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Understanding the Impacts of Climate Change on Rice Production: A Qualitative Perspective

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ABSTRACT

Several quantitative studies have concluded that climate change would negatively affect the Asian rice supply. Recently, as temperatures in Asia have approached the temperature threshold for rice growth, the Asian rice supply has become vulnerable to climate change in the near future. To complement quantitative studies' projections of the negative impacts of climate change on rice supply, this paper offers a qualitative analysis using system archetypes to understand the impacts of climate change on rice production. Two structures of the system archetypes are identified including Limits to Growth and Success to Successful. Both archetypes explain that rice production is hampered by high minimum temperature, as photosynthesis output is decreased by an increasing respiration. This paper shows that using this simple tool, system archetypes, we can describe the impacts of climate change on rice production. The outputs of this study, such as the causal loop diagram and system archetypes, can be the basis for the development of a simulation model used for understanding the impacts of climate change on major crops.

Keywords: Asian rice; Climate change; Global rice production; Rice production; System archetypes; System dynamics

1. Introduction

Assessing the impacts of climate change on crop production has attracted the interest of several scholars [1-5]. Worldwide, rice is arguably the most important crop, as it is the primary food source in Asia, where more than half of the world's population is located [6-8]. Rice is also a main source of employment and economic activity, as Asia also accounts for about 90% of the world's rice production and total rice farming areas.

Despite its importance, farmed rice is considered highly vulnerable to climate change [6-8] as elevated temperatures and changing rainfall patterns are associated with climate change. As our society grows more concerned about the elevated CO_2 levels leading to climate change, the impacts on rice

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should be seen as a critical issue.

Rice should be sown in areas with temperatures within its optimum temperature range [9-11]. As temperature increases beyond its optimum temperature, rice yield tends to decline [10-12]. This means that rice yield tends to increase as temperature increases, but over its temperature threshold, yield tends to decrease [9-13]. Since rice farming areas in Asia have experienced temperatures of about 33^0C [6, 10-11], climate change is likely to affect global rice production.

Furthermore, other studies [7, 10-11] have explained that rice is vulnerable to climate change since the recent maximum temperature and recent minimum temperature in regions of Asia are close to and higher than the temperature thresholds of rice, respectively. [11, 14].

Existing studies [11-12] have confirmed the negative impacts of climate change on Asian rice. Unfortunately, to the best of the author's knowledge, there is no study that offers a qualitative explanation of the impacts of climate change on rice. Thus, this study uses system archetypes for understanding the negative impacts of climate change on rice. This study would help policymakers in developing countries to understand the impacts of climate change on rice, through a concise qualitative analysis.

As this study aims to provide a qualitative analysis of the impacts of climate change on rice, it uses system archetypes to explain the impacts of change.

The system archetypes firstly were named by Senge [15] in his book "*The Fifth Discipline: The Art and Practice of the Learning Organization*". At the time this paper was written, there were about 10 archetypes such as Limits to Growth, Success to Successful, Shifting Burden, and Escalation.

System archetypes are recurring or regular patterns of complex systems that give insights into the system structures [15-16]. Moreover, system archetypes have been used to analyze multiple types of observed systems, such as the water resource system [17], agriculture [18], the Australian electricity market [19], and the construction industry [20].

This suggests that system archetypes can be applied across a diverse range of subjects, scenarios, and contexts. In other words, system archetypes are generic patterns of systems or templates that represent usual practices in our world. Furthermore, Senge [15] points out that system archetypes enable us to identify leverage points which in turn can improve system performance. Further discussion of system archetypes can be found in many studies [17-19].

Since system archetypes are generic structures of systems that describe dynamic systems, system archetypes are a useful tool for analyzing dynamic and complex systems, such as the impacts of climate change on rice. Hence, system archetypes are a suitable tool for analyzing the impacts of climate change on rice production.

2. Methods

In the first step, causal links between two influential variables are defined. If a loop of causal links self-amplifies, then the loop is called a reinforcing loop (R). Otherwise, a loop of causal links is called a balancing loop (B). For convenience, all balancing and reinforcing loops in this study will be numbered.

In the following steps, all causal links consisting of influential variables are summarized as a causal loop diagram (CLD). Afterwards, from the CLD, identified system archetypes will be identified and explained. Based on identified system archetypes, how climate change influences rice production and the proposed solution in tackling the negative impacts of climate change will be explained.

