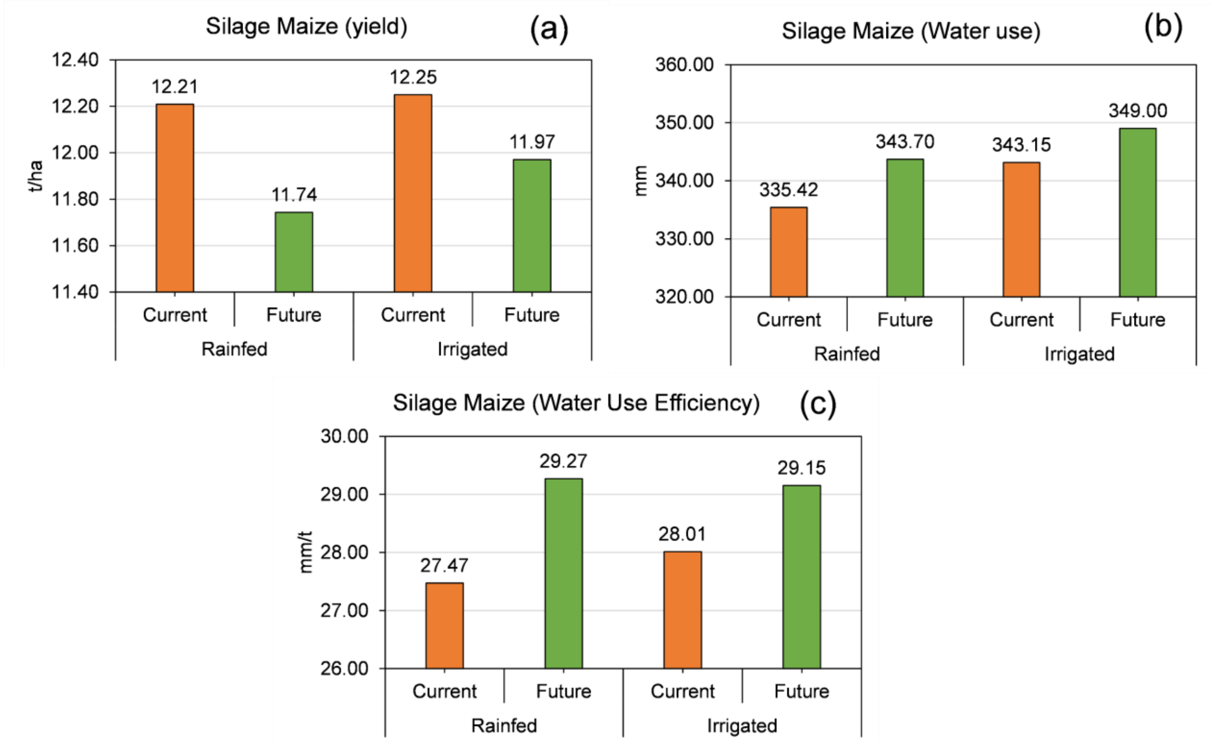

Figure 6: a) Simulated yields, b) water use (evapotranspiration), and c) water use efficiency of silage maize for different agronomic practices (Rainfed and Irrigated) and different timesteps.

3.1.2 Grassland

Over 50% of its highly productive agricultural land is grassland dedicated to supporting the dairy industry. There are more than 100 types of grass varieties grown in the Netherlands. However, in recent times, to optimize yield, farmers have started growing only a single type of highly productive grass (monoculture) at the expense of maintaining less productive but more herbaceous grassland (Ellipsis Drive, 2021). An increase in temperature and CO_2 concentration in the air has a favorable effect on grassland production in the Netherlands. However, this favorable effect is (partly) undone by the increased probability of a water shortage (reduction in rainfall) in summer (Schipper et al., 2014). Supporting this statement, Figure 7 shows the decrease in yields with the decrease in water use efficiency from the current to the future.

