Coupled Water-Rice Systems under Multiple Driving Forces: Soft Limits of Adaptations to Climate Change in Japan

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Abstract

The impacts of climate change and increased water use for irrigation make it difficult to manage sustainable water use and food production. Sufficient research has not been conducted on how humans adapt to water risks due to climate change. One of the difficulties in considering adaptation measures is that adaptation actions in one sector conflict with the interests of other stakeholders in the basin and trade-off relationships emerge among various sectors. Here, we examined how an effective adaptation in one sector (agriculture) influences the other (water resources) by calculating the "benefits of agricultural production" and "drought risk" under current and future climate scenarios. We built a framework consisting of two process-based models of hydrology and crop science and evaluated shifting of the transplantation date as a promising measure to avoid the degradation of rice quality in Japan. Shifting the transplantation date had opposing effects on the total yield and quality of rice, with an earlier date increasing the total yield and a later date increasing the quality. Furthermore, an earlier transplantation date reduced the drought risk. Thus, in terms of the preferred adaptation options, total yield and drought were synergistic, whereas rice quality and drought were trade-offs. Our results imply that the current transplantation date has resulted from the farmers' motivation to maximize total yield, but this motivation may change to other factors, possibly rice quality, due to climate change. Overall, this study contributes to the understanding of how interconnected systems evolve when climate or socio-economic conditions change.

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Key Points:

- We propose water–rice coupled systems that enable evaluating the side effects of an adaptation measure on other factors.
- We advance the understanding of principles that determine human behavior and indicate possible changes in behavior due to climate change.
- We showed an example of "soft adaptation limits" that can arise between farmers and water managers in Japan.

Abstract

The impacts of climate change and increased water use for irrigation make it difficult to manage sustainable water use and food production. Sufficient research has not been conducted on how humans adapt to water risks due to climate change. One of the difficulties in considering adaptation measures is that adaptation actions in one sector conflict with the interests of other stakeholders in the basin and trade-off relationships emerge among various sectors. Here, we examined how an effective adaptation in one sector (agriculture) influences the other (water resources) by calculating the "benefits of agricultural production" and "drought risk" under current and future climate scenarios. We built a framework consisting of two process-based models of hydrology and crop science and evaluated shifting of the transplantation date as a promising measure to avoid the degradation of rice quality in Japan. Shifting the transplantation date had opposing effects on the total yield and quality of rice, with an earlier date increasing the total yield and a later date increasing the quality. Furthermore, an earlier transplantation date reduced the drought risk. Thus, in terms of the preferred adaptation options, total yield and drought were synergistic, whereas rice quality and drought were trade-offs. Our results imply that the current transplantation date has resulted from the farmers' motivation to maximize total yield, but this motivation may change to other factors, possibly rice quality, due to climate change. Overall, this study contributes to the understanding of how interconnected systems evolve when climate or socio-economic conditions change.

1 Introduction

Irrigation water, which accounts for approximately 70% of the world's water use, is important to meet the demand for food production as the population continues to grow (Gerland et al., 2014). Agriculture is one of the industries most vulnerable to climate change, with climate change resulting in 24–43% losses in food production compared to that under pre-warming conditions (Elliott et al., 2014, Iizumi et al., 2018). Model assessments have suggested that the decrease in water resources available for irrigation (Elliott et al., 2014) due to climate change is accelerated by the increased water use for irrigation (Haddeland et al., 2014). These factors make it even more difficult to sustainably manage water use and food production.

Research on the mechanisms and uncertainties of global climate change has progressed, and the impact on regional water risks (damage risks from floods and droughts) has come to be understood in more detail. However, sufficient research has not progressed on how humans adapt to water risks due to climate change. One of the difficulties in considering adaptation measures is that adaptation actions in one sector conflict with the interests of other stakeholders in the basin and trade-off relationships emerge among various sectors. The sixth report (AR6) of the International Panel on Climate Change (IPCC) by Working Group II (WG2) summarized the cases of adaptive actions to climate change and emphasized the importance of methods to evaluate the limits and feasibility of adaptive actions involving multiple stakeholders (IPCC, 2022).

Van Loon (2016) argued that the analysis of water risks in the Anthropocene epoch should consider human activities as dynamic rather than static and include their impacts on the natural water cycle. The shared socioeconomic pathway (SSP), which is commonly used to assess the impacts of climate change on human societies, only represents the potential pathways of socioeconomic development (e.g., population and GDP) and does not include feedback on human activities and water resources. The development of the interdisciplinary research field of socio-hydrology has attempted to understand the relationship between human society and water resources. The central idea of socio-hydrology is that the current status of human water use has 'coevolved' through the interaction between human society and water resources (Sivapalan et al., 2012). This approach allows us to thoroughly understand how interconnected systems evolve when the boundary conditions (i.e., climate or socio-economic conditions) change. To explore the evolutionary pathways of the interconnected systems, many studies have attempted to mimic human behavior within the human–nature coupling system. Cai et al. (2002) compiled the first version of the human–water coupled model that combined short-term (annual) decisions and long-term (inter-year) decisions to help find sustainable development pathways in irrigation-dominated watersheds. They proposed the function to assess the sustainability of a watershed, based on long-term environmental risks, equality within watersheds, and equality between generations and solve it mathematically. Giuliani et al. (2016) also simulated the interactions between irrigated agriculture and lake operation in the Adda River watershed in Italy, mainly focusing on how humans could make better decisions with the given annual variabilities in meteorological and hydrological conditions of the watersheds. The human behaviors were modeled with complete rationality by assuming the irrational behaviors of the individual farmers could be filtered when decisions were made at district levels (i.e., group of farmers), which they termed the normative meta-modeling approach. They assumed that farmers decide cropping patterns to maximize their expected net profit in each agricultural season, while lakes are maintained to balance water supply and flood protection on a daily basis, and showed the interdependency between the behaviors of the lake operator and farmers. The approach allowed the seasonal negotiation of water allocation plans, and the simultaneous adaptation of water supply operations successfully enlarged the potential benefits of coadaptation.

However, water resources and agricultural planning are generally based on the experiences of the climate during the last decades, thus the adaptation could not be happening at once; instead, it would be the combination of the inertia of the system and human decisions that drive the changes. With confronting the challenges of climate change, we need to simulate the interactive consequences between the short-term adaptation strategy and the long-term environmental risks. This is especially the case when climate change has already negatively impacted on human–water coupled systems. Li & Sivapalan (2020) found the possible long-term (85 years) coevolution of urban human–water systems under climate change by using a holistic urban sociohydrologic model that was proposed by Li et al. (2019) and analyzed the sensitivity of the social and physical aspects of the coevolutionary dynamics to system properties that could be changed by human adaptive actions. Their findings enhanced our understanding of the future coevolution of urban human–water systems and their sensitivity to human adaptive actions. The approach looking at the decision-making processes infers behavioral rules and parameters from observational data or general theories; however, the need for long-term observational data to infer behavioral rules makes the construction of descriptive tools difficult. Also, given the complexity and uncertainty associated with predicting human activities, their study is "not aimed at predicting an accurate future of the water situation. Instead, the model outcomes are deemed as just possibilities" (Li & Sivapalan, 2020).

This study aimed to make manageable and tractable forecasts by focusing on a single aspect of the human–nature coupling systems: agricultural society and water risks in Japan. We predicted how cropping schedule decisions, as adaptive measures in an irrigated district, will affect regional water resources. Japan is located in a humid region with an annual mean precipitation of 1,700 mm. However, because of the rapid expansion of irrigated rice paddies in the 17th and 18th centuries, river flow during drought periods was exhausted at the beginning of the 20th century (Satoh and Ishii, 2021). Irrigation requires a large amount of water during the most productive periods of the year, namely during the puddling (May) and heading (August) periods. Therefore, irrigation and water resources are mutually restricted, and the rules for water use have coevolved over the years. Rapid socio-economic development during the 20th century further deteriorated the water resources, even with the construction of water use facilities in the modern period. Climate change affects these tightly coupled water–rice systems in two ways. First, the heavy snowfall areas in the temperate zone of Japan were projected to be markedly vulnerable to temperature changes, showing a large reduction in snow and earlier snowmelt due to climate change (Kudo et al., 2017a, 2017b). Second, the appearance quality of rice is predicted to deteriorate with the occurrence of white immature grains owing to high temperatures during the heading period (Takimoto et al., 2019). Both farmers and governments are particularly concerned about the occurrence of white immature grains, and adaptation measures to reduce the occurrence of such grains have attracted considerable attention. Various adaptation measures to reduce the negative impacts on rice quality have been proposed, ranging from incremental to transformative (Iizumi, 2019). Shifting the transplantation date is relatively inexpensive and easier to implement than other adaptation measures. Thus, it has been widely implemented in Japan (MAFF, 2006).

To investigate the side effects of an adaptation measure for rice quality on water resources, we built a framework consisting of two process-based models of hydrology and crop science. We selected shifting the transplantation date (i.e., the starting date of irrigation) as a promising measure to avoid the degradation of rice quality. The same transplantation date was then applied to both models, while the other boundary conditions were not changed. We examined how an effective measure in one sector (agriculture) influences the other (water resources) by comparing the agricultural benefit and drought risk under current and future climate scenarios. We addressed the following questions: What will happen to the water–rice coupled systems due to climate change and the associated adaptive actions? How and why did the principles that determine farmers' behavior change?

2 Materials and Methods

2.1 Framework for assessing the impact of adaptation measures on two stakeholders

The impact of the adaptation measure was evaluated based on the outcome of an adaptation action on two stakeholders (X and Y). If the outcomes of an adaptation option on the two elements were beneficial to both, then the adaptation measure creates a "synergistic" relationship between the two (Figure 1(a)). However, if the benefits of one obtained through an adaptation option resulted in the detriment of another, then the adaptation measure creates a "trade-off" relationship (Figure 1(b)). The evaluation method included the following steps: (1) two process-based models that can evaluate the benefits (e.g., yield, quality, and economic income) and risks (e.g., 10-year probability of drought and number of days of water withdrawal restriction) obtained through adaptation options were prepared; (2) the benefits and risks were calculated under several adaptation options and climate scenarios; and (3) the calculation results were plotted as shown in Figure 1. If the plots were distributed upward and to the right (Figure 1(b)), it was determined that the benefits and risks were in a trade-off relationship. The two stakeholders would have a synergistic relationship if the plots were distributed downward and to the right (Figure 1(a)).

Using this model, we set "benefits of agricultural production" on the X-axis and "drought risk" on the Y-axis, and investigated the relationship between agriculture and water resources within the watershed if the adaptation measure of shifting the transplantation date was implemented. We selected shifting the transplantation date because it is relatively inexpensive and quicker to implement than other adaptation measures. Here, the "benefits of agricultural production" and "drought risk" resulting from shifting the current transplantation date every week up to five weeks before and after, as adaptation options, were calculated.

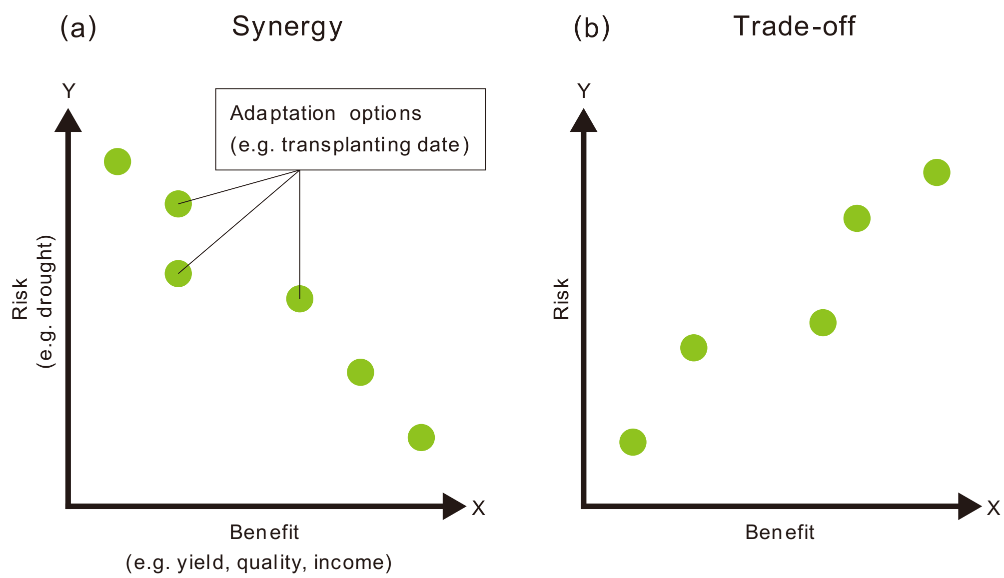

Figure 1. Relationships between two stakeholders (X and Y) to the adaptation options: (a) if the outcomes of an adaptation option on the two elements were beneficial to both, then the adaptation measure creates a "synergistic" relationship, (b) if the benefits of one obtained through an adaptation option resulted in the detriment of another, then the adaptation measure creates a "trade-off" relationship.

