Analysis of rice yield response to various cropping seasons to develop optimal cropping calendars in Mwea, Kenya

Hiroaki Samejima, Keisuke Katsura, Mayumi Kikuta, Symon Mugo Njinju, John Munji Kimani, Akira Yamauchi and Daigo Makihara

ABSTRACT
Cropping calendar optimization contributes to an increase in rice yield. Information on the seasonal variation in grain yield and climate conditions is necessary to determine an appropriate cropping calendar. We sought to find the optimal cropping calendar in Mwea, Kenya, in a tropical highland in equatorial East Africa. We conducted a series of 58 experiments using a local popular rice variety, Basmati 370, between 2013 and 2016, using a secured water supply and adequate blast control, sowing every 15 days. The grain yield was 0–2 t ha⁻¹ when the variety was sown between March and June. This poor grain yield was attributable to the low temperature and low solar radiation from May to September. In contrast, the grain yield was always more than 3 t ha⁻¹ when the variety was sown between July and February. Sowing Basmati 370 between March and June is not recommended, because it may lead to a suboptimal yield due to cold stress. The current cropping calendar (July–December or August–January) is acceptable even under abundant year-round water supply, but sowing between October and February is a good alternative sowing period for single rice cropping. Rice production per year is expected to increase to >100% with the introduction of double cropping by adding cultivation from between January and February before the current cropping calendar. These findings serve as useful references for considering and determining the appropriate calendar options for single and double cropping of rice in tropical highlands in equatorial East Africa.
Introduction

Africa is far from self-sufficient in rice, and this situation is projected to worsen in the future (van Oort & Zwart, 2018). There are five options to close the gap between demand and production: (1) expansion of land under cultivation, (2) intensification in existing farmlands by growing two or three crops a year, (3) narrowing the yield gap in farmers’ fields by introducing new technologies, (4) raising yield ceiling by introducing high-yielding cultivars, and (5) reducing postharvest losses (van Oort et al., 2015). Cropping calendar optimization contributes to options 2 and 3. In general, the cropping calendar for double or triple rice is tight as each location has a climatically inappropriate period for rice cultivation. To narrow the yield gap in farmers’ field and to achieve yield ceiling (potential) of high-yielding varieties, introducing good agricultural practices (GAP), an integrated set of the recommended crop, soil, water, and weed management practices (Senthilkumar, Tesa, Mghase & Rodenburg, 2018), is important. Selection of the most appropriate cropping calendar should be a component of GAP. Crop calendar optimization is well studied for rice cultivation in Sahel (Dingkuhn, 1995; van Oort et al., 2016), but studies in tropical highlands in central (equatorial) East Africa is limited (Sekiya et al., 2015). For preparing a globally complete and spatially explicit rice cropping calendar, which is a valuable global public good for food security (Laborte et al., 2017), more information is necessary to consider the appropriate crop calendar in each region of the world including tropical highlands in equatorial East Africa.

In this study, we analyzed the optimal rice cropping calendar in Mwea, Kenya, representing tropical highlands in equatorial East Africa. This study area, located near to the equator and at an altitude of approximately 1200 m, has the largest rice-growing irrigation scheme in Kenya, covering 9,000 ha, with the potential for 4,000 ha expansion. It produces 80–88% of rice in the country (Mati, Wanjogu, Odongo & Home, 2011; Ndiiri, Mati, Home & Odongo, 2013; Onyango, 2014). Most farmers in Mwea grow rice once a year, sowing between July and August and harvesting between December and January (Abdullahi, Mizutani, Tanaka, Goto & Matsui, 2003; Ngige, 2004). This cropping calendar means rice growth must continue over the dry season (July–September) when water is least available to irrigate the crop between long rains (March–June) and short rains (October–December) (Kihoro, Bosco & Murage, 2013a; Kihoro, Bosco, Murage, Ateka & Makihiara, 2013b; Mati et al., 2011). Although adequate supplies of irrigation water are usually secured during the long rains, it is recognized that the temperature in Mwea is too low to start rice cultivation between March and June (Kihoro et al., 2013b; Muhunyu, 2012; Ndiiri et al., 2013). Outbreaks of rice blast disease are also the heaviest during long rains (Muhunyu, 2012). However, the crop calendar tool provided by the FAO (2019) predicts that sowing and harvesting of rice including the locally most popular variety, Basmati 370, are possible throughout the year under tropical highland conditions in Central Kenya. The optimal cropping calendar is still unknown in Mwea.