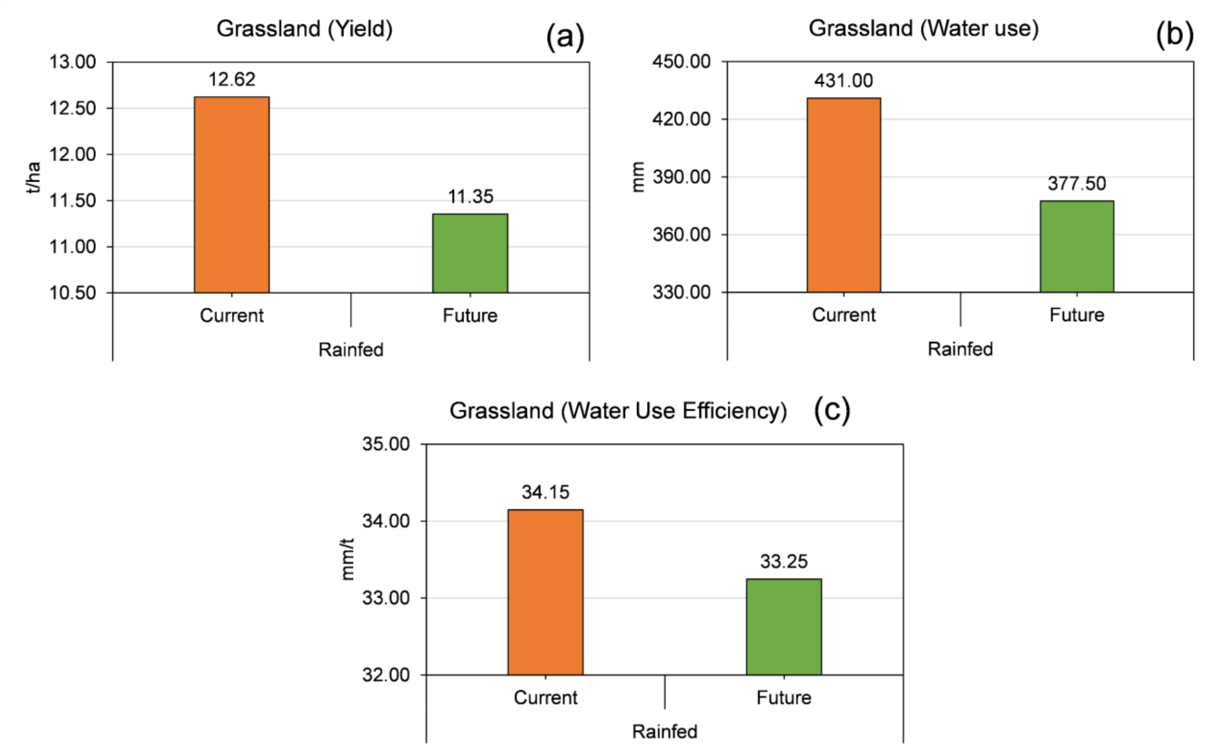

Figure 7: a) Simulated yields, b) water use (evapotranspiration), and c) water use efficiency of grassland for different timesteps.

3.1.3 Wheat

Approximately 1.2 million tons of wheat are produced each year, and this represents around 1% of EU production. Of this production, 55% becomes animal feed, 20% is milled into flour, 20% goes to the starch industry, and 5% is for bio-ethanol production (Trejo, 2015). Figure 8 shows simulated yields, water use, and water use efficiency of wheat in the Netherlands. Overall, yields are projected to have decreased (around 1 t/ha) in the future compared to the current, likely water use. At the same time, also increase in temperature could be a significant cause of increasing water use efficiency in the future, which indicates more water is required than the current to produce 1 ton of wheat.

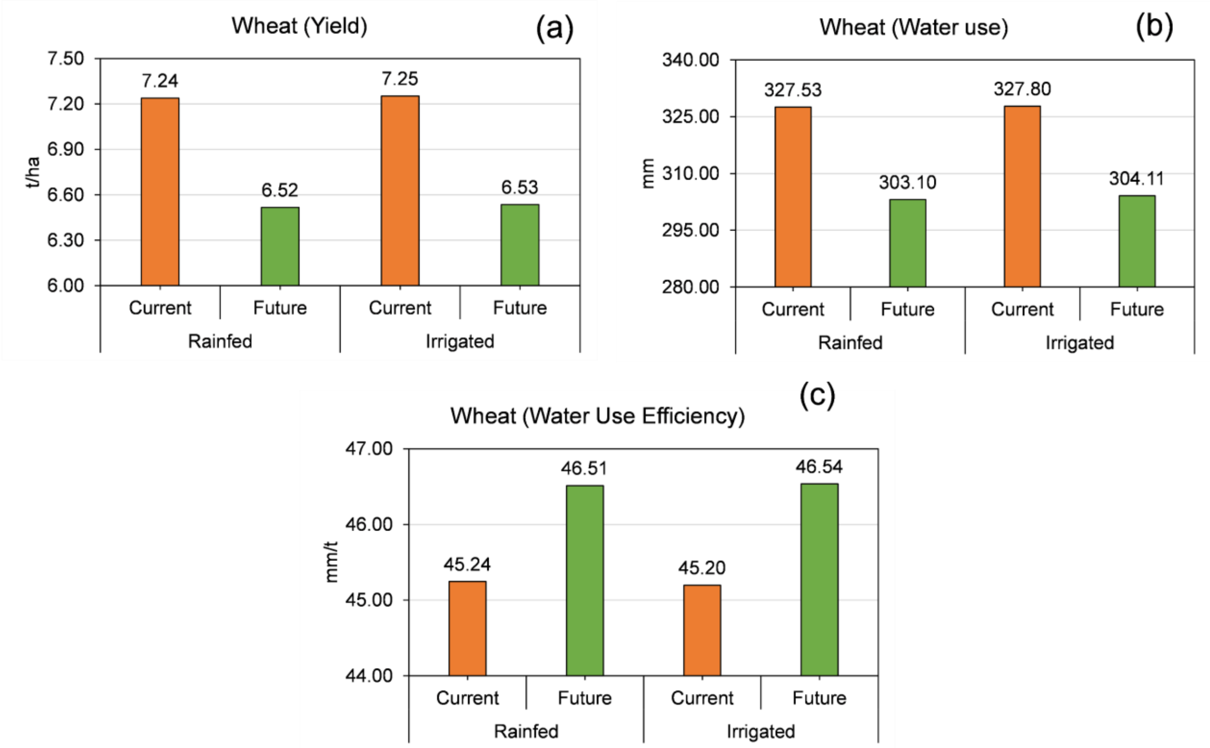

Figure 8: a) Simulated yields, b) water use (evapotranspiration), and c) water use efficiency of wheat for different agronomic practices (Rainfed and Irrigated) and different timesteps.

3.1.4 Soybean

Soybean in the Netherlands is mainly imported. However, it is possible to cultivate soya plants in the Netherlands, but they have to be varieties adapted to the northwest European climate. Soybeans were cultivated on a small scale in the Netherlands during the 1930s, but that did not prove very successful. Nevertheless, in this study, we attempted to replace milk proteins with soy protein, which also recommends growing soybean in the Netherlands. As an initial step, the WOFOST model has projected soybean yields for the current and future. Figure 9 shows yield, water use, and water use efficiency for soybean simulation in the Netherlands. Overall, soybean yields are projected to decrease, but with efficient water usage. Increasing temperature is optimal for soybean cultivation as frost days are critical for soybean crop growth; additional irrigation water could be a potential factor that can increase the soybean yield.

