What's land got to do with it? Exploring the potential of land-based carbon mitigation strategies in Turkey[1]

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Abstract

Impact of land-use activities on climate change has been well documented, and creates complex trade-offs across different spheres. On one hand, land plays a significant role in sustaining livelihoods with food and energy production. On the other hand, production activities result in significant greenhouse gas emissions as well as consumption of freshwater resources, and the allocation of lands for means of production results in deforestation and loss of biodiversity, all of which contributes to anthropogenic climate change. Several negative emissions technologies have been proposed to minimize trade-offs in this context, such as bioenergy and forestation. We argue that building effective land-based carbon mitigation strategies requires a systems approach that would account for interactions and dynamic complexity across different spheres. In this regard, we adopt a nexus perspective and build a multi-sector System Dynamics model to observe and understand these short- and long- term trade-offs and increase co-benefits across sectors. We parametrize our model for Turkey data and validate structurally through extreme condition testing. Results for the base scenario are analyzed to get a clear picture ahead for the land, water, food and energy future of Turkey. As a final output, we designed a flight simulator interface to be used as a policy analysis tool.

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Table of Contents

1. Introduction

In the last two decades, international efforts towards mitigating climate change have gained widespread popularity and swift implementation by government bodies on a global scale. However, the approach towards this issue has transformed significantly as the generation of new evidence has questioned the effectiveness and limitations of past approaches. Following the frameworks of the Kyoto Protocol (2002) and Millennium Development Goals (2000-2015), the international community adopted new means of sustainable development strategies through the Paris Agreement (2015) and Sustainable Development Goals (2015-2030) (UNDP, 2016). The major differences between the past and recent narratives can be described in two elements. First, the focus of SDGs is on global development on a wider scale for both developed and developing nations, compared to the narrower focus of MDGs which was mainly directed towards developing nations. Second, SDGs include a wider array of goals with a further emphasis on a unified approach that holds society, environment, and economy as embedded systems that are not, in principle, separate entities (Woodbridge, 2015). Therefore, an advocacy for unified solutions to different goals became prevalent in the current approach towards sustainable development (UNDP, 2016), indicating the need for a holistic view such as the Nexus approach.

Paris Agreement, as well as SDG #13, directly emphasizes climate change mitigation, aiming to put the global temperature increase below 1.5 - 2 C° compared to pre-industrial levels (UNDP, 2016). This level is within the limits but necessitates swift and radical actions to reduce and remove emissions (Roe *et al.*, 2017). Our study aims to explore the role of land use as a negative emissions technology to mitigate climate change and analyze its trade-offs in energy production, food security, and biodiversity conservation. In this regard, we examine the role of land on major sustenance of global life; climate, water, food, and energy.

The world's land surface has been shaped by human activities tremendously. The anthropogenic actions are associated with harvesting resources for human life and it ranges from clearing of forests for wood harvesting, expansion of croplands for food production to extensive development of urban areas (Foley *et al.*, 2005). The role of land-use activities has significant impacts on ecosystem balance through various mechanisms.

Water required for land-use activities directly impacts the water resources, resulting in withdrawals and diversions. This, in many cases, results in a disruption of freshwater resource balance between the surface and the ground (Stone, 2009). The greatest effect of land-use on water is associated with irrigation, where it accounts for 85% of global water consumption annually. Another negative impact of land-use on water is a reduction in water quality. As more fertilizers are used and agricultural practices get more aggressive, consequent increase in erosion and chemicals from fertilizers degrade the groundwater and soil substantially (Foley *et al.*, 2005; Stone, 2009). We can also observe an increased impact in modern times; evidenced by 700% increase in fertilizer use and 70% increase in irrigated croplands only in the last few decades (Foley *et al.*, 2005).

Land-use activities also take their toll on biodiversity. The main driver behind the impairment of biodiversity is habitat destruction. Bio-productive fields are being converted to agricultural croplands and biofuel production fields. Moreover, tropical humid forests that house nearly two-thirds of all species are being extensively reduced by clear cutting or selective logging (Pimm & Raven, 2000). This change in land-use leaves the vulnerable species lose their natural habitats, either forcing them to shrink in population size, or go extinct. In some cases, habitat reduction plays a key role in transmission of infectious diseases. Species under habitat loss migrate to urban areas, carrying infectious diseases such as malaria (Foley *et al.*, 2005).

The greatest debate on the impact of land use activities concentrates on their impact on climate change. It is estimated that, since 1850, human land-use has directly caused one third of CO2 emissions (Foley *et al.*, 2005). In recent years, land uses such as agriculture and forestry account for 35% of global GHG emissions (Roe *et al.*, 2017). Apart from this enormous contribution in emissions, land use activities also have direct radioactive and physiological effects on the local region (Costa & Foley, 2000). Extensive deforestation reduces the rainfall and cloud formation while increasing the temperature of the region, an effect comparable to the effects of atmospheric composition (Stone, 2009).

The presence of such a wide range of effects imposes a great deal of environmental potential on land use activities, making it a good topic of study in climate mitigation strategies. Several land-based emission reduction strategies and negative emission technologies are proposed as effective solutions in order to meet the climate goals of the Paris Agreement and SDGs (UNDP, 2016; Roe *et al.*, 2017) while some of these strategies propose additional benefits such as bioenergy. These technologies include biofuel, bioenergy carbon capture and storage (BECCS), and forestation.

Besides their promising potential, possible effects of such land-based climate mitigation methods on a macro level are far from predictable via trivial unidirectional thinking. Intertwined cause and effect relations, different time scopes of the required analysis and impact of accumulated stocks such as current emission levels or available land areas at hand require a systemic and dynamic approach.

In this study, we aim to analyze short- and long- term impacts of land use activities in Turkey from the climate, water, food, and energy nexus perspective. Our analysis will focus on minimization of trade-offs, harnessing of synergies and increasing of co-benefits among differing elements within our scope, using a multi-sector System Dynamics model. The paper is organized as follows: In section 2, we provide a problem definition that is bounded within our objectives. Section 3 will provide the background, and review the previous modeling and assessment studies in this line of research while skimming the current environmental research in Turkey. Section 4 will introduce our stock-flow model structure and parametrization. We validate our model in section 5 with extreme condition tests, and analyse our results in section 6.

2. Problem Definition

The accumulation of greenhouse gas in our atmosphere has been raising concerns in local and international communities. Increasing emissions from various sources (agriculture, transportation, industry, livelihoods) contribute to this accumulation tremendously. Significant steps in emission reductions are deemed necessary to alleviate climate change. However, reduction by itself is not sufficient to reduce the atmospheric gas accumulation. Negative emissions strategies prove to be a promising remedy in this manner. These negative emission methods include several land use activities such as bioenergy production and forestation. Since land acts as the limiting resource, its usage creates trade-offs and synergies across different spheres of human life, that is water, energy and food.

Land use changes for bioenergy production will require deployment of different land types for bioenergy crops. On the down side, conversion of agricultural lands may result in a shortage of food supply to feed the population demand, creating risks for food security. Conversion of forests causes decreased carbon sequestration, which would increase GHG accumulation in the atmosphere, decrease rainfall and contribute to climate change. However, on the positive side, produced renewable energy has the potential to offset the emissions from fossil fuels, which would yield a negative net carbon budget. Also it is worth mentioning that both bioenergy crops and agricultural crops have significant water footprints that can severely impact freshwater resources and overall water quality.

Wide arrays of effects, potentials and interactions these strategies accommodates requires a systems approach to come up with effective policies and incentives for the decisions of micro and macro actors who are influential on human land-use activities. In this respect, we will be modeling this system with special attention to spatio-temporal characteristics, causal relations and interaction effects.

3. Background & Literature Review

Forestation is a biogenic negative emissions strategy in land use mitigation. Afforestation refers to the establishment of a new forest while reforestation is the forestation of degraded previous forest areas. Trees capture (sequester) and store CO_2 in living biomass, dead organic matter, and soil during their growth (Fawzy *et al.*, 2020). Carbon capture continues for 20-100 years and decreases significantly thereafter. Maturated trees are then utilized for harvesting. There are two things to point here. First, it takes several years for a seeded tree to start capturing carbon. Second, if the harvested tree is burned, it releases the captured carbon back into the atmosphere (Sterman *et al.*, 2018). Therefore, the assessment of this strategy should account for the delays and rebounds associated with this cycle, as well as human use and risks such as forest fires.

Biofuel has long been deemed as a more environmentally friendly alternative to fossil fuels due to its low carbon budget and renewability. A major substitution strategy is the use of biofuel (such as ethanol) produced by fermentation of carbohydrate crops (wood, corn, soybeans, etc.) to be used in transportation, offsetting fossil fuels (Righelato & Spracklen, 2007). The implementation of this action is wide and popular; however, studies show that the net benefit of biofuel consumption may not be as it is thought to be due to opportunity costs for other options and -for wood bioenergy- underlying time delays (Righelato & Spracklen, 2007; Gnansounou *et al.*, 2008; Sterman et. al, 2018).

In a similar manner, BECCS technology refers to capturing and storing atmospheric CO_2 in biomass to be used as bioenergy. During photosynthesis in biomass, atmospheric CO_2 is captured. After their harvest, biomass is burned for energy production, releasing the captured CO_2 as well. Released CO_2 is then stored in suitable reservoirs without emitting into the atmosphere (Fawzy *et al.*, 2020). Overall, the BECCS technology differs from the traditional biofuel in terms of released CO_2 in energy production, having the potential to produce energy with a negative carbon budget. However, the BECCS is a less mature technology compared to biofuels which means it requires a significant amount of investment in technology and facilities (Roe *et al.*, 2017). Also, the effectiveness of BECCS use, likewise the biofuel, significantly depends on the choice of biomass used in its production, as different crops have different carbon capture and storage potential (Gnansounou *et al.*, 2008; Harper *et al.*, 2018).

The main challenge in the biofuel and BECCS technologies is their requirement of large-scale deployment of land to build a significant amount of reservoir to implement an effective climate-energy policy (Naylor *et al.*, 2007; Righelato & Spracklen, 2007; Fawzy *et al.*, 2020). This deployment may involve the conversion of natural forests and grasslands to arable lands for bioenergy production. In addition to direct changes in land use, biofuels also lead to indirect land-use changes (ILUC) through displacement and clustering of activities (Gnansounou *et al.*, 2008). The potential detrimental effects of land conversion on ecosystems make a large-scale adoption strategy questionable. Additionally, in a

30-year period, forestation of an equal area of land would capture carbon 2 to 9 times more than the emission reduction by biofuels (Righelato & Spracklen, 2007). A trade-off between these two options arises from; the additional energy and the faster implementation potential of biofuels & BECCS over forestation, and the ecological advantage of forestation over biofuels & BECCS. Additionally, it has been shown that there is a large uncertainty in future land demand and carbon capture potentials of these strategies (Krause *et al.*, 2018).

The major issue with all these land-based options is that the land is a limiting resource among those alternatives. Forestation, biofuels, and BECCS all require a certain level of land-use change of grasslands, wetlands, and croplands. This conversion may impair the ecosystem conditions and livelihoods in terms of food security and biodiversity (Naylor *et al.*, 2007; Roe *et al.*, 2017). Decreased farmlands will impede the peoples' access to food from agriculture. However, it should be noted that according to World Bank data, demand for energy has a greater rate of increase compared to the demand for food (Naylor *et al.*, 2007). In order to meet this demand, bioenergy can be considered a viable renewable option, even against the loss of food. Trade-offs regarding the energy and food, impacts on biodiversity, as well as carbon mitigation potential requires a careful assessment in policy design.

In summary, land-based mitigation activities have strong interaction, as well as risks and trade-offs stemming from their impacts on ecosystem conditions and livelihoods (Roe *et al.*, 2017). The nexus approach provides a useful qualitative framework; to reach a comprehensive and unified solution to this issue, to analyze the trade-offs and to assess the environmental impacts for different strategies. Also, system structure with long time delays and strong feedback makes the system dynamics a good match as the quantitative methodology.

3.1. Previous modeling and assessment studies

Given the potential of the land-based climate mitigation techniques and their intertwined nature with the other ecosystem services, modeling works concerning the analysis of such techniques are quite vast in the literature. Many models focus on the implications at a global scale (Krause *et al.*, 2018; Krause *et al.*, 2017; Holmatov *et al.*, 2019; Smith *et al.*, 2018; Frank *et al.*, 2021; Harper *et al.*, 2018) or impacts on specific regions (Krause *et al.*, 2020; Hasegawa *et al.*, 2016; Law *et al.*, 2018) while some others serve as generic models to be implemented in other regions as a further step (Nunez *et al.*, 2020). Concerning the land use, models mostly consider the trade-off between the allocation of lands for BECCS based mitigation techniques or land allocation for afforestation, reforestation, or the decrease in deforestation. Although the common aim for these models is to compare the effectiveness of different scenarios in terms of the emissions, some of the works focus on particular effects of land-based mitigation strategies such as the impact on biodiversity (Law *et al.*, 2018; Nunez *et al.*, 2020; Smith *et al.*, 2018), food security (Hasegawa *et al.*, 2018), or carbon costs (Hasegawa *et al.*, 2016). Usually, other ecosystem models (such as EURO-CORDEX, LPJ-GUESS, JULES) and huge datasets are incorporated to account for the climate projections, the dynamic growth of vegetation and forests, changes in land use, and shifts in the air and soil composition.

