# WATER-ENERGY-FOOD RELATIONSHIP EVALUATION IN GREENHOUSE USING SYSTEM DYNAMICS AND SUSTAINABILITY INDEX

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## ABSTRACT

Due to the population growth, food production demands and water use increase. There is a wide variety of global discussions on resource management in terms of securing resources such as water and food considering sustainability. The concept of “Water-Food-Energy Nexus” has emerged to interpret the linkage of water, energy and food resources and to suggest an integrated management plan. There is a trade-off relationship among input resources such as energy, water and cost, for increasing food productivity, therefore, it is necessary to analyze the relationships comprehensively rather than single resource analysis. This study was conducted to evaluate the relationship between water and food among the water-food-energy nexus of upland crops in the greenhouse. Because the greenhouse could control the environmental condition such as the temperature, humidity, and wind speed for growing the upland crops . Theanalysis based on the scenarios according to the environmental conditions could be conducted. Also, in the greenhouse, because the energy resources are put to provide an appropriate growth environment for crops, it is necessary to analyze the relationship between energy and other resources. Thus, this study included estimating the crop yield, irrigation water requirement and water productivity and simulating the response of crops to water stress, soil condition using AquaCrop model. Also, linking with energy resources such as heating, pumping energy, fertilizer, and calculating the equations between resources, Water-Energy-Food Nexus was constructed using System Dynamics. Assessment and comparison of scenarios can be accomplished through the calculation of a sustainability index to decide which scenario to choose and how much we can endure in terms of different resource requirement. Finally, the sustainability index for the scenario was calculated for decision-making and policy assessment.

**Keywords:** Water-Food-Energy Nexus, Greenhouse, AquaCrop, System dynamics, Sustainability index.

## 1. INTRODUCTION

Four of the ten most likely and influential global risk factors presented by Global Risks 2015 are related to climate change, water security and food security. To cope with such changes in the future environment, it is necessary to secure and utilize limited

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resources sustainably. Water-Energy-Food Nexus interprets water-energy-food interrelations to achieve efficient use of resources and ultimately to the sustainability of agriculture (Choi, 2017). Sustainable water resource management using WEF Nexus can increase the sustainability of available water resources by using balanced water resources between water, food and energy. There is a trade-off relationship among input resources such as energy, water and cost, for increasing food productivity, therefore, it is necessary to analyze the relationships comprehensively rather than single resource analysis (Bassel& Rabi, 2015). Using Water-Energy-Food Nexus, the evaluation of the sustainability of water, energy, and food resources could be conducted by applying various scenarios and analyzing the trade-off between resources.

The purpose of this study is to evaluate the relationship between water and food among the water-food-energy nexus of the upland crops in the greenhouse. Also, because the water stress and soil fertility have a significant influence on the crop growth and yields, this study included simulating the response of the crops to water, soil fertility using AquaCrop model.Finally, the objective of this study is to construct water-food-energy nexus considering the heating energy to understand the relationship between resources and estimate the sustainability index to compare the various scenarios and regional results.

## 2. MATERIALS &METHODS

### 2.1 Study Area

One of the best examples of water-energy-food nexus is greenhouse cultivation. Greenhouse cultivation is resource-intensive farming, and productivity is high, and there are few time and space constraints, which enables production throughout the year. Greenhouse cultivation is to cut off outdoor environmental conditions such as temperature, precipitation, and wind speed, and resources such as water and energy are put to provide an appropriate growth environment for crops (Udink ten Cate, 1983). Therefore, water-food-energy nexus was applied to the greenhouse cultivation area as a test bed for analyzing the trade-off between water, energy and food resources according to the environmental conditions in the greenhouse. The study area was selected as the greenhouse cultivation site located in Jinju Danmok-ri in South Korea. Here, tomatoes, hot peppers, and squash are cultivated throughout the year, and in this study, tomatoes were selected as the study crop.

### 2.2 Aquacrop Model

In this study, using AquaCrop model, crop yield, evapotranspiration and the amount of irrigation water use are estimated.AquaCrop model is designed to simulate the crop growth, biomass production, yield and evapotranspiration of herbaceous crop types (FAO, 2017).AquaCrop model concept represents yield response to water as a linear, crop-specific function of the ratio of actual to potential evapotranspiration over a growing season.AquaCrop model accounts for the dynamic effects of water and temperature stress on crop growth, and the impact of evaluated atmospheric CO2 concentrations on crop water productivity.