2.2 Process-based models to evaluate "drought risk" and "benefits of agricultural production"

To assess "drought risk" within a watershed, a distributed water circulation model (Yoshida et al., 2016) was prepared. This model is capable of integrally analyzing the natural water cycle (e.g., evapotranspiration, snowmelt, and river discharge) and the water used in agriculture (e.g., water withdrawal and water allocation)—the largest water user in Japan—at the watershed scale. It can accurately represent river flows during droughts in highly disturbed watersheds owing to agricultural water withdrawal and return flow, which are characteristic of

Japanese rivers. It calculates the amount of water resource at each grid cell that divides a watershed through daily input of meteorological data, such as precipitation, temperature, wind speed, and short- and long-wave radiation. The water withdrawal period for each facility in the water circulation model was externally input as the current period; thus, changes in rice growth due to climate change (e.g., shortening of the growing period) were not considered.

We investigated the impact of irrigation water withdrawal on society as a whole, including the environment and other water uses. This is represented as "hydrological drought", which was described by Mishra and Singh (2010) as follows: "Hydrological drought is related to a period with inadequate surface and subsurface water resources for established water uses of a given water resources management system." A given water management system in Japan is based on the streamflow and minimum required flow defined at a water use reference point. To evaluate the "drought risk" resulting from shifting the transplantation date, the cumulative amount of water that fell below the minimum required flow (hereafter, drought volume) during the irrigation period defined at a water use reference point was calculated for each transplantation date in each year.

To assess the "benefits of agricultural production" resulting from the shifting of the transplantation date, we used a process-based rice growth model (Hasegawa and Horie, 1997; Ishigooka et al., 2017). The model was described in full by Hasegawa and Horie (1997) and Ishigooka et al. (2017). This model has three major components: phenological development, biomass production, and yield formation. The model quantified the developmental stages (emergence, panicle initiation, heading, and maturity) from the daily mean air temperature (average of daily maximum and minimum) and day length (Ishigooka et al., 2017). It estimated the daily increases in biomass and leaf area based on biophysical processes, and the daily biomass production was calculated as the difference between the products assimilated by photosynthesis and consumed by respiration, accounting for the effect of increasing atmospheric CO_2 concentration on the enhancement of photosynthesis (Ishigooka et al., 2017). Through this process, total biomass was calculated as the accumulation of daily biomass increases (dry matter). The brown rice yield (hereafter called "total yield") was calculated by multiplying the biomass (dry weight production of the aboveground portion) and the harvest index that takes into account three factors of yield reduction: spikelet sterility caused by low or high temperatures and insufficient grain filling due to delayed maturity (Ishigooka et al., 2017). Note that the rice growth model does not consider the effects of water resources such as precipitation and evapotranspiration on rice growth and assumes that the amount of water resources necessary for rice production is sufficient.

We used two indices to evaluate the "benefit of rice production": total yield and yield with the highest appearance quality. The second index corresponds to rice quality. The total yield was calculated using a rice growth model. The yield with the highest appearance quality was estimated based on the heat stress index for rice quality, as defined by Ishigooka et al. (2011). The heat stress index (hereafter, "HD_m26") is related to the emergence of chalky grains due to high temperatures, that is, deterioration of rice appearance quality, calculated as the cumulative value of positive differences in daily average air temperature above 26 °C within 20 days after the heading date. Ishigooka et al. (2011) classified the yield into three classes based on the degree of quality degradation risk due to high temperature during the early grain-filling period: Class A (low risk), HD_m26 < 20°C·days; Class B (moderate risk), 20°C·days ≤ HD_m26 <

40°C·days; or Class C (high risk), HD_m26 ≥ 40°C·days. Among the three classes, we used "Class A yield" as an indicator of rice appearance quality in the evaluation.

2.3 Climate change scenarios

To apply the framework proposed in Section 2.1 under different climate change scenarios, we used the Historical (1981–2000) and RCP 2.6 and 8.5 (2011–2030, 2031–2050, 2051–2070, and 2071–2090) climate scenarios from three general circulation models (GCMs), namely MIROC5, MRI-CGCM3, and HadGEM2-ES. These datasets were obtained from Ishizaki (2020). To describe regional climate conditions, GCMs outputs with spatial resolutions of approximately 100–200 km are insufficient, thus we spatially interpolated the outputs to 1-km grids by means of simple linear interpolation using the inverse distance weighted method. Then, the CDF mapping method (Ines and Hansen, 2006; Li et al., 2010) was used to bridge statistical gaps in climate variables between observations and GCMs simulations. The observations (1981–2005) were interpolated to a 1-km grid using daily meteorological data recorded at the Japan Meteorological Agency observation stations by means of the inverse distance weighted method. For the evaluation of "drought risk," the drought volume was calculated for each year; thus, the number of data used for evaluation per period was 60 (3 GCMs × 20 years). For the evaluation of "benefits of rice production," the 20-year average of total and Class A yields was calculated for each period (1981–2000, 2011–2030, 2031–2050, 2051–2070, and 2071–2090); thus, the number of data used for evaluation per period was three (three GCMs).

2.4 Study area

The Shinano River is one of the largest rivers in Japan, with a main channel length of 367 km. It has a catchment area of 11,900 km^2, making it the third-largest catchment area in Japan (Figure 2). It runs through both the Niigata and Nagano prefectures and flows into the Sea of Japan. The spatial distribution of precipitation in the basin is complex. The upper area of the Shinano River watershed, located in the middle of mainland Japan, is surrounded by mountains that are more than 2,000 m high and have remarkable inland weather. This area has low precipitation, with an annual precipitation of only 938 mm in Nagano City. Conversely, the lower watershed on the Niigata Prefecture side, where the weather is specific to areas along the Sea of Japan, is known as one of the heaviest snowfall areas in Japan, including Nagaoka City, which has an annual precipitation of 2,310 mm and a great deal of precipitation during winter. The basin of the Uono River, which joins the Shinano River in its middle reaches, is also known for heavy snowfall, with snow accumulating over 2 m in thickness. The flow volume from March to May accounts for 30–50% of the annual outflows. This snowmelt period coincides with the puddling period when irrigation water is most required downstream.

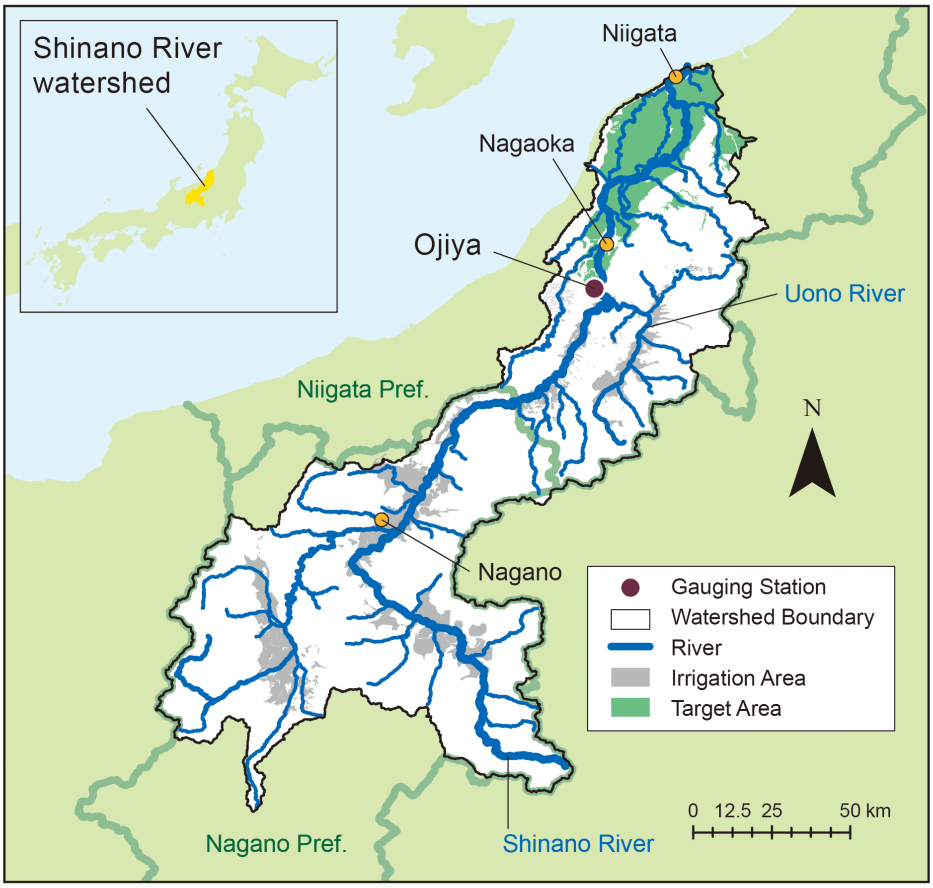

Figure 2. Map of the Shinano River watershed and target irrigation area.

The daily mean temperature and total precipitation for each year in the Shinano River watershed during the summer (June–August) are shown in Figure 3. In the future period (2011–2090), the daily mean temperature gradually increased under both RCP 2.6 and 8.5 scenarios, with a particularly high rate of increase under the RCP 8.5 scenario. The total precipitation showed large inter-annual variations for both scenarios, and no clear changing trend was observed for future periods.

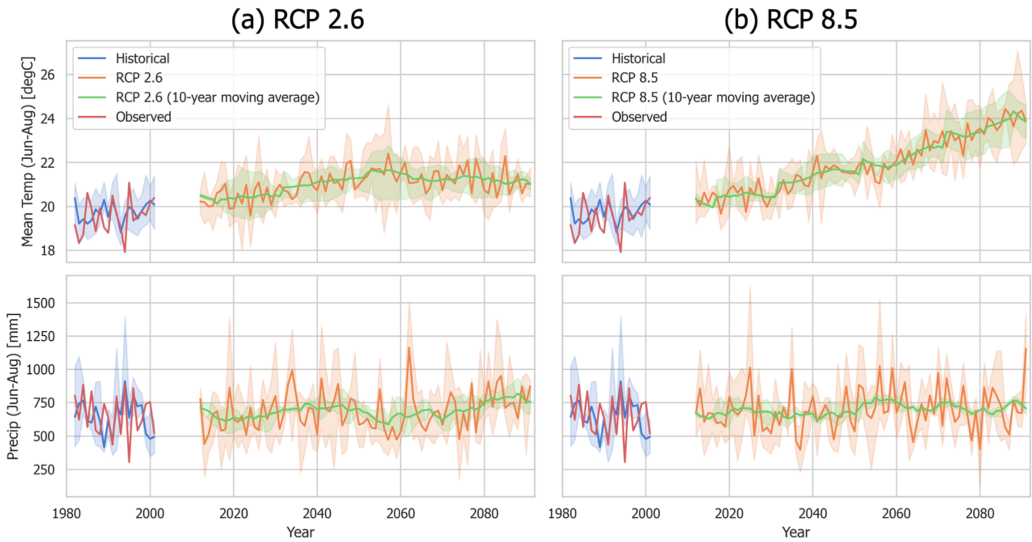

Figure 3. Changes in mean temperature and precipitation during summer (June–August) under two climate change scenarios: (a) RCP 2.6 and (b) RCP 8.5 in 2011–2090. Arithmetic mean and 10-year moving average of the three GCMs for each scenario are shown by solid lines, while the 95% confidence intervals for each element are indicated as filled areas.

