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# Policy Analysis to Reduce Climate Change-Induced Risks in Urban and Rural Areas in Korea

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**Abstract:** The purpose of this paper was to project changes in climate change-induced risks over time and to investigate policy alternatives to mitigate the risks from increases in sea level, heavy rains, and heat waves in urban and rural areas. System dynamics simulation was used to build a model and conduct policy analysis for a simulation period over the years 2000–2050. The model was built with a focus on the interaction among three factors: damage restoration costs from heavy rains, heat waves, and sea level rise; the total cost of food imports due to decreases in arable land and agricultural productivity; and changes in the government budget to respond to climate change problems. A policy experiment was conducted with the model under four scenarios mainly based on the government budget for climate change. The results indicated, firstly, that the climate budget needs to be increased to at least 13 trillion Korean Won (US $11.6 billion) per year. Secondly, an earlier budget increase would more effectively reduce the total disaster restoration cost than a delayed budget increase. Third, if an earlier budget increase is difficult, the next best alternative would be to allocate a greater fraction of the climate budget to urban rather than to rural areas. Lastly, an early response to climate change would more effectively reduce food import costs, maintain agricultural productivity, and improve infrastructure for climate change adaptation than a delayed response. In conclusion, an earlier increase in the climate change budget would be more effective than a delayed budget increase of the same amount, and allocating a larger fraction of the climate budget to urban areas could be more cost-effective than increasing the budget, if urban and rural parties could agree on the method of allocation.

**Keywords:** climate change policy; risk management; system dynamics simulation; urban and rural areas

## 1. Introduction

Climate change is one of the most important issues facing human beings in the 21st century among others such as depleting fossil fuels and natural resources, securing clean water resources, decreasing biodiversity, low economic growth, low birth rate and increased aged population, spread of new diseases, widening gap between the rich and poor, terrorism, and conflicts between nations, etc. [1]. Increases in the average temperature of the earth's climate will have detrimental effects on the environment, society, and the economy. The International Panel on Climate Change (IPCC) has anticipated that, even if the average global temperature increase is successfully limited to 2 °C, more than 2 billion people will suffer from water shortage and 20–30% of species will go extinct [2,3]. Even worse, the impact of climate change on the Korean peninsula will be more serious than the average world impact. During the 100-year period from 1906 to 2005, the average temperature increase on the Korean peninsula was 1.5 °C, while the world average was 0.74 °C. The Korean Meteorological Administration (KMA) has projected that, by the end of this century, the temperature in Korea will be 4 °C greater than the average temperature, and the precipitation level will be 17% greater than it was during the end of the 20th century (1971–2000). The sea level is also expected to increase by as much as 1 m, submerging some of the 870 $km^2$ of coastal area. Since more than 20% of the $CO_2$ produced remains in the atmosphere for more than 1000 years, climate warming is expected to continue even if we immediately stop producing greenhouse gases [4]. For all of these reasons, climate adaptation policy has become important. The Korean government has established the Second National Climate Adaptation Policy (2016–2020) in response to these challenges.

While the effects of climate change on the environment, society, and economy are known to be mutually interactive and cause domino-type serial effects over time, the scope and intensity of these effects remain unclear. Thus, climate adaptation policies tend to be based on risk evaluation [5]. In this context, the IPCC, international organizations, and leading countries are actively engaging in climate adaptation policy with strong consideration of risk evaluation, and are striving to coordinate adaptation policy with national policy [6].

## 2. Study Purpose and Research Method

Given this background, this study aims to project changes in climate change-induced risks over time in urban and rural areas and to investigate policy alternatives to mitigate those risks. The climate change-induced risks evaluated in this study are heavy rains, heat waves, and sea level rises because these are projected as the most damaging in Korea [4]. For this purpose, system dynamics simulation was used to build a model and conduct policy analysis for a simulation period from 2000 to 2050. The model was built with a focus on the interactions among the following interrelated areas: damage restoration costs from heavy rains, heat waves, and sea level rises; the total cost of food imports due to decreases in arable land and agricultural productivity; and changes in the government budget to respond to these problems.

In fact, the strength and frequency of climate change-induced natural disasters such as heavy rains, heat waves, and sea level rises have been increasing rapidly, especially in recent years. In light of the interrelated effects of climate change on the natural environment, society, and the economy, it is very likely that climate change will trigger serial crises affecting the economy, population, food, resources, and environment in Korea. The system dynamics method is especially useful for analyzing complex problems that involve highly interrelated/interactive factors and circular feedback structures, thus, this method was used to evaluate the interactive and interrelated effects of climate change.

The two key components of system dynamics are system thinking and system dynamics simulation. System thinking is a framework for understanding certain problems or phenomena from a dynamic and circular causation perspective. This framework is used to translate problematic phenomena into a computer simulation model with the help of system dynamics simulation software. The simulation results reveal dynamic changes in variables of interest over time, allowing the researcher to experiment with various policy alternatives to mitigate problems [7,8].

System dynamics has been under development since the publication of *Industrial Dynamics* by Jay Forrester in 1961. It was first referred to as "industrial dynamics" and pertained to problems in the corporate setting; the original name was soon replaced with the more general term "system dynamics". System dynamics is not focused on a system, but rather on a problem that is handled from a dynamic and feedback perspective [8–10].

System dynamics modelling involves several stages of problem identification and definition, system conceptualization, model formulation, analysis of model behavior, model evaluation, and policy analysis. It is at the system conceptualization stage that the variables to include and exclude are determined. This process of defining system boundaries is closely related to problem definition. Only the variables that are interacting and directly related to the defined problem are included in the model for simulation, and other variables that are external to the system variables are treated as exogenous variables. Relationships among variables included in the model are structured as a circular feedback causation process, and this process is usually based on literature review. With a closed loop causality perspective on problem definition, a system dynamics model is constructed, allows dynamic changes in the interest variables over time and enables the performance of various kinds of policy tests.

## 3. Literature Review

The climate change problem has typical characteristics of environmental problems such as changing conditions, complex nature of causes and effects, uncertainty of information and consequences, and conflict involvement [11]. Abundant studies on climate change have been performed with diverse perspectives and emphases. Research on the impact of climate change has dealt with environmental issues, as well as social and economic issues such as health, agriculture, forestry, water resources, ecology, industry, and human habitation, to name just a few. In addition, some climate change studies deal with administrative and governance issues [12]. However, most studies have focused on specific areas within a certain academic discipline, without due attention to the interrelated and interactive effects of climate change on the environment, society, and the economy. At a highly aggregated level, the most notable studies on integrated models have been conducted by economists. Aside from the integrated models from economists, numerous system dynamics models on climate change have been developed and have more accurately reflected the interactive and interrelated effects of climate change. The world models developed from serial studies of the limits to growth [13–18] have also provided a good foundation for more recent climate change-related models, including Threshold21 by the Millennium Institute [19], the Climate Rapid Overview And Decision Support (C-ROADS) model [20], and the Behavioral Climate–Economy model [21–23]. In addition to these aggregated world-level dynamics models, relatively small and regional-level climate change impact models have also been developed [24].