In their work, Krause and his colleagues (2017) uses a variety of process-based ecosystem models to evaluate the impacts of different land-use scenarios on various ecosystem indicators which are reflective of climate change, water availability, flood protection, food production, and water/air quality. Though not constructed from a nexus perspective, their work provides a holistic view of the system and reveals the potential trade-offs and synergies at a global scale. As a remark authors point out that policy scenarios are not unidirectional in terms of their effects on environmental indicators and the trade-offs are not robust to spatial and temporal scales.

Since the implementation of land-based carbon mitigation practices has substantial implications for multiple dimensions, the nexus approach is widely employed in the literature (Moioli *et al.*, 2018; Rulli *et al.*, 2016). Fan *et al.* (2020) propose a Land-Water-Energy nexus framework for managing agriculture to limit greenhouse gas emissions based on a case study of the Sanjiang Plain (China). As a result, the authors evaluate the greenhouse gas emissions from each source for the scenarios of different crops and technical alternatives that enable efficient use of water and other nutrients. Fajardy and colleagues (2018) develop a resource nexus based on BECCS for which the KPI's are determined through three main channels: Technical Performance (Carbon removal, energy production/use), Economic-environmental impacts (Land use change, biodiversity), and Resource efficiency (Water and land use, Biomass use/CO2 efficiency). They evaluate the effectiveness of BECCS value chain using this prism of KPIs. Some examples of qualitative works concerning the nexus approach include dimensions such as social systems, human security, conflicts, and cooperation (Froese and Schilling, 2019; Stoy *et al.*, 2018).

3.2. System Dynamics modeling in Nexus research

Implementation of the nexus perspective with System Dynamics methodology is gaining momentum as the advantages such as interpretability, participatory practices and ease of multidisciplinary collaboration are acknowledged. Several studies concentrate on specific regions and build SD models regarding various nexus dimensions: Water-Energy-Food in Khuzestan (Iran) (Keyhanpour *et al.*, 2020), in Egypt (Ali, 2019), or globally (Sušnik, 2018); Water supply- Power generation- Environment in Hehuang (China) (Feng 2016); Water-

Energy- Food- Land- Climate in Latvia (Sušnik *et al.*, 2021) and in Greek (Laspidou *et al.*, 2019). Most of the models serve as a policy analysis tool to surface possible synergies and disharmonies.

González-Rosell *et al.* take a participatory approach to analyze the dynamics of Water- Energy- Food in Andalusia (Spain) within a context of transition to sustainable policies. 14 representatives from water, energy, and food sectors including government authorities, academicians, experts from non-governmental organizations, and independent experts were involved in model building, validation, and analysis.

Different from the aforementioned SD models, Sušnik *et al.* (2021) and Laspidou *et al.* (2019) consider land use as one of the main nexus dimensions. Though for Laspidou *et al.* the land and energy sectors are not directly connected through the possible use of bioenergy, Sušnik *et al.* (2021) account for the allocation of lands to bioenergy crops and the potential impact on biodiversity.

Though not constructed as a nexus approach, concerning land-use and bioenergy, Sterman and his colleagues (2018) compare the effectiveness of using wood-based combustion as opposed to energy proportion with coal. They isolate the carbon sector of previously published model C-ROADS (Sterman *et al.*, 2012) and disaggregate particular stocks to obtain an extendable model for other geographic regions and land types. Their model is successful in revealing a counterintuitive increase in short-term carbon emissions and serves as a generic model for the bioenergy life-cycle analysis.

3.3. Environmental Endeavor in Turkey

Turkey is one of the countries with increasing power demand and CO2 emissions per capita. Although the portion of renewables in the electric supply has increased, the total energy supply is still highly dependent on fossil fuels up to 82% (Climate Transparency, 2020). Aydın *et al.* (2017) argue that part of the emissions is a result of carbon loss from the soil caused by changes in land use. Furthermore, Climate Transparency (2020), an international organization preparing annual reports on climate policies and resulting indicators in collaboration with multiple credible partners, indicates that Turkey lacks the instruments for informative decisions on sustainable policies. Increased production of biofuels and BECCS has the potential to offset fossil fuel use to some extent, to consequently decrease the overall transportation-related carbon emissions. However, potential environmental impacts of those options vary greatly for different regions, necessitating precaution against the implementation of such high-investment policies.

4. Model Structure

4.1. Method

Potential strengths and a good degree of fit of System Dynamics Methodology to the subject account for the prevalent use of SD models in nexus literature. Analyzing the dynamics of land-based mitigation strategies using the nexus perspective also falls into such subjects having a good match with the SD method. Previous modeling attempts of the problem points out that the regional parameters are effective in defining the final results of the simulations thus encouraging a region-based approach. In addition, the existence of generic models and exemplary case studies pave the way for improved applications to other regions that benefit from such a body of work.

To our knowledge, there has not been any dynamic modeling or environmental impact assessment study of land-based carbon mitigation strategies for the case of Turkey, leaving this policy domain yet to be explored. We aim to fill this gap in the literature with our main focus being on the land-based carbon mitigation strategies' potential trade-offs in water, energy, food, and climate nexus. We will treat the land as the limiting resource to be allocated for mainly four land-based activities (i.e., food agriculture, bioenergy production, forestation, bio-productive fields) and explore the role of land based options on various elements of this social, environmental and economic system in the context of Turkey. Such an analysis will provide useful policy implications to be utilized in future policy design processes in the path towards a low-carbon society and a low-carbon land.

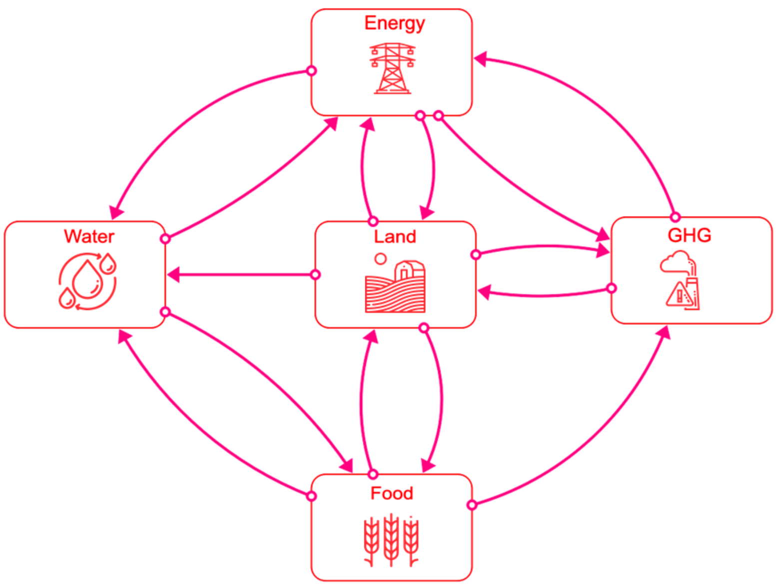

Figure 1: Macro-level interactions between the sectors

4.2. Stock-Flow Model

In line with our objective, we have devised a draft model structure in stock-flow architecture. In this section, we will describe our envisioned model with its dynamic feedbacks and causal relations. Our model consists of 5 distinct but connected sectors: Land, Food, Energy, Water and GHG. An overview diagram of the intersectoral linkage is provided in Figure 1.

Land Sector

As described before, land acts as the limiting resource to be allocated between four land usages; Food Production, Bioenergy, Forests and Bio-productive Lands.

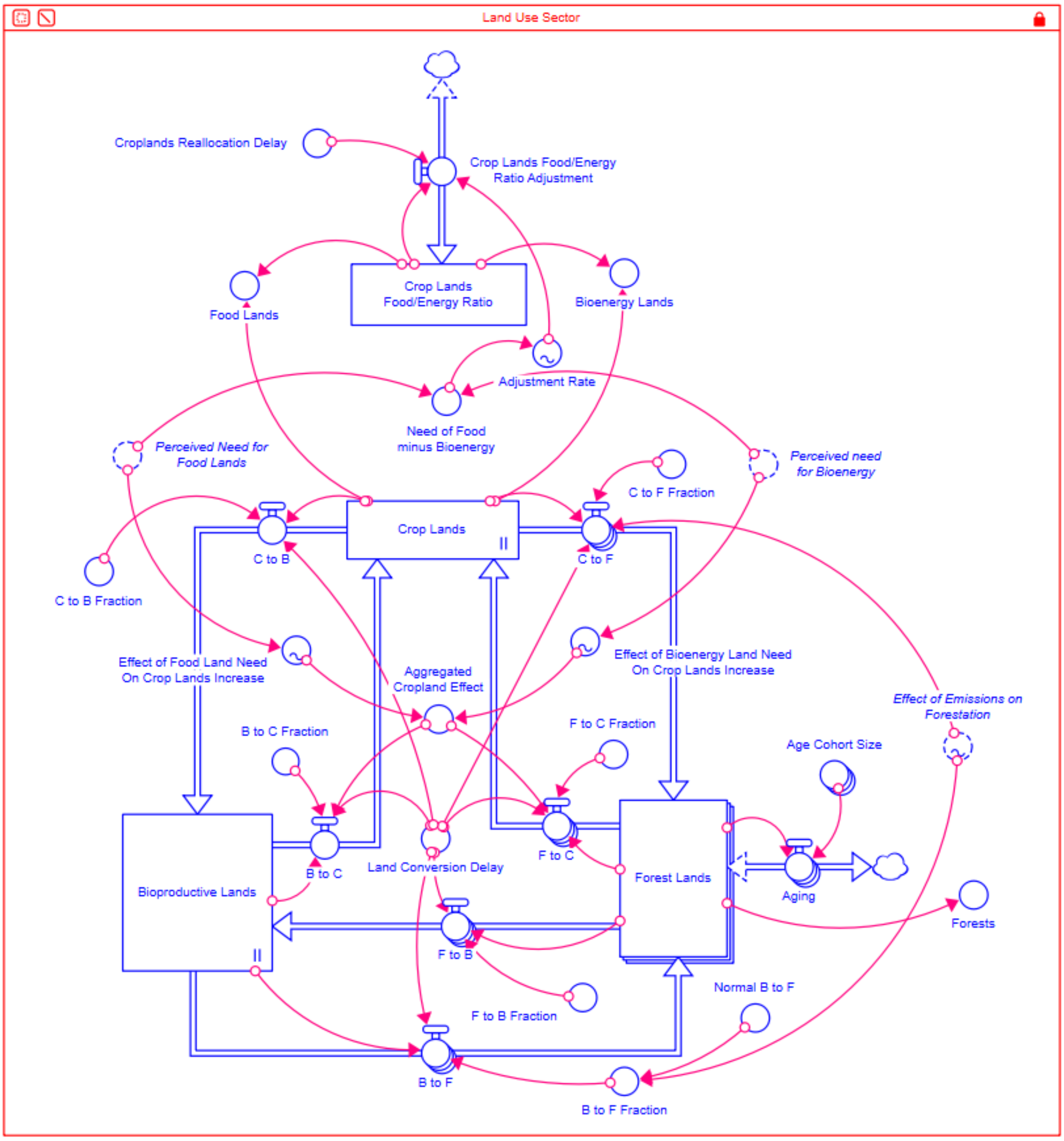

Figure 2: Land use sector

The conversion and allocation of land occurs in two folds. In the first fold, land conversion is modeled as a threeway flow exchange between Croplands, Forests and Biodiversity Lands stocks. *Croplands* stock represents the total amount of land allocated for food production and bioenergy production. *Forest Lands* and *Bio-productive Lands* are converted to *Croplands* depending on increased bioenergy needs and food needs, with feedback coming respectively from Energy and Food sectors. Forestation of *Bio-productive Lands* and *Croplands* occurs with incoming feedback from the GHG sector. As emissions increase, policymakers are modeled to have more inclination to build new forests.

In the second level, the ratio of croplands allocated for bioenergy and food productions (*Croplands Food/Energy Ratio* stock) is modeled with an adjustment biflow. Depending on the perceived need for bioenergy and food, more croplands are allocated for cultivation of bioenergy and food respectively.

Food Sector

Production of food is mainly determined by the product of *Food Lands* and *Food Productivity*. *Food Demand* is calculated by the multiplication of *Population* which is obtained as a predicted exogenous time series data and *Food Demand Per Capita*. Depending on the current *Food Demand* and *Food Production* levels, import or export decisions are made to satisfy the demand. *Share of Domestic Food in Consumption* is calculated as the minimum of 1 and the ratio of Food Production to Food Demand, which is the determinant of *Perceived Need for Food Lands,* thus impacting the possible land conversion decisions.