To capture a deeper understanding of the underlying structures of the impacts of climate change on rice, system archetype structures are identified as seen in the next section.

This study used Vensim Plus® to translate a conceptual model into a CLD. Then, system archetypes were identified based on the identified CLD.

3. Results and Discussion

3.1 A causal loop diagram of rice production

Rice growth is the product of the dynamic interaction between important variables such as carbon dioxide, precipitation, and temperature [3, 10, 21]. Crops absorb CO_2 to develop organic compounds supporting rice growth [10, 21]. Besides carbon dioxide, precipitation and temperature are important for rice production. Less precipitation leads to lower yield [21] previous studies [3, 10, 21] have also pointed out that climate change negatively impacts crops, as it relates to high minimum temperatures and high maximum temperatures.

The dynamic relationships between carbon dioxide, precipitation, and temperature are shown in Fig. 1. As climate change is associated with higher temperatures [2-3, 22], connecting lines between climate change and temperature [minimum and maximum temperature] have a "+" sign.

Opposite to this, the relationship between climate change and precipitation has a "-" sign, designating it a so-called balancing loop. This is supported by existing studies [22-23] that have projected Asia will experience lower seasonal precipitation. Climate change also has connecting lines with land-use change and fossil fuel burning [22], so fossil fuel burning and land-use change each have a "+" sign with "climate change".

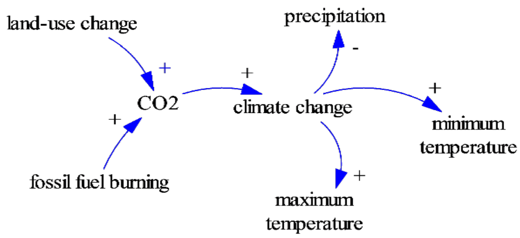

Fig. 1. Relationships among CO_2, climate change, temperatures, and precipitation.

Chemical substances containing phosphorus and nitrogen are important for rice growth [21, 24]. The main sources of these elements are fertilizers and water (from reservoirs or rainfall). Photosynthesis combines chemical substances and carbon dioxide to form the assimilation pool [21, 24]. The assimilation pool is important for supporting rice biomass, such as in leaves. Fig. 2 summarizes dynamic interactions between water, photosynthesis, and fertilizer.

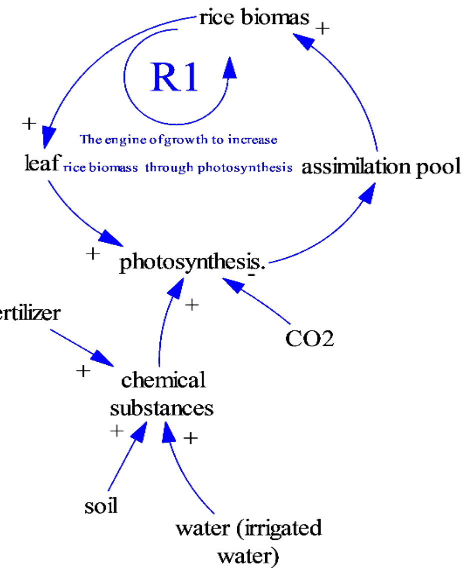

Fig. 2. Photosynthesis.

Compounds within the assimilation pool are also converted to form roots, stems, leaves, and rice panicle, as seen in Fig. 3 [21, 24]. Rice panicle is important in supporting rice spikelet growth. More rice panicles lead to more rice spikelets on the top of the panicles. As rice panicles will affect the volume of rice spikelets, the number of panicles per farming area can affect rice grain per panicle [21, 24].

Fig. 3 is a combination of Figs. 1-2. So, Fig. 3 combines the negative impacts of high minimum temperatures on rice yield (B1) and the growth engines that support photosynthesis and respiration (R1-R3). While R2 leads to increasing carbon dioxide owing to climate change, R3 supports more photosynthesis after fertilizer and carbon dioxide. As reinforcing loops, such as R2 and R3, lead to more resources, reinforcing loops are known as engine growths.

It should be acknowledged that two types of rice farming are practiced: rainfed rice and irrigated rice. While irrigated rice is supported by irrigation facilities, rainfed rice depends solely on rainfall. To accommodate the two types of rice farming, a link between precipitation and chemical substances is embedded in Fig. 3 to represent rainfed rice, while another link of precipitation-irrigated water-chemical substances represents irrigated rice.