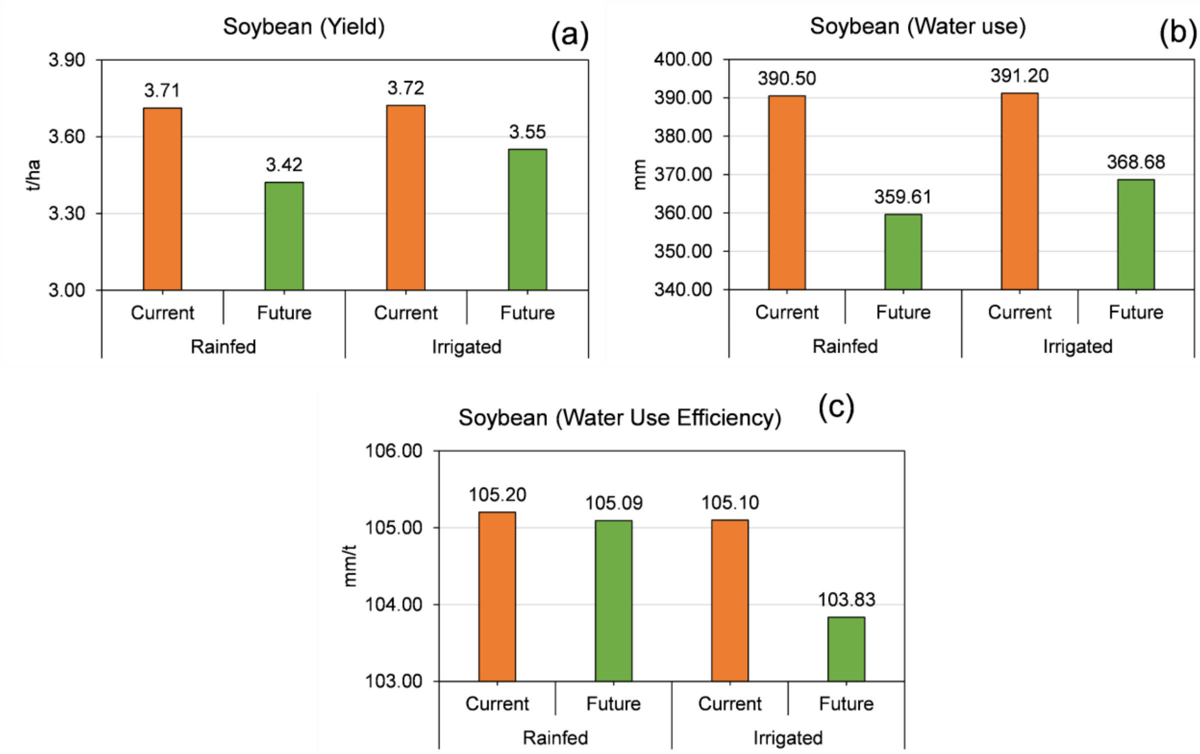

Figure 9: a) Simulated yields, b) water use (evapotranspiration), and c) water use efficiency of soybean for different agronomic practices (Rainfed and Irrigated) and different timesteps.

3.2 Impacts of protein transition

3.2.1 Impacts on production

We estimated production changes in various crops based on simulated yields from the WOFOST. Table 3 shows the changes in production in different agronomic and time scenarios if the area remains as current in the future. Rainfed and irrigated yields in the current were not projected with much difference; therefore, the production remains the same. However, due to changes in the yields, the production was projected to decrease in the future (55.59 ktonnes in rainfed and 57.52 in irrigation).

Table 3: Impacts of 10% of protein transition in production

	Rainfed				**Irrigated**			
	Current		**Future**		**Current**		**Future**	
	Yield	**Production**	**Yield**	**Production**	**Yield**	**Production**	**Yield**	**Production**
Silage maize	12.21	-77.1	11.74	-74.16	12.25	-77.1	11.97	-75.34
Grassland	12.62	-200.46	11.35	-180.33	12.62	-200.46	11.35	-180.33
Wheat	7.24	-87.38	6.52	-78.66	7.25	-87.38	6.53	-78.73
Soybean	3.71	**60.3**	3.42	**55.59**	3.72	**60.3**	3.55	**57.52**
Yield - t/ha ; Production- ktonnes								

3.2.2 Impacts on area

We estimated changes in the area in 4 different scenarios (Figure 10).

- Scenario I - Current & Rainfed to achieve 60.3 ktonnes of soy production
- Scenario II - Current & Irrigated to achieve 60.3 ktonnes of soy production
- Scenario III - Future & Rainfed to achieve 60.3 ktonnes of soy production
- Scenario IV - Future & Irrigated to achieve 60.3 ktonnes of soy production

Combining the lower milk production of 514 ktonnes with additional soybean production to achieve 60.3 ktonnes, no longer needed 15.8 Kha of grassland, 6.31 Kha of silage maize, and 12.07 Kha wheat in the current. It reflects around 16.2 Kha of land available for soybean cultivation, and 18.02 Kha remains empty, which can be used for any purpose. In the same way, the land availability is shown in Figure 10 for other scenarios. We analyzed these changes with equal partitions from all cultivated lands. However, these changes and analysis can be done with 'n' number probabilities depending on the cultivation land, which policymakers/users choose to replace/change/keep remain.