Another feedback pathway is centered at soil quality through *Nutrients* and *Soil Top Thickness* stocks. In case of a decrease in *Crop Productivity*, *Farming Aggression* increases which in turn completes a balancing loop through the *Nutrients* via fertilizer use. Fertilizer use will induce more oxidation and reduce *Water Quality*. Moreover, as excessive agricultural activity results in soil erosion, it decreases the *Soil Top Thickness* through the *Erosion* outflow. As in other natural regenerative processes, *Soil Top Thickness* is also assumed to recover when left alone with a self regulating *Regeneration* adjustment flow. However, the time required for topsoil regeneration is extremely long. The last factors that are effective on crop productivity are *Water Availability* and *Water Quality*. Effect of water availability is envisioned as a dominant effect which should eliminate all possible agricultural production in case of water scarcity.

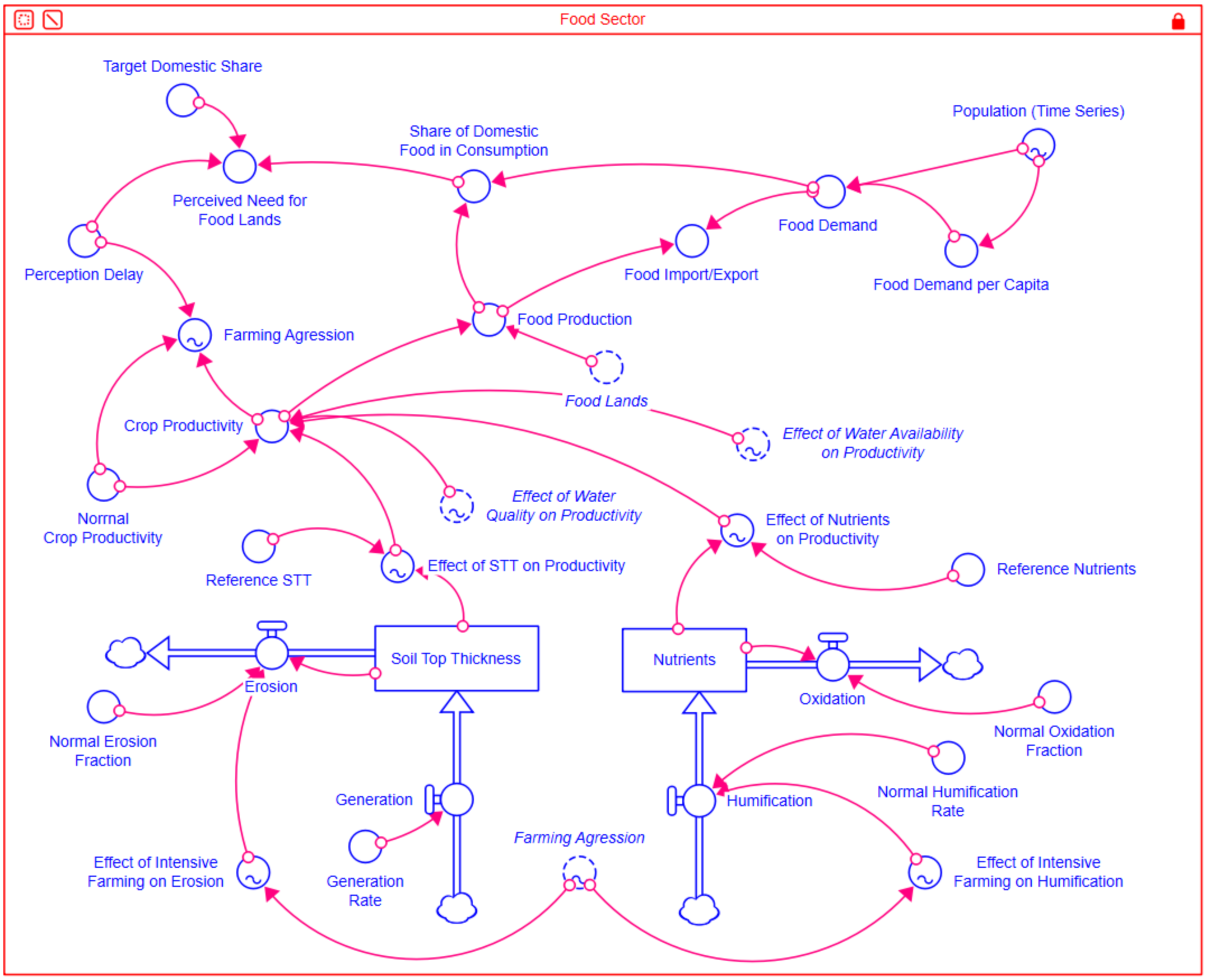

Figure 3: Food Sector

Energy Sector

Energy Demand is calculated as a function of population size. In our model, this demand is fulfilled by 4 sources of energy production: Non-renewables, Biofuel, BECCS and Other Renewables. Lands allocated for bioenergy are used to partly fulfil this demand. Bioenergy productivity, like agricultural productivity, is affected by water availability via feedback from the water sector. Initial conditions will see the traditional biofuel as the sole bioenergy production method. With increased adoption of BECCS, which is an infant technology, the share of bioenergy land use will shift from biofuels to BECCS. The remaining energy demand is fulfilled using other renewable energy alternatives and non-renewable resources.

First, Energy production from bioenergy and other renewables are calculated. Consumption of non-renewables occurs with the remainder of energy demand left from this supply of renewable alternatives. A portion of non-renewable consumption is satisfied via N*on-renewable Extraction* (extraction of *Non-renewable Resources* such as coal and oil from local reserves) while the rest is imported.

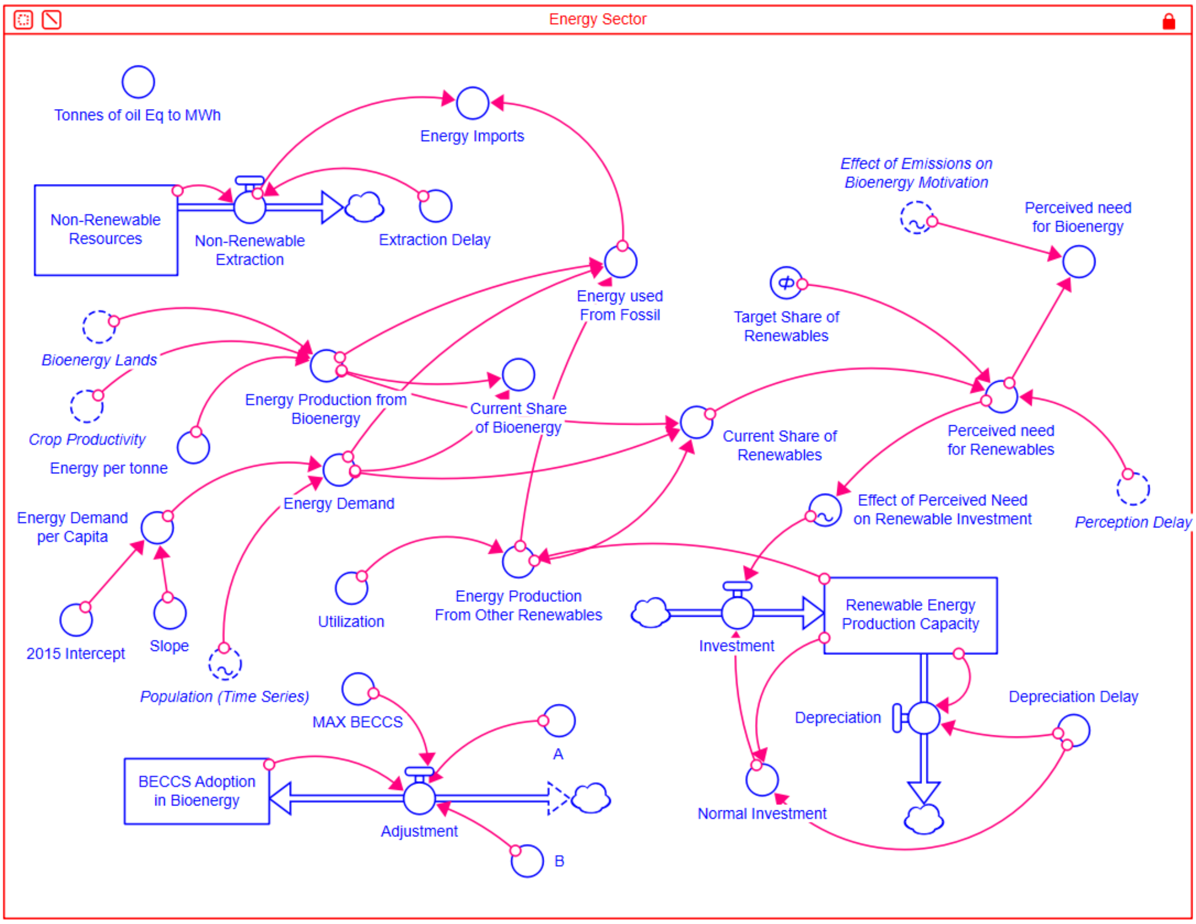

Figure 4: Energy Sector

The Government will have a *Target Share of Renewables* in energy supply, that is positively affected by GHG emissions. The discrepancy between current share and the target will bore a *Perceived Need for Renewables* which shows itself as a motivation to increase *Bioenergy Lands* and *Investment in Renewable Energy*.

Water Sector

In the water sector, available water resources are represented with two stocks: *Usable Groundwater* and *Usable Surface Water*. *Rainfall*, positively affected by available forest lands, fill the *Natural Reservoirs*. Water percolation from Natural Reservoirs to groundwater and surface water occurs with an effect of Bioproductive Lands.

Water consumption is split into three different types: *Water Use of Population, Irrigation for Agriculture,* and *Water Consumption of Industry. Water Use of Population* is mainly determined through the population whereas irrigation consumptions are driven by multiplication of the current produced amount of bioenergy or food crops and their water footprint. *Water Availability* has a limiting effect on *Crop Productivity* which limits the production amount of both crops. Upon scarcity of freshwater resources, *Crop Productivity* decreases resulting in limited consumption of water. Similar effects are also observed for other water consumptions.

Another dimension in the water sector is *Water Quality*. The quality depreciates with increased use of fertilizer whereas it recovers with natural cycles with trivial anchor and adjustment heuristic.