We targeted the Ojiya gauging station and its downstream irrigated area. The lower areas of Ojiya are among the largest rice-producing regions in Japan, including approximately 14,700 ha developed through national land improvement projects. We treated the target area as a single irrigation district because there were no major differences in weather conditions and rice production conditions downstream from Ojiya, as shown by the difference of 0.3°C in monthly mean temperature during the heading period (August) between Nagaoka City and Niigata City from 1991 to 2020 and a maximum difference of 5 transplantation days in 2019. The Ojiya gauging station is a reference point for water use in the middle and lower areas of the Shinano River watershed. The minimum required flow of 145 m^3/s was allocated during the irrigation period (from April 28 to September 15) at the Ojiya station. Because the minimum required flow includes not only irrigation water but also environmental water requirement, a hydrological drought can be defined as a situation in which the flow rate falls below the minimum required flow. According to a dataset of annual statistical data on rice yield and cultivation schedule (dates of sowing, transplanting, heading, and harvesting) provided by Niigata Prefecture, May 9 was the peak transplantation date in the target area in 2019. Thus, we defined this date as the "current" transplantation date.

Since this study focused on changes in the transplantation date, the peak transplantation dates in Niigata Prefecture from 1953 to 2021 and the middle of the prefecture (called "*Chuetsu*") from 1969 to 2021 are shown in Figure 4. The data were obtained from a dataset of the Ministry of Agriculture, Forestry and Fisheries (MAFF) that provides yearly statistics of rice yield and cultivation schedule. These data were summarized at the prefectural level until 1968 and by sub-administrative regions called "sub-regions for yield statistics" (*sakugara hyouji chitai* in Japanese) after 1969. The transplantation date, which was on June 5 in 1953, gradually moved to May 4 in 1998. This may be due to the spread of transplanting using machinery, changes in rice varieties, and the higher price that early rice can be sold at. However, the transplantation date tended to be delayed by one week in the 2000s (the latest date was May 13 in 2012). In Japan, concerns about high-temperature injury to paddy rice began to grow in the 2000s, and studies were conducted to develop countermeasures (MAFF, 2006). Recently, countermeasures to delay the transplantation date were implemented in the Niigata Prefecture to avoid the risk of the heading period coinciding with abnormally high temperatures immediately after the end of the rainy season (MAFF, 2006), which may have resulted in the data.

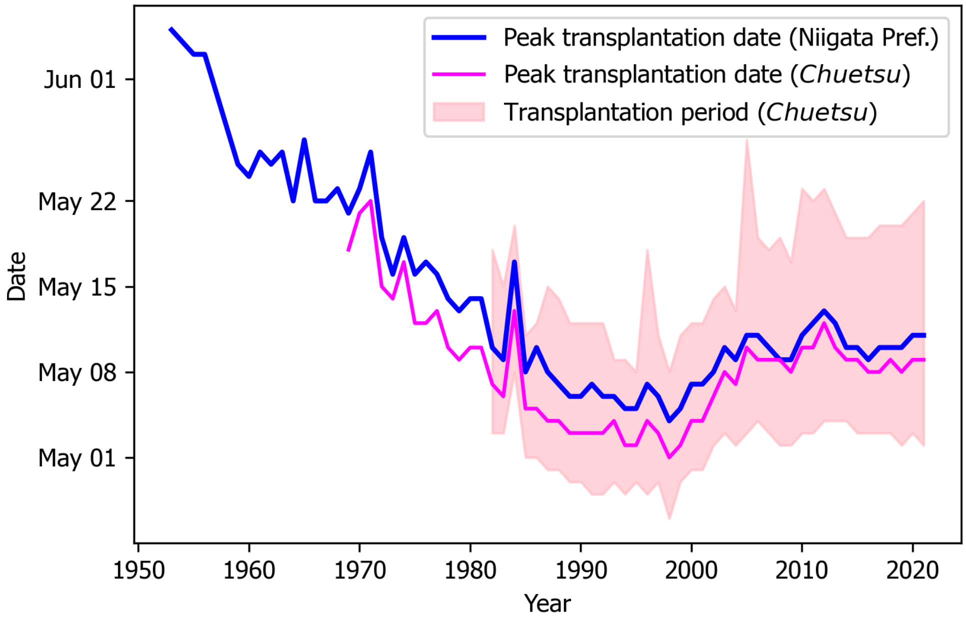

Figure 4. Changes in the transplantation date (solid lines) in Niigata Prefecture from 1953 to 2021 and the middle of Niigata Prefecture (called by "*Chuetsu*") from 1969 to 2021. Transplanting period (filled area) from 1982 to 2021 was calculated as the difference between the start and end dates of rice transplantation in *Chuetsu*.

3 Results and Discussion

3.1 Effects of farmers' and water managers' motivation on the transplantation date

To assess the changes in drought volume and yield with weeks of shifting the transplantation date, the results calculated by the two process models in the Historical (1981–2000) and RCP 2.6 (2011–2030) scenarios are shown in Figure 5. The upper panel shows the mean (solid lines) and 95% confidence interval (filled area) of cumulative drought volume for the drought years from the 60 years of data. The drought volume in the Historical scenario was

4.52 million m^3 at the current transplantation date (Figure 5). The drought volume decreased as transplantation was shifted to an earlier date, and drought did not occur when transplantation was performed more than four weeks earlier. The drought volume gradually increased when transplantation was shifted to a later date, and it was 20.9 million m^3 when transplantation was delayed by five weeks.

The lower panel in Figure 5 shows the mean and 95% confidence intervals of the total and Class A yields for the three GCMs. Focusing on the total yields with each transplantation date, the mean of total yields was 606.2 kg/10a at the current transplantation date, which increased when the transplantation date was shifted earlier and decreased when the transplantation date was shifted later, as confirmed by Ishigooka et al. (2017). The highest total yield was 622.2 kg/10a when the transplantation date was shifted four weeks earlier while it decreased to 506.4 kg/10a when transplantation was delayed by five weeks. The Class A yields with each transplantation date decreased when transplantation was shifted to an earlier date and increased when transplantation was shifted to a later date, compared to 427.9 kg/10a at the current transplantation date. The lowest Class A yield was 418.6 kg/10a when transplantation was performed five weeks earlier, and the highest yield was 475.5 kg/10a when transplantation was delayed by five weeks. The adaptation measure of shifting the transplantation date showed opposing effects on total yield and quality, with earlier dates increasing total yields and later dates increasing Class A yields.

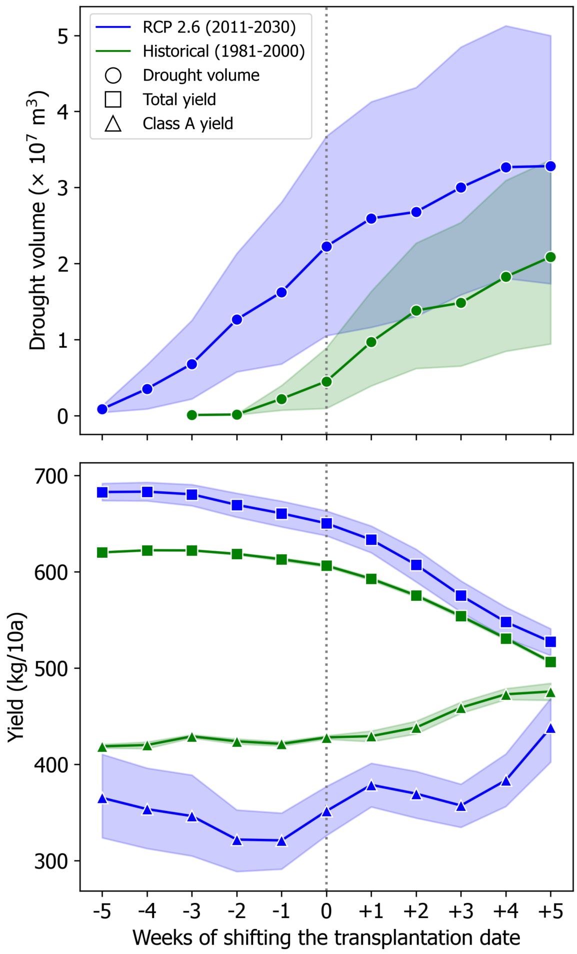

Figure 5. Arithmetic mean (points, solid lines) and 95% confidence interval (filled area) of drought volume, total yield, and Class A yields with each transplantation date in the Historical (1981–2000) and RCP 2.6 (2011–2030) scenarios.

The relationship between drought (risk) and yield (benefit) in the Historical scenario (1981–2000), for each transplantation date, is shown in Figure 6. The relationship between drought volume and total yield (Figure 6(a)) showed a synergistic effect as the drought volume decreased and the total yield increased when transplantation was shifted to an earlier date. The current transplantation date was plotted in the lower right corner of the graph, where the drought volume was low and the total yield was high. The relationship between drought volume and Class A yield (Figure 6(b)) showed a trade-off effect, as both the drought volume and Class A yield increased when transplantation was shifted to a later date. The current transplantation date was not plotted at the location of maximum quality, although the drought volume was low.

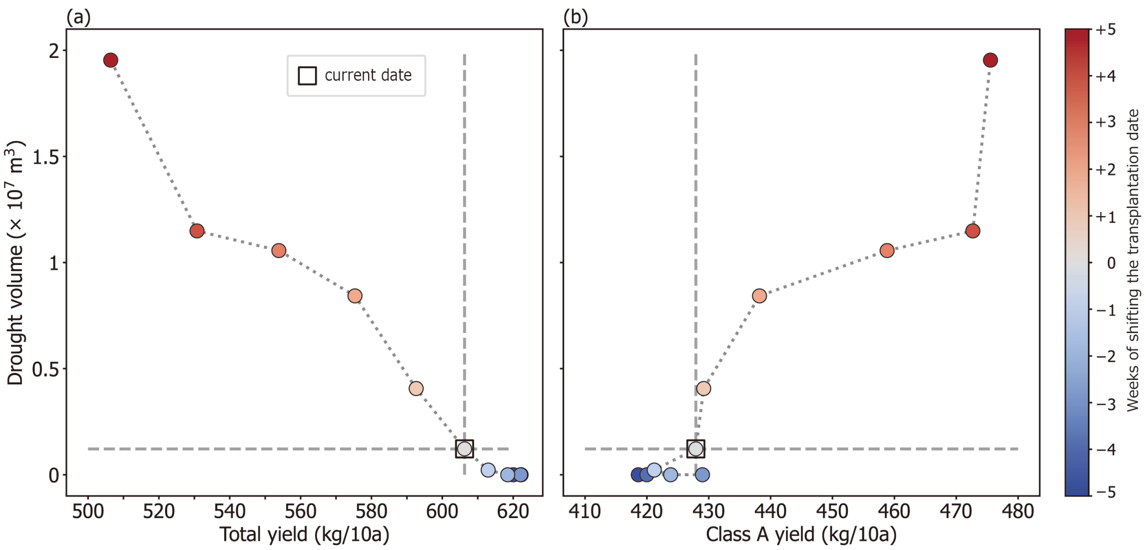

Figure 6. Relationship between (a) drought volume and total yield, (b) drought volume and Class A yield, when the current transplantation date (square point) was shifted in the Historical scenario (1981–2000). The dotted lines indicate total and Class A yields and drought volume on the current transplantation date.

This result indicates that total yield was more important than quality in setting the current transplantation date, and a driving force has been working to ensure a high total yield. The peak transplantation period in the 1950s was about four weeks later than that of the present times (Figure 4); thus, the transplantation date in the 1950s corresponds to the +4 weeks plot in Figure 6. The current transplantation date has settled into a date that facilitates a higher total yield and lower drought, although the rice quality is lower. Possible reasons for the earlier transplantation dates include a more flexible timing for water use due to improved overall agricultural technology and a longer growing period to ensure a higher total yield. We inferred that the transplantation date could have been shifted smoothly as long as the emphasis was on the total yield because the transplantation date can be selected to increase the total yield without increasing the drought risk. Our results imply that the current transplantation date has resulted from the coevolution of farmers' behavior to maximize benefits (total yield) and water managers' behavior to reduce drought.