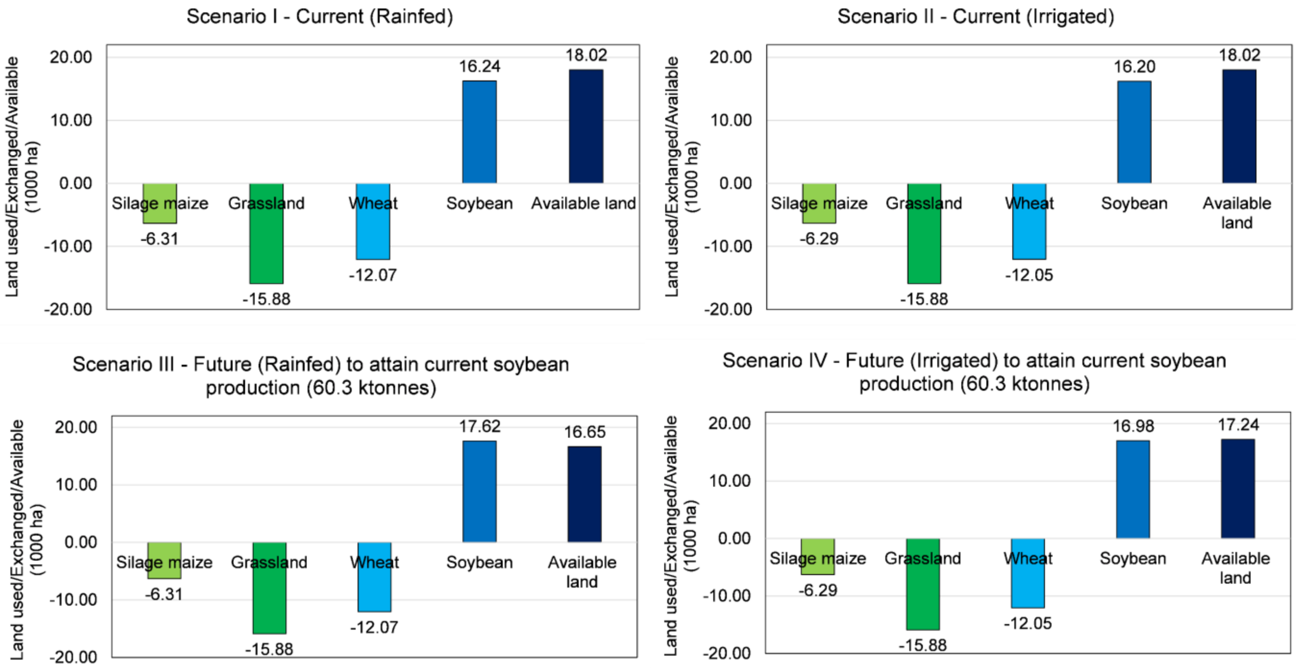

Figure 10: Changes in the area in 10% protein transition scenario

4 Conclusion

A diet shifting of 10% protein to soy from milk production could free up approximately >16 Kha of land from combined grassland, wheat, and silage maize cultivation in the scenarios taken in this study. Accounting climate change impacts, loss in productivity has been projected in all crops (cereal and fodder) in the future. Due to a loss in productivity, there is a slight increase in land required for soybean cultivation in the future to match the current production required in soybean. In terms of water usage, silage maize and wheat might need more water than the current situation to produce 1 tonne in the future. However, soybean and grassland are projected to require less water than the current due to optimal climate conditions in the future (an increase in temperature is optimal for soybean and grassland). The current analyses were done for a scenario where 10% of the protein source was shifted. It would be informative to explore the impact of various shift options, such as 20%, 30%, etc., on land use and other explored variables. This could open up a lot more land for other purposes. However, this exploration should also involve the impact that such a shift would have on the overall diet, as other macro and micronutrient demands also still need to be covered.

Understanding the indirect impacts of climate change on food security requires more comprehensive analytical approaches and sophisticated modeling, including links to the political economy. This study investigated the national level land requirement and climate change impacts on production for cereal and fodder crops using a biophysical and empirical modeling approach. However, we have not investigated location-specific information on the suitability and production of cereals and fodder crops. Integrated crop modeling and suitability modeling approach could be the best opting methodology to find soy production suitability, which requires in soy transition. Location-specific information on suitability could help to avoid misleading on choosing land for alternative cultivation. Additionally, by linking crop models with economic models and approaches, crop model outputs can be effectively used as inputs into socioeconomic modeling efforts for priority setting and policy advice using ex-ante impact assessment of technologies and scenario analysis. Bio-economic models are used for exploratory studies to understand the potential impacts of drivers, for instance, climate change and alternative crop management practices.