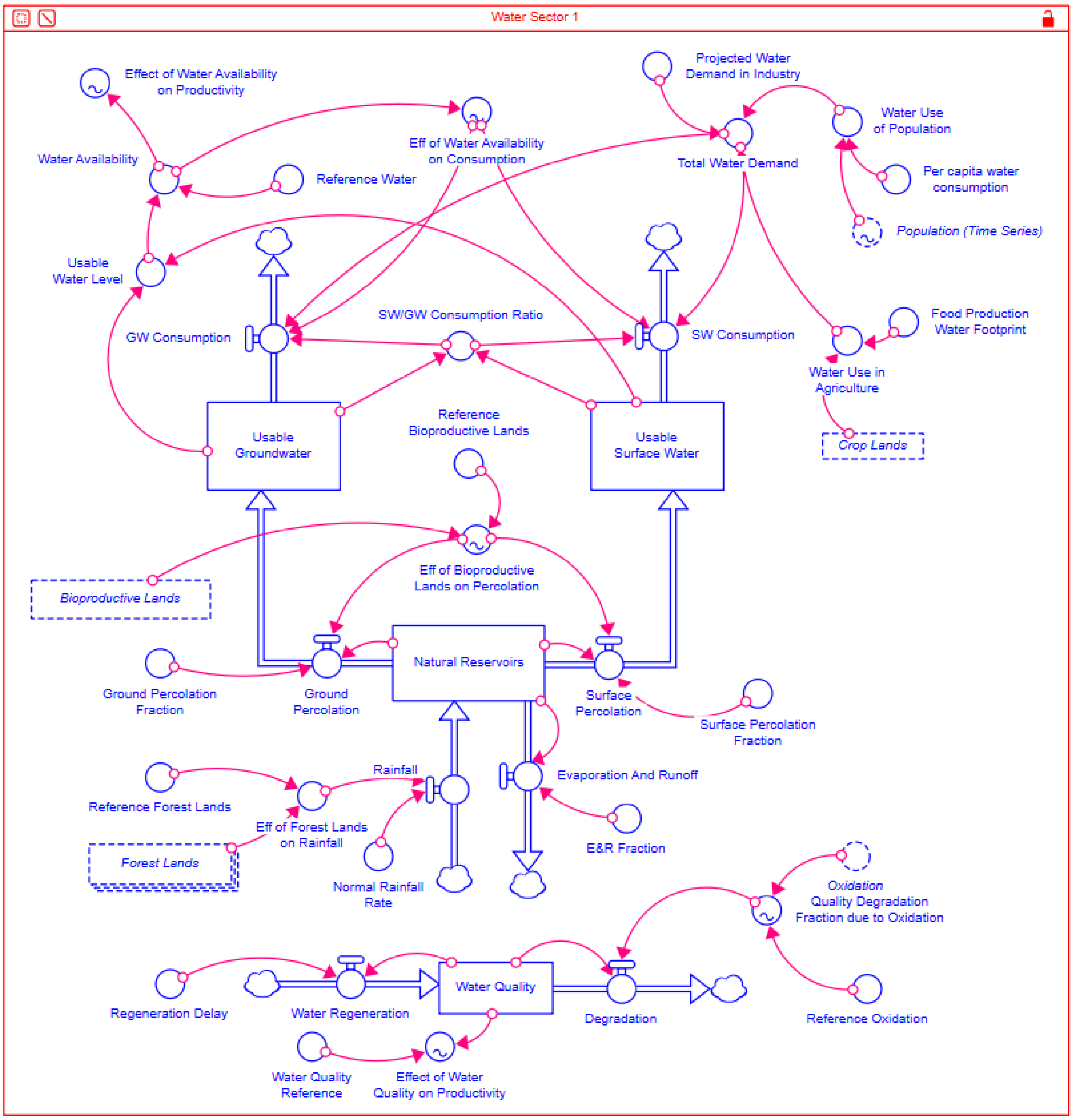

Figure 5: Water Sector

GHG Sector

GHG sector consists of a single stock variable that captures the accumulation of GHG emissions, but only as a recorder with no real life counterpart. Disaggregation of the inflows and outflows, that is emissions and sequestrations per unit time, are chosen to capture the comparative results of the net emissions for different scenarios. The emission inflows include; emissions from agricultural activities in the food sector, emissions from both production and combustion of bioenergy crops, emissions from the use of fossil fuels, and emissions from other sources such as transportation or urban use that are outside of our model boundary. Sequestration by forests is mainly determined through the Forest Lands and average capture per forest land. The gap between the net emissions and emission target determines the decisions on forest land allocation and bioenergy use.

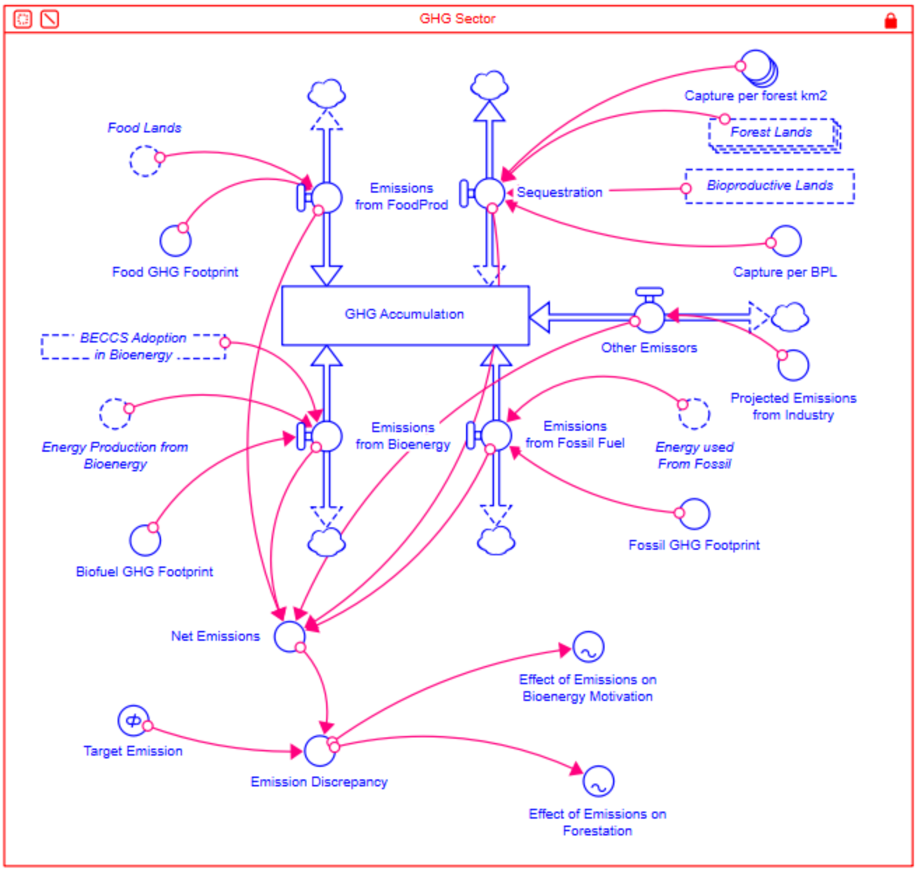

Figure 6: GHG Sector

4.3. Parametrization

Model parameters including initial stock levels, variables and coefficients are set with the data for Turkey for the year 2015 (Table 1). Population level over time is taken as a time series, having real data till 2020 and projection onwards.

Parameter Name	Unit	Value	Source
Stock Levels			
Forest Lands	square km	193143.44	EEA (2020)
Crop Lands	square km	340889.8	EEA (2020)
Bioproductive Lands	square km	212927.6	EEA (2020)
Crop Lands Food/Energy Ratio	fraction	0.96	Balat & Öz (2008)
Non-Renewable Resources	MWh	18377609.7	Eurostat (2021, Energy - Flow Sankey Diagram)
Renewable Energy Production Capacity	MWh/year	574076156	Eurostat (2021, Energy - Flow Sankey Diagram)
Nutrients	kg/squared kilometers	400	Bach & Saeed (1992)
Soil top thickness	cm	20 [5]	Bowen et al. (2005)
Usable Groundwater	billion cubic meters	98	World Bank Group (2016)
Usable Surface Water	billion cubic meters	14	World Bank Group (2016)
Natural Reservoirs	billion cubic meters	500	World Bank Group (2016)
Water Quality	dimensionless	0.5	World Bank Group (2016)
Converters			
Water			
Normal Rainfall Rate	billion cubic meters / year	501	World Bank Group (2016)
Food Water footprint	cubic meters/ square km * year	93871.98	World Bank Group (2016)
Per Capita Water Consumption	cubic meters/ person * year	93.33	World Bank Group (2016)
Projected Water Demand in Industry	billion cubic meters/ year	5	World Bank Group (2016)
Evaporation and Runoff Fraction	year ^-1	0.914	World Bank Group (2016)
GHG			
Fossil GHG Footprint	Tonnes/MWh	0.263	Climate Watch Historical GHG Emissions (2021)
Projected Emissions from Industry	Tonnes/year	6.10^7	“Turkey CO2 Emissions.” Worldometer
Capture per forest km2	Tonnes/square km * year	111-447	Climate Watch Historical GHG Emissions (2021)
Food GHG Footprint	Tonnes/square km * year	140.9	Climate Watch Historical GHG Emissions (2021)
Biofuel GHG Footprint	Tonnes/ MWh	0.16164	Mekonnen et al. (2018)
Food			
Normal Crop Productivity	Tonnes/ square km	102.9189	Eurostat (2021, Cereal Balance Items for the Main Cereals)
Per capita Food Consumption	Tonnes/ person	0.405	Eurostat (2021, Cereal Balance Items for the Main Cereals)
Energy			
Energy per tonne (biofuel crop)	MWh/ tonne	7.5	Forest Research (Potential Yields of Biofuels per Ha P.a.)
Energy Demand Per Capita	(Intercept)	20.244	Ritchie et al (2020)
	(Slope)	0.34125	Ritchie et al (2020)

Table 1: Model Parameters

Different sources have different classifications of land use. We take our land data from EEA (2020) Croplands stock is initialized with the sum of Arable lands (2A) and Pastures (2B). Bioproductive lands stock takes the sum of Natural Lands (3B) and Open Space (3C), while the initial value for Forest Lands is taken directly (3A). Three unequal cohorts were defined for Forest Age: Juvenile, Junior (the most sequestration) and Senior. Forests respectively spend 10, 30 and 10 years in these cohorts, in a circular manner. Initially 4% of croplands are used for cultivation of bioenergy crops (Balat & Öz, 2008). Normal fractions of land exchange between different types are selected to be at equilibrium, under the influence of many feedbacks.

Energy demand per capita is modeled as a linear function of time. The intercept is selected to be the energy demand per capita for 2015 which is increasing with a slope calculated from the per capita demand increase in 2015-2019. Share of renewables in energy supply is estimated to be 13-14% as of 2015, thus *Other Renewable Energy Capacity* and its *Utilization* is calibrated to produce this result.

We take cereal production and consumption as the focal variable for the food sector. Total cereal consumption of Turkey and *Food Lands* is used to calculate food consumption per capita. Initial levels of *Nutrients* stock is taken from Saeed.

Current water levels of Turkey are taken from World Bank Group Report (2016) with data from DSI. Water footprint of agricultural practices is calculated with a division of *Agricultural Water Consumption* and *Food Lands*. Similarly, per capita water consumption is calculated by dividing *Domestic Water Use* to *Population*. Annual water use by industry is given as a constant, directly from the data source.

In the GHG sector, carbon footprints of every aspect are taken from the literature, with sources indicated in Table 1. Target emission level is treated as an external input variable.

5. Model Validation

To validate the model equations structurally, we employ structure-oriented behavior tests to detect formulation flaws of our model (Barlas, 1997). In this section we validate our model structurally through equilibrium analysis and extreme condition tests.

5.1. Equilibrium Run

We defined an equilibrium lever that initializes the model with a constant population and no governmental targets (on domestic share of food supply, on emissions and on share of renewables in energy supply) and no stable increasing variables (like energy demand per capita). When the model is run with this lever activated, the system stays in a dynamic equilibrium as in Figure 7.

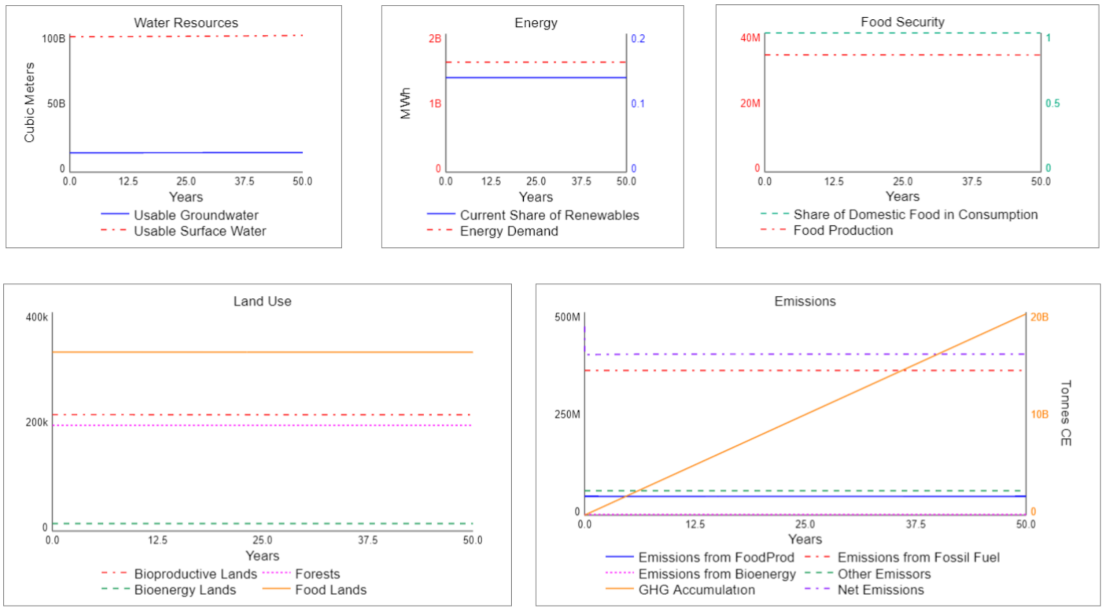

Figure 7: Dynamic Equilibrium Run

In this case, there are still exchanges in land use but we observe no net land use change. Net CO2 emissions are constant. Similarly, water stocks and soil stocks stay the same. This is because all the overarching feedback arcs between and within sectors take the initial level as reference. Consequently, all graphical effect functions yield unit (1) level of effect. This might be concerning as it assumes that with our current practices, the system is healthy with no water, food and energy shortage on the horizon. However, by its fundamentals our model treats the increasing population and increasing energy needs per individual of Turkey as the main driving forces behind nexus dynamics, as well as the main problem of the system. Due to this, having an initial dynamic equilibrium would not jeopardize our objective, as the base condition (described in Section 6.1) will take all these elements into consideration.

5.2. Extreme Condition Tests

Valid model behavior under extreme conditions is especially important to build confidence in the model. With this aim, we run extreme condition tests on selected elements and observe the model behavior across different sectors. It should also be noted that the equilibrium lever is deactivated hereafter.