With the current cropping calendar, double cropping is prevented by the lack of water for irrigation. However, solutions to water shortage are likely to be found. The Thiba Mega Dam is currently under construction with funds from the Japan International Cooperation Agency and the Government of Japan and will store 15 million m$^3$ of water suitable for crop irrigation (Mwangi, 2019). Intermittent irrigation of rice as a water-saving technique (de Vries et al., 2010; Krupnik, Shennan & Rodenburg, 2012) is being disseminated in Mwea and would save water not only for individual farmers but also across the area (RiceMAPP, 2016). Under these situations, sufficiently abundant year-round water would be available for rice cropping and, thus, enable double cropping. This has drastically increased rice production elsewhere in Africa (Dolo et al., 2004; Sekiya et al., 2017). Indeed, farmers in Mwea who already have a good access to water do carry out double cropping (Kimani, Tongona, Derera & Nyende, 2011; Muhunyu, 2012; Ngige, 2004). This demonstrates that double cropping is possible in Mwea based on temperature and solar radiation if irrigation water shortages can be alleviated.

In this study, we evaluated the performance of rice in Mwea throughout the year. We used a continuous supply of irrigation water and sowed a lowland rice variety every 15 days. Blast disease was controlled through frequent chemical application. The specific objective of this research was to judge the appropriate calendar options for both single and double rice cropping in Mwea under sufficiently abundant year-round water supply. The optimal cropping calendar may differ depending on rice variety. A lowland variety, Basmati 370, was used in this study. Owing to its aromatic white grains, Basmati 370 is the most popular variety among farmers in Mwea and consumers in Kenya, and it fetches premium prices (Kimani et al., 2011).

Materials and methods

From 2013 to 2016, a series of 58 experiments was conducted in a research farm belonging to the Kenya
Agricultural and Livestock Research Organization, Mwea, Kenya (0°37′S, 37°20′E) at an elevation of 1,162 m above sea level. Basmati 370 rice was sown on the 1st and 15th day of every month from October 2013 to February 2015, and from September 2015 to August 2016. The seeds were first soaked in water to germinate, and then sown into seedling trays, each with 448 circular cells (16 mm diameter and 25 mm depth) (Minoru pot 448; Minoru Industrial Co., Ltd., Akaiwa, Japan) at one seed per cell. The trays were transferred into the seedling nursery in a greenhouse. Growing the seedlings was possible throughout the year as the temperature was controlled by opening and closing the greenhouse windows. In all experiments, 21-day-old seedlings, which is the same seedling age in farmers’ practice, were transplanted. Hill spacing was 30 cm × 15 cm in the October 2013 to February 2015 experiments, and 20 cm × 20 cm in the September 2015 to August 2016, with one seedling per hill. Effects of different planting densities on grain yield were assumed to be negligible as grain yield of rice is generally stable over a wide range of planting densities because of the compensatory and competitive relationships among the number of tillers and size of panicles (Wu, Wilson & McClung, 1998). The plot sizes were 2.8 m × 2.8 m (9 rows and 18 plants per row) in the earlier 34 experiments and 1.8 m × 2.6 m (9 rows and 13 plants per row) in the latter 24 experiments. Effects of different plot sizes on grain yield were assumed to be negligible as more than four rows per plots are necessary for accurate estimation of rice grain yield (Jearakongman, Immark, Noenplub, Fukai & Cooper, 2003). The plots were laid out in a randomized complete block design with three replications. The basal fertilization was 25 kg N, P, and K per hectare and was applied in the form of an NPK (17:17:17) compound fertilizer. Additional ammonium sulfate was top dressed at 25 kg N ha⁻¹ twice at 21 and 45 days after transplanting. This fertilizer application is the standard practice among farmers in Mwea (Njinju et al., 2018). All experiments were conducted under continuously flooded conditions. Hand weeding and insecticide application were performed as required. Rodazin 50SC (Cooper K-Brand LTD, Nairobi, Kenya) was applied when the weather conditions were favorable for rice blast infection.