### 2.3 Scenarios (Temperature, Water Stress, Soil Fertility Scenario)

Scenarios based on the temperature, water stress, and soil fertility condition were constructed for simulating the crop growth and agricultural water use by the various environmental conditions. The temperature scenarios refer to the greenhouse inner setting temperature scenarios, which isrelated to the heating energy and the heating energy provides the growth environment of the crops. The greenhouse inner setting temperature was set as minimum 13℃ to maximum 30℃, which is a temperature range suitable for growing crops and was set by statistical data and field surveys.

The water stress and soil fertility conditions are the factors that greatly influence crop growth, yields, and water productivity. Then, water stress scenarios were constructed to analyze crop growth by water stress,and the net irrigation water requirement was adjusted by the soil water content RAW (Readily Available soil Water). The water stress scenarios were four (Not irrigated, irrigated at the point of 10% RAW remained (Readily available soil water), irrigated at the point of the 50% RAW remained, irrigated at the point of 10% RAW remained (potentially irrigated)).Also, soil fertility conditions were also adjusted to analyze the effect of fertilizer that related to the energy resources on crop growth. Soil fertility scenarios were based on soil fertility stress 0% to 70% which indicates soil fertility conditions (potential, optimal, moderate, half, poor, very poor).

### 2.4 System Dynamics and Sustainability Index

The heating energy according to the greenhouse inner setting temperature scenarios was calculated and linked to the crop yields and irrigation water requirement results. Heating load equation with heating degree-hour (HDH) was applied to estimate the heating energy in the greenhouse. System dynamics which is the methodology and mathematical modeling technique to frame, understand and discuss complex problems. In this study, using the system dynamics, the relationship among the Nexus component resources such as water, food, and energy could be defined.

Finally, to analyze the trade-off between resources through comparison between various scenarios applied to water-food-energy nexus, an index that can evaluate the sustainability of resources is needed. In this study, water productivity and energy productivity concept were used as the sustainability index. In the water-food-energy nexus, water and energy are inputs to produce food, and the resulting output is food, so sustainability index was defined as the product of water and energy productivity, in other words, the productivity of inputs, as follows.

$$\begin{aligned} Sustainability\ index &= water\ productivity \times energy\ productivity \\ &= \frac{Crop\ yield\ (ton/ha)}{Irrigation\ water\ (mm)} \times \frac{Crop\ yield\ (ton/ha)}{Energy\ (GJ)} \\ &= \frac{Crop\ yield\ (ton/ha)^2}{Irrigation\ water\ (mm) \times Energy\ (GJ)} \end{aligned}$$