5.2.1. Water Shortage

Water Shortage is expected to reduce agricultural productivity. In the most extreme condition, water depletion, agricultural production among other activities of human life cannot exist. In this test, we run our model with half the normal amount of rainfall in effect.

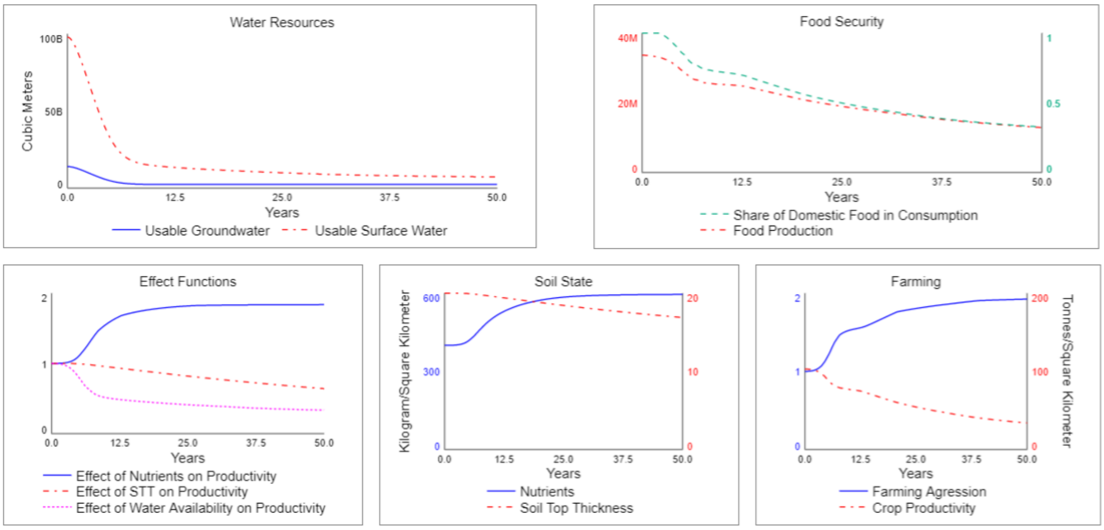

Figure 8: Extreme Condition Run: Water Shortage

From the first glance, it is impossible to miss water scarcity. Usable Surface Water and Usable Groundwater stocks decrease tremendously. After a while, we observe a saturating behavior much lower than the initial levels. This saturation is due to Effect of Water Availability on Water Consumption. As water sources get scarce, the country limits the consumption of domestic stocks and becomes more dependent on exported water.

We can also observe a significant decrease in the share of domestic food in consumption. As water availability decreases, crop productivity and hence agricultural production decreases. This in turn increases farming aggression. As farming practices get more aggressive, more fertilizers are used and crop productivity recovers a bit (slight increase in year 12). But it also results in loss of topsoil, which decreases crop productivity in the long run (linear downward trend year 15 onward).

5.2.2. Death of Topsoil and Depletion of Soil Nutrients

Soil Top Thickness and Nutrient concentration of soil are also major determinants of agricultural production like water availability. Therefore, in order to test their positive relation with crop productivity, we test the model behavior for a complete death of topsoil and depletion of soil nutrients by setting their initial stock levels to zero.

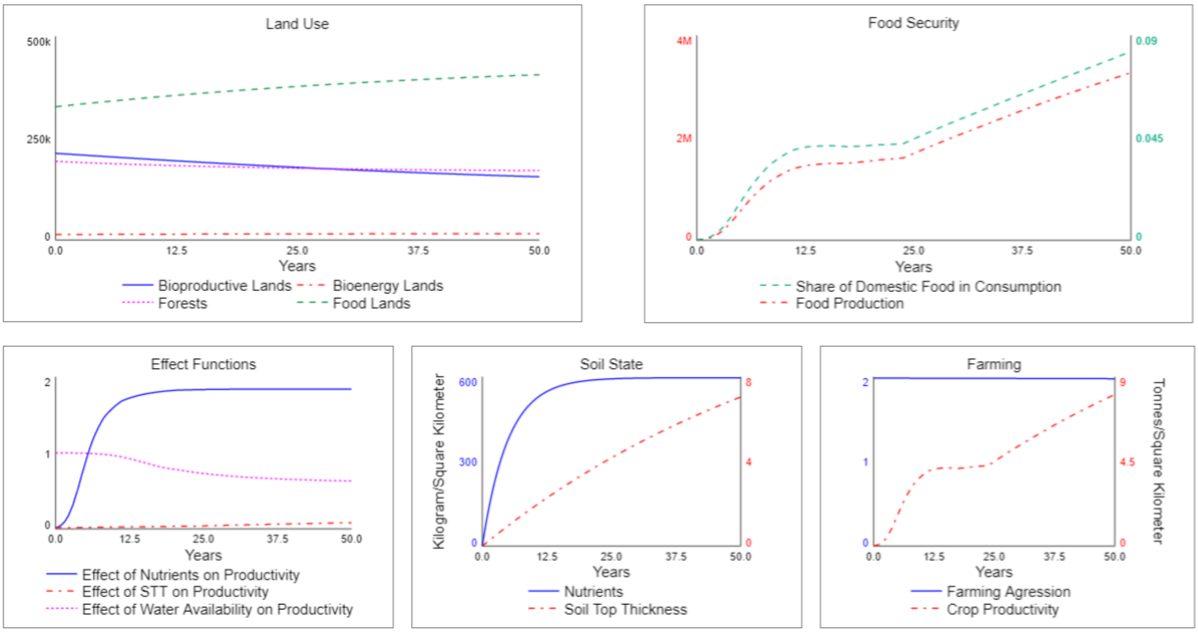

Figure 9: Extreme Condition Run: Soil Death

Resulting behavior in food sector parameters seems to be consistent with intuitive thinking. As the nutrient is more open to external intervention such as use of fertilizers it recovers quickly while the recovery of the soil top thickness occurs with a decreasing rate due to opposite signals from aggressive farming practices. Given the state of the soil quality in total, crop productivity is quite low (around annually 9 tonnes per square kilometer compared to its normal value 103) even at the end of 50 year period. Not having domestic food production, almost all of the consumption is imported which increases the need for food lands resulting in an increase in food lands at the expense of forest and bioproductive lands. As a resulting condition, we have a large amount of infertile land allocated for food production at the end of 50 years. Farming practices continue with highest aggression, but with very little effectiveness; being able to satisfy only 10% of the domestic food demand.

5.2.3. Excess Population

Food, water and energy needs of the population are major driving forces behind land use changes, emissions, and resource depletion. An excessive or a little level of population is expected to influence these factors tremendously. In this context, we run simulations with an excessively high level of population (nearly twice the initial, 150 million) to test model response.

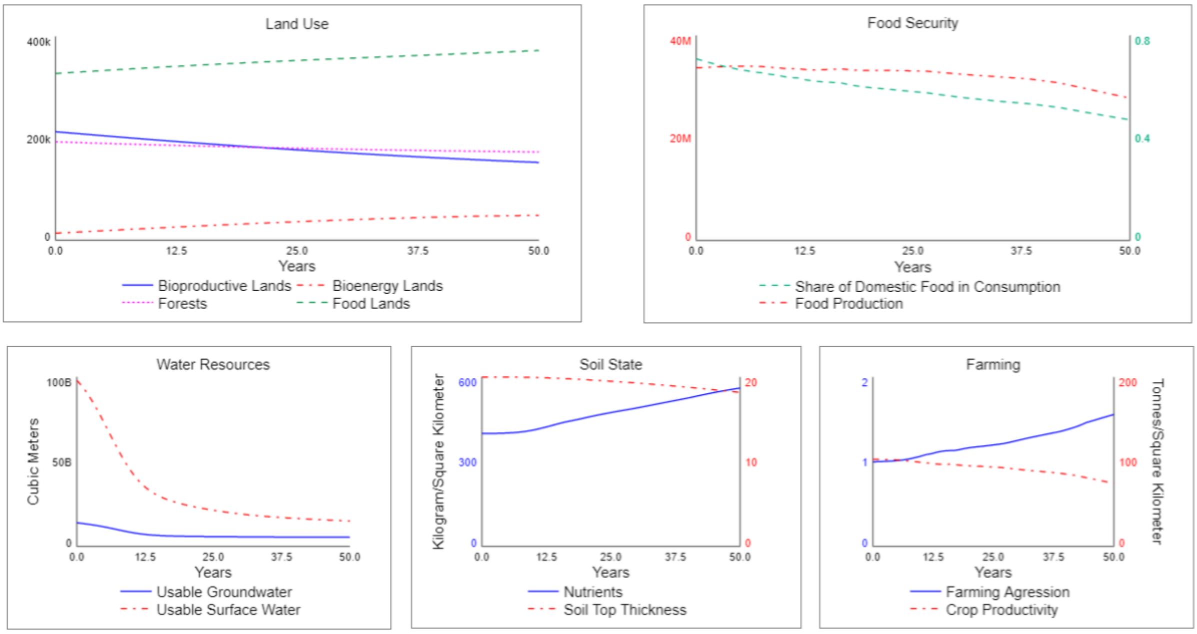

Figure 10: Extreme Condition Run: Overpopulation

For this condition, by nearly doubling the food demand, overpopulation decreases the current share of domestic food in consumption thus increasing the need for more lands allocated for food production, as well as farming aggression. Similarly, increased energy needs induce more lands allocated for bioenergy as well. Food lands and bioenergy lands increase. Through irrigation needs and domestic consumption, water resources face a significant decrease, which in turn decreases crop productivity. With low productivity, even with more lands allocated for food and more fertilizer used, food production decreases.

6. Simulation Experiments

After construction and structural justification of our model, we move on to experimentation. In this section, we first simulate the model for the base case scenario to observe and analyze the results. We then apply several policy interventions in terms of aforedescribed governmental targets and some other parameters using the user-friendly simulation interface we designed. Simulation horizon is selected to be 50 years, spanning from the initial year of 2015 to 2065.

6.1. Base Scenario

We define the base scenario as where all stock levels are their initial levels from the literature and governmental targets are set to reasonable levels. Our aim here is to analyze the potential future direction of the system stemming from the endogenous aspects of our model, subjected to some reasonable targets and projected population levels.

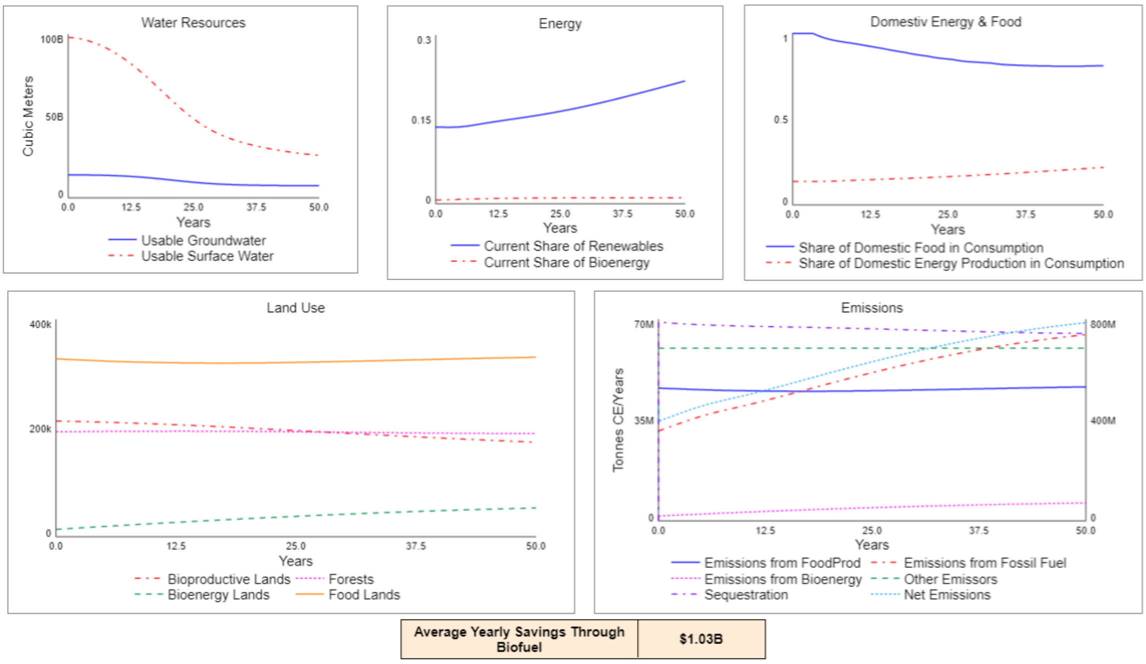

Figure 11: Base Scenario Run

In the base run, the target share of renewables is set to a modest level of 30%. Target domestic share of food consumption is set to 0.95, while the initial share is more than 1; indicating the presence of exports in 2015.