3.2 Changes in driving force of farmers' decision-making

Coupling models representing multiple driving forces, especially humans and nature, have recently been proposed in the field of socio-hydrology to enable more accurate hydrological prediction under the joint natural and socio-economic driving forces (e.g., Sivapalan et al., 2012). Two main approaches are proposed for modeling human behavior within the human–nature coupling model (Smith, 1991; Giuliani et al., 2016). One is the normative approach, which focuses on motivational behavior based on economics (Becker, 1978) and assumes that human decisions are designed to maximize a given utility function, that is, to act with perfectly rational behavior (Giuliani et al., 2016). Although this assumption has often been contradicted by observations of real behaviors, this approach was largely adopted in the field of environmental modeling. The other is a descriptive approach that represents the decision-making processes based on cognitive psychology and social sciences (Kahneman and Tversky, 1979; Camerer et al., 2011) and infers behavioral rules from observational data or general theories (Giuliani et al., 2016). The normative approach is critical important when decision-making processes involve other factors than those that cannot easily be interpreted as economic values (e.g., environmental risks). Although many studies tried finding evidence of the changes in behavioral rules from the record of socioeconomic factors, identifying reliable parameters for capturing human decision-making is a daunting task because of the complexity and uncertainty of the hidden mechanism and the lack of long-term data on socioeconomic factors.

Here, we focused on how the farmers' decisions were made on the transplantation date in the Shinano River watershed. The data presented in Figure 4 depict long-term (69 years) human behaviors that can be divided into two phases. In the first phase (1953–1998), the transplantation date gradually became earlier by approximately five weeks, resulting in higher total yield and less drought risk (Figure 6). In the second phase (after 1999), the transplantation date was delayed by one weeks, resulting in the improvement of rice quality while the drought risk could have been increased. One possible factor for this shift is the implementation of the adaptation measure for high-temperature injuries. In other words, the driving force of farmers' decision-making has changed to another factor, possibly rice quality. Thus, the transplantation date may be further delayed if high-temperature injuries become more apparent.

The normative approach can represent the change in the first phase but not in the second because the delay in the transplantation date was not induced by economic incentives. The shift in transplantation dates since the 2000s implies that the motivation of farmers changed from economic benefits to rice quality. The price of rice ("*Koshihikari*", the most common variety in Niigata Prefecture) was 12,300 yen/60 kg for the first-grade and 11,700 yen/60 kg for the second-grade rice in 2021. The small difference in price between first and second grades indicates that a higher total yield leads to higher income, regardless of the grade. In other words, the current pricing of rice grades supports the motivation for changes in transplantation date during the first phase: the higher yield, the higher income, and vice versa.

It is also intriguing to note that the transplantation period (filled areas in Figure 4) has become longer since 2005: 12.5 days for the period of 1982–2004 and 17.5 days for 2005–2021. The spread of the transplantation periods after 2005 may reflect the farmers' decisions to avoid the risks in two directions: quality degradation due to high-temperature injury and loss of yield due to shorter growing periods. We admit that the selection of the transplantation date could be more variable and flexible in the future; however, we continue assuming a single transplantation date in the following section for simplicity.

We argue that the data we presented could contribute to helping to find the hidden changes in the behavioral rules of farmers and thus transform the normative approach into a descriptive tool. A rigorous investigation is required for the reason for these changes in the transplantation date. However, the overall data of this study serves as a material for building descriptive models of Japanese rice farmers.

3.3 Coupled assessment of multiple driving forces under climate change

Between the two drivers presented in Section 3.1 and 3.2, we first assumed that total yield is likely to be the primary driving force in future periods. The relationship between drought volume and total yield for each transplantation date is shown in Figure 7. In addition to the results of the RCP 2.6 and 8.5 scenarios (2011–2050), the results in the Historical (1981–2000) scenario are also shown for comparison. Focusing on the drought volume in the current transplantation date, RCP 2.6 scenario showed a stronger drought trend than the Historical and RCP 8.5 scenarios (Figure 7(a)), while the drought trend in the RCP 8.5 scenario did not differ significantly from that in the Historical scenario (Figure 7(b)). The total yield at the current transplantation date in all future scenarios was higher than that in the Historical scenario. The plots were in the right downward direction, indicating that drought volume and total yield have a synergistic relationship when shifting the transplantation date in future periods. The drought volume can be kept lower if an earlier transplantation date is selected to increase the total yield in future periods.

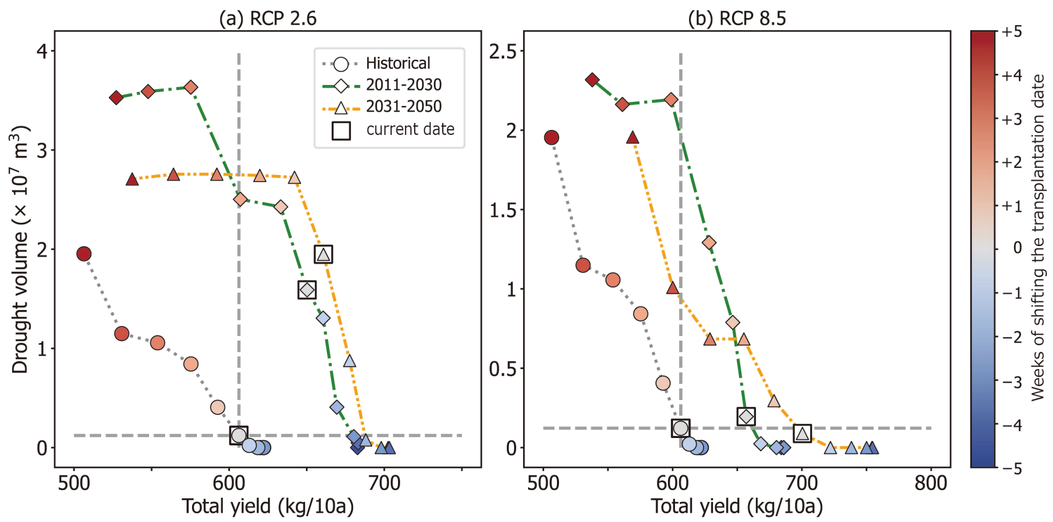

Figure 7. Relationship between drought volume and total yield, when the current transplantation date (square point) was shifted in (a) RCP 2.6 and (b) RCP 8.5 scenarios (2011–2030 and 2031–2050). The dotted lines indicate drought volume and total yield on the current transplantation date in the Historical scenario (1981–2000).

On the other hand, we explored another possibility, that is, rice quality would be the primary driving force in future periods. As shown in Figure 8, Class A yields decreased in the future under both scenarios. In 2011–2030, under the RCP 2.6 scenario, a five-week delay in the transplantation date resulted in a Class A yield equal to or greater than that under the current situation (at the current transplantation date in the Historical scenario); however, the drought volume was 28.9 times higher than that under the current situation. Furthermore, it would be difficult to achieve the same level of Class A yields as the current situation, even with a five-week delay in transplanting in 2031–2050 under the RCP 2.6 scenario. Similarly, in the RCP 8.5

scenario, a five-week delay in the transplantation date in 2011–2030 resulted in Class A yields equal to or greater than that under the current situation; however, the drought volume was 19.0 times higher than that under the current situation. In 2031–2050, changing the transplantation date did not ensure the same level of Class A yield as in the current situation. After 2051, in both RCP 2.6 and 8.5 scenarios, Class A yield of the same level as that achieved with the current transplantation date was not achieved even if the transplantation date was changed. The results indicated that drought volume and rice quality have a trade-off relationship in the future; thus, selecting a transplantation date to improve rice quality without allowing for higher drought volume is impossible.

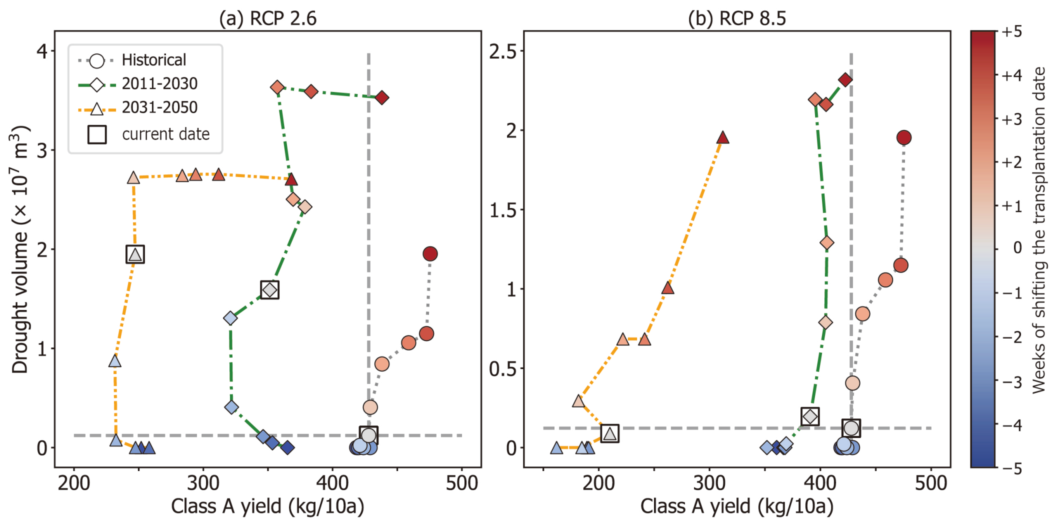

Figure 8. Relationship between drought volume and Class A yield, when the current transplantation date (square point) was shifted in (a) RCP 2.6 and (b) RCP 8.5 scenarios (2011–2030 and 2031–2050). The dotted lines indicate drought volume and Class A yield on the current transplantation date in the Historical scenario (1981–2000).

Two contrasting worlds emerged depending on the farmers' motivation for selecting adaptative measures. When the adaptive behavior for the two driving forces is synergistic, such as in the case of total yield and drought volume, adaptation measures can be implemented smoothly. In contrast, when the adaptive behavior for the two driving forces is a trade-off, such as in the case of rice quality and drought volume, adaptation measures cannot be implemented without allowing for disadvantages to the other driving force. Our results indicate that shifting the transplantation date as an incremental adaptative measure was effective in the Shinano River watershed, while we found that other factors may hamper the feasibility of implementing adaptative measures.

The IPCC AR6 report coined the term "soft adaptation limit" to describe situations in which adaptation measures are hampered by other factors. The report defines "soft adaptation limit" as situations wherein "options may exist but are currently not available to avoid intolerable risks through adaptive action" (IPCC, 2022). Our results are an example of the "soft adaptation limit" that can arise between farmers and water managers because the adaptation option of delaying transplantation cannot be available without allowing drought above the current level. We identified the "soft adaptation limit" by coupling two process models representing the driving forces of farmers and water managers. This study highlights the importance of evaluation using coupling models that represent multiple driving forces when adaptation measures are implemented.

4 Conclusion

We examined how an effective measure in one sector (agriculture) influences the other (water resources) by comparing "benefits of agricultural production" and "drought risk" under current and future climate scenarios. We built a framework consisting of two process-based models of hydrology and crop science and selected shifting of the transplantation date (i.e., starting date of irrigation) as a promising measure to avoid degradation of rice quality. The framework was applied to a downstream irrigated area of the Shinano River watershed, a typical watershed in Japan that has tightly coupled water–rice systems.

Shifting of the transplantation date showed opposing effects on the total yield and quality of rice, with an earlier date increasing the total yield and a later date increasing the quality. Drought risk was reduced by shifting transplantation to an earlier date; thus, in terms of the preferred adaptation options, total yield and drought were synergistic, whereas rice quality and drought were trade-offs. The current transplantation date was set on a schedule that minimized drought volume and maximized total yield, not quality. The results imply that the current transplantation date has resulted from the driving forces of farmers' to maximize total yield and water managers' to reduce drought. However, the long-term data of transplantation date indicated that since the 2000s, farmers' motivation changed to other factors, possibly rice quality. We argue that the data we presented could contribute to helping find the hidden changes in the behavioral rules of farmers and thus transform modeling human behavior from the normative approach to a descriptive tool within the human–nature coupling model. The overall data of this study serves as a material for building descriptive models of Japanese rice farmers, although a rigorous investigation is required for the reason for these changes in the transplantation date as a future work. The water–rice coupled systems also enabled the evaluation of whether adaptation measures for one sector (rice quality) are hampered by other factors (drough risk) and showed an example of the "soft adaptation limit" that can arise between farmers and water managers. This study highlights the importance of evaluation using coupling models that represent multiple driving forces when adaptation measures are implemented.

The framework presented in this study is not limited to agriculture and water resources but can evaluate the impact of adaptation measures on any two closely related stakeholders. Overall, this study contributes to the understanding of how interconnected systems evolve when the boundary conditions (i.e., climate or socio-economic conditions) change.