One problem with studies of aggregated models like the world model [13–18] is that they are often too large and complex and have limitations in reflecting national-scale characteristics and issues. On the other hand, local-scale models specific to certain areas of a country are too narrow in focus to be used in different contexts or with different purposes. Although this study also aims to analyze the impact of climate change, the main purpose is to explore policy options to mitigate climate change-induced risks at the national level. Risk is a function of hazard, exposure, and vulnerability, where a hazard is a climate-related physical event or trend, exposure is the extent to which human, environmental, social, and economic assets are exposed to climate-related effects, and vulnerability is the propensity of human, environmental, social, and economic assets to be adversely affected ([25], pp. 3–5). Since impact is the outcome of risk, future climate-related risk could be estimated based on the costs expected to be incurred from climate change-induced effects. Climate change-induced effects in this study were operationalized as the expected costs resulting from heavy rains, heat waves, and sea level rises because previous studies on climate damage have shown those variables to be the most important to climate change damage. With regard to sea level rise, for example, about 30% of the population, 44% of public facilities, 45% of industrial complexes, and 37% of agriculture and industry complexes are located in coastal areas. When sea level rises about 1.36m by 2100, as projected by previous studies [26,27], the estimated damage is enormous. The same is true for damage caused by heavy rain and heat waves. According to the National Institute of Meteorological Research and the Korea Environment Institute, heat waves and tropical night phenomena will increase 3-fold and 6-fold, respectively, and expected deaths from heat waves are projected to increase 2-fold by 2050 [28–30]. Heat waves are also associated with drought and result in crop damage and reduced agricultural productivity. Damage from heavy rain is also expected to increase with climate change. Frequency of heavy rain is expected to increase 32%, and precipitation is projected to increase about 17% in 2050 [31]. Heavy rain damage during the last 10 years (2006–2015) accounts for the largest proportion, 63%, of total natural disaster damage [32].

The model was built with a focus on the interactions among the restoration of climate damage, the development of urban areas to substitute for flooded coastal areas, the impact of climate change on agricultural products, changes in agricultural productivity, and the government climate budget.

## 4. Model Building and Analysis

### 4.1. Causal Loop Diagram

System dynamics is a method of dealing with questions about the dynamic tendencies of complex systems and the behavioral patterns they generate over time. The primary assumption of the system dynamics paradigm is that the persistent dynamic tendencies of any complex system arise from its causal structure [33]. System dynamics modelling starts with the definition of the problem from a circular feedback perspective. Thus, a causal loop diagram was drawn to depict the relationships of variables with serial, interactive, and circular effects on coastal areas, arable land, agricultural productivity, disaster restoration costs, food import costs, and government budget for climate change. Inclusion of variables in the model is closely associated with problem definition and model purpose. Since the purpose of this model is to find policy alternatives to mitigate climate change-induced risk from an interactive and dynamic feedback perspective, variables from existing studies or from interviews with specialists or practitioners are restructured in a circular feedback perspective manner. The model is presented as a causal loop diagram to represent a dynamic hypothesis of the structure underlying the problems [9,10,34].

The causal loop diagram in Figure 1 displays the underlying structure of the interrelated physical and economic effects of climate change.

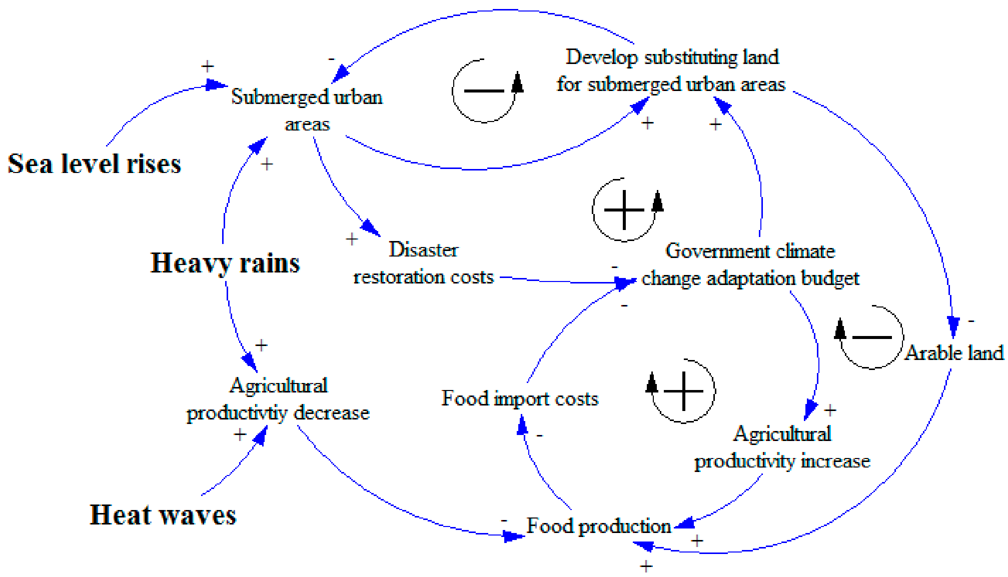


**Figure 1.** Causal loop diagram for climate change impact.

Climate impact was operationalized in this model as sea level rises, heavy rains, and heat waves. All of these effects of climate change were treated as exogenous variables that were not affected by the endogenous variables in the circular feedback loops.

In Figure 1, the upper left part of the causal loop diagram indicates the impact of rising sea levels on coastal areas, while the lower left part represents the impacts of heavy rains and heat waves. The development of land to substitute for submerged coastal areas usually occurs in urban areas, while decreases in agricultural productivity mostly occur in rural areas. Thus, the upper part of the diagram represents the response to urban effects of climate change, while the lower part depicts the response to rural effects of climate change.

In this model, firstly, starting from the upper left part of the figure, sea level rises increase the area of land submerged under sea water, which increases the need to develop land to substitute the submerged areas. As substitute land is developed, urban functions in flooded areas move to the substitute land; as a result, there is less coastal area at risk of being submerged. However, government budget is used not only for preventive purposes, like developing substitute land for submerged areas, but is also used for immediate disaster restoration with higher priority. Thus, the increase in submerged land area will increase disaster restoration costs, which will constrain the budget available for developing substitute land for submerged areas. When substitute land development is delayed and people and urban functions cannot relocate to safer areas, damage in submerged areas can be increased. As a result, immediate disaster restoration costs will be increased, and this will further constrain the climate change adaptation budget for developing substitute land. Thus, when the submerged area is large and costly to restore, the government budget available for the development of substitute land becomes smaller, which increases the submerged area, increasing disaster restoration costs, and reducing the development of substitute land. This further increases the submerged area and reduces the government budget available to develop substitute land, forming a vicious cycle.

Secondly, the lower part of the figure depicts another positive feedback loop. Heavy rains and heat waves reduce agricultural productivity and food production and thus increase food import costs. Increasing food import costs also constrains the government climate adaptation budget and thereby reduces agricultural infrastructure investments, agricultural productivity, and food production, which further increases food import costs.

Thirdly, the right part of the causal loop diagram in Figure 1 displays the interrelation between substitute area development and food production. The development of substitute land reduces the arable land, which reduces food production and increases food import costs, thus reducing the climate adaptation budget for preventive purposes, reducing agricultural productivity, and further reducing food production. This part of the causal loop diagram reveals that there is a trade-off in the policy response to urban and rural areas.