## 3. RESULTS AND DISCUSSION

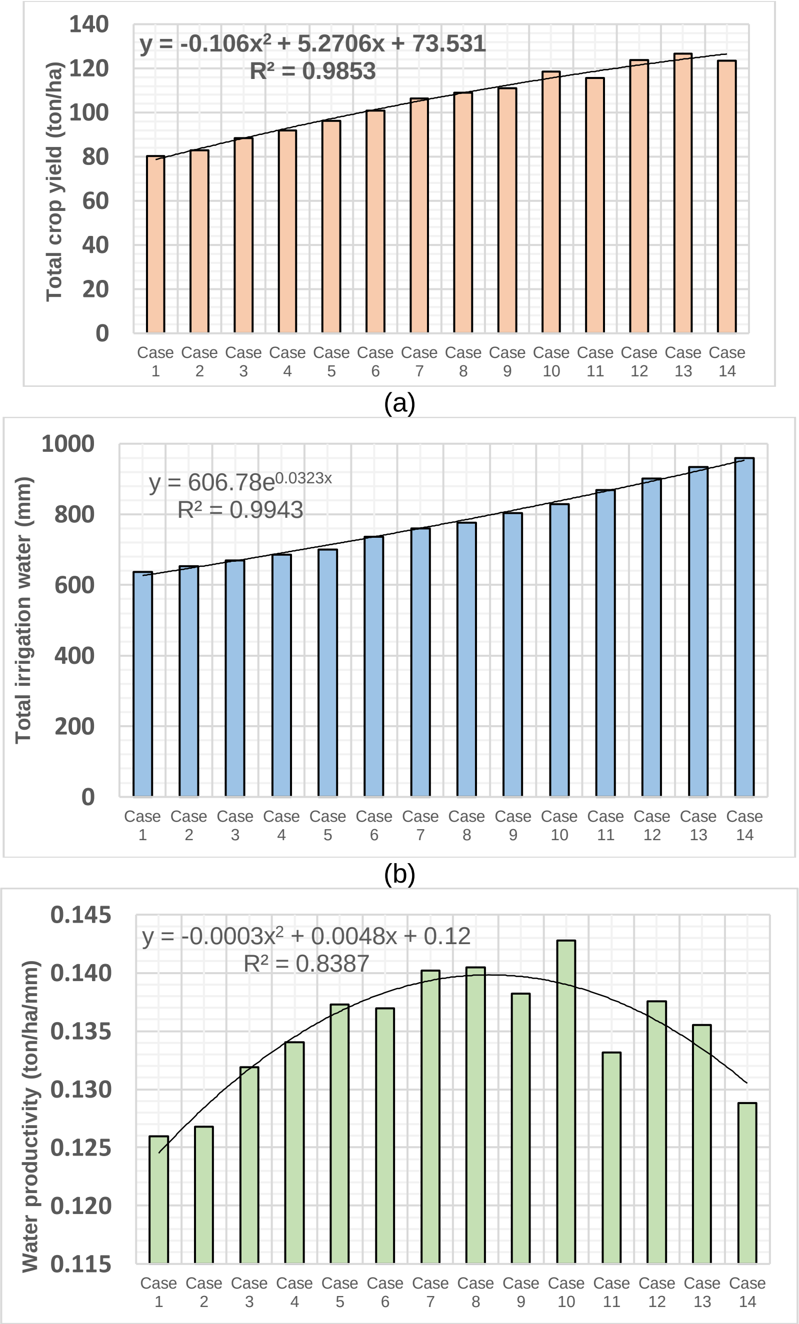
### 3.1 Total Yield, Total Irrigation Water, and Water Productivity Simulation Results

Total crop yield, the amount of irrigation water and water productivity simulation results by the temperature conditions were estimated using the AquaCrop model. Simulation scenarios were set according to the crop environmental temperature conditions from 13℃ to 30℃ to evaluate the crop response to the cold and heat stress.1-year total yield and irrigation water were calculated by multiplying the unit yield and irrigation water per day by the growing period to consider that the growing period varies depending on the temperature conditions. Besides, water productivity is a concept that links crop yield and agricultural water use and is an indicator of agricultural water use efficiency. Water productivity was estimated by dividing crop yield (ton/ha) by the amount of irrigation water (mm).

**Table 1.** Total yield, the irrigation water requirement of 1-year and water productivity results by the temperature scenarios

| Case | Minimum Temperature (℃) | Maximum Temperature (℃) | Total yield (ton/ha/year) | Total irrigation water requirement (mm) | Water productivity (ton/ha/mm) |
|---|---|---|---|---|---|
| Case 1 | 13 | 17 | 80.2 | 636.9 | 0.126 |
| Case 2 | 14 | 18 | 82.9 | 654.1 | 0.127 |
| Case 3 | 15 | 19 | 88.3 | 669.4 | 0.132 |
| Case 4 | 16 | 20 | 92.0 | 686.3 | 0.134 |
| Case 5 | 17 | 21 | 96.2 | 700.5 | 0.137 |
| Case 6 | 18 | 22 | 100.9 | 737.1 | 0.137 |
| Case 7 | 19 | 23 | 106.5 | 759.7 | 0.140 |
| Case 8 | 20 | 24 | 109.0 | 775.8 | 0.140 |
| Case 9 | 21 | 25 | 111.0 | 803.1 | 0.138 |
| Case 10 | 22 | 26 | 118.4 | 829.6 | 0.143 |
| Case 11 | 23 | 27 | 115.6 | 868.4 | 0.133 |
| Case 12 | 24 | 28 | 123.9 | 900.8 | 0.138 |
| Case 13 | 25 | 29 | 126.7 | 934.5 | 0.136 |
| Case 14 | 26 | 30 | 123.6 | 959.3 | 0.129 |

The total annual crop yield, irrigation water requirement and water productivity results for each temperature scenarios are as above. As the temperature increased, both crop yield and irrigation water requirement tended to increase. However, in the case of crop yield, the increasing slope gradually decreased, and it is considered that the high-temperature stress acts as the temperature continuously increases. On the other hand, in the case of irrigation water requirement, it continuously increased to show the form of the exponential function.Water productivity, which is the ratio of crop yield (ton/ha)to irrigation water requirement (mm), can be used as an indicator of water use efficiency and can be used to select the most efficient scenarios and the environmental conditions in policy or decision making.