Acknowledgments

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Data Availability Statement

The simulation outputs, figure data and files are available at https://doi.org/10.5281/zenodo.7379631. Observed daily meteorological data were obtained from the Japan Meteorological Agency and can be found online (at https://www.jma.go.jp/bosai/#lang=en&pattern=default). The outputs of GCMs, namely MIROC5, MRI-CGCM3, and HadGEM2-ES were obtained from Ishizaki (2020). The data of yearly statistics of rice yield and cultivation schedule were obtained from a dataset of the Ministry of Agriculture, Forestry and Fisheries (MAFF) and can be found online (at https://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_kome/index.html).

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Coupled Water–Rice Systems under Multiple Driving Forces: Soft Limits of Adaptations to Climate Change in Japan

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Key Points:

- We propose water–rice coupled systems that enable evaluating the side effects of an adaptation measure on other factors.
- We advance the understanding of principles that determine human behavior and indicate possible changes in behavior due to climate change.
- We showed an example of "soft adaptation limits" that can arise between farmers and water managers in Japan.

Abstract

The impacts of climate change and increased water use for irrigation make it difficult to manage sustainable water use and food production. Sufficient research has not been conducted on how humans adapt to water risks due to climate change. One of the difficulties in considering adaptation measures is that adaptation actions in one sector conflict with the interests of other stakeholders in the basin and trade-off relationships emerge among various sectors. Here, we examined how an effective adaptation in one sector (agriculture) influences the other (water resources) by calculating the "benefits of agricultural production" and "drought risk" under current and future climate scenarios. We built a framework consisting of two process-based models of hydrology and crop science and evaluated shifting of the transplantation date as a promising measure to avoid the degradation of rice quality in Japan. Shifting the transplantation date had opposing effects on the total yield and quality of rice, with an earlier date increasing the total yield and a later date increasing the quality. Furthermore, an earlier transplantation date reduced the drought risk. Thus, in terms of the preferred adaptation options, total yield and drought were synergistic, whereas rice quality and drought were trade-offs. Our results imply that the current transplantation date has resulted from the farmers' motivation to maximize total yield, but this motivation may change to other factors, possibly rice quality, due to climate change. Overall, this study contributes to the understanding of how interconnected systems evolve when climate or socio-economic conditions change.

1 Introduction

Irrigation water, which accounts for approximately 70% of the world's water use, is important to meet the demand for food production as the population continues to grow (Gerland et al., 2014). Agriculture is one of the industries most vulnerable to climate change, with climate change resulting in 24–43% losses in food production compared to that under pre-warming conditions (Elliott et al., 2014, Iizumi et al., 2018). Model assessments have suggested that the decrease in water resources available for irrigation (Elliott et al., 2014) due to climate change is accelerated by the increased water use for irrigation (Haddeland et al., 2014). These factors make it even more difficult to sustainably manage water use and food production.

Research on the mechanisms and uncertainties of global climate change has progressed, and the impact on regional water risks (damage risks from floods and droughts) has come to be understood in more detail. However, sufficient research has not progressed on how humans adapt to water risks due to climate change. One of the difficulties in considering adaptation measures is that adaptation actions in one sector conflict with the interests of other stakeholders in the basin and trade-off relationships emerge among various sectors. The sixth report (AR6) of the International Panel on Climate Change (IPCC) by Working Group II (WG2) summarized the cases of adaptive actions to climate change and emphasized the importance of methods to evaluate the limits and feasibility of adaptive actions involving multiple stakeholders (IPCC, 2022).

Van Loon (2016) argued that the analysis of water risks in the Anthropocene epoch should consider human activities as dynamic rather than static and include their impacts on the natural water cycle. The shared socioeconomic pathway (SSP), which is commonly used to assess the impacts of climate change on human societies, only represents the potential pathways of socioeconomic development (e.g., population and GDP) and does not include feedback on human activities and water resources. The development of the interdisciplinary research field of socio-hydrology has attempted to understand the relationship between human society and water resources. The central idea of socio-hydrology is that the current status of human water use has 'coevolved' through the interaction between human society and water resources (Sivapalan et al., 2012). This approach allows us to thoroughly understand how interconnected systems evolve when the boundary conditions (i.e., climate or socio-economic conditions) change. To explore the evolutionary pathways of the interconnected systems, many studies have attempted to mimic human behavior within the human–nature coupling system. Cai et al. (2002) compiled the first version of the human–water coupled model that combined short-term (annual) decisions and long-term (inter-year) decisions to help find sustainable development pathways in irrigation-dominated watersheds. They proposed the function to assess the sustainability of a watershed, based on long-term environmental risks, equality within watersheds, and equality between generations and solve it mathematically. Giuliani et al. (2016) also simulated the interactions between irrigated agriculture and lake operation in the Adda River watershed in Italy, mainly focusing on how humans could make better decisions with the given annual variabilities in meteorological and hydrological conditions of the watersheds. The human behaviors were modeled with complete rationality by assuming the irrational behaviors of the individual farmers could be filtered when decisions were made at district levels (i.e., group of farmers), which they termed the normative meta-modeling approach. They assumed that farmers decide cropping patterns to maximize their expected net profit in each agricultural season, while lakes are maintained to balance water supply and flood protection on a daily basis, and showed the interdependency between the behaviors of the lake operator and farmers. The approach allowed the seasonal negotiation of water allocation plans, and the simultaneous adaptation of water supply operations successfully enlarged the potential benefits of coadaptation.

However, water resources and agricultural planning are generally based on the experiences of the climate during the last decades, thus the adaptation could not be happening at once; instead, it would be the combination of the inertia of the system and human decisions that drive the changes. With confronting the challenges of climate change, we need to simulate the interactive consequences between the short-term adaptation strategy and the long-term environmental risks. This is especially the case when climate change has already negatively impacted on human–water coupled systems. Li & Sivapalan (2020) found the possible long-term (85 years) coevolution of urban human–water systems under climate change by using a holistic urban sociohydrologic model that was proposed by Li et al. (2019) and analyzed the sensitivity of the social and physical aspects of the coevolutionary dynamics to system properties that could be changed by human adaptive actions. Their findings enhanced our understanding of the future coevolution of urban human–water systems and their sensitivity to human adaptive actions. The approach looking at the decision-making processes infers behavioral rules and parameters from observational data or general theories; however, the need for long-term observational data to infer behavioral rules makes the construction of descriptive tools difficult. Also, given the complexity and uncertainty associated with predicting human activities, their study is "not aimed at predicting an accurate future of the water situation. Instead, the model outcomes are deemed as just possibilities" (Li & Sivapalan, 2020).

This study aimed to make manageable and tractable forecasts by focusing on a single aspect of the human–nature coupling systems: agricultural society and water risks in Japan. We predicted how cropping schedule decisions, as adaptive measures in an irrigated district, will affect regional water resources. Japan is located in a humid region with an annual mean precipitation of 1,700 mm. However, because of the rapid expansion of irrigated rice paddies in the 17th and 18th centuries, river flow during drought periods was exhausted at the beginning of the 20th century (Satoh and Ishii, 2021). Irrigation requires a large amount of water during the most productive periods of the year, namely during the puddling (May) and heading (August) periods. Therefore, irrigation and water resources are mutually restricted, and the rules for water use have coevolved over the years. Rapid socio-economic development during the 20th century further deteriorated the water resources, even with the construction of water use facilities in the modern period. Climate change affects these tightly coupled water–rice systems in two ways. First, the heavy snowfall areas in the temperate zone of Japan were projected to be markedly vulnerable to temperature changes, showing a large reduction in snow and earlier snowmelt due to climate change (Kudo et al., 2017a, 2017b). Second, the appearance quality of rice is predicted to deteriorate with the occurrence of white immature grains owing to high temperatures during the heading period (Takimoto et al., 2019). Both farmers and governments are particularly concerned about the occurrence of white immature grains, and adaptation measures to reduce the occurrence of such grains have attracted considerable attention. Various adaptation measures to reduce the negative impacts on rice quality have been proposed, ranging from incremental to transformative (Iizumi, 2019). Shifting the transplantation date is relatively inexpensive and easier to implement than other adaptation measures. Thus, it has been widely implemented in Japan (MAFF, 2006).

To investigate the side effects of an adaptation measure for rice quality on water resources, we built a framework consisting of two process-based models of hydrology and crop science. We selected shifting the transplantation date (i.e., the starting date of irrigation) as a promising measure to avoid the degradation of rice quality. The same transplantation date was then applied to both models, while the other boundary conditions were not changed. We examined how an effective measure in one sector (agriculture) influences the other (water resources) by comparing the agricultural benefit and drought risk under current and future climate scenarios. We addressed the following questions: What will happen to the water–rice coupled systems due to climate change and the associated adaptive actions? How and why did the principles that determine farmers' behavior change?

2 Materials and Methods

2.1 Framework for assessing the impact of adaptation measures on two stakeholders

The impact of the adaptation measure was evaluated based on the outcome of an adaptation action on two stakeholders (X and Y). If the outcomes of an adaptation option on the two elements were beneficial to both, then the adaptation measure creates a "synergistic" relationship between the two (Figure 1(a)). However, if the benefits of one obtained through an adaptation option resulted in the detriment of another, then the adaptation measure creates a "trade-off" relationship (Figure 1(b)). The evaluation method included the following steps: (1) two process-based models that can evaluate the benefits (e.g., yield, quality, and economic income) and risks (e.g., 10-year probability of drought and number of days of water withdrawal restriction) obtained through adaptation options were prepared; (2) the benefits and risks were calculated under several adaptation options and climate scenarios; and (3) the calculation results were plotted as shown in Figure 1. If the plots were distributed upward and to the right (Figure 1(b)), it was determined that the benefits and risks were in a trade-off relationship. The two stakeholders would have a synergistic relationship if the plots were distributed downward and to the right (Figure 1(a)).

Using this model, we set "benefits of agricultural production" on the X-axis and "drought risk" on the Y-axis, and investigated the relationship between agriculture and water resources within the watershed if the adaptation measure of shifting the transplantation date was implemented. We selected shifting the transplantation date because it is relatively inexpensive and quicker to implement than other adaptation measures. Here, the "benefits of agricultural production" and "drought risk" resulting from shifting the current transplantation date every week up to five weeks before and after, as adaptation options, were calculated.

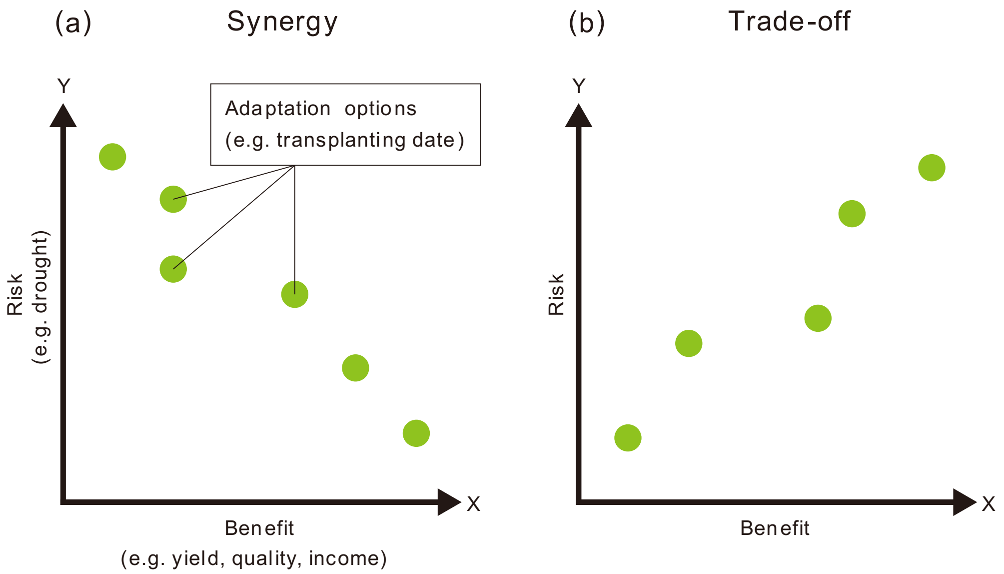

Figure 1. Relationships between two stakeholders (X and Y) to the adaptation options: (a) if the outcomes of an adaptation option on the two elements were beneficial to both, then the adaptation measure creates a "synergistic" relationship, (b) if the benefits of one obtained through an adaptation option resulted in the detriment of another, then the adaptation measure creates a "trade-off" relationship.