Air temperature, solar radiation, and rainfall were recorded every 10 min in a weather station (Weather Bucket; Agriweather Inc. Sapporo, Japan) in the research farm. The monthly averages of daily mean, maximum, and minimum temperatures; monthly average of daily solar radiation; and monthly rainfall are shown in Figure 1. The bimodal rainfall pattern characterized by two peaks observed around April and November was confirmed. Solar radiation was in the range of 10.3–19.6 MJ m⁻² d⁻¹. The maximum (24.5–31.3°C), mean (19.7–23.9°C), and minimum (14.0–19.2°C) temperatures varied substantially. Each year, there was a light rains, low solar radiation, and low temperature period between two rainy seasons, 1 to 2 months before and after July.

![Figure 1](image-url)  
**Figure 1.** Changes in the monthly average of the daily maximum, mean, and minimum temperatures; monthly average of daily solar radiation; and monthly rainfall from October 2014 to December 2016.
A few months before and after January were the periods of the lowest minimum temperature. In contrast, the solar radiation, and maximum and mean temperatures were higher in the period around January than in other periods.

The number of days to 50% heading was recorded based on daily observations in a series of 24 experiments, in which Basmati 370 was sown between September 2015 and August 2016. We assumed that plants were in a vegetative stage from transplanting to 30 days before 50% heading and in the reproductive and ripening stages for 30 days before and 40 days after heading, respectively. At maturity, the shoots were harvested at the ground level from 10 hills in all cultivation plots. The harvested shoots were placed in paper bags and sun dried for more than 1 month. The panicles were then removed from the stems and hand threshed. Filled and unfilled spikelets were separated by hand. Using the panicles and spikelets, grain yield (filled grain weight converted to 14% moisture content) and yield components were determined. The moisture content of the filled grains was measured using a grain moisture tester (Riceter f; Kett Electric Laboratory, Tokyo, Japan). The straws, panicle rachis, and unfilled spikelets were oven dried at 70°C for 1 day and weighed. Shoot dry weight was determined as the sum of grain yield and dry weight of straws, panicle rachis, and unfilled spikelets.

The statistical package R (Version 3.0.2, R Core Team, 2015) was used for the statistical analyses. The average grain yield was compared among sowing dates using Tukey’s honest significant difference (HSD) test with the built-in TukeyHSD function. The built-in cor.test function was used for the correlation analysis.

**Results**

There were significant differences in grain yield among different sowing dates (Figure 2). Grain yield ranged from 0 to 2.0 t ha⁻¹ when Basmati 370 was sown on the 1st and 15th day of March, April, and May, and the 1st day of June, irrespective of the year. Sowing in April and May was particularly low yielding and led to almost 0 t ha⁻¹ of grain yield, irrespective of year. Sowing on June 15 led to an unstable grain yield: 3.9 t ha⁻¹ in 2014, but 1.3 t ha⁻¹ in 2016. When the variety was sown between July and February, grain yield was always more than 3.0 t ha⁻¹, except for sowing on 1 August 2014 (2.6 t ha⁻¹). Sowing on 15 October 2013 had the highest grain yield, 8.2 t ha⁻¹, throughout the experiments.

Grain yield showed a strong positive correlation with grain filling rate ($r = 0.843$, $p < 0.001$, Figure 3) and a moderate positive correlation with 1000-grain weight ($r = 0.396$, $p < 0.01$, data not shown) throughout the 58 experiments. The number of panicles per m², number of spikelets per panicle, and dry weight of shoot did not significantly correlate with grain yield ($r = 0.119, 0.105, 0.225$, respectively, $p > 0.05$; data not shown).

The number of days to 50% heading; averages of daily maximum, mean, and minimum temperatures, and cumulative solar radiation during the vegetative, reproductive, and ripening stages in the series of 24 experiments in which Basmati 370 was sown between September 2015 and