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6 Appendix

Table 4: The crop file (a sample of wheat) for the WOFOST simulation.

```
CRPNAM='Winter wheat, EC'

** emergence
TBASEM   =  -10.0    ! lower threshold temp. for emergence [cel]
TEFFMX   =  30.0    ! max. eff. temp. for emergence [cel]
TSUMEM   = 60.     ! temperature sum from sowing to emergence [cel d]

** phenology
IDSL     =   0      ! indicates whether pre-anthesis development depends
                 ! on temp. (=0), daylength (=1) , or both (=2)
DLO      = 8.0    ! optimum daylength for development [hr]
DLC      = 0.0    ! critical daylength (lower threshold) [hr]
TSUM1    = 850.     ! temperature sum from emergence to anthesis [cel d]
TSUM2    = 850.     ! temperature sum from anthesis to maturity [cel d]

DTSMTB   =   0.00,    0.00,     ! daily increase in temp. sum
          30.00,   30.00,     ! as function of av. temp. [cel; cel d]
          45.00,   30.00
DVSI = 0.           ! initial DVS
DVSEND   =   2.00   ! development stage at harvest (= 2.0 at maturity [-])

** initial
TDWI     =   210.00   ! initial total crop dry weight [kg ha-1]
LAIEM    =   0.1365  ! leaf area index at emergence [ha ha-1]
RGRLAI   =   0.00817 ! maximum relative increase in LAI [ha ha-1 d-1]

** green area
SLATB    =   0.00,    0.00212,   ! specific leaf area
           0.50,    0.00212,    ! as a function of DVS [-; ha kg-1]
           2.00,    0.00212,


SPA      =   0.000  ! specific pod area [ha kg-1]
SSATB =  0.0, 0.0,  ! specific stem area [ha kg-1]
        2.0, 0.0   ! as function of DVS
SPAN     =  31.3.     ! life span of leaves growing at 35 Celsius [d]
TBASE    =   0.0    ! lower threshold temp. for ageing of leaves [cel]

** assimilation
KDIFTB = 0.0, 0.60, ! extinction coefficient for diffuse visible light [-]
        2.0, 0.60  ! as function of DVS

EFFTB  = 0.0, 0.45, ! light-use effic. single leaf [kg ha-1 hr-1 j-1 m2 s]
       40.0, 0.45  ! as function of daily mean temp.

AMAXTB   =   0.00,   35.83,     ! max. leaf CO2 assim. rate
                  1.00,   35.83,
           1.30,   35.83,     ! function of DVS [-; kg ha-1 hr-1]
           2.00,   4.48
TMPFTB   =   0.00,    0.01,     ! reduction factor of AMAX
          10.00,    0.60,     ! as function of av. temp. [cel; -]
          15.00,    1.00,
          25.00,    1.00,
          35.00,    0.00
TMNFTB   =   0.00,    0.00,     ! red. factor of gross assim. rate
           3.00,    1.00      ! as function of low min. temp. [cel; -]

CO2 = 360.

CO2AMAXTB     40., 0.00,      ! multiplication factor for AMAX
           360.,  1.00,       ! to account for an increasing CO2 concentration
           720.,  1.35,
          1000.,  1.50,
          2000.,  1.50

CO2EFFTB   =  40., 0.00,                          ! multiplication factor for EFF
           360.,  1.00,                   ! to account for an increasing CO2 concentration
           720.,  1.11,
          1000.,  1.11,
          2000.,  1.11
```

```
CO2TRATB   =  40., 0.00,                              ! multiplication factor for maximum transpiration rate TRAMX
          360.,  1.00,                   ! to account for an increasing CO2 concentration
          720.,  0.9,
         1000.,  0.9,
         2000.,  0.9

** conversion of assimilates into biomass
CVL      =   0.685  ! efficiency of conversion into leaves [kg kg-1]
CVO      =   0.709  ! efficiency of conversion into storage org. [kg kg-1]
CVR      =   0.694  ! efficiency of conversion into roots [kg kg-1]
CVS      =   0.662  ! efficiency of conversion into stems [kg kg-1]

** maintenance respiration
Q10      =   2.0    ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]
RML      =   0.030  ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]
RMO      =   0.010  ! rel. maint. resp. rate stor.org. [kg CH2O kg-1 d-1]
RMR      =   0.015  ! rel. maint. resp. rate roots [kg CH2O kg-1 d-1]
RMS      =   0.015  ! rel. maint. resp. rate stems [kg CH2O kg-1 d-1]
RFSETB   =   0.00,    1.00,     ! red. factor for senescence
          2.00,    1.00      ! as function of DVS [-; -]

** partitioning
FRTB     =   0.00,    0.50,     ! fraction of total dry matter to roots
          0.10,    0.50,     ! as a function of DVS [-; kg kg-1]
          0.90,    0.03,
          2.00,    0.00
FLTB     =   0.00,    0.65,     ! fraction of above-gr. DM to leaves
          0.10,    0.65,     ! as a function of DVS [-; kg kg-1]
          0.25,    0.70,
          0.50,    0.50,
          1.50,    0.00,
          2.00,    0.00
FSTB     =   0.00,    0.35,     ! fraction of above-gr. DM to stems
          0.10,    0.35,     ! as a function of DVS [-; kg kg-1]
          0.25,    0.30,
          0.646,    0.70,
          0.95,    1.00,
          2.00,    0.00
FOTB     =   0.00,    0.00,     ! fraction of above-gr. DM to stor. org.
          0.50,    0.00,     ! as a function of DVS [-; kg kg-1]
          0.95,    0.00,
          1.00,    1.00,
          2.00,    1.00

** death rates
PERDL    =   0.030  ! max. rel. death rate of leaves due to water stress
RDRRTB   =   0.00,    0.000,    ! rel. death rate of stems
          1.50,    0.000,    ! as a function of DVS [-; kg kg-1 d-1]
          1.5001,  0.020,
          2.00,    0.020
RDRSTB   =   0.00,    0.000,    ! rel. death rate of roots
          1.50,    0.000,    ! as a function of DVS [-; kg kg-1 d-1]
          1.5001,  0.020,
          2.00,    0.020

** water use
CFET     =   1.00   ! correction factor transpiration rate [-]
DEPNR    =   4.5    ! crop group number for soil water depletion [-]
IAIRDU   =   0      ! air ducts in roots present (=1) or not (=0)
IOX      =   0      ! switch calculation of oxygen stress on (1) or off (0)

** rooting
RDI      =  10.     ! initial rooting depth [cm]
RRI      =   1.2.   ! maximum daily increase in rooting depth [cm d-1]

RDMCR    = 125.     ! maximum rooting depth [cm]
DVSDR    =  1.0     ! development stage above which death of roots and stems starts
DVSDLT   =  1.0     ! development stage above which death of leaves starts in dependence of mean daily temperature

** nutrient (N-P-K) use
RDRLV_NPK        = 0.05     ! max. relative death rate of leaves due to nutrient (N-P-K) stress
DVS_NPK_STOP      = 1.3      ! development stage above which no crop N-P-K uptake does occur
DVS_NPK_TRANSL    = 0.8      ! development stage above which N-P-K translocation to storage organs does occur
NPK_TRANSLRT_FR   = 0.15     ! N-P-K translocations from roots as a fraction of resp. total N-P-K amounts translocated from leaves and stems
NCRIT_FR      = 1.00     ! optimal N concentration as fraction of maximum N concentration
PCRIT_FR      = 1.00     ! optimal P concentration as fraction of maximum P concentration
KCRIT_FR      = 1.00     ! optimal K concentration as fraction of maximum K concentration
```

```
NMAXRT_FR     = 0.50     ! maximum N concentration in roots as fraction of maximum N concentration in leaves
NMAXST_FR     = 0.50     ! maximum N concentration in stems as fraction of maximum N concentration in leaves
PMAXRT_FR     = 0.50     ! maximum P concentration in roots as fraction of maximum P concentration in leaves
PMAXST_FR     = 0.50     ! maximum P concentration in stems as fraction of maximum P concentration in leaves
KMAXRT_FR     = 0.50     ! maximum K concentration in roots as fraction of maximum K concentration in leaves
KMAXST_FR     = 0.50     ! maximum K concentration in stems as fraction of maximum K concentration in leaves
NLAI_NPK     = 1.0      ! coefficient for the reduction due to nutrient (N-P-K) stress of the LAI increase (during juvenile phase)
NLUE_NPK     = 1.1      ! coefficient for the reduction of RUE due to nutrient (N-P-K) stress
NMAXSO   = 0.0176   ! maximum N concentration (= 1.6*min. N conc.) in storage organs [kg N kg-1 dry biomass]
PMAXSO   = 0.0026  ! maximum P concentration (= 1.6*min. P conc.) in storage organs [kg P kg-1 dry biomass]
KMAXSO   = 0.0048  ! maximum K concentration (= 1.6*min. K conc.) in storage organs [kg K kg-1 dry biomass]
NPART    = 1.0      ! coefficient for the effect of N stress on leaf allocation
NSLA_NPK    = 0.5      ! coefficient for the effect of nutrient (N-P-K) stress on SLA reduction
NRESIDLV    = 0.004   ! residual N fraction in leaves [kg N kg-1 dry biomass]
NRESIDST    = 0.002  ! residual N fraction in stems [kg N kg-1 dry biomass]
NRESIDRT    = 0.002  ! residual N fraction in roots [kg N kg-1 dry biomass]
PRESIDLV    = 0.0005  ! residual P fraction in leaves [kg P kg-1 dry biomass]
PRESIDST    = 0.0003  ! residual P fraction in stems [kg P kg-1 dry biomass]
PRESIDRT    = 0.0003  ! residual P fraction in roots [kg P kg-1 dry biomass]
KRESIDLV    = 0.009  ! residual K fraction in leaves [kg K kg-1 dry biomass]
KRESIDST    = 0.005  ! residual K fraction in stems [kg K kg-1 dry biomass]
KRESIDRT    = 0.005  ! residual K fraction in roots [kg K kg-1 dry biomass]
TCNT        = 10.      ! time coefficient for N translocation to storage organs [days]
TCPT        = 10.      ! time coefficient for P translocation to storage organs [days]
TCKT        = 10.      ! time coefficient for K translocation to storage organs [days]
NFIX_FR     = 1.0     ! fraction of crop nitrogen uptake by biological fixation [-]

NMAXLV_TB    =  0.0, 0.060,   ! maximum N concentration in leaves as function of development stage [kg N kg-1 dry biomass]
            0.4, 0.040,
            0.7, 0.03,
            1.0, 0.02,
            2.0, 0.014,
            2.1, 0.014

PMAXLV_TB    =  0.0, 0.011,   ! maximum P concentration in leaves as function of development stage [kg P kg-1 dry biomass]
            0.4, 0.008,
            0.7, 0.006,
            1.0, 0.004,
            2.0, 0.0027,
            2.1, 0.0027

KMAXLV_TB    =  0.0, 0.12,   ! maximum K concentration in leaves as function of development stage [kg K kg-1 dry biomass]
            0.4, 0.08,
            0.7, 0.06,
            1.0, 0.04,
            2.0, 0.028,
            2.1, 0.028
```