In light of the causal loop diagram, it seems clear that there are both negative and positive feedback loops in the dynamics of climate change impact. Loops for response to climate change impact have negative feedback, which stabilizes the climate impact, while loops for disaster restoration costs and substitute land development have positive feedback. When a system is dominated by a positive feedback loop with unfavorable conditions, a vicious cycle is formed and becomes very difficult to manage. For example, when the government does not promptly respond to climate change, it becomes much more difficult to manage climate change-induced risk. To examine the comprehensive effects of climate change structured in both positive and negative loops, we built a model and performed simulations.

### *4.2. Model Flow Diagram*

The causal loop diagram in Figure 1 was translated into a flow diagram for simulation, as shown in Figure 2. The rectangles, arrows with a valve sign, and blue arrows in the flow diagram represent stock variables, flow variables, and auxiliary variables, respectively. Stock variables represent physical accumulation, and flow variables represent the movement of stock. Auxiliary variables are used to provide mathematical information for simulations.

The structure of the model in Figure 2 corresponds to the causal loop diagram in Figure 1. The upper left part of this flow diagram represents the impact of sea level rises on urban areas, and the lower left part represents the impacts of heat waves and heavy rains on land cultivation in rural areas. Put differently, the upper part of Figure 2 depicts the disaster restoration costs incurred from sea level rises and heavy rains, while the lower part depicts the food cost burden resulting from reduced agricultural productivity due to heavy rains and heat waves. While the left part of this figure represents the physical impact of climate change, the right part indicates the social response to the physical impact. The social response was operationalized as the government budget for climate impact that could be used to develop substitute land for submerged urban areas and to increase agricultural productivity through investment in agricultural facilities and infrastructure.

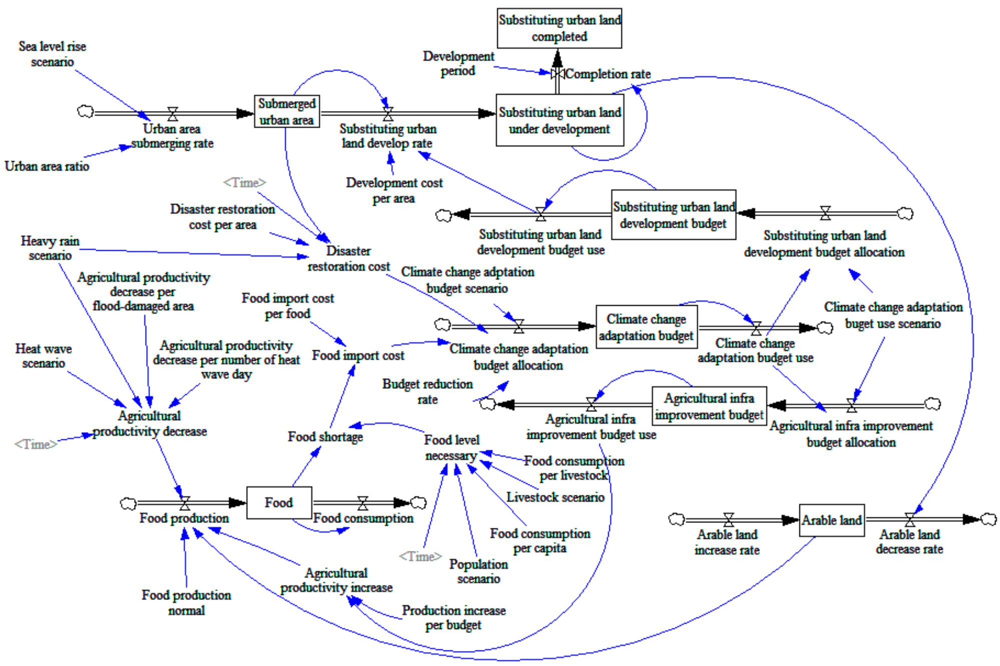


**Figure 2.** Flow diagram of the system dynamics model on climate change impact.

In the middle of the figure, there is a stock variable named "climate change adaptation budget", and directly to its left is "climate change adaptation budget scenario", which affects the flow variable named "climate change adaptation budget allocation". The "climate change adaptation budget scenario" variable was used here as an exogenous variable for policy experiments with different climate budget sizes. Since data on the climate change adaptation budget were available after 2011, the most recent budget amount, approximately nine trillion Korean Won (US $8 billion) was used in the base simulation. This budget has been used first for disaster damage restoration and for food-import-related costs, and the remainder has been used for climate change prevention. It was assumed that the climate budget was allocated evenly between urban and rural areas. The stock variable "substitute urban land under development" in the upper center part of the figure is connected to "arable land decrease rate" in the lower right part of the figure. This indicates that the new development of urban land uses arable land and thus reduces the land available for agricultural food production. Arable land reduction is related to "food production" in the lower left part of the figure. Together with "agricultural productivity decrease", reduced "food" leads to "food shortage" and increases the "food import costs", which in turn reduces the available budget for climate change adaptation, which otherwise could have been used to develop substitute urban land and improve agricultural infrastructure and facilities to reduce climate-change-induced damage.

### *4.3. Model Parameters*

The parameters used in the simulation model were estimated based on historical data as much possible. However, when there were no concrete historical data, such as submerged areas due to sea level rises, damage restoration costs resulting from sea level rises, or heavy rains and heat waves, partial information was used from existing studies or data. For example, to estimate the damage due to heavy rains from 2015 to 2050, we used the available data for annual flooded urban and rural areas between 2000 and 2014 to project future damage. To estimate the annual restoration costs for submerged areas due to sea level rises, we used data from the Korea Environment Institute. In their research, the projected submerged area in 2100 was 3733 km$^2$, and this was backcasted to estimate the annual flooded area from 2006 to 2100. Based on this information and method, we evenly distributed the total projected submerged area from 2000 to 2050 in order to estimate the annual flooded area and the annual restoration cost for submerged urban and rural areas.

For the annual climate change adaptation budget, data have been available since 2011. These data exhibit a decreasing trend in climate change budget size. Therefore, we used the most recent budget amount to reflect recent trends in our model. The "disaster restoration cost per unit area" was estimated as the average damage cost divided by the average flooded area from 2000 to 2013. Details about the data and data sources used for estimating parameters are shown in the Appendix A. Data explained in the Appendix A and parameters estimated from those data are used to simulate behavior of interest variables in the flow diagram. The dynamic value of each variable in the flow diagram is calculated with delta time, and the result is presented either in graphic or table form according to time interval; for example, month, year, or day. For this, software Vensim (simulation software produced by Ventana System Inc., Harvard, MA, USA) was used. For more details of logic and method of calculation, see [8,35].