This study also accommodates two types of rice varieties: japonica and indica. Although earlier studies [25-26] have acknowledged the different sensitivities of the two rice varieties to high temperature, recent studies [14, 25, 27] have confirmed the negative impacts of high temperature on both japonica and indica rice. With this point in mind, Fig. 3 applies to all rice regardless of variety.

Besides photosynthesis, crops such as rice also need respiration. Through respiration, rice can maintain ion concentration and lipid and protein turnover [21, 27]. If the minimum temperature exceeds a critical level, it tends to induce excessive respiration [14, 27]. Hence, excess respiration tends to decrease the size of the assimilation pool, leading to lower rice biomass and lower rice yield [27].

In general, there are two mechanisms by which higher temperatures negatively influence rice yield [28-29]. The first mechanism is by decreasing spikelet sterility, thus reducing rice yield [28-29]. However, transpirational cooling (more irrigated water) can negate this negative impact [28-29]. The second mechanism is by increasing respiration, thus reducing the assimilation pool size [27]. Dynamic relationships between transpirational cooling, high temperature, and assimilation pool can be seen in Fig. 4.

Fig. 5 is a CLD that shows the relationships between climate factors, non-climate factors, and rice growth. Fig. 5 also consists of some loops – both reinforcing and balancing loops.

The first reinforcing loop (**R1**) is a reinforcing loop that explains the dynamic interaction between photosynthesis, rice biomass, and assimilation pool [photosynthesis – assimilation pool – rice biomass – leaf – photosynthesis]. This loop (**R1**) is the growth engine supporting rice biomass development and the assimilation pool.