Table 5: The soil file used in the WOFOST simulation

```
** $Id: ec3.new 1.2 1997/09/18 17:33:54 LEM release $
**
** SOIL DATA FILE for use with WOFOST Version 5.0, June 1990
**
** EC3-medium fine

SOLNAM='EC3-medium fine'

** physical soil characteristics

** soil water retention
SMTAB    =  -1.000,   0.410,    ! vol. soil moisture content
          1.000,   0.398,    ! as function of pF [log (cm); cm3 cm-3]
          1.300,   0.389,
          1.491,   0.380,
          2.000,   0.340,
          2.400,   0.287,
          2.700,   0.241,
          3.400,   0.148,
          4.204,   0.104,
          6.000,   0.090

SMW      =   0.104  !  soil moisture content at wilting point [cm3/cm3]
SMFCF    =   0.300  !  soil moisture content at field capacity [cm3/cm3]
SM0      =   0.410  !  soil moisture content at saturation [cm3/cm3]
```

```
CRAIRC   =   0.060  ! critical soil air content for aeration [cm3/cm3]

** hydraulic conductivity
CONTAB   =   0.000,   1.408,    ! 10-log hydraulic conductivity
          1.000,   0.167,    ! as function of pF [log (cm); log (cm/day)]
          1.300,  -0.215,
          1.491,  -0.638,
          1.700,  -0.854,
          2.000,  -1.155,
          2.400,  -1.796,
          2.700,  -2.260,
          3.000,  -2.745,
          3.400,  -3.357,
          3.700,  -3.824,
          4.000,  -4.276,
          4.204,  -4.678


K0      =  25.586  ! hydraulic conductivity of saturated soil [cm day-1]
SOPE     =   1.47   ! maximum percolation rate root zone[cm day-1]
KSUB     =   1.47   ! maximum percolation rate subsoil [cm day-1]

** soil workability parameters
SPADS    =   0.100  !  1st topsoil seepage parameter deep seedbed
SPODS    =   0.030  !  2nd topsoil seepage parameter deep seedbed
SPASS    =   0.200  !  1st topsoil seepage parameter shallow seedbed
SPOSS    =   0.050  !  2nd topsoil seepage parameter shallow seedbed
DEFLIM   =  -0.300  !  required moisture deficit deep seedbed

** soil depth
RDMSOL = 250
```