## 5. Model Simulation Results

A policy experiment was conducted with the above system dynamics model for a 50-year simulation period from 2000 to 2050, with four scenarios based on the government budget for climate change adaptation. In the first scenario, 9 trillion Korean Won (US $8 billion (US $1 = 1123 Korean Won (average US $ exchange rate between 2000 and 2015, Bank of Korea))) in government budget are allocated to climate adaptation in the year 2000, and the same budget level is maintained throughout the simulation period. In the second scenario, the same amount of government budget for climate adaptation (9 trillion Won) is allocated in the year 2000, but the budget increases to 13 trillion Won (US $11.7 billion) in 2016. The third scenario is the same as the second, but with a 10-year delay in the budget increase (i.e., increasing to 13 trillion Won in 2026). In the fourth scenario, a greater proportion of the budget is allocated to urban areas, where most climate change-related damage occurs. In this scenario, 70% of the budget is allocated to urban areas, whereas in the first three scenarios, the budget is distributed equally between urban and rural areas.

The first scenario will be called the 'normal budget scenario', the second will be the 'early budget increase scenario', the third will be the 'delayed budget increase scenario', and the last one will be called the 'greater budget allocation to urban areas scenario'.

### *5.1. Normal Climate Change Adaptation Budget Scenario*

In the first scenario, 9 trillion Korean Won (US $8 billion) in government budget are allocated for climate adaptation in the year 2000, and the same budget level is maintained throughout the simulation period. The climate adaptation budget is used to restore climate damage and improve infrastructure for preventive purposes in order of priority. The simulation results for the first scenario (including the changes in selected variables over time) are shown in Figure 3. The variables shown in the figure include the climate change adaptation budget (line #1), disaster restoration costs (line #2), food import costs (line #3), arable land (line #4), and substitute urban land developed (line #5). In the figure, line #1 for "climate change adaptation budget" decreases rapidly over time and reaches zero before 2040. This is because disaster restoration costs incurred from flooded areas increase rapidly, so resources that could have been allocated for climate adaptation for preventive purposes are instead used for disaster restoration. In Figure 3, disaster restoration costs (line #2) increase rapidly to nearly 20 trillion Won (US $17.8 billion). Since increasing disaster restoration costs reduce the budget available for preventive purposes, climate damage restoration costs increase further, creating a vicious cycle. The temporary decrease in climate adaptation budget in the year 2010 is due to the sudden increase in disaster restoration costs resulting from extremely heavy rains that year. Food import costs, line #3, decrease after 2030 because the population begins to decrease in 2030, and thus food consumption begins to decrease after that year.

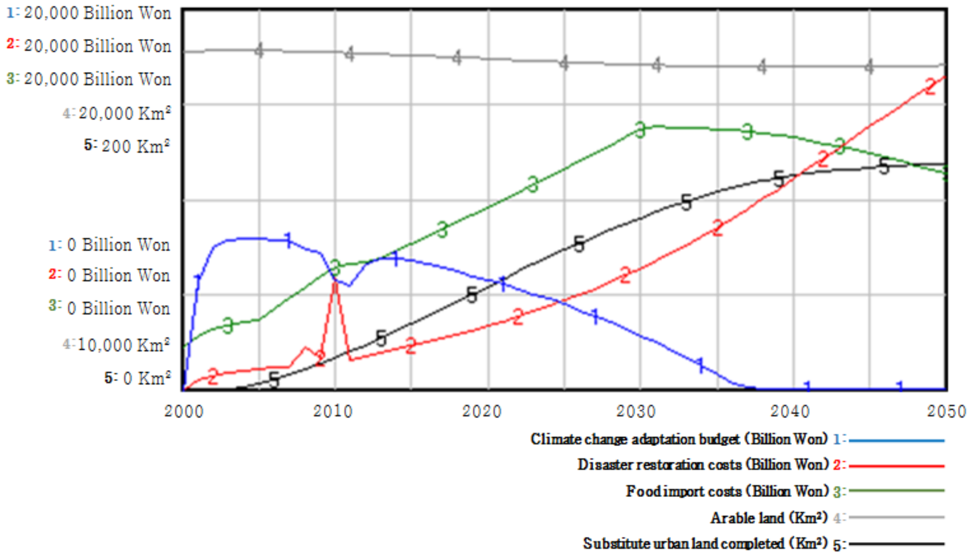


**Figure 3.** Normal climate change adaptation budget scenario.

### *5.2. Early Climate Change Adaptation Budget Increase Scenario*

In the second scenario, the climate adaptation budget begins the same as in the first scenario, but is increased by 4 trillion Won (US $3.6 billion) to 13 trillion Won (US $11.6 billion) in 2016 and thereafter. This budget increase reflects the recognition of the budget depletion problem in the first scenario. The simulation results for the second scenario are shown in Figure 4. With the budget increase in 2016, the dynamic behavior of the system is quite different from that in scenario 1. The climate change adaptation budget is quite stable and does not end in bankruptcy. With the increased budget, urban land can be developed to substitute for submerged urban areas, so the "substitute urban land developed" exceeds 200 km$^2$. As a result, climate damage from "submerged urban land" decreases, and the disaster restoration costs are much lower, remaining under 5 trillion Won (US $4.5 billion) in 2050.

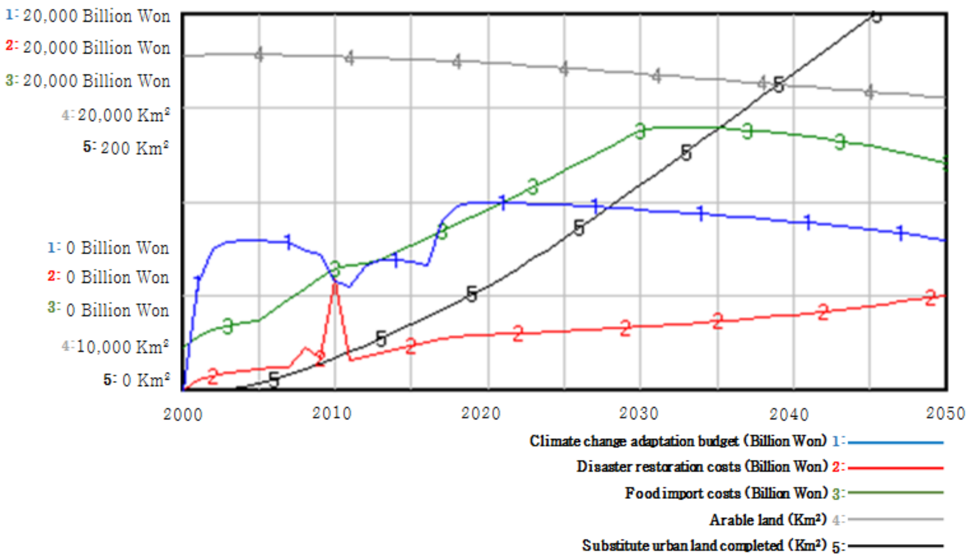


**Figure 4.** Early climate change adaptation budget increase scenario.

The total area of "arable land" (line #4) decreases more in scenario 2 than in scenario 1 because arable land is used to develop substitute urban land for submerged urban land. The reduction in "arable land" reduces food production and thus increases food import costs. However, the difference in food import costs between scenarios 1 and 2 is not large because the reduction in disaster restoration costs frees more of the climate adaptation budget for improvements in agricultural productivity, which in turn compensates for a substantial portion of the increased food import costs.