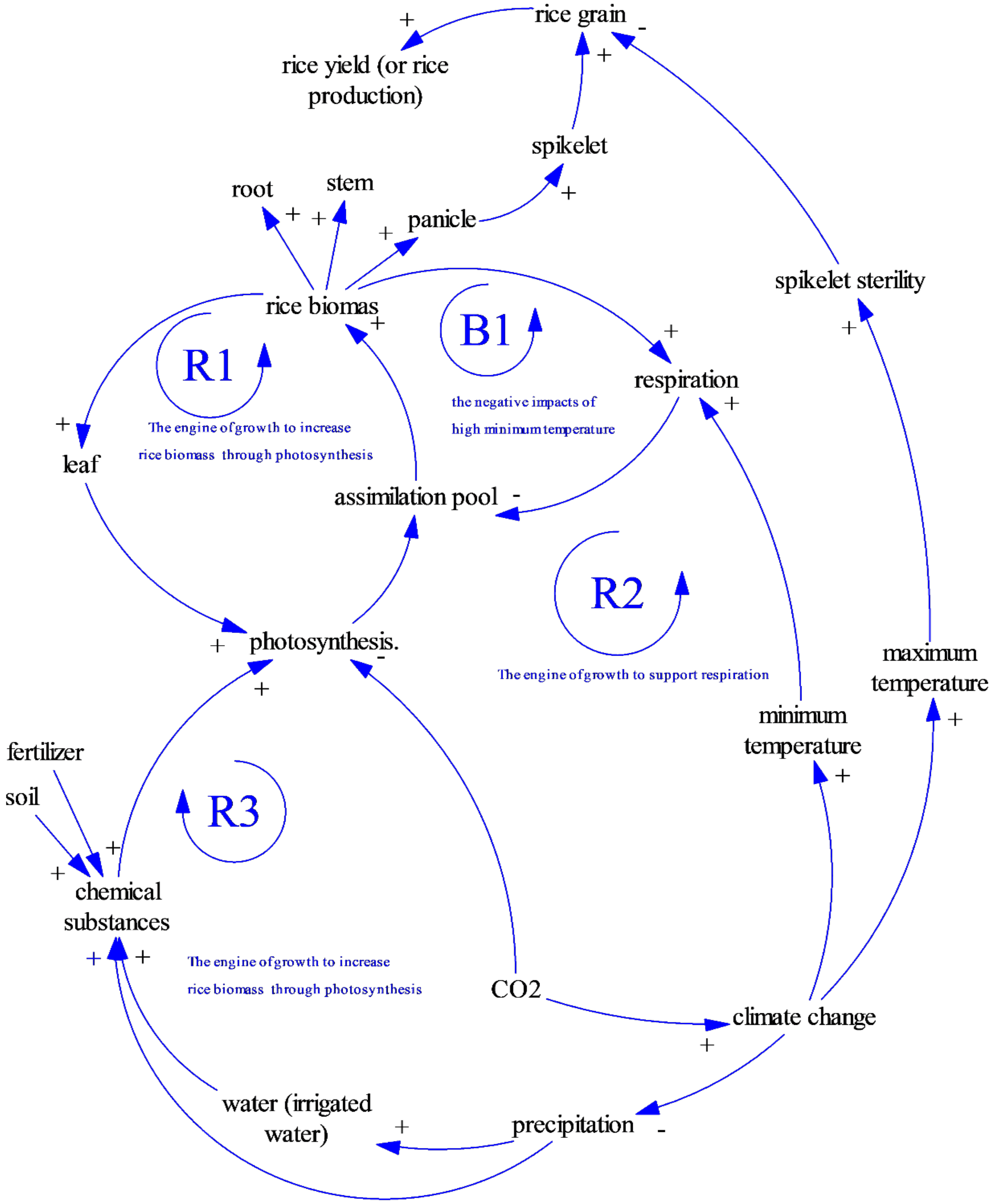

Fig. 3. Photosynthesis and respiration.

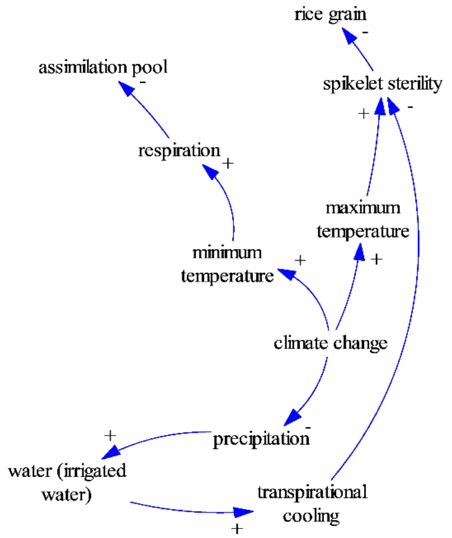

Fig. 4. Respiration and temperature relationships.

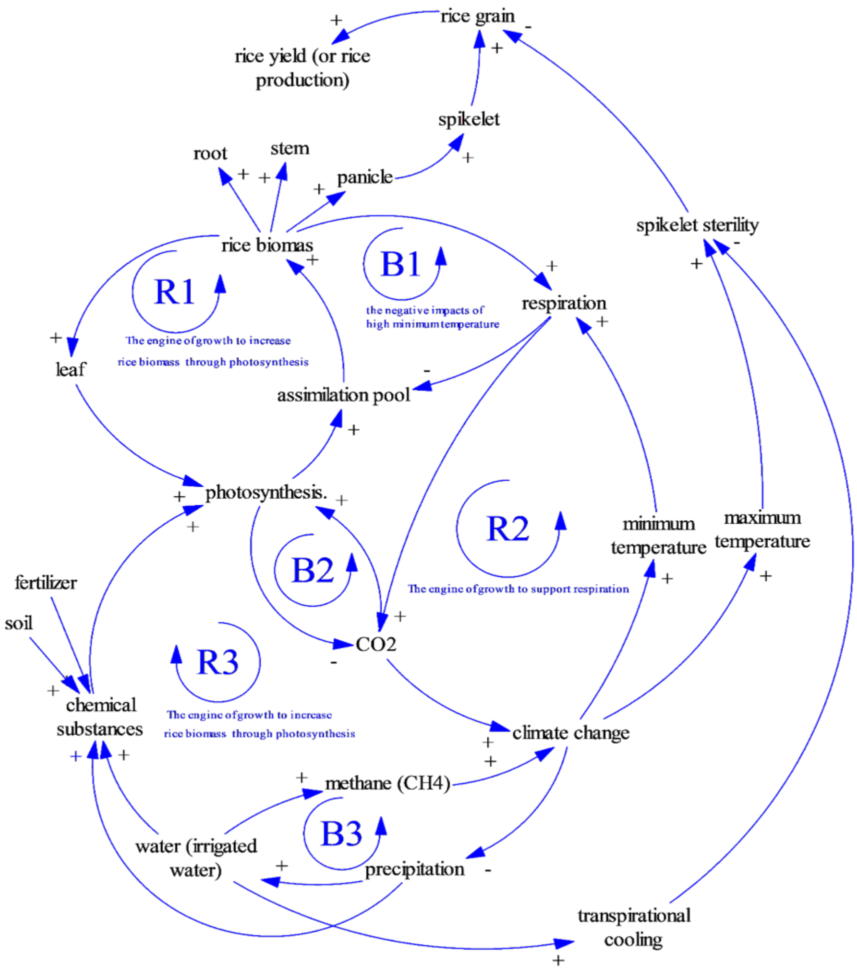

Fig. 5. A complete causal loop relationship between climate change and rice production.