Table 6: The site file used in the WOFOST simulation for the Netherlands

```
IZT    = 0
IFUNRN = 0
IDRAIN = 0
SSMAX  = 0.000000
WAV    = 20.000000
ZTI    = 350.000000
DD     = 0.000000
RDMSOL = 250.000000
NOTINF = 0.000000
SSI    = 0.000000
SMLIM  = 0.300000
CO2    = 360

NINFTB = 0.0,   0.0,
       0.5,   0.0,
       1.5,   0.0
```

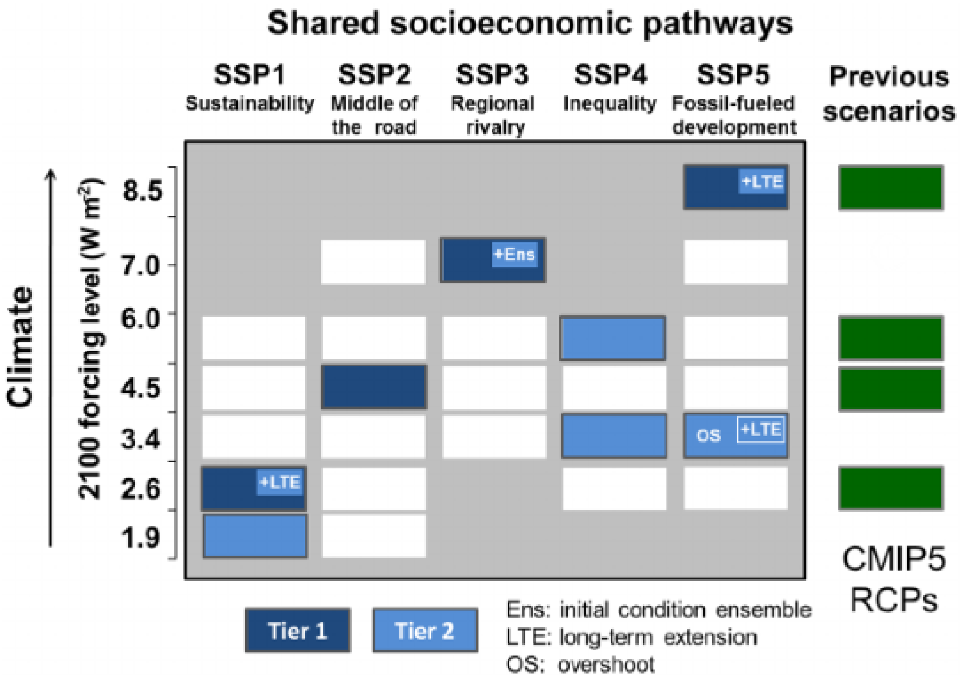

Figure 11 Matrix of shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs, forcing level). It is taken from (O'Neill et al., 2016).