*5.3. Delayed Climate Change Adaptation Budget Increase Scenario*

This scenario is the same as the second one, except that the climate budget increase is delayed by 10 years due to delayed social consensus. Thus, the climate adaptation budget increases from 9 trillion to 13 trillion Won in 2026. Figure 5 displays the simulation results. It is evident that the delayed climate budget increase does not reduce climate damage much. The climate budget decreases rapidly after 2026 because the increase in submerged urban land rapidly increases the disaster restoration costs and depletes the climate budget. As can be seen in Figure 5, "substitute urban land developed" increases more slowly and disaster restoration costs increase more rapidly in this scenario than in scenario 2. Thus, the 10-year delay nullifies the effects of the 4 trillion Won budget increase.

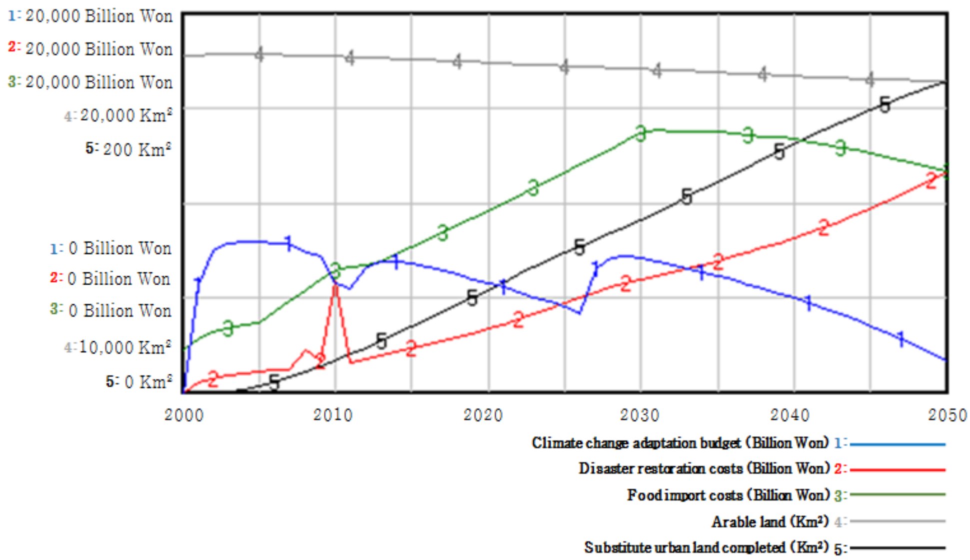


**Figure 5.** Delayed climate change adaptation budget increase scenario.

*5.4. Greater Climate Change Adaptation Budget Allocation to Urban Areas Scenario*

In the three scenarios so far, it has been evident that the climate damage from submerged land in urban areas is much greater than the damage from reduced food production in rural areas. In recognition of this difference, the fourth scenario simulates the policy alternative in which a greater portion of the climate budget is allocated to urban areas than to rural areas. In the first three scenarios, the climate change budget is allocated equally to urban and rural areas, while in the fourth scenario, the urban-to-rural budget allocation ratio is 70:30. Figure 6 displays the simulation results. When these results are compared to those of Figure 5, it is clear that allocating a greater portion of the budget to urban areas reduces climate damage and manages the climate budget much more effectively than increasing the budget in 2026. In Figure 5, the climate budget is almost depleted by 2050, and disaster restoration costs are well over 10 trillion Won (US $8.9 billion). However, in Figure 6, the climate budget in 2050 is sustained at more than 5 trillion Won, and disaster restoration costs remain well under 5 trillion Won. These results were expected, considering that the damage from submerged urban land due to sea level rises and heavy rains is much greater than the damage from reduced food production. The simulation results for scenario 4 demonstrate that allocating more of the budget to urban areas could reduce climate damage more effectively. In this scenario, the total budget for climate change is maintained at 9 trillion Won, so only the proportion of the budget allocated to urban and rural areas differs from that in the other scenarios. Thus, increasing the proportion of the climate budget allocated to urban areas could achieve substantial climate budget savings while maintaining a low level of disaster restoration costs.

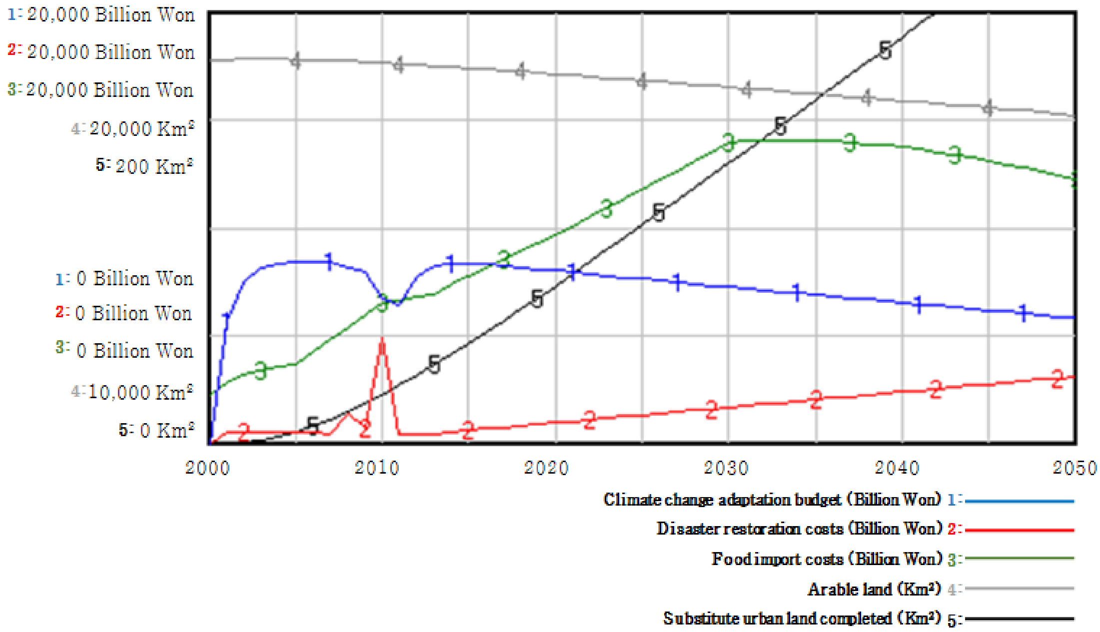


**Figure 6.** Greater climate change adaptation budget allocation to urban areas scenario.

The simulation results explained so far are summarized in Table 1.