(a)

(b)

(c)

**Figure 1.** Total yield, irrigation water requirement of 1-year and water productivity results by the temperature scenarios ((a): Total irrigation water requirement (mm), (b): Total yield (ton/ha), (c): Water productivity (ton/ha/mm))

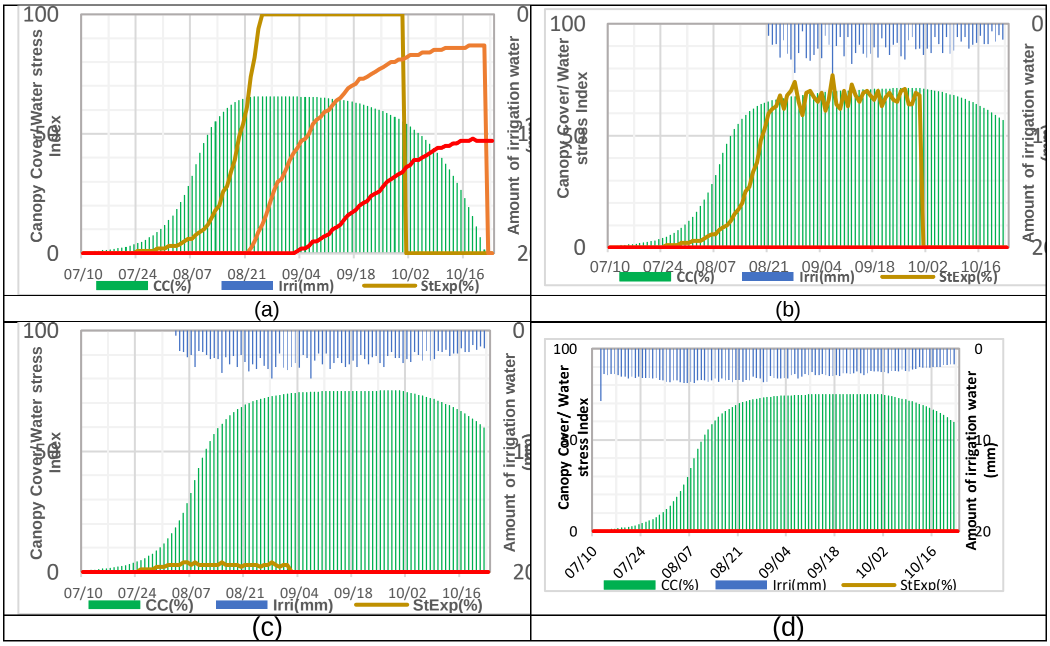
### 3.2 Crop Growth Simulation Results by Water Stress

For simulating the crop growth response to water stress and, the biomass, crop yield and the amount of the irrigation water were estimated under the water stress conditions by the irrigation method. The study crop was tomato and the growing period was from January/10 to August/7 which is the one growing cycle of tomato.

**Table 2.** Biomass, yield, amount of the irrigation water results by the irrigation method

| Irrigation method scenario | Biomass (ton/ha) | Yield (ton/ha) | Irrigation water requirement (mm) |
|---|---|---|---|
| Not irrigated | 6.04 | 3.41 | 0 |
| Irrigated at 10% RAW remained | 12.97 | 8.17 | 135.8 |
| Irrigated at 50% RAW remained | 13.42 | 8.47 | 191.4 |
| Irrigated at 100% RAW remained (potential) | 13.48 | 8.50 | 307.7 |

※ CC: Canopy cover (%), Irri: The amount of irrigation water (mm),
StExp: Percent of water stress reducing leaf expansion (%),
StSto: Percent of water stress inducing stomatal closure (%),
StSen: Percent of water stress triggering early canopy senescence (%)



(a)

(b)

(c)

(d)