The UN projects a saturating increase in Turkey's population till 2065, to a maximum level of 97 million. This increase in population shows itself in our results as a significant decrease in water reserves, increase in energy and food demand. Consequently, the system carries itself to a state where there are more lands allocated for food and bioenergy. Even with more food lands, the share of domestic food in consumption starts decreasing after a while, due to lowered water availability and increased population.

Carbon action targets for share of renewables and emissions fail to achieve their deeds by 50 years. Share of renewables can reach only 23% from its initial 14%. As per capita energy demand and total energy demand increases, net emissions continue to increase without showing a saturating behavior. Apart from the obvious energy need, this is also because of the decreased forest and bioproductive lands, which are used for more food and bioenergy production to feed the population. Carbon sequestration of 2065 is consequently less than 2015, thus net emissions increase without limits.

Overall, projected decrease of forests have a significant effect in net emissions through sequestration, and water reserves through rainfall. Even though there are targets given, endogenous aspects of the model prefers feeding the population and sustaining their energy needs rather than fulfilling the carbon action and water.

6.2. Policy Analysis Flight Simulator

An user interface is designed in STELLA Architect to easily simulate the model with different policy treatments. Target Domestic Share of Food Consumption, Target Share of Renewables and Target Emission are selected as input variables of the interface. Model can be run with different policies in effect and results of different sectors are provided. Graphical outputs include the results of the current run along with that of the base condition, enabling an easy comparative analysis. Also, a numeric display shows the average yearly savings through biofuel with cost offset information from (Uyanik et al., 2018).

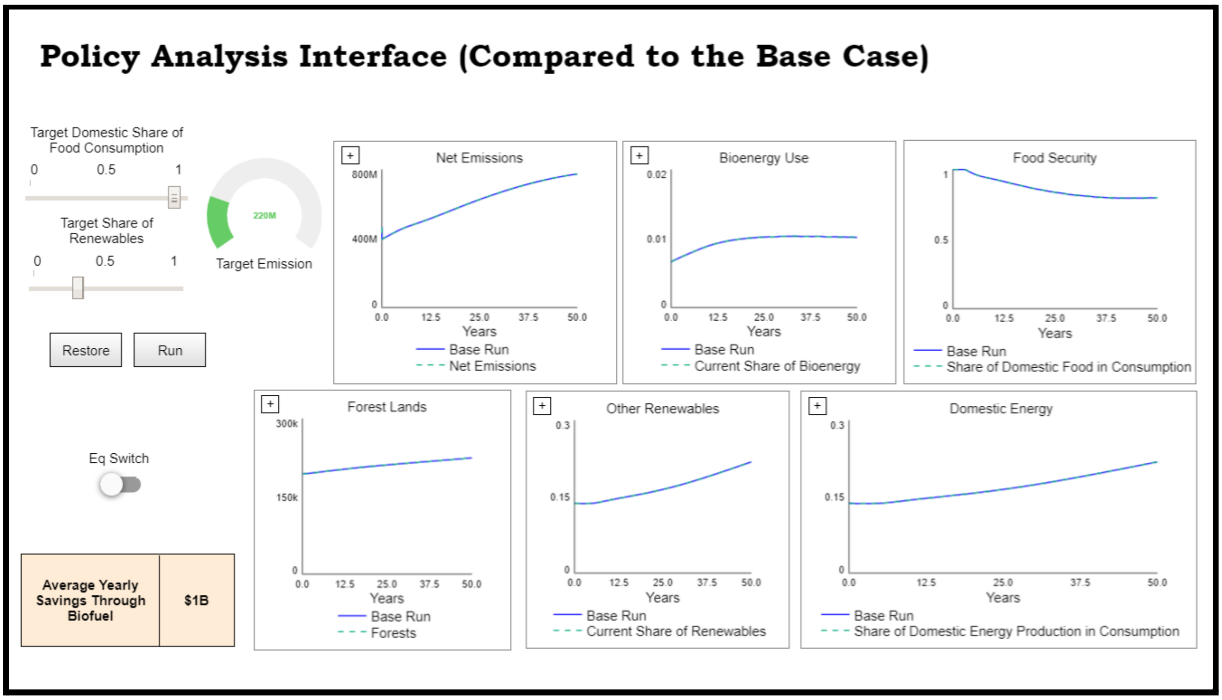

Figure 12: Policy Interface Flight Simulator

We tested different policy treatments to check their performance with the base run. An exemplary policy analysis for green development is presented in Figure 13.

Reduction in the target emission drives more lands to be converted to forests which in turn decreases the net emissions. Moreover, the target share of renewables requires more bioenergy lands which decreases the food lands even further. Consequently, the target share of domestic food production fails to be obtained for the sake of energy security and lower net emissions. It is important to note that economic feasibility of such policies is another key factor that should be considered, however such analysis is not presented since it is beyond the limits of this study.

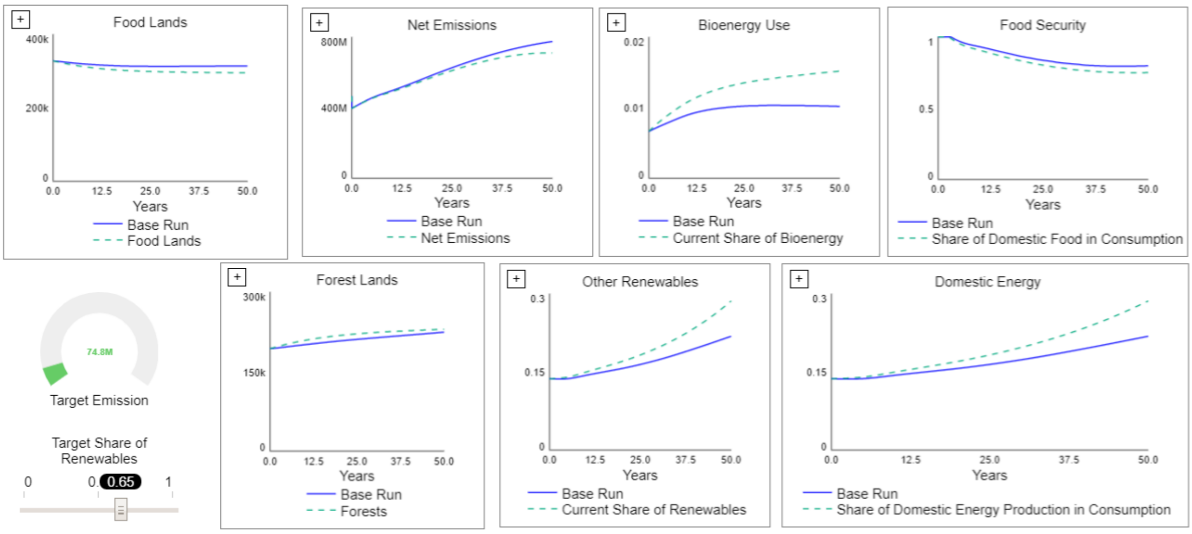

Figure 13: Scenario for low target emission and high share of renewables

It should also be noted that similar to the base case scenario, simply setting a target does not mean that the system will eventually reach that target. Of course it gives the model trajectory a drift toward that objective but the endogenous aspects of the model are very resistant. It should be noted that the reason behind this is that the formulation of the anchor-and-adjust heuristics is not very strong. But we believe this is valid as the need for food and energy also represents very strong societal mechanisms affecting every part of public and national life.

7. Concluding Remarks

Our System Dynamics model performs well in terms of covering the interrelated feedbacks across sectors. Our structural validation tests not only allowed us to find and correct structural flaws within our formulation, but also helped us link effects and causes that are happening in multiple scenes at once, as the premise of Nexus approach suggests.

In the base scenario, we project that increased population level and per capita energy demand will result in more lands allocated for food and bioenergy production. Forest and bioproductive areas face significant declines even with carbon emission targets issued by the government. Decreased rainfall and increased water consumption for domestic and irrigation needs will drain the water reserves in the long run, producing a water shortage. Even though we see a significant increase in bioenergy production, it fails to reduce the GHG emissions for two reasons: still insufficient land deployment, and less significant benefits compared to other renewables and forestation strategies. Therefore, it can be concluded that policies in forestation and investments in emission-free energy sources should be sought for in order to stabilize and decrease net GHG emissions. However, it still manages to offset a significant amount of the fossil fuel import costs.

Policy implementation flight simulator we designed can be used to implement different policies and observe outcomes. This output can be used in two objectives. First, to make further analysis on this system to observe the trade-offs and synergies across different sectors. Second, as an interactive learning environment to be used for pedagogical purposes.

We had several limitations through this project. The foremosts is the lack and inconsistency of data for Turkey. Different organizations reported significantly different values for multiple model parameters. Especially the national agency reports where the data is always reported rather optimistically may raise suspicion of some form of governmental pressure. Second is that the model formulations are very robust, partly because of the initial dynamic equilibrium. A further rework, which was overlooked due to the time constraint, is required to produce a better material. Another limitation is the endogenization of demographics, the inclusion of socio-economic structure and perhaps the political agenda. Due to short-time and little-expertise limitations, we had to omit these aspects, at least for now. These may well be the focal points of our future steps with this subject.

06 July 2021

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Appendix - Model Equations

Top-Level Model:

Average_Yearly_Savings_Through_Biofuel(t) = Average_Yearly_Savings_Through_Biofuel(t - dt) + (Adj) * dt {NON-NEGATIVE}
INIT Average_Yearly_Savings_Through_Biofuel = 0

BECCS_Adoption_in_Bioenergy(t) = BECCS_Adoption_in_Bioenergy(t - dt) + (Adjustment) * dt {NON-NEGATIVE}
INIT BECCS_Adoption_in_Bioenergy = 0

Bioproductive_Lands(t) = Bioproductive_Lands(t - dt) + (F_to_B[1] + F_to_B[2] + F_to_B[3] + C_to_B - B_to_C - B_to_F[1] - B_to_F[2] - B_to_F[3]) * dt {NON-NEGATIVE}
INIT Bioproductive_Lands = 212927.6
UNITS: Square Kilometers

Crop_Lands(t) = Crop_Lands(t - dt) + (B_to_C + F_to_C[1] + F_to_C[2] + F_to_C[3] - C_to_F[1] - C_to_F[2] - C_to_F[3] - C_to_B) * dt {NON-NEGATIVE}
INIT Crop_Lands = 340889.8
UNITS: Square Kilometers

"Crop_Lands_Food/Energy_Ratio"(t) = "Crop_Lands_Food/Energy_Ratio"(t - dt) + ("Crop_Lands_Food/Energy_Ratio_Adjustment") * dt {NON-NEGATIVE}
INIT "Crop_Lands_Food/Energy_Ratio" = 0.96
DOCUMENT: Challenges and Opportunities for Bio-diesel Production in Turkey

Forest_Lands[1](t) = Forest_Lands[1](t - dt) + (C_to_F[1] + B_to_F[1] - F_to_C[1] - F_to_B[1] - Aging[1]) * dt {NON-NEGATIVE}
INIT Forest_Lands[1] = 193143.44/5
UNITS: Square Kilometers

Forest_Lands[2](t) = Forest_Lands[2](t - dt) + (C_to_F[2] + B_to_F[2] - F_to_C[2] - F_to_B[2] - Aging[2]) * dt {NON-NEGATIVE}
INIT Forest_Lands[2] = 193143.44*3/5
UNITS: Square Kilometers

Forest_Lands[3](t) = Forest_Lands[3](t - dt) + (C_to_F[3] + B_to_F[3] - F_to_C[3] - F_to_B[3] - Aging[3]) * dt {NON-NEGATIVE}
INIT Forest_Lands[3] = 193143.44/5
UNITS: Square Kilometers

GHG_Accumulatıon(t) = GHG_Accumulatıon(t - dt) + (Emissions_from_Bioenergy + Emissions_from_Fossil_Fuel + Emissions_from_FoodProd + Other_Emissors - Sequestration) * dt {NON-NEGATIVE}
INIT GHG_Accumulatıon = 0
UNITS: Tonnes CE

Natural_Reservoirs(t) = Natural_Reservoirs(t - dt) + (Rainfall - Surface_Percolation - Ground_Percolation - Evaporation_And_Runoff) * dt {NON-NEGATIVE}
INIT Natural_Reservoirs = 500*10^9
UNITS: Cubic Meters

"Non-Renewable_Resources"(t) = "Non-Renewable_Resources"(t - dt) + (- "Non-Renewable_Extraction") * dt {NON-NEGATIVE}
INIT "Non-Renewable_Resources" = 15801.9*11.63*100

Nutrients(t) = Nutrients(t - dt) + (Humification - Oxidation) * dt {NON-NEGATIVE}
INIT Nutrients = 400
UNITS: Kilogram/Square Kilometer
DOCUMENT: Saeed

Renewable_Energy_Production_Capacity(t) = Renewable_Energy_Production_Capacity(t - dt) + (Investment - Depreciation) * dt {NON-NEGATIVE}
INIT Renewable_Energy_Production_Capacity = 574076156
UNITS: MWh