**Table 1.** Simulation results for variables of interest in different scenarios in 2050.

| Variable Scenario | Climate Budget | Disaster Restoration Costs | Food Costs | Arable Land | Substitute Urban Land |
|---|---|---|---|---|---|
| Scenario 1: Normal budget | Zero in 2040 | Over 15 trillion Won (US $13.4 billion) | Around 11 trillion Won (US $9.8 billion) | Around 17,400 km$^2$ | Around 12 km$^2$ |
| Scenario 2: Early budget increase | Around 8 trillion Won (US $7.1 billion) | Around 5 trillion Won (US $4.5 billion) | Around 12.5 trillion Won (US $11.1 billion) | Around 16,000 km$^2$ | Over 200 km$^2$ in 2045 |
| Scenario 3: Delayed budget increase | Around 1.25 trillion Won (US $1.1 billion) | Over 10 trillion Won (US $8.9 billion) | Around 12 trillion Won (US $10.7 billion) | Around 17,000 km$^2$ | Around 170 km$^2$ |
| Scenario 4: Greater budget allocation to urban areas | A little more than 5 trillion Won (US $4.5 billion) | Less than 5 trillion Won (US $4.5 billion) | Around 12.5 trillion Won (US $11.1 billion) | Around 15,000 km$^2$ | Over 200 km$^2$ after 2043 |

Table 1 shows approximate simulation results at the end of the simulation period, 2050, as presented in Figures 3–6. The table shows that the current level of climate change budget falls far short for adequate climate change management and needs to be increased earlier for better climate change adaptation. In addition, the table shows that the early budget increase policy (Scenario 1) and the greater budget allocation to urban areas policy (Scenario 4) are better strategies when considering disaster restoration costs and food import costs. However, when considering climate budget, the scenario 4 policy is the best, achieving better results (smaller disaster restoration cost) with a smaller budget. However, a scenario 4 policy must be enacted with caution because it involves allocating more budgetary resources to urban areas than rural areas, which can cause serious conflict between these areas.

## 6. Policy Implications

This study analyzed the impacts of climate change risks of sea level rises, heavy rains, and heat waves on urban and rural areas. The impact of climate risk was measured as the disaster restoration costs for submerged urban areas and food import costs resulting from reduced agricultural productivity. The response to these climate effects was the allocation of government climate budget. The analysis was focused on changes in interrelated variables, including damage restoration costs and climate change adaptation budget, over the simulation period. To observe these changes, we conducted a simulation experiment with four different scenarios. Several policy implications can be derived from the analysis, as described below.

Firstly, if the climate change budget is left at its current level in the future, it is very likely that the government will be unable to perform climate change adaptation activities. This is because the climate adaptation budget since 2000 has only been enough to respond to traditional natural disasters such as flooding and heat waves. Since only a negligible amount of budget is used for preventive purposes for climate adaptation, climate-related damage is ever increasing, and the budget available for preventive purposes is decreasing, thus further increasing the climate damage and forming a vicious cycle.

Secondly, if the government recognizes this problem and increases the budget early, according to the simulation results of scenario 2, it seems possible to limit the climate damage to a manageable range and maintain the government's capacity to respond to it. However, if the budget increase is delayed, as in scenario 3, it will be difficult to obtain the desired results, as disaster restoration costs for increased flooding and submerged urban areas will increase rapidly to an unmanageable level.

Thirdly, if an early budget increase would be difficult, the next best alternative could be to allocate a greater fraction of the climate budget to urban areas, as this would increase the "substitute urban land developed" and reduce disaster restoration costs. This, in turn, would increase the available climate budget to improve the agricultural infrastructure and facilities to prevent climate damage. However, this alternative would require social consensus, because without agreement from rural areas, such a plan could trigger intensive social conflict between urban and rural areas and lose political support from rural areas. In fact, when the Korean government began to push for a strong economic development policy in the mid-1960s, the government relied on an outward-oriented, industry-oriented, and growth-oriented strategy [36]. This unbalanced growth strategy has been widening the gap between urban and rural areas, and the government has been trying to compensate for this unbalanced growth through various policies such as purchasing autumnal harvest grain at higher than market price until 2005 and providing various kinds of agricultural subsidies after agricultural import opening in the 1990s and after free trade agreements (FTA) in the early 2010s. Under such circumstances, if the government budget is again allocated in favor of urban areas in the name of climate change adaptation, it will be difficult to avoid strong opposition and withdrawal of support from rural areas. Given these problems, this alternative needs to be considered as the second-best one, to be used only when an early budget increase is impossible. In addition, the total damage from submerged urban areas and reduced food production needs to be compared before this alternative is chosen.

In short, the simulation analysis in this study revealed the importance of responding early to climate change problems. If an early response is made with the appropriate level of climate budget, it will be possible to reduce climate damage substantially with a smaller budget. If we fail to respond early, far more resources will be needed to restore and prevent damage from climate change. With regard to climate change policy, the simulation results demonstrate that an early budget increase is more effective than a delayed increase.

## 7. Conclusions

Climate change is expected to have far-reaching effects, ranging from the natural environment to society and the economy. However, the scope and intensity of these effects are very difficult to project, because each area affected by climate change interacts with other areas. In Korea, the impact of climate change is expected to be greater than the average world impact. In addition, problems in each area (e.g., population, economy, resources, food, and environment) alone or together could trigger serial and interrelated crises in Korea. In this context, we constructed and analyzed a climate risk model to determine the patterns of risk for parameters such as natural disaster restoration costs and food import costs and to determine strategies and policies to mitigate those effects.

The simulation results demonstrated that the total disaster restoration cost in 2050 would be over 15 trillion Won (US $13.4 billion) in the normal budget scenario, 5 trillion Won (US $4.5 billion) in the early budget increase scenario, over 10 trillion Won (US $8.9 billion) in the delayed budget increase scenario, and under 5 trillion Won (US $4.5 billion) in the greater budget allocation to urban areas scenario. These results indicate that the climate budget needs to be increased to at least 13 trillion Won (US $11.7 billion) per year. In addition, an earlier budget increase was shown to be more effective than a later increase as a means of reducing total disaster restoration costs. If an earlier budget increase is difficult, the next best alternative would be to allocate a larger fraction of the climate budget to urban areas. In short, the study results indicate that an earlier response to climate change is the most important strategy, even if the climate budget could be increased by the same amount in a delayed scenario.

The findings of this study are consistent with the results of previous research on climate change. Climate change evaluation reports from the IPCC and existing studies demonstrate that earlier government spending on climate change could substantially reduce climate change mitigation and adaptation costs. In this study, earlier government response was also shown to substantially reduce climate change damage restoration costs. In addition, this study demonstrates that an early response is more effective than a later response in reducing food import costs, maintaining agricultural productivity, and improving infrastructure for climate change adaptation.

The policy experiments in this study focused mainly on disaster restoration costs for flooded areas and food import costs due to reduced agricultural productivity. Since the model used in this study focused only on small number of variables with narrow focus and different context, its applicability to other countries could be limited. However, the policy implications drawn from this study could be applied in other countries as well. In addition, the system dynamics simulation method used in this study can be applied to a wide variety of issues and problems, especially when they are characterized by complex, interrelated, and interactive problems, like climate change. In future research, policy experiments conducted in research should be extended to fully consider the interaction among detailed variables in economic, social, and environmental areas. To this end, our model needs to be developed further into a comprehensive climate change risk model that accounts for the social, economic, and environmental sectors with variables such as population, economic growth, industry, jobs, energy, natural resources, biodiversity, and climate change-induced disease.