**Figure 2.** Canopy cover, the amount of the irrigation water, water stress by the irrigation method ((a): Not irrigated, (b): Irrigated at 10% RAW remained (Readily available soil water), (c): Irrigated at 50% RAW remained, (d): Irrigated at 100% RAW remained (potentially irrigated))

The crop yield, irrigation water requirement and water stress results of the one crop growing cycle according to the irrigation method are as above. Yellow, orange, and red lines indicate growth inhibition water stress, stomatal closure water stress, and early canopy senescence water stress, respectively. First, without irrigation, yields were significantly lower, and all three water stresses were found to occur. In the case of irrigation when the soil moisture content remained 10%, growth inhibition water stress only occurred, and the yield was estimated to be 8 tons per one crop growing cycle. Secondly, when irrigation is carried out when the soil moisture content is 50%, there is a slight growth inhibition water stress, but there is no significant difference in the total yield compared to the case of irrigated potentially (Irrigated at 100% RAW remained), and the amount of irrigation water requirement is about 1.5 times.

### 3.3 Crop Growth Simulation Results by Soil Fertility

For the simulating the crop growth response to soil fertility condition, the biomass, crop yield, the amount of the irrigation water and water productivity were estimated under the soil fertility stress condition. The soil fertility stress conditions were six (Potential (soil fertility stress 0%), Optimal (23%), Moderate (42%), Half (51%), Poor (59%), Very poor (69%)).

**Table 3.** Biomass, yield, amount of the irrigation water, water productivity results by the soil fertility condition

| Soil condition (Soil fertility stress) | Biomass (ton/ha) | Yield (ton/ha) | Irrigation water (mm) | Water productivity |
|---|---|---|---|---|
| Potential (0%) | 13.42 | 8.45 | 191.4 | 4.42 |
| Optimal (23%) | 10.77 | 6.79 | 174.1 | 3.90 |
| Moderate (42%) | 8.09 | 5.10 | 150.8 | 3.38 |
| Half (51%) | 6.70 | 4.22 | 136.9 | 3.08 |
| Poor (59%) | 5.43 | 3.42 | 122.3 | 2.80 |
| Very poor (69%) | 3.90 | 2.45 | 101.5 | 2.42 |

## 4. CONCLUSIONS

In this study, water-food-energy nexus was applied to resource-intensive greenhouse cultivation. Scenarios according to the inner greenhouse temperature, water stress and soil fertility conditions were set, and the relationship between water and food resources were analyzed. Besides, water-food-energy nexus was constructed considering the heating energy in the greenhouse, and the sustainability index according to each scenario and region were calculated and compared.

As a result, as the greenhouse temperature increases, crop yield and irrigation water requirement increased, but in the case of the increasing slope, crop yield decreased, and irrigation water requirement increased steadily. Through this, it could be calculated the water productivity, which is an indicator of agricultural water use efficiency. As a result of the water stress scenarios, there was no significant difference in the crop yields when irrigation water was supplied potentially and when 50% of the soil moisture remained. The soil fertility scenario can also be linked with the amount of fertilizer to form a water-food-energy nexus in terms of energy resources and costs.

Also, the heating energy according to the greenhouse inner setting temperature was calculated to construct the water-food-energy nexus, and the relationship between the resources would be analyzed using system dynamics. Finally, sustainability index which is suitable for water-food-energy nexus analysis would be improved, and it would be estimated by various scenarios and regions.

Since the results of this study are simulation results using the crop growth model, it is necessary to verify and calibrate using field data and statistical data. In the future study, nexus could be applied to various testbeds such as paddy field and upland open field. Besides, the water-food-energy relationship by adding the energy of various items such as fertilizer and agricultural machinery could be analyzed.

## 5. ACKNOWLEDGMENT

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## 6. REFERENCES

FAO. 2017AquaCrop training handbooks: Understanding AquaCrop.

Bassel T.D. & Rabi H. M. 2015 Water-energy-food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water International. 40:5-6, 728-771.

Choi, J. 2017 Sustainable resource management with Water-Energy-Food Nexus. World Agriculture 206: 3-19 (in Korean).

Udink ten Cate, A. J. 1983 Modelling and (adaptive) control of greenhouse climates. Ph.D. diss., Wageningen, the Netherlands: Wageningen Agricultural University.