2.2 Process-based models to evaluate "drought risk" and "benefits of agricultural production"

To assess "drought risk" within a watershed, a distributed water circulation model (Yoshida et al., 2016) was prepared. This model is capable of integrally analyzing the natural water cycle (e.g., evapotranspiration, snowmelt, and river discharge) and the water used in agriculture (e.g., water withdrawal and water allocation)—the largest water user in Japan—at the watershed scale. It can accurately represent river flows during droughts in highly disturbed watersheds owing to agricultural water withdrawal and return flow, which are characteristic of

Japanese rivers. It calculates the amount of water resource at each grid cell that divides a watershed through daily input of meteorological data, such as precipitation, temperature, wind speed, and short- and long-wave radiation. The water withdrawal period for each facility in the water circulation model was externally input as the current period; thus, changes in rice growth due to climate change (e.g., shortening of the growing period) were not considered.

We investigated the impact of irrigation water withdrawal on society as a whole, including the environment and other water uses. This is represented as "hydrological drought", which was described by Mishra and Singh (2010) as follows: "Hydrological drought is related to a period with inadequate surface and subsurface water resources for established water uses of a given water resources management system." A given water management system in Japan is based on the streamflow and minimum required flow defined at a water use reference point. To evaluate the "drought risk" resulting from shifting the transplantation date, the cumulative amount of water that fell below the minimum required flow (hereafter, drought volume) during the irrigation period defined at a water use reference point was calculated for each transplantation date in each year.

To assess the "benefits of agricultural production" resulting from the shifting of the transplantation date, we used a process-based rice growth model (Hasegawa and Horie, 1997; Ishigooka et al., 2017). The model was described in full by Hasegawa and Horie (1997) and Ishigooka et al. (2017). This model has three major components: phenological development, biomass production, and yield formation. The model quantified the developmental stages (emergence, panicle initiation, heading, and maturity) from the daily mean air temperature (average of daily maximum and minimum) and day length (Ishigooka et al., 2017). It estimated the daily increases in biomass and leaf area based on biophysical processes, and the daily biomass production was calculated as the difference between the products assimilated by photosynthesis and consumed by respiration, accounting for the effect of increasing atmospheric CO_2 concentration on the enhancement of photosynthesis (Ishigooka et al., 2017). Through this process, total biomass was calculated as the accumulation of daily biomass increases (dry matter). The brown rice yield (hereafter called "total yield") was calculated by multiplying the biomass (dry weight production of the aboveground portion) and the harvest index that takes into account three factors of yield reduction: spikelet sterility caused by low or high temperatures and insufficient grain filling due to delayed maturity (Ishigooka et al., 2017). Note that the rice growth model does not consider the effects of water resources such as precipitation and evapotranspiration on rice growth and assumes that the amount of water resources necessary for rice production is sufficient.

We used two indices to evaluate the "benefit of rice production": total yield and yield with the highest appearance quality. The second index corresponds to rice quality. The total yield was calculated using a rice growth model. The yield with the highest appearance quality was estimated based on the heat stress index for rice quality, as defined by Ishigooka et al. (2011). The heat stress index (hereafter, "HD_m26") is related to the emergence of chalky grains due to high temperatures, that is, deterioration of rice appearance quality, calculated as the cumulative value of positive differences in daily average air temperature above 26 °C within 20 days after the heading date. Ishigooka et al. (2011) classified the yield into three classes based on the degree of quality degradation risk due to high temperature during the early grain-filling period: Class A (low risk), HD_m26 < 20°C·days; Class B (moderate risk), 20°C·days ≤ HD_m26 <

40°C·days; or Class C (high risk), HD_m26 ≥ 40°C·days. Among the three classes, we used "Class A yield" as an indicator of rice appearance quality in the evaluation.

2.3 Climate change scenarios

To apply the framework proposed in Section 2.1 under different climate change scenarios, we used the Historical (1981–2000) and RCP 2.6 and 8.5 (2011–2030, 2031–2050, 2051–2070, and 2071–2090) climate scenarios from three general circulation models (GCMs), namely MIROC5, MRI-CGCM3, and HadGEM2-ES. These datasets were obtained from Ishizaki (2020). To describe regional climate conditions, GCMs outputs with spatial resolutions of approximately 100–200 km are insufficient, thus we spatially interpolated the outputs to 1-km grids by means of simple linear interpolation using the inverse distance weighted method. Then, the CDF mapping method (Ines and Hansen, 2006; Li et al., 2010) was used to bridge statistical gaps in climate variables between observations and GCMs simulations. The observations (1981–2005) were interpolated to a 1-km grid using daily meteorological data recorded at the Japan Meteorological Agency observation stations by means of the inverse distance weighted method. For the evaluation of "drought risk," the drought volume was calculated for each year; thus, the number of data used for evaluation per period was 60 (3 GCMs × 20 years). For the evaluation of "benefits of rice production," the 20-year average of total and Class A yields was calculated for each period (1981–2000, 2011–2030, 2031–2050, 2051–2070, and 2071–2090); thus, the number of data used for evaluation per period was three (three GCMs).

2.4 Study area

The Shinano River is one of the largest rivers in Japan, with a main channel length of 367 km. It has a catchment area of 11,900 km^2, making it the third-largest catchment area in Japan (Figure 2). It runs through both the Niigata and Nagano prefectures and flows into the Sea of Japan. The spatial distribution of precipitation in the basin is complex. The upper area of the Shinano River watershed, located in the middle of mainland Japan, is surrounded by mountains that are more than 2,000 m high and have remarkable inland weather. This area has low precipitation, with an annual precipitation of only 938 mm in Nagano City. Conversely, the lower watershed on the Niigata Prefecture side, where the weather is specific to areas along the Sea of Japan, is known as one of the heaviest snowfall areas in Japan, including Nagaoka City, which has an annual precipitation of 2,310 mm and a great deal of precipitation during winter. The basin of the Uono River, which joins the Shinano River in its middle reaches, is also known for heavy snowfall, with snow accumulating over 2 m in thickness. The flow volume from March to May accounts for 30–50% of the annual outflows. This snowmelt period coincides with the puddling period when irrigation water is most required downstream.

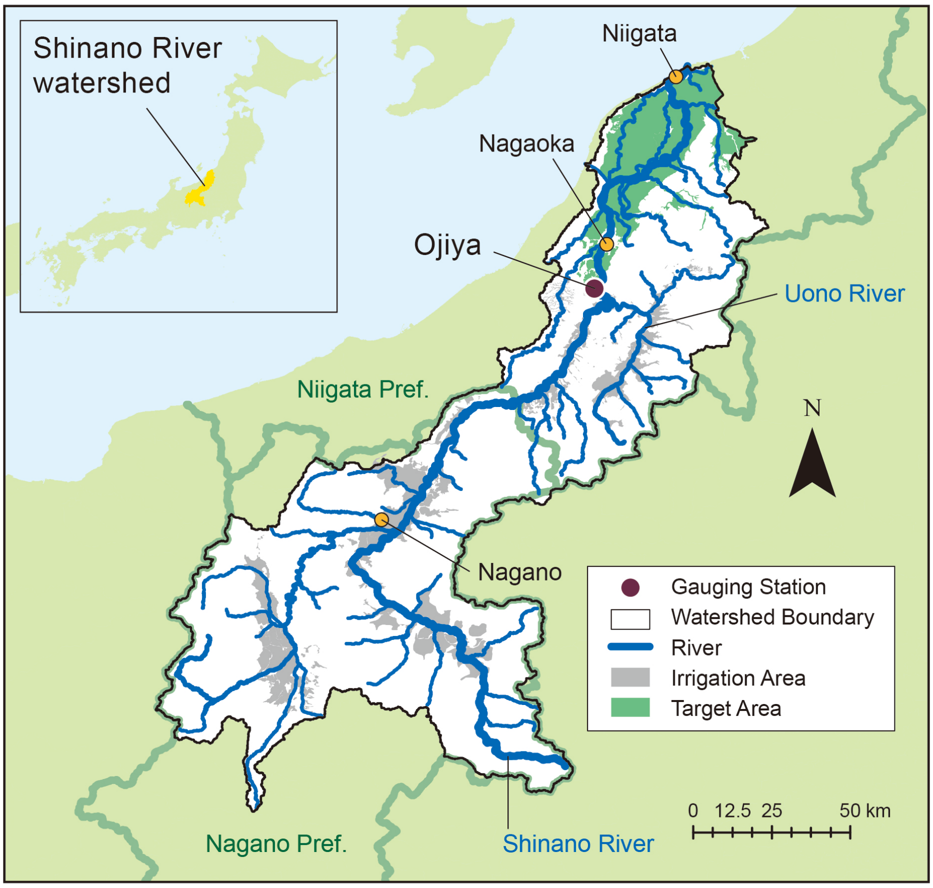

Figure 2. Map of the Shinano River watershed and target irrigation area.

The daily mean temperature and total precipitation for each year in the Shinano River watershed during the summer (June–August) are shown in Figure 3. In the future period (2011–2090), the daily mean temperature gradually increased under both RCP 2.6 and 8.5 scenarios, with a particularly high rate of increase under the RCP 8.5 scenario. The total precipitation showed large inter-annual variations for both scenarios, and no clear changing trend was observed for future periods.

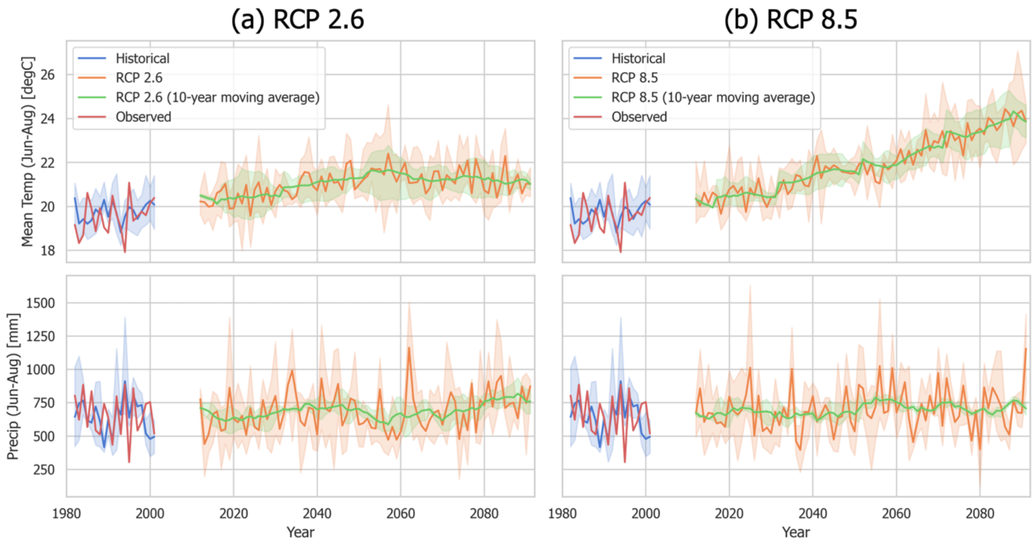

Figure 3. Changes in mean temperature and precipitation during summer (June–August) under two climate change scenarios: (a) RCP 2.6 and (b) RCP 8.5 in 2011–2090. Arithmetic mean and 10-year moving average of the three GCMs for each scenario are shown by solid lines, while the 95% confidence intervals for each element are indicated as filled areas.

We targeted the Ojiya gauging station and its downstream irrigated area. The lower areas of Ojiya are among the largest rice-producing regions in Japan, including approximately 14,700 ha developed through national land improvement projects. We treated the target area as a single irrigation district because there were no major differences in weather conditions and rice production conditions downstream from Ojiya, as shown by the difference of 0.3°C in monthly mean temperature during the heading period (August) between Nagaoka City and Niigata City from 1991 to 2020 and a maximum difference of 5 transplantation days in 2019. The Ojiya gauging station is a reference point for water use in the middle and lower areas of the Shinano River watershed. The minimum required flow of 145 m^3/s was allocated during the irrigation period (from April 28 to September 15) at the Ojiya station. Because the minimum required flow includes not only irrigation water but also environmental water requirement, a hydrological drought can be defined as a situation in which the flow rate falls below the minimum required flow. According to a dataset of annual statistical data on rice yield and cultivation schedule (dates of sowing, transplanting, heading, and harvesting) provided by Niigata Prefecture, May 9 was the peak transplantation date in the target area in 2019. Thus, we defined this date as the "current" transplantation date.