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**Author Contributions:** All authors contributed to this paper. Tae Hoon Moon and Chang Sug Park conceived and designed the research direction and simulation experiment, Tae Hoon Moon and Dong-Hwan Kim constructed simulation model and wrote the paper, and Dong-Sung Lee gathered all data, estimated parameters, and performed numerous policy simulations.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Model parameters, equations, statistics, and sources.

| Sector | Variable | Parameter | Unit | Equations | Data Source |
|---|---|---|---|---|---|
| Urban | Development cost per area | 781.4 | Billion Korean Won/km$^2$ | Average construction cost of second new towns (second new towns: Pan'gyo, Dongtan, Gimpo, Paju, Gwang'gyo, Yangju, Wi'rye, Godeok, Gumdan)/Average area of second new towns | [37] |
| | Urban area ratio | 0.16 | Fraction | Total urban area of South Korea/Total land in South Korea (2013) | [38] |
| | Disaster restoration cost per area | 79.7 | Billion Korean Won/km$^2$ | Average flood-damage assessment value of urban areas (flood-damaged assessment of urban areas: flood-damaged assessment of buildings, ships, and public facilities)/Average flood-damaged urban areas (flood-damaged urban area = flood-damaged area – flood-damaged arable land) (2010~2013) | [39] |
| Agriculture | Arable land | 18,890 | km$^2$ | Arable land increase rate/Arable land decrease rate | [40] |
| | Food (Grains, Vegetables, Fruit, Livestock) | 23,024,000,000 | kg | Food production – Food consumption | [41] |
| | Normal food production | 1,178,006.1 | kg/km$^2$ | Average food/Average arable land (2000−2013) | [42] |
| | Food consumption per livestock | 66.3 | kg/livestock | Average food consumption of livestock/Average number of livestock (Livestock: Korean beef, milking cows, pigs, chickens) (2000−2013) | [43] |
| | Food consumption per capita (food consumption per capita: grains, vegetables, fruit, livestock per capita) | 387.6 | kg | Average food consumption per capita (2000-2013) | [44] |
| | Food production increase cost per unit food | 0.000000843 | Billion Korean Won/kg | Cost of increasing food production (wheat, beans, corn)—According to research conducted by the Korea Rural Economic Institute, the cost to increase food self-sufficiency by 1% is 153.9 billion Won for wheat, 499.7 billion Won for beans, and 129.8 billion Won for corn; 1% of grain self-sufficiency is equivalent to 200,000 tons of grain. Based on this information, the government budget needed to increase food self-sufficiency for wheat, beans, and corn was calculated, and the average budget amount was used for this parameter. | [43] |
| | Arable land increase rate | 9.7 | km$^2$ | Average arable land increase rate between 2000 and 2012 | [45] |
| | Population scenario | - | People | Lookup function using population projection (2000–2050) | [46] |

**Table A1.** *Cont.*

| Sector | Variable | Parameter | Unit | Equations | Data Source |
|---|---|---|---|---|---|
| Scenario | Sea level rise scenario | 36.9 | $km^2$ | Use projected value of submerged area due to sea level rises in 2100 from the research conducted by the Korea Environment Institute (2012). According to research carried out by the Korea Environment Institute (2012), the submerged area due to sea level rises in 2100 was projected as 3733 $km^2$. With this projected value and process, we calculated the annual submerged area by evenly distributing the projected value from 2000 to 2100, and applied this value to the simulation period, 2000 to 2050. | [27]. |
| | Heavy rain scenario | 33.2 | $km^2$ | Estimate linear trend function using annual flood damage data between 2000 and 2014 and extrapolate it to 2050 (estimated linear trend function was $Y = 0.6588X - 0.34$, and the flooded area in 2050 was projected as 33.2 $km^2$) | [47] |
| | Heat wave scenario | 7.5 | Days | Build lookup function using both the average number of heat wave days (7.5 days per year) from 1986 to 2005 and the projected additional 7.4 heat wave days per year in the middle of this century, 2046–2065 (following Representative Concentration Pathways 8.5 scenario) | [48] |
| | Climate change adaptation budget scenario | 11,286 | Billion Won | Average annual climate change adaptation budget between 2011 and 2013 | [49] |

## References


1. Park, Y.S.; Glenn, J.; Gorden, T.; Florescu, E. *UN Future Report 2030*; Kyobo: Seoul, Korea, 2013. (In Korean)
2. Intergovernmental Panel on Climate Change (IPCC). *Synthesis Report of the IPCC Fourth Assessment Report, Climate Change*; Korean Meteorological Administration: Seoul, Korea, 2007. (In Korean)
3. Intergovernmental Panel on Climate Change (IPCC). *Climate Change in 2013: The Physical Science Basis*; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Korean Meteorological Administration: Seoul, Korea, 2013. (In Korean)
4. Ministry of Environment (MOE); National Institute of Environmental Research (NIER). *Korean Climate Change Assessment Report 2014*; NIER: Seoul, Korea, 2015. (In Korean)
5. Cho, G.W.; Chung, S.H.; Lee, H.M. *Study on Quantifying Risk of the Effects of Climate Change*; Korea Environment Institute: Seoul, Korea, 2014. (In Korean)
6. Park, C.S.; Song, Y.I.; Lee, H.S. *Climate-Environmental Risks Outlook and the National Strategy (I)*; Korea Environment Institute: Seoul, Korea, 2014. (In Korean)
7. Moon, T.H. *Sustainable City from the View of System Thinking Perspective*; Jipmundang: Seoul, Korea, 2007. (In Korean)
8. George, P.R.; Pugh, A.L., III. *Introduction to System Dynamics Modelling with Dynamo*; The MIT Press: Cambridge, MA, USA, 1981.
9. Sterman, J.D. *Business Dynamics, System Thinking and Modeling for a Complex World*; Irwin McGraw-Hill: Seoul, Korea, 2000.
10. Morecroft, J. *Strategic Modelling and Business Dynamics: A Feedback Systems Approach*; John Wiley & Sons, Ltd.: West Sussex, UK, 2007.
11. Mitchell, B. *Resource and Environmental Management*, 2nd ed.; Pearson Education Limited: Harlow, Essex, UK, 2002.
12. Cooke, P. Green governance and green clusters: Regional & national policies for the climate change of Central & Eastern Europe. *J. Open Innov. Technol. Market Complex.* **2015**, *1*, 1.
13. Forrester, J.W. *World Dynamics*; Wright-Allen Press, Inc.: Cambridge, MA, USA, 1971.
14. Meadows, D.H.; Meadows, D.L.; Randers, J.; Behrens, W.W., III. *The Limit to Growth*; Universe Book: New York, NY, USA, 1972.
15. Meadows, D.L.; Behrens, W.W., III; Meadows, D.H.; Naill, R.F.; Randers, J.; Zahn, E.K.O. *The Dynamics of Growth in a Finite World*; Wight Allen Press: Cambridge, MA, USA, 1974.
16. Meadows, D.H.; Meadows, D.L.; Randers, J. *Beyond the Limit, Global Collapse or a Sustainable Future*; Earthscan Publications Limited: London, UK, 1992.
17. Meadows, D.H.; Randers, J.; Meadows, D.H. *Limits to Growth: The 30-Year Update*; Chelsea Green Publishing Company: Windsor County, VT, USA, 2004.
18. Randers, J. *2052: A Global Forecast for the Next Forty Years*; Chelsa Green Publishing: Windsor County, VT, USA, 2012.
19. Millennium Institute. Threshold 21 Model. Available online: http://www.millennium-institute.org/index.html (accessed on 29 June 2015).
20. Sterman, J.; Fiddaman, T.; Franck, T.; Jones, A.; McCauley, S.; Rice, P.; Sawin, E.; Siegel, L. Climate interactive: the C-ROADS climate policy model. *Syst. Dynam. Rev.* **2012**, *29*, 295–305. [CrossRef]
21. Fiddaman, T. Feedback Complexity in Integrated Climate-Economy Models. Available online: https://dspace.mit.edu/handle/1721.1/10154 (accessed on 24 March 2017).
22. Fiddaman, T. Exploring policy options with a behavioral climate-economy model. *Syst. Dynam. Rev.* **2002**, *18*, 243–267. [CrossRef]
23. Fiddaman, T. Formulation experiments with a simple climate–economy model. In Proceedings of the 1995 System Dynamics Conference, Tokyo, Japan, 30 July–4 August 1995.
24. Huera, J.M.; Esquivel-Longoria, M.I.; Arellano-Lara, F. A System Dynamics Approach to Examine Climate Change Impact: The Case of the State of Guanajuato, Mexico. In Proceedings of the 29th International Conference of the System Dynamics, Washington, DC, USA, 24–28 July 2011.