The second reinforcing loop (**R2**) is the growth engine of respiration, as high minimum temperature associated with climate change tends to induce excessive respiration (respiration – CO_2 – climate change – minimum temperature – respiration). The other growth engine is the third reinforcing loop (**R3**), describing the continuous photosynthesis upon the interaction between water and chemical substances (photosynthesis – CO_2 – climate change – precipitation – irrigated water – chemical substances – photosynthesis).

The first balancing loop (**B1**) explains an important relationship between respiration and rice biomass (rice biomass – respiration– assimilation pool – rice biomass). This means that more respiration leads to less rice biomass or lower rice yield. Another balancing loop (**B2**) is a "clearing mechanism" where CO_2 supports photosynthesis and in turn, photosynthesis decreases CO_2 availability.

It should be noted that rice-farming areas are an important emitter of methane (CH_4), associated with climate change [7-8]. The last balancing loop (**B3**) shows that less precipitation leads to decreased methane. Sustainable rice practices such as manure application and intermittent irrigated water also lead to reduced methane emission [7-8]. For simplification, the latter is not shown in Figure 5.

3.2 System Archetypes

3.2.1 The limits to growth

Based on the CLD, two system archetypes are identified. The structure of the limits to growth is the first system archetype as seen in Fig. 6. As seen in Figs. 7-8, the second type of system archetype present is the success to successful.

The structure of the limits to growth enhances photosynthesis to produce an assimilation pool and rice biomass (R1), leading to higher rice yield. Unfortunately, the growth engine is negated by a balancing loop (B1). The balancing loop (B1) induces more respiration or decreases rice biomass, owing to the negative impacts of high minimum temperature. As a high minimum temperature is associated with climate change, changing climate tends to increase respiration, threatening rice yield.

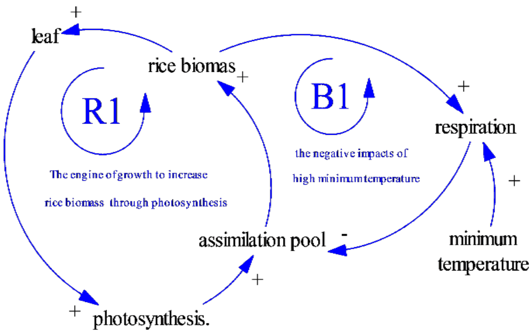

Fig. 6. The limits to growth #1

Several studies [15-16] suggest possible leverage points to cope with negative impacts detected in the limits to growth structure. Heat-tolerant rice varieties are one leverage point to minimize the negative impacts of climate change on rice production. As heat-tolerant rice varieties may negate excess respiration, heat-tolerant varieties are likely to reduce the negative impacts of high minimum temperature. Mitigation of climate change, leading to low minimum temperature, may be another leverage point.

3.2.2 The success to successful

The success to successful structure is the second archetype, seen in Figs. 7-8. In this structure, one more successful activity will consequently gain more support, so the other activity ends with less support [15-16].

Fig. 7 shows two growth engines. The first growth engine (R3), photosynthesis, increases rice biomass, leading to higher rice production. The second growth engine (R2), high minimum temperature, leads to more respiration.

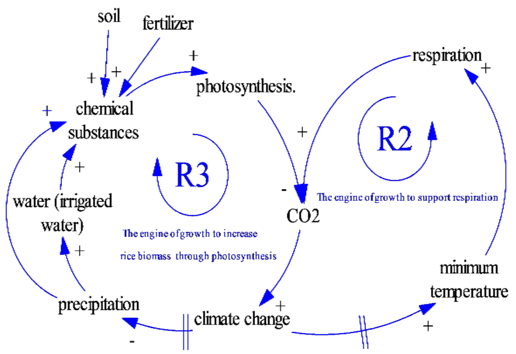

Fig. 7. Success to successful #1.