Since this study focused on changes in the transplantation date, the peak transplantation dates in Niigata Prefecture from 1953 to 2021 and the middle of the prefecture (called "*Chuetsu*") from 1969 to 2021 are shown in Figure 4. The data were obtained from a dataset of the Ministry of Agriculture, Forestry and Fisheries (MAFF) that provides yearly statistics of rice yield and cultivation schedule. These data were summarized at the prefectural level until 1968 and by sub-administrative regions called "sub-regions for yield statistics" (*sakugara hyouji chitai* in Japanese) after 1969. The transplantation date, which was on June 5 in 1953, gradually moved to May 4 in 1998. This may be due to the spread of transplanting using machinery, changes in rice varieties, and the higher price that early rice can be sold at. However, the transplantation date tended to be delayed by one week in the 2000s (the latest date was May 13 in 2012). In Japan, concerns about high-temperature injury to paddy rice began to grow in the 2000s, and studies were conducted to develop countermeasures (MAFF, 2006). Recently, countermeasures to delay the transplantation date were implemented in the Niigata Prefecture to avoid the risk of the heading period coinciding with abnormally high temperatures immediately after the end of the rainy season (MAFF, 2006), which may have resulted in the data.

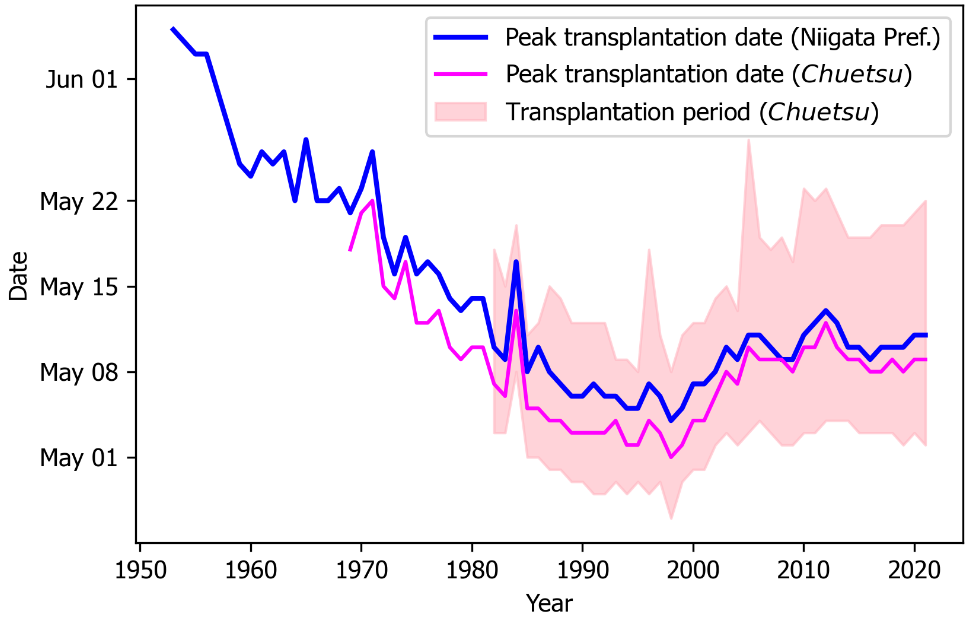

Figure 4. Changes in the transplantation date (solid lines) in Niigata Prefecture from 1953 to 2021 and the middle of Niigata Prefecture (called by "*Chuetsu*") from 1969 to 2021. Transplanting period (filled area) from 1982 to 2021 was calculated as the difference between the start and end dates of rice transplantation in *Chuetsu*.

3 Results and Discussion

3.1 Effects of farmers' and water managers' motivation on the transplantation date

To assess the changes in drought volume and yield with weeks of shifting the transplantation date, the results calculated by the two process models in the Historical (1981–2000) and RCP 2.6 (2011–2030) scenarios are shown in Figure 5. The upper panel shows the mean (solid lines) and 95% confidence interval (filled area) of cumulative drought volume for the drought years from the 60 years of data. The drought volume in the Historical scenario was

4.52 million m^3 at the current transplantation date (Figure 5). The drought volume decreased as transplantation was shifted to an earlier date, and drought did not occur when transplantation was performed more than four weeks earlier. The drought volume gradually increased when transplantation was shifted to a later date, and it was 20.9 million m^3 when transplantation was delayed by five weeks.

The lower panel in Figure 5 shows the mean and 95% confidence intervals of the total and Class A yields for the three GCMs. Focusing on the total yields with each transplantation date, the mean of total yields was 606.2 kg/10a at the current transplantation date, which increased when the transplantation date was shifted earlier and decreased when the transplantation date was shifted later, as confirmed by Ishigooka et al. (2017). The highest total yield was 622.2 kg/10a when the transplantation date was shifted four weeks earlier while it decreased to 506.4 kg/10a when transplantation was delayed by five weeks. The Class A yields with each transplantation date decreased when transplantation was shifted to an earlier date and increased when transplantation was shifted to a later date, compared to 427.9 kg/10a at the current transplantation date. The lowest Class A yield was 418.6 kg/10a when transplantation was performed five weeks earlier, and the highest yield was 475.5 kg/10a when transplantation was delayed by five weeks. The adaptation measure of shifting the transplantation date showed opposing effects on total yield and quality, with earlier dates increasing total yields and later dates increasing Class A yields.

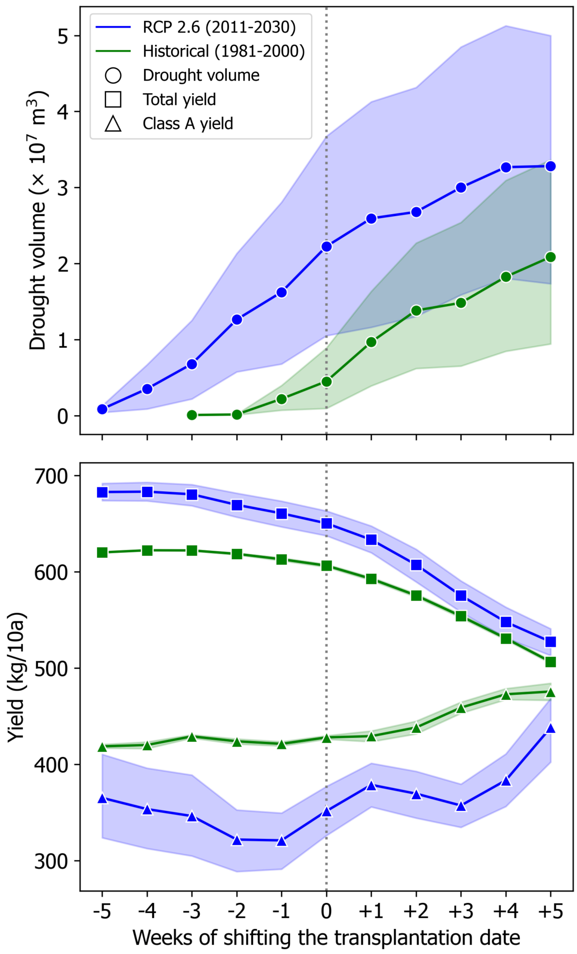

Figure 5. Arithmetic mean (points, solid lines) and 95% confidence interval (filled area) of drought volume, total yield, and Class A yields with each transplantation date in the Historical (1981–2000) and RCP 2.6 (2011–2030) scenarios.

The relationship between drought (risk) and yield (benefit) in the Historical scenario (1981–2000), for each transplantation date, is shown in Figure 6. The relationship between drought volume and total yield (Figure 6(a)) showed a synergistic effect as the drought volume decreased and the total yield increased when transplantation was shifted to an earlier date. The current transplantation date was plotted in the lower right corner of the graph, where the drought volume was low and the total yield was high. The relationship between drought volume and Class A yield (Figure 6(b)) showed a trade-off effect, as both the drought volume and Class A yield increased when transplantation was shifted to a later date. The current transplantation date was not plotted at the location of maximum quality, although the drought volume was low.

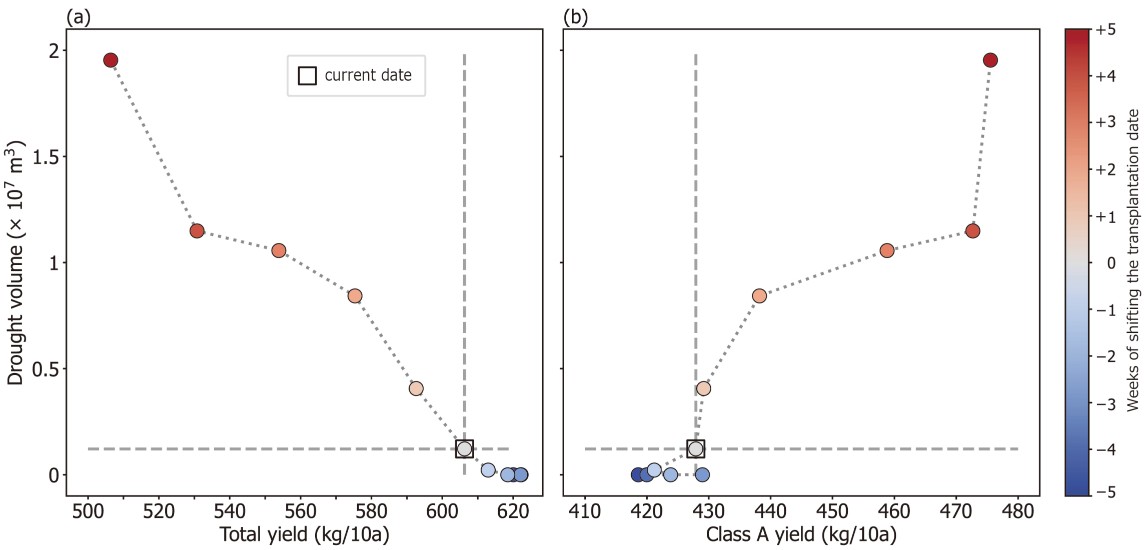

Figure 6. Relationship between (a) drought volume and total yield, (b) drought volume and Class A yield, when the current transplantation date (square point) was shifted in the Historical scenario (1981–2000). The dotted lines indicate total and Class A yields and drought volume on the current transplantation date.

This result indicates that total yield was more important than quality in setting the current transplantation date, and a driving force has been working to ensure a high total yield. The peak transplantation period in the 1950s was about four weeks later than that of the present times (Figure 4); thus, the transplantation date in the 1950s corresponds to the +4 weeks plot in Figure 6. The current transplantation date has settled into a date that facilitates a higher total yield and lower drought, although the rice quality is lower. Possible reasons for the earlier transplantation dates include a more flexible timing for water use due to improved overall agricultural technology and a longer growing period to ensure a higher total yield. We inferred that the transplantation date could have been shifted smoothly as long as the emphasis was on the total yield because the transplantation date can be selected to increase the total yield without increasing the drought risk. Our results imply that the current transplantation date has resulted from the coevolution of farmers' behavior to maximize benefits (total yield) and water managers' behavior to reduce drought.

3.2 Changes in driving force of farmers' decision-making

Coupling models representing multiple driving forces, especially humans and nature, have recently been proposed in the field of socio-hydrology to enable more accurate hydrological prediction under the joint natural and socio-economic driving forces (e.g., Sivapalan et al., 2012). Two main approaches are proposed for modeling human behavior within the human–nature coupling model (Smith, 1991; Giuliani et al., 2016). One is the normative approach, which focuses on motivational behavior based on economics (Becker, 1978) and assumes that human decisions are designed to maximize a given utility function, that is, to act with perfectly rational behavior (Giuliani et al., 2016). Although this assumption has often been contradicted by observations of real behaviors, this approach was largely adopted in the field of environmental modeling. The other is a descriptive approach that represents the decision-making processes based on cognitive psychology and social sciences (Kahneman and Tversky, 1979; Camerer et al., 2011) and infers behavioral rules from observational data or general theories (Giuliani et al., 2016). The normative approach is critical important when decision-making processes involve other factors than those that cannot easily be interpreted as economic values (e.g., environmental risks). Although many studies tried finding evidence of the changes in behavioral rules from the record of socioeconomic factors, identifying reliable parameters for capturing human decision-making is a daunting task because of the complexity and uncertainty of the hidden mechanism and the lack of long-term data on socioeconomic factors.