Soil_Top_Thickness(t) = Soil_Top_Thickness(t - dt) + (Generation - Erosion) * dt

{NON-NEGATIVE}
INIT Soil_Top_Thickness = 20
DOCUMENT: Wikipedia "Topsoil"
Usable_Groundwater(t) = Usable_Groundwater(t - dt) + (Ground_Percolation - GW_Consumption) * dt {NON-NEGATIVE}
INIT Usable_Groundwater = 14*10^9
UNITS: Cubic Meters
Usable_Surface_Water(t) = Usable_Surface_Water(t - dt) + (Surface_Percolation - SW_Consumption) * dt {NON-NEGATIVE}
INIT Usable_Surface_Water = 98*10^9
UNITS: Cubic Meters
Water_Quality(t) = Water_Quality(t - dt) + (Water_Regeneration - Degradation) * dt {NON-NEGATIVE}
INIT Water_Quality = 0.5
Adj = Energy_Production_from_Bioenergy*38/50 {UNIFLOW}
Adjustment = BECCS_Switch*(IF BECCS_Adoption_in_Bioenergy<MAX_BECCS THEN A + B*BECCS_Adoption_in_Bioenergy*(MAX_BECCS-BECCS_Adoption_in_Bioenergy) ELSE 0)
Aging[1] = Forest_Lands[1]/Age_Cohort_Size[1]-Forest_Lands[3]/Age_Cohort_Size[3]
OUTFLOW PRIORITY: 3
UNITS: Square Kilometers/Years
Aging[2] = Forest_Lands[2]/Age_Cohort_Size[2]-Forest_Lands[1]/Age_Cohort_Size[1]
OUTFLOW PRIORITY: 3
UNITS: Square Kilometers/Years
Aging[3] = Forest_Lands[3]/Age_Cohort_Size[3]-Forest_Lands[2]/Age_Cohort_Size[2]
OUTFLOW PRIORITY: 3
UNITS: Square Kilometers/Years
B_to_C = Bioproductive_Lands*B_to_C_Fraction/Land_Conversion_Delay*Aggregated_Cropland_Effect {UNIFLOW}
OUTFLOW PRIORITY: 1
UNITS: Square Kilometers/Years
B_to_F[1] = Bioproductive_Lands*B_to_F_Fraction/Land_Conversion_Delay {UNIFLOW}
OUTFLOW PRIORITY: 2
UNITS: Square Kilometers/Years
B_to_F[2] = 0 {UNIFLOW}
OUTFLOW PRIORITY: 2
UNITS: Square Kilometers/Years
B_to_F[3] = 0 {UNIFLOW}
OUTFLOW PRIORITY: 2
UNITS: Square Kilometers/Years
C_to_B = Crop_Lands*C_to_B_Fraction/Land_Conversion_Delay {UNIFLOW}
OUTFLOW PRIORITY: 4
UNITS: Square Kilometers/Years
C_to_F[1] = Effect_of_Emissions_on_Forestation*C_to_F_Fraction*Crop_Lands/Land_Conversion_Delay {UNIFLOW}
OUTFLOW PRIORITY: 1
UNITS: Square Kilometers/Years
C_to_F[2] = 0 {UNIFLOW}
OUTFLOW PRIORITY: 1
UNITS: Square Kilometers/Years
C_to_F[3] = 0 {UNIFLOW}
OUTFLOW PRIORITY: 1

UNITS: Square Kilometers/Years
"Crop_Lands_Food/Energy_Ratio_Adjustment" = (IF Adjustment_Rate < 0 THEN "Crop_Lands_Food/Energy_Ratio"*Adjustment_Rate/Croplands_Reallocation_Delay ELSE (1 - "Crop_Lands_Food/Energy_Ratio")*Adjustment_Rate/Croplands_Reallocation_Delay)
Degradation = Water_Quality*Quality_Degradation_Fraction_due_to_Oxidation {UNIFLOW}
Depreciation = Renewable_Energy_Production_Capacity/Depreciation_Delay {UNIFLOW}
UNITS: MWh/Years
Emissions_from_Bioenergy = (Biofuel_GHG_Footprint*Energy_Production_from_Bioenergy)*(1-BECCS_Adoption_in_Bioenergy)
UNITS: Tonnes CE/Years
Emissions_from_FoodProd = Food_Lands*Food_GHG_Footprint
UNITS: Tonnes CE/Years
Emissions_from_Fossil_Fuel = Energy_used_From_Fossil*Fossil_GHG_Footprint
UNITS: Tonnes CE/Years
Erosion = Normal_Erosion_Fraction*Soil_Top_Thickness*Effect_of_Intensive_Farming_on_Erosion {UNIFLOW}
Evaporation_And_Runoff = Natural_Reservoirs*E&R_Fraction {UNIFLOW}
OUTFLOW PRIORITY: 3
UNITS: Cubic Meters/Years
F_to_B[TreeAge] = Forest_Lands*F_to_B_Fraction/Land_Conversion_Delay {UNIFLOW}
OUTFLOW PRIORITY: 2
UNITS: Square Kilometers/Years
F_to_C[TreeAge] = Forest_Lands*F_to_C_Fraction/Land_Conversion_Delay*Aggregated_Cropland_Effect {UNIFLOW}
OUTFLOW PRIORITY: 1
UNITS: Square Kilometers/Years
Generation = Generation_Rate {UNIFLOW}
Ground_Percolation = Natural_Reservoirs*Ground_Percolation_Fraction*Eff_of_Bioproductive_Lands_on_Percolation {UNIFLOW}
OUTFLOW PRIORITY: 2
UNITS: Cubic Meters/Years
GW_Consumption = Total_Water_Demand*(1-"SW/GW_Consumption_Ratio")*Eff_of_Water_Availability_on_Consumption {UNIFLOW}
UNITS: Cubic Meters/Years
Humification = Normal_Humification_Rate*Effect_of_Intensive_Farming_on_Humification {UNIFLOW}
UNITS: Kilogram/Square Kilometer/Years
Investment = Effect_of_Perceived_Need_on_Renewable_Investment*Normal_Investment {UNIFLOW}
UNITS: MWh/Years
"Non-Renewable_Extraction" = "Non-Renewable_Resources"/Extraction_Delay {UNIFLOW}
Other_Emissors = Projected_Emissions_from_Industry
UNITS: Tonnes CE/Years
Oxidation = Nutrients*Normal_Oxidation_Fraction {UNIFLOW}
UNITS: Kilogram/Square Kilometer/Years
Rainfall = Normal_Rainfall_Rate*Eff_of_Forest_Lands_on_Rainfall {UNIFLOW}
UNITS: Cubic Meters/Years
Sequestration = Forest_Lands[1]*Capture_per_forest_km2[1]

+Forest_Lands[2]*Capture_per_forest_km2[2]
+Forest_Lands[3]*Capture_per_forest_km2[3] +Bioproductive_Lands*Capture_per_BPL
UNITS: Tonnes CE/Years
Surface_Percolation =
Natural_Reservoirs*Surface_Percolation_Fraction/Eff_of_Bioproductive_Lands_on_Percolation {UNIFLOW}
OUTFLOW PRIORITY: 1
UNITS: Cubic Meters/Years
SW_Consumption =
"SW/GW_Consumption_Ratio"*Total_Water_Demand*Eff_of_Water_Availability_on_Consumption {UNIFLOW}
UNITS: Cubic Meters/Years
Water_Regeneration = (1-Water_Quality)/Regeneration_Delay {UNIFLOW}
"2015_Intercept" = 20.244
UNITS: MWh
A = 0.02
Adjustment_Rate = GRAPH(Need_of_Food_minus_Bioenergy)
Points: (-2.000, -0.01), (-1.600, -0.008), (-1.200, -0.006), (-0.800, -0.004), (-0.400, -0.002), (0.000, 0), (0.400, 0.002), (0.800, 0.004), (1.200, 0.006), (1.600, 0.008), (2.000, 0.01)
Age_Cohort_Size[1] = 10
Age_Cohort_Size[2] = 30
Age_Cohort_Size[3] = 10
Aggregated_Cropland_Effect =
Effect_of_Food_Land_Need_On_Crop_Lands_Increase*Effect_of_Bioenergy_Land_Need_On_Crop_Lands_Increase
B = 0.1
B_to_C_Fraction = 0.01600966
B_to_F_Fraction = Normal_B_to_F*Effect_of_Emissions_on_Forestation
BECCS_Switch = 0
Bioenergy_Lands = Crop_Lands*(1-"Crop_Lands_Food/Energy_Ratio")
Biofuel_GHG_Footprint = 44.9/0.000277777778/1000000
UNITS: Tonnes/MWh
DOCUMENT: https://en.wikipedia.org/wiki/Environmental_impact_of_biodiesel
C_to_B_Fraction = 0.01
C_to_F_Fraction = 0.01
Capture_per_BPL = 20
Capture_per_forest_km2[1] = 111.92
DOCUMENT: http://urbanforestrynetwork.org/benefits/air%20quality.htm
Capture_per_forest_km2[2] = 447.68
DOCUMENT: http://urbanforestrynetwork.org/benefits/air%20quality.htm
Capture_per_forest_km2[3] = 223.84
DOCUMENT: http://urbanforestrynetwork.org/benefits/air%20quality.htm
Crop_Productivity =
Norrnal_Crop_Productivity*Effect_of_Water_Availability_on_Productivity*Effect_of_STT_on_Productivity*Effect_of_Nutrients_on_Productivity*Effect_of_Water_Quality_on_Productivity
UNITS: Tonnes/Square Kilometer
Croplands_Reallocation_Delay = 1
Current_Share_of_Bioenergy = Energy_Production_from_Bioenergy/Energy_Demand
Current_Share_of_Renewables =
(Energy_Production_from_Bioenergy+Energy_Production_From_Other_Renewables)/Energy_Demand
Depreciation_Delay = 15
E&R_Fraction = 0.9133416

Eff_of_Bioproductive_Lands_on_Percolation =
GRAPH(Bioproductive_Lands/Reference_Bioproductive_Lands)
Points: (0.000, 1.98661429815), (0.200, 1.96402758008), (0.400, 1.90514825364), (0.600, 1.76159415596), (0.800, 1.46211715726), (1.000, 1.000), (1.200, 0.53788284274), (1.400, 0.238405844044), (1.600, 0.0948517463551), (1.800, 0.0359724199242), (2.000, 0.0133857018486)
Eff_of_Forest_Lands_on_Rainfall = SUM(Forest_Lands)/Reference_Forest_Lands
Eff_of_Water_Availability_on_Consumption = GRAPH(Water_Availability)
Points: (0.000, 0.000), (0.0344827586207, 0.131245067676), (0.0689655172414, 0.245580359348), (0.103448275862, 0.345184551361), (0.137931034483, 0.431955616721), (0.172413793103, 0.507546991256), (0.206896551724, 0.573399080088), (0.241379310345, 0.630766704769), (0.275862068966, 0.680743014101), (0.310344827586, 0.724280314247), (0.344827586207, 0.762208215073), (0.379310344828, 0.79524943849), (0.413793103448, 0.824033590028), (0.448275862069, 0.849109156065), (0.48275862069, 0.870953955321), (0.51724137931, 0.889984243762), (0.551724137931, 0.906562646426), (0.586206896552, 0.921005067292), (0.620689655172, 0.933586708884), (0.655172413793, 0.944547316293), (0.689655172414, 0.954095745557), (0.724137931034, 0.962413943446), (0.758620689655, 0.969660414484), (0.793103448276, 0.975973241277), (0.827586206897, 0.981472715699), (0.862068965517, 0.98626363107), (0.896551724138, 0.99043727901), (0.931034482759, 0.994073189014), (0.965517241379, 0.997240643899), (1.000, 1.000)
Effect_of_Bioenergy_Land_Need_On_Crop_Lands_Increase =
GRAPH(Perceived_need_for_Bioenergy)
Points: (-1.000, 0.210708561479), (-0.800, 0.228777935939), (-0.600, 0.275881397084), (-0.400, 0.390724675235), (-0.200, 0.630306274192), (0.000, 1.000), (0.200, 1.36969372581), (0.400, 1.60927532476), (0.600, 1.72411860292), (0.800, 1.77122206406), (1.000, 1.78929143852)
Effect_of_Emissions_on_Bioenergy_Motivation = GRAPH(Emission_Discrepancy)
Points: (0.000, 1.00133857018), (0.100, 1.00359724199), (0.200, 1.00948517464), (0.300, 1.0238405844), (0.400, 1.05378828427), (0.500, 1.1000), (0.600, 1.14621171573), (0.700, 1.1761594156), (0.800, 1.19051482536), (0.900, 1.19640275801), (1.000, 1.19866142982)
Effect_of_Emissions_on_Forestation = GRAPH(Emission_Discrepancy)
Points: (0.000, 1.01338570185), (0.100, 1.03597241992), (0.200, 1.09485174636), (0.300, 1.23840584404), (0.400, 1.53788284274), (0.500, 2.000), (0.600, 2.46211715726), (0.700, 2.76159415596), (0.800, 2.90514825364), (0.900, 2.96402758008), (1.000, 2.98661429815)
Effect_of_Food_Land_Need_On_Crop_Lands_Increase =
GRAPH(Perceived_Need_for_Food_Lands)
Points: (-0.500, 0.210708561479), (-0.400, 0.228777935939), (-0.300, 0.275881397084), (-0.200, 0.390724675235), (-0.100, 0.630306274192), (0.000, 1.000), (0.100, 1.36969372581), (0.200, 1.60927532476), (0.300, 1.72411860292), (0.400, 1.77122206406), (0.500, 1.78929143852)
Effect_of_Intensive_Farming_on_Erosion = GRAPH(Farming_Agression)
Points: (0.000, 0.506692850924), (0.200, 0.517986209962), (0.400, 0.547425873178), (0.600, 0.619202922022), (0.800, 0.76894142137), (1.000, 1.000), (1.200, 1.23105857863), (1.400, 1.38079707798), (1.600, 1.45257412682), (1.800, 1.48201379004), (2.000, 1.49330714908)
Effect_of_Intensive_Farming_on_Humification = GRAPH(Farming_Agression)
Points: (0.000, 0.506692850924), (0.200, 0.517986209962), (0.400, 0.547425873178), (0.600, 0.619202922022), (0.800, 0.76894142137), (1.000, 1.000), (1.200, 1.23105857863), (1.400, 1.38079707798), (1.600, 1.45257412682), (1.800, 1.48201379004), (2.000, 1.49330714908)
Effect_of_Nutrients_on_Productivity = GRAPH(Nutrients/Reference_Nutrients)
Points: (0.000, 0.0133857018486), (0.133333333333, 0.0259074550614), (0.266666666667, 0.0498488532942), (0.400, 0.0948517463551), (0.533333333333, 0.176799354414), (0.666666666667, 0.317738209762), (0.800, 0.53788284274), (0.933333333333, 0.834859587075), (1.06666666667, 1.16514041292), (1.200, 1.46211715726), (1.33333333333, 1.68226179024), (1.46666666667, 1.82320064559), (1.600, 1.90514825364), (1.73333333333, 1.95015114671), (1.86666666667, 1.97409254494), (2.000, 1.98661429815)
Effect_of_Perceived_Need_on_Renewable_Investment =