As the high minimum temperature is the cause of increased respiration, heat-tolerant rice varieties and the mitigation of climate change can be solutions. Cultivating heat-tolerant rice or mitigating climate change will negate the reinforcing loop (R2).

The other success to successful structure is illustrated in Figure 8. In this archetype structure, two reinforcing loops, R1 and R3, compete to support photosynthesis. This reinforcing loop (R1) elucidates that the conversion of rice biomass to leaf will increase photosynthesis. This archetype structure also describes that more irrigated water and chemical substances lead to more photosynthesis (R3). This archetype structure implies that decreased carbon dioxide and increased rice biomass are supported by photosynthesis. This means that more photosynthesis or more cultivated rice should be available to support rice biomass and to decrease carbon dioxide associated with climate change.

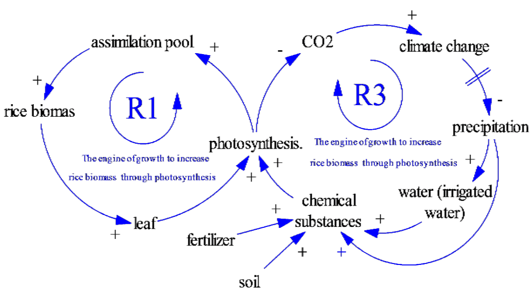

Fig. 8. Success to successful #2.

3.3 Comparing solutions

This study discusses the impacts of climate change on rice production and possible solutions qualitatively, rather than quantitatively. Hopefully, this qualitative study can broaden our perspectives in sustaining rice production under a changing climate. This study, as it is a qualitative study, can increase the whole of society's awareness of the impacts of climate change on rice supply, especially policymakers, despite possibly having educational backgrounds unrelated to this topic.

3.3.1 Irrigation negates the negative impacts of high temperature

Transpirational cooling due to increased irrigated water has been reported on [12, 29]. Those studies claimed that irrigated water can decrease the ambient temperature, so the negative impacts of high temperature can be reduced. Unfortunately, the role of irrigated water in minimizing the negative impacts of high minimum temperature is limited [29].

In reality, more irrigated water can increase rice production through lengthening growing seasons. In terms of climate change impacts, irrigation facilities should be seen as a short-term solution for coping with the negative impacts of climate change on rice yield.

3.3.2 Developing heat-tolerant rice varieties and the benefit of increased CO_2

Possible higher rice yield was reported by some studies [30-32] as higher CO_2 leads to an increase in spikelet numbers. It is thus important to realize the positive impacts of elevated CO_2 on rice yield. Moreover, another study [33] suggested developing heat-tolerant rice varieties before realizing the positive impacts of elevated CO_2 on rice yield. This suggestion is owed to an experiment [33] showing that the negative impacts of high temperature are likely to negate the positive impacts of elevated CO_2.

Developing heat-tolerant rice varieties is making promising progress, especially after some studies [34-36] confirmed the development of heat-tolerant genes.

4. Conclusion

Asian rice production, as a representation of global rice production, is threatened by climate change. The rising temperatures associated with climate change negatively affect rice production. At the same time, the benefit of elevated CO_2 is negated by the negative impacts of high minimum temperatures on respiration, ultimately leading to lower biomass and rice production.

The application of system archetypes as seen in this study can be used to understand the impacts of climate change on rice production and identify possible solutions. With the causal loop diagram, depicting interactions between climate and non-climate factors, archetype structures can be identified and explained. These archetype structures explain the dynamic interactions between the regulation of photosynthesis and the respiration process during rice growth. The negative impacts of climate change and the role of growth engines are described to capture the system archetype structures.

Through system archetype analysis, promising solutions under a changing climate are explained. While irrigation facilities offer a short-term solution, heat-tolerant rice varieties can be seen as a sustainable, long-term solution to balance the supply and demand of rice, as well as to increase rice production under a changing climate.

A quantitative model based on the causal loop diagram can be developed further to simulate the impacts of climate change on rice production as seen in another study [37]. The quantitative model may capture the dynamics of rice growth as well as the negative impacts of climate change on rice production. Moreover, possible solutions can be derived from the system archetype structures explained in this study.

Another possible benefit taken from this study is that the information herein can serve as a basis to qualitatively explain the negative impacts of climate change on other major crops, such as wheat and corn. In the future, possible quantitative models can be developed for other major crops.

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