Here, we focused on how the farmers' decisions were made on the transplantation date in the Shinano River watershed. The data presented in Figure 4 depict long-term (69 years) human behaviors that can be divided into two phases. In the first phase (1953–1998), the transplantation date gradually became earlier by approximately five weeks, resulting in higher total yield and less drought risk (Figure 6). In the second phase (after 1999), the transplantation date was delayed by one weeks, resulting in the improvement of rice quality while the drought risk could have been increased. One possible factor for this shift is the implementation of the adaptation measure for high-temperature injuries. In other words, the driving force of farmers' decision-making has changed to another factor, possibly rice quality. Thus, the transplantation date may be further delayed if high-temperature injuries become more apparent.

The normative approach can represent the change in the first phase but not in the second because the delay in the transplantation date was not induced by economic incentives. The shift in transplantation dates since the 2000s implies that the motivation of farmers changed from economic benefits to rice quality. The price of rice ("*Koshihikari*", the most common variety in Niigata Prefecture) was 12,300 yen/60 kg for the first-grade and 11,700 yen/60 kg for the second-grade rice in 2021. The small difference in price between first and second grades indicates that a higher total yield leads to higher income, regardless of the grade. In other words, the current pricing of rice grades supports the motivation for changes in transplantation date during the first phase: the higher yield, the higher income, and vice versa.

It is also intriguing to note that the transplantation period (filled areas in Figure 4) has become longer since 2005: 12.5 days for the period of 1982–2004 and 17.5 days for 2005–2021. The spread of the transplantation periods after 2005 may reflect the farmers' decisions to avoid the risks in two directions: quality degradation due to high-temperature injury and loss of yield due to shorter growing periods. We admit that the selection of the transplantation date could be more variable and flexible in the future; however, we continue assuming a single transplantation date in the following section for simplicity.

We argue that the data we presented could contribute to helping to find the hidden changes in the behavioral rules of farmers and thus transform the normative approach into a descriptive tool. A rigorous investigation is required for the reason for these changes in the transplantation date. However, the overall data of this study serves as a material for building descriptive models of Japanese rice farmers.

3.3 Coupled assessment of multiple driving forces under climate change

Between the two drivers presented in Section 3.1 and 3.2, we first assumed that total yield is likely to be the primary driving force in future periods. The relationship between drought volume and total yield for each transplantation date is shown in Figure 7. In addition to the results of the RCP 2.6 and 8.5 scenarios (2011–2050), the results in the Historical (1981–2000) scenario are also shown for comparison. Focusing on the drought volume in the current transplantation date, RCP 2.6 scenario showed a stronger drought trend than the Historical and RCP 8.5 scenarios (Figure 7(a)), while the drought trend in the RCP 8.5 scenario did not differ significantly from that in the Historical scenario (Figure 7(b)). The total yield at the current transplantation date in all future scenarios was higher than that in the Historical scenario. The plots were in the right downward direction, indicating that drought volume and total yield have a synergistic relationship when shifting the transplantation date in future periods. The drought volume can be kept lower if an earlier transplantation date is selected to increase the total yield in future periods.

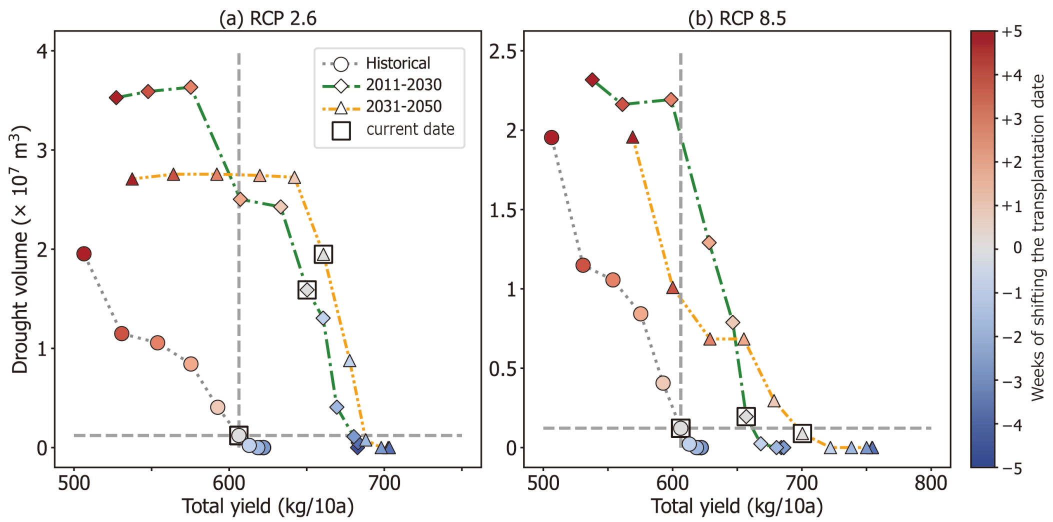

Figure 7. Relationship between drought volume and total yield, when the current transplantation date (square point) was shifted in (a) RCP 2.6 and (b) RCP 8.5 scenarios (2011–2030 and 2031–2050). The dotted lines indicate drought volume and total yield on the current transplantation date in the Historical scenario (1981–2000).

On the other hand, we explored another possibility, that is, rice quality would be the primary driving force in future periods. As shown in Figure 8, Class A yields decreased in the future under both scenarios. In 2011–2030, under the RCP 2.6 scenario, a five-week delay in the transplantation date resulted in a Class A yield equal to or greater than that under the current situation (at the current transplantation date in the Historical scenario); however, the drought volume was 28.9 times higher than that under the current situation. Furthermore, it would be difficult to achieve the same level of Class A yields as the current situation, even with a five-week delay in transplanting in 2031–2050 under the RCP 2.6 scenario. Similarly, in the RCP 8.5

scenario, a five-week delay in the transplantation date in 2011–2030 resulted in Class A yields equal to or greater than that under the current situation; however, the drought volume was 19.0 times higher than that under the current situation. In 2031–2050, changing the transplantation date did not ensure the same level of Class A yield as in the current situation. After 2051, in both RCP 2.6 and 8.5 scenarios, Class A yield of the same level as that achieved with the current transplantation date was not achieved even if the transplantation date was changed. The results indicated that drought volume and rice quality have a trade-off relationship in the future; thus, selecting a transplantation date to improve rice quality without allowing for higher drought volume is impossible.

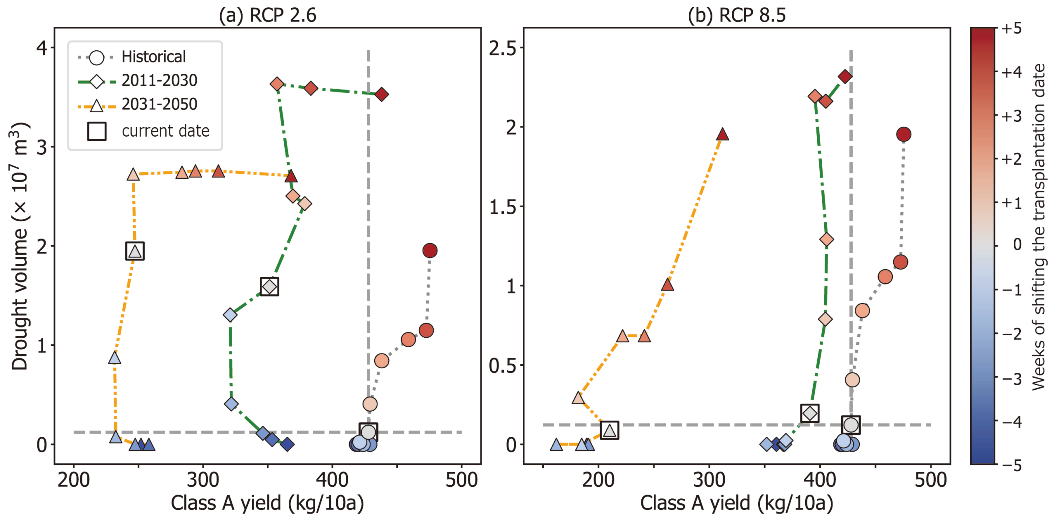

Figure 8. Relationship between drought volume and Class A yield, when the current transplantation date (square point) was shifted in (a) RCP 2.6 and (b) RCP 8.5 scenarios (2011–2030 and 2031–2050). The dotted lines indicate drought volume and Class A yield on the current transplantation date in the Historical scenario (1981–2000).

Two contrasting worlds emerged depending on the farmers' motivation for selecting adaptative measures. When the adaptive behavior for the two driving forces is synergistic, such as in the case of total yield and drought volume, adaptation measures can be implemented smoothly. In contrast, when the adaptive behavior for the two driving forces is a trade-off, such as in the case of rice quality and drought volume, adaptation measures cannot be implemented without allowing for disadvantages to the other driving force. Our results indicate that shifting the transplantation date as an incremental adaptative measure was effective in the Shinano River watershed, while we found that other factors may hamper the feasibility of implementing adaptative measures.

The IPCC AR6 report coined the term "soft adaptation limit" to describe situations in which adaptation measures are hampered by other factors. The report defines "soft adaptation limit" as situations wherein "options may exist but are currently not available to avoid intolerable risks through adaptive action" (IPCC, 2022). Our results are an example of the "soft adaptation limit" that can arise between farmers and water managers because the adaptation option of delaying transplantation cannot be available without allowing drought above the current level. We identified the "soft adaptation limit" by coupling two process models representing the driving forces of farmers and water managers. This study highlights the importance of evaluation using coupling models that represent multiple driving forces when adaptation measures are implemented.

4 Conclusion

We examined how an effective measure in one sector (agriculture) influences the other (water resources) by comparing "benefits of agricultural production" and "drought risk" under current and future climate scenarios. We built a framework consisting of two process-based models of hydrology and crop science and selected shifting of the transplantation date (i.e., starting date of irrigation) as a promising measure to avoid degradation of rice quality. The framework was applied to a downstream irrigated area of the Shinano River watershed, a typical watershed in Japan that has tightly coupled water–rice systems.

Shifting of the transplantation date showed opposing effects on the total yield and quality of rice, with an earlier date increasing the total yield and a later date increasing the quality. Drought risk was reduced by shifting transplantation to an earlier date; thus, in terms of the preferred adaptation options, total yield and drought were synergistic, whereas rice quality and drought were trade-offs. The current transplantation date was set on a schedule that minimized drought volume and maximized total yield, not quality. The results imply that the current transplantation date has resulted from the driving forces of farmers' to maximize total yield and water managers' to reduce drought. However, the long-term data of transplantation date indicated that since the 2000s, farmers' motivation changed to other factors, possibly rice quality. We argue that the data we presented could contribute to helping find the hidden changes in the behavioral rules of farmers and thus transform modeling human behavior from the normative approach to a descriptive tool within the human–nature coupling model. The overall data of this study serves as a material for building descriptive models of Japanese rice farmers, although a rigorous investigation is required for the reason for these changes in the transplantation date as a future work. The water–rice coupled systems also enabled the evaluation of whether adaptation measures for one sector (rice quality) are hampered by other factors (drough risk) and showed an example of the "soft adaptation limit" that can arise between farmers and water managers. This study highlights the importance of evaluation using coupling models that represent multiple driving forces when adaptation measures are implemented.

The framework presented in this study is not limited to agriculture and water resources but can evaluate the impact of adaptation measures on any two closely related stakeholders. Overall, this study contributes to the understanding of how interconnected systems evolve when the boundary conditions (i.e., climate or socio-economic conditions) change.

Acknowledgments

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Data Availability Statement

The simulation outputs, figure data and files are available at https://doi.org/10.5281/zenodo.7379631. Observed daily meteorological data were obtained from the Japan Meteorological Agency and can be found online (at https://www.jma.go.jp/bosai/#lang=en&pattern=default). The outputs of GCMs, namely MIROC5, MRI-CGCM3, and HadGEM2-ES were obtained from Ishizaki (2020). The data of yearly statistics of rice yield and cultivation schedule were obtained from a dataset of the Ministry of Agriculture, Forestry and Fisheries (MAFF) and can be found online (at https://www.maff.go.jp/j/tokei/kouhyou/sakumotu/sakkyou_kome/index.html).

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