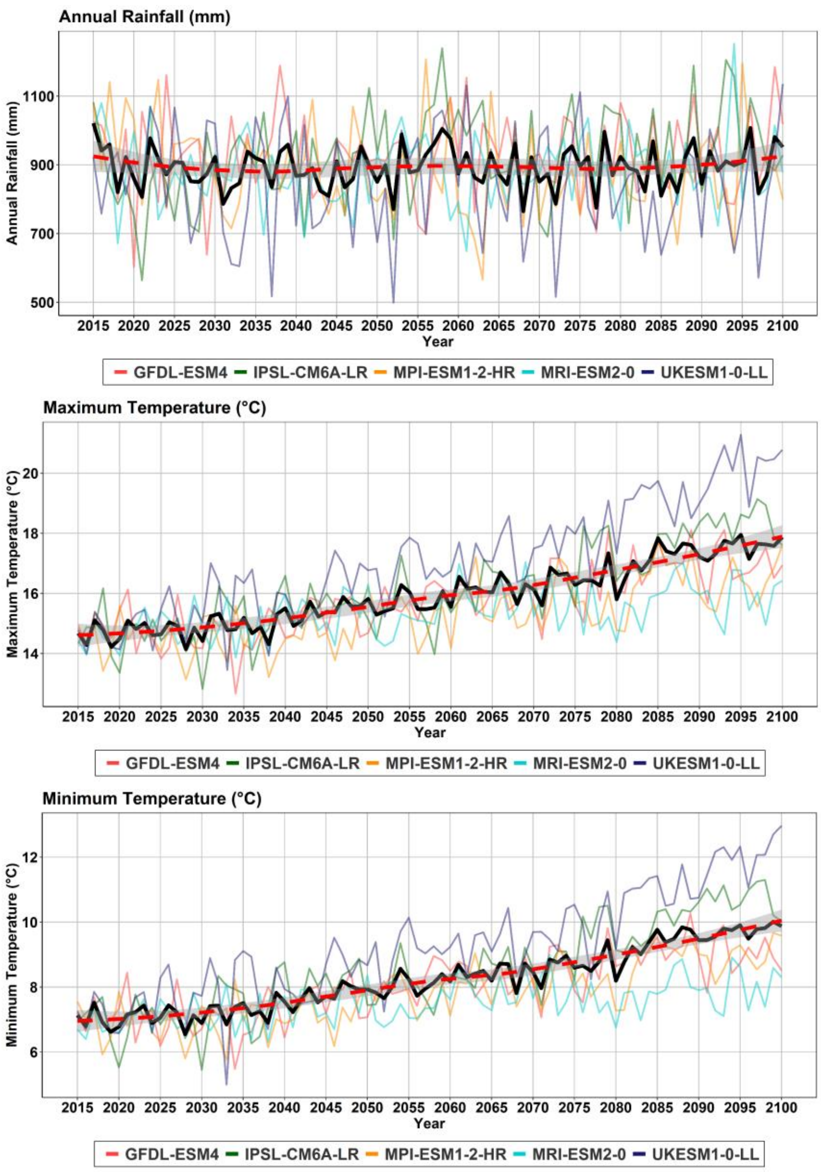

Figure 12: Time series plot for annual rainfall, maximum temperature, and minimum temperature for various GCMs. The dark black line indicates the ensemble mean of all GCMS, and the red dashed line indicates the trend over time (2015 to 2100)

6.1 Diet and Production (The Netherlands, 2015)

Table 7: The calculation results assess the effects on the production of replacing 10% of milk protein intake with the same absolute amount of soya drink protein.

Food Balance sheet (the Netherlands, 2015)	Milk - Excluding Butter			Soya drink[1]			Total (Milk+Soy drink)		
Element	**2015**	**-10%**	**ratio**	**2015**	**-10%**	**ratio**	**2017**	**-10%**	**ratio**
Fat supply quantity (g/capita/day)	26.61	23.95	0.900	0.00	1.754		**26.61**	**25.70**	**0.966**
Protein supply quantity (g/capita/day)	**30.7**	**27.63**	**0.900**	**0.00**	**3.070**		**30.70**	**30.70**	**1.00**
Food supply (kcal/capita/day)	458	412	0.900	0.00	2.544		**458.00**	**414.74**	**0.906**
Food supply quantity (kg/capita/yr)	303.9	273.5	0.900	0.0	32.0		303.89	305.52	1.005
				Soya beans[2]					
Food[1] (1000 tonnes/y)[3]	5147	4633	0.900	2.0	62.3				
Residuals	-6	-6	1.000	-623	-623				
Other uses (non-food)	0	0	NA	0	0				

Processing	3585	3585	1.000	3138	3138				
Seed	0	0	NA	0	0				
Feed	39	39	1.000	0	0				
Losses	0	0	NA	0.0	0.0				
Domestic supply quantity	8765	8251	0.941	2517	2577				
Export Quantity	7912	7912	1.000	938	938				
Stock Variation	423	423	1.000	54	54				
Import Quantity	3550	3550	1.000	3509	3509				
Production	**13550**	**13036**	**0.9620**	**0.0**	**60.3**				

[1] For soya drink food supply values, the additional amounts in the protein transition scenario are shown (-10%). In the FBS, only the protein and food supply quantities had non-zero values (0.01 g/cap/d and 0.1 kg/cap/y, respectively), but it is not known whether this was a soya drink or some other soya product.

[2] For soya bean values, both those from the original FBS and those with additional soya drinks are shown. The additional soya bean in food (60.3 ktonnes/y) has been calculated from the additional soya drink in the food supply quantity (32 kg /cap/y).

[3] All categories from food up to production are expressed in ktonnes per year of primary milk (raw milk) and soya bean commodities.

6.2 Soya and feed crop parameters (The Netherlands, 2015)

Table 8: Parameters used in the calculations for the protein transition scenario in The Netherlands.

Product	Nitrogen	Protein	Fat	Source:
Soya beans	6.6%	38%	18%	(Charrondière et al., 2013)
Soya drink	**0.61%**	**3.5%**	**2.0%**	(Wiki, 2021)
Ratios		0.092	0.11[1]	
g protein / g N	**5.75**			(Timmer & De Visser, 2014)
Feed	**FCR [2,3]**	**DM yield [4]**		
Grass	0.39	9.40		
Silage maize	**0.15**	**15.6**		
Wheat	0.17	8.10		
Soya bean		**3.00**		(Verstand et al., 2020)

[1] Assuming that 100% of the fat in the soya bean is included in the soya drink, a share of 0.83 (0.092/0.11) can be estimated for the protein of the soya bean that ends up in the soya drink.

[2] FCR: Feed Conversion Ratio in g feed DM / g milk produced, DM yield in tonnes feeds DM per ha. Here, feed DM includes feeding losses in the stable.

[3] Based on a feed efficiency of 1.45 kg fat and protein corrected milk per kg feed dry matter, 1.06 kg fat and protein corrected milk per kg produced milk, dry matter shares in the total ratio of 50% grass, 20% silage maize, and 30% other feed and feeding losses of 5% for roughages and 2% for concentrates (Bruggen et al., 2015; NZO, 2021; Van Dijk et al., 2020; Wicke et al., 2020; WUR, 2018).

[4] CBS: Statline, 2015 (CBS, 2015)