25. Intergovernmental Panel on Climate Change (IPCC). Summary for policy makers. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*; Contribution of Working Group II to the Fifth Assessment Report of the IPCC; Cambridge University Press: Cambridge, UK, 2014.
26. Cho, K.W.; Lee, H.M.; Noh, B.H.; Kang, J.E.; Nobuoka, H. *National Assessment on Sea Level Rise Impact of Korea Coast in the Socioeconomic Context I*; Korea Environmental Institute: Seoul, Korea, 2011. (In Korean)
27. Cho, K.W.; Lee, H.M.; Noh, B.H.; Kang, J.E.; Nobuoka, H. *National Assessment on Sea Level Rise Impact of Korea Coast in the Socioeconomic Context II*; Korea Environmental Institute: Seoul, Korea, 2012. (In Korean)
28. Ha, J.S.; Chung, W.C.; Lee, J.H.; Kim, D.H.; Choi, J.H. *A Study on Establishment and Management of a Long-Term Heatwave Plan Addressing Climate Change*; Korea Environment Institute: Seoul, Korea, 2014. (In Korean)
29. National Institute of Meteorological Research (NIMR). *Climate Change Scenario Report*; NIMR: Seoul, Korea, 2011. (In Korean)
30. Shin, Y.S.; Ha, J.S.; Jung, J.H.; Kim, S.D. *Introduction on Environmental Burden of Disease as a National Environmental Health Policy Indicator*; Korea Environment Institute: Seoul, Korea, 2012. (In Korean)
31. Korea Meteorological Administration (KMA). *Korean Climate Change Assessment Report*; KMA: Seoul, Korea, 2014. (In Korean)
32. Ministry of Public Safety and Security (MPSS). *2015 Statistical Yearbook of Natural Disaster*; MPSS: Seoul, Korea, 2016.
33. Meadows, D.H. The Unavoidable A Priori. In *Elements of the System Dynamics Method*; Randers, J., Ed.; MIT Press: Cambridge, MA, USA, 1980.
34. Bell, J.A.; Bell, J.F. System Dynamics and Scientific Method. In *Elements of the System Dynamics Method*; Randers, J., Ed.; MIT Press: Cambridge, MA, USA, 1980.
35. Forrester, J.W. *Principle of Systems*; 10th Printing; MIT Press: Cambridge, MA, USA, 1982.
36. Song, B.N. *The Rise of the Korean Economy*; Oxford University Press: New York, NY, USA, 1990.
37. Joongang Ilbo. Construction Cost of Second New Towns. Available online: http://news.joins.com/article/3076405 (accessed on 4 September 2015).
38. Statistics Korea. Urban Area of South Korea. Available online: http://kosis.kr/statisticsList/statisticsList_01List.jsp?vwcd=MT_ZTITLE&parmTabId=M_01_01 (accessed on 4 September 2015).
39. Ministry of Public Safety and Security. Flood-Damage Assessment Value of Urban Area, Flood-Damaged Urban Area. Available online: http://www.safekorea.go.kr/idsiSFK/367/menuMap.do?w2xPath=/idsiSFK/wq/sfk/cs/csc/bbs_conf.xml&bbs_no=26 (accessed on 4 September 2015).
40. Statistics Korea. Arable Land Increas, Decrease Rate. Available online: http://kosis.kr/statisticsList/statisticsList_01List.jsp?vwcd=MT_ZTITLE&parmTabId=M_01_01 (accessed on 4 September 2015).
41. Statistics Korea. Food Production and Consumption. Available online: http://www.index.go.kr/potal/main/EachDtlPageDetail.do?idx_cd=2747#quick_02 (accessed on 4 September 2015).
42. Statistics Korea. Food Production, Arable Land. Available online: http://www.index.go.kr/potal/main/EachDtlPageDetail.do?idx_cd=2747#quick_02 (accessed on 4 September 2015).
43. Ministry of Agriculture, Food and Rural Affairs. Major Stastics for Agriculture, Animal Husbandary, Food. Available online: http://www.mafra.go.kr/list.jsp?id=30154&pageNo=1&NOW_YEAR=2017&group_id=1&menu_id=52&link_menu_id=&division=B&board_kind=C&board_skin_id=C1&parent_code=34&link_url=&depth=2&code=left&link_target_yn=&menu_introduction=&menu_name=%EC%B5%9C%EA%B7%BC%ED%86%B5%EA%B3%84%EC%9E%90%EB%A3%8C&popup_yn=N&reference=2&tab_yn=N (accessed on 4 September 2015).
44. Statistics Korea. Food Consumption per Capita. Available online: http://www.index.go.kr/potal/main/EachDtlPageDetail.do?idx_cd=2747#quick_02 (accessed on 4 September 2015).
45. Korea Rural Corporation. Arable Land Increase Rate. Available online: http://rims.ekr.or.kr/stat_print/stat_print.aspx (accessed on 4 September 2015).
46. Statistics Korea. Population Trend and Projection 1960–2065. Available online: http://kosis.kr/statisticsList/statisticsList_01List.jsp?vwcd=MT_ZTITLE&parmTabId=M_01_01 (accessed on 4 September 2015).
47. Ministry of Public Safety and Security. Annual Flood Damage Data. Available online: http://www.safekorea.go.kr/idsiSFK/367/menuMap.do?w2xPath=/idsiSFK/wq/sfk/cs/csc/bbs_conf.xml&bbs_no=26 (accessed on 4 September 2015).

48. Korea Adaptation Center for Climate Change (KACC). Number of Heat Wave Days. Available online: http://ccas.kei.re.kr/main/pg.do?pg=climate_change/menu_3_5_tab2 (accessed on 4 September 2015).
49. Korea Adaptation Center for Climate Change (KACC). Climate Change Adaptation Budget. Available online: http://ccas.kei.re.kr/budget/list.do (accessed on 4 September 2015).