GRAPH(Perceived_need_for_Renewables)
Points: (-1.000, 0.506692850924), (-0.800, 0.517986209962), (-0.600, 0.547425873178), (-0.400, 0.619202922022), (-0.200, 0.76894142137), (0.000, 1.000), (0.200, 1.23105857863), (0.400, 1.38079707798), (0.600, 1.45257412682), (0.800, 1.48201379004), (1.000, 1.49330714908)
Effect_of_STT_on_Productivity = GRAPH(Soil_Top_Thickness/Reference_STT)
Points: (0.000, 0.0133857018486), (0.200, 0.0359724199242), (0.400, 0.0948517463551), (0.600, 0.238405844044), (0.800, 0.53788284274), (1.000, 1.000), (1.200, 1.46211715726), (1.400, 1.76159415596), (1.600, 1.90514825364), (1.800, 1.96402758008), (2.000, 1.98661429815)
Effect_of_Water_Availability_on_Productivity = GRAPH(Water_Availability)
Points: (0.000, 0.000), (0.100, 0.386744810206), (0.200, 0.625100742507), (0.300, 0.772002650339), (0.400, 0.862540235521), (0.500, 0.918339744538), (0.600, 0.952729718606), (0.700, 0.973924713637), (0.800, 0.986987468889), (0.900, 0.995038217405), (1.000, 1.000)
Effect_of_Water_Quality_on_Productivity = GRAPH(Water_Quality/Water_Quality_Reference)
Points: (0.000, 0.753346425462), (0.200, 0.758993104981), (0.400, 0.773712936589), (0.600, 0.809601461011), (0.800, 0.884470710685), (1.000, 1.0000), (1.200, 1.11552928932), (1.400, 1.19039853899), (1.600, 1.22628706341), (1.800, 1.24100689502), (2.000, 1.24665357454)
Emission_Discrepancy = IF Eq_Switch THEN 0 ELSE (Net_Emissions-Target_Emission)/Net_Emissions
Energy_Demand = Population*Energy_Demand_per_Capita
UNITS: MWh
Energy_Demand_per_Capita = "2015_Intercept"+Slope*TIME*(1-Eq_Switch)
UNITS: MWh/capita
DOCUMENT: https://www.iea.org/countries/turkey
Energy_Imports = Energy_used_From_Fossil-"Non-Renewable_Extraction"
Energy_per_tonne = 27*0.000277777778*1000
UNITS: MWh/Tonne
DOCUMENT: https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/potential-yields-of-biofuels-per-ha-pa/
Energy_Production_from_Bioenergy = Bioenergy_Lands*Crop_Productivity*Energy_per_tonne
UNITS: MWh
Energy_Production_From_Other_Renewables = Renewable_Energy_Production_Capacity*Utilization
Energy_used_From_Fossil = Energy_Demand-(Energy_Production_From_Other_Renewables+Energy_Production_from_Bioenergy)
Eq_Switch = 0
Extraction_Delay = 100
F_to_B_Fraction = 0.01102432
F_to_C_Fraction = 0.01764957
Farming_Agression = GRAPH(SMTH1(Crop_Productivity/Norrnal_Crop_Productivity, Perception_Delay))
Points: (0.000, 1.98661429815), (0.200, 1.96402758008), (0.400, 1.90514825364), (0.600, 1.76159415596), (0.800, 1.46211715726), (1.000, 1.000), (1.200, 0.53788284274), (1.400, 0.238405844044), (1.600, 0.0948517463551), (1.800, 0.0359724199242), (2.000, 0.0133857018486)
Food_Demand = (Population)*Food_Demand_per_Capita
Food_Demand_per_Capita = 31770000/INIT("Population_(Time_Series)")
Food_GHG_Footprint = 140.9
UNITS: Tonnes/km2
DOCUMENT: https://www.nature.com/articles/s41598-017-04182-x
"Food_Import/Export" = Food_Production-Food_Demand

Food_Lands = Crop_Lands*"Crop_Lands_Food/Energy_Ratio"
Food_Production = Crop_Productivity*Food_Lands
Food_Production_Water_Footprint = 93871.98
DOCUMENT: Valuing Water Resources in Turkey
A Methodological Overview and Case Study
Forests = SUM(Forest_Lands)
Fossil_GHG_Footprint = 0.26
UNITS: Tonnes/MWh
DOCUMENT:
https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/carbon-emissions-of-different-fuels/
Generation_Rate = 0.2
Ground_Percolation_Fraction = 0.0110823
Land_Conversion_Delay = 5
MAX_BECCS = 0.6
Need_of_Food_minus_Bioenergy = Perceived_Need_for_Food_Lands-Perceived_need_for_Bioenergy
Net_Emissions = Emissions_from_FoodProd+Emissions_from_Fossil_Fuel+Emissions_from_Bioenergy+Other_Emissors-Sequestration
Normal_B_to_F = 0.01
Normal_Erosion_Fraction = 1/100
Normal_Humification_Rate = 80
Normal_Investment = Renewable_Energy_Production_Capacity/Depreciation_Delay
Normal_Oxidation_Fraction = 0.2
Normal_Rainfall_Rate = 501*10^9
UNITS: My Cubic Meters
Norrnal_Crop_Productivity = 102.9189
UNITS: Tonnes/Square Kilometer
Overpopulation_Constant = 1
Per_capita_water_consumption = 93.33
Perceived_need_for_Bioenergy = Perceived_need_for_Renewables*Effect_of_Emissions_on_Bioenergy_Motivation
Perceived_Need_for_Food_Lands = IF Eq_Switch THEN 0 ELSE SMTH3(1-Share_of_Domestic_Food_in_Consumption/Target_Domestic_Share, Perception_Delay)
Perceived_need_for_Renewables = IF Eq_Switch THEN 0 ELSE SMTH3(1-Current_Share_of_Renewables/Target_Share_of_Renewables, Perception_Delay)
Perception_Delay = 1
Population = IF Eq_Switch THEN INIT("Population_(Time_Series)") ELSE "Population_(Time_Series)"*Overpopulation_Constant
"Population_(Time_Series)" = GRAPH(TIME)
Points: (0.00, 78529409), (1.00, 79827871), (2.00, 81116450), (3.00, 82340088), (4.00, 83429615), (5.00, 84339067), (6.00, 85042738), (7.00, 85561976), (8.00, 85957253), (9.00, 86316463), (10.00, 86705224), (11.00, 87141804), (12.00, 87612950), (13.00, 88114632), (14.00, 88633175), (15.00, 89157785), (16.00, 89692564), (17.00, 90242360), (18.00, 90796629), (19.00, 91340898), (20.00, 91864241), (21.00, 92362476), (22.00, 92836744), (23.00, 93287930), (24.00, 93718886), (25.00, 94131585), (26.00, 94525087), (27.00, 94897553), (28.00, 95249264), (29.00, 95580757), (30.00, 95892325), (31.00, 96183920), (32.00, 96455071), (33.00, 96705210), (34.00, 96933570), (35.00, 97139570), (36.00, 97323026), (37.00, 97483895), (38.00, 97621906), (39.00, 97736771), (40.00, 97828330), (41.00, 97896655), (42.00, 97941894), (43.00, 97964175), (44.00, 97963683), (45.00, 97940717), (46.00, 97895585), (47.00, 97828840), (48.00, 97741351), (49.00, 97634200), (50.00, 97508360), (51.00, 97364550), (52.00, 97203385), (53.00, 97025691), (54.00, 96832380), (55.00,

96624270), (56.00, 96402046), (57.00, 96166441), (58.00, 95918370), (59.00, 95658808), (60.00, 95388601), (61.00, 95108404), (62.00, 94818685), (63.00, 94519899), (64.00, 94212422), (65.00, 93896595), (66.00, 93572831), (67.00, 93241482), (68.00, 92902721), (69.00, 92556633), (70.00, 92203329), (71.00, 91843046), (72.00, 91476052), (73.00, 91102460), (74.00, 90722371), (75.00, 90335919), (76.00, 89943272), (77.00, 89544663), (78.00, 89140354), (79.00, 88730592), (80.00, 88315631), (81.00, 87895714), (82.00, 87471058), (83.00, 87041855), (84.00, 86608269), (85.00, 86170458)
Projected_Emissions_from_Industry = 6*10^7
DOCUMENT: https://www.worldometers.info/co2-emissions/turkey-co2-emissions/
Projected_Water_Demand_in_Industry = 5*10^9
UNITS: Cubic Meters
Quality_Degradation_Fraction_due_to_Oxidation = GRAPH(Oxidation/Reference_Oxidation)
Points: (1.000, 0.1000), (1.100, 0.103597241992), (1.200, 0.109485174636), (1.300, 0.123840584404), (1.400, 0.153788284274), (1.500, 0.2000), (1.600, 0.246211715726), (1.700, 0.276159415596), (1.800, 0.290514825364), (1.900, 0.296402758008), (2.000, 0.298661429815)
Reference_Bioproductive_Lands = 212927.6
UNITS: Square Kilometers
Reference_Forest_Lands = 193143.44
UNITS: Square Kilometers
Reference_Nutrients = 400
Reference_Oxidation = 80
Reference_STT = 20
Reference_Water = 112*10^9
UNITS: Cubic Meters
Regeneration_Delay = 10
Share_of_Domestic_Energy_Production_in_Consumption = 1-Energy_Imports/Energy_Demand
Share_of_Domestic_Food_in_Consumption = MIN(1, Food_Production/Food_Demand)
Slope = (21.609-20.244)/4
Surface_Percolation_Fraction = 0.0775761
"SW/GW_Consumption_Ratio" = Usable_Surface_Water/(Usable_Surface_Water+Usable_Groundwater)
Target_Domestic_Share = 0.95
Target_Emission = 220*10^6
Target_Share_of_Renewables = 0.3
Total_Water_Demand = Water_Use_in_Agriculture+Water_Use_of_Population+Projected_Water_Demand_in_Industry
Usable_Water_Level = Usable_Groundwater+Usable_Surface_Water
Utilization = 0.36
DOCUMENT: SUNKEY
Water_Availability = Usable_Water_Level/Reference_Water
Water_Quality_Reference = 0.5
Water_Use_in_Agriculture = Crop_Lands*Food_Production_Water_Footprint
Water_Use_of_Population = (Population)*Per_capita_water_consumption
{ The model has 148 (164) variables (array expansion in parens).
In root model and 0 additional modules with 5 sectors.
Stocks: 15 (17) Flows: 30 (40) Converters: 103 (107)
Constants: 51 (55) Equations: 82 (92) Graphicals: 17 (17)
There are also 25 expanded macro variables.
}