![Figure 2. Grain yield of Basmati 370 sown at every 15-day intervals from October 2013 to February 2015 and from September 2015 to August 2016. Vertical bars indicate the standard error. The dotted line indicates the changes in the average yield in each sowing date. Average values followed by different letters are significantly different according to Tukey’s honest significant difference test ($p < 0.05$).](image-url)
August 2016 are shown in Table 1. The grain filling rate presented significant (p < 0.001) and strong positive correlations with cumulative solar radiation, and average daily maximum and mean temperatures during the reproductive stage (r = 0.789, 0.725, and 0.707, respectively). Correlations of the grain filling rate with other parameters were moderate (0.5 < r < 0.6, p < 0.01 or 0.05) or not significant (p > 0.05, Table 2). Grain yield presented a significant and moderate positive correlation with average daily maximum temperature (r = 0.687, p < 0.001) and a significant and strong positive correlation with cumulative solar radiation during the reproductive stage (r = 0.767, p < 0.001, Figure 4). In the series of 24 experiments, the cumulative solar radiation, and average daily maximum and mean temperatures during the reproductive stage were lower for plants sown in March, April, May, and on June 1 (253–384 MJ m⁻², 23.2–26.4°C, and 19.7–21.8°C, respectively) than for those sown on other dates (420–563 MJ m⁻², 26.3–31.2°C, and 21.9–24.5°C, respectively, Table 1).

The number of days to 50% heading presented a significant (p < 0.001) and strong negative correlation with the average daily maximum and mean temperatures during the vegetative stage (r = −0.869 and −0.876, respectively), but correlations of the number of days to 50% heading with other parameters were moderate (0.4 < r < 0.6, p < 0.01) or not significant (p > 0.05, Table 2).

### Discussion

**Poor grain yield of Basmati 370 sown during the long rains**

It is widely recognized that the temperature in Mwea is too low to start rice cultivation during the long rains (March–June) (Kihoro et al., 2013b; Muhunyu, 2012; Ndii et al., 2013); this was supported by our study. We documented low temperature and low solar radiation before and after July in Mwea, and Basmati 370 sown between March and June had poor grain yield. Cold periods during the reproductive stage have the highest effect on final grain yield, and the most common symptom is poor grain filling rate (da Cruz et al., 2013). Low light intensity aggravates rice

### Table 1. Number of days to 50% heading; cumulative solar radiation; average daily maximum, mean, and minimum temperature during the vegetative (Ve), reproductive (Re), and ripening (Ri) stages in the series of 24 experiments in which Basmati 370 was sown from September 2015 to August 2016.

| Sowing date | Days to heading | Solar radiation (MJ m⁻²) | Maximum temperature (°C) | Mean temperature (°C) | Minimum temperature (°C) |
|-------------|-----------------|--------------------------|--------------------------|-----------------------|--------------------------|
|             | Ve  Re  Ri      | Ve  Re  Ri               | Ve  Re  Ri               | Ve  Re  Ri            | Ve  Re  Ri               |
| 2015/9/1    | 70 469 679      | 29.0 27.0 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/9/15   | 70 402 687      | 27.8 27.0 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/10/1   | 72 467 678      | 28.7 27.0 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/10/15  | 72 597 759      | 27.1 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/11/1   | 73 545 723      | 27.3 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/11/15  | 73 546 712      | 27.3 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/12/1   | 73 649 707      | 27.3 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2015/12/15  | 73 707 691      | 27.3 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2016/1/1    | 73 740 687      | 27.3 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2016/1/15   | 73 807 725      | 27.3 27.1 28.7           | 22.2 21.9 22.6           | 17.9 17.5 16.5         |
| 2016/2/1    | 73 716 449      | 30.6 27.8 25.7           | 24.3 23.5 21.4           | 17.9 19.1 17.1         |
| 2016/2/15   | 73 543 496      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/3/1    | 73 639 371      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/3/15   | 73 613 367      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/4/1    | 73 601 363      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/4/15   | 73 457 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/5/1    | 73 460 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/5/15   | 73 457 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/6/1    | 73 457 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/6/15   | 73 457 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/7/1    | 73 457 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
| 2016/7/15   | 73 457 658      | 29.2 25.9 24.4           | 25.7 23.0 19.8           | 16.8 15.9 17.3         |
sterility caused by cold stress during the reproductive stage (Wada, Kunihiro & Honma, 1972). In this study, the grain filling rate was the most important factor explaining changes in grain yield throughout the 58 experiments. The low solar radiation, and daily maximum and mean temperatures during the reproductive stage coincided with the low grain filling rate of Basmati 370. Thus, poor grain yield of rice sown during the long rains was attributable to the low grain filling rate, due to seasonal weather conditions.

Table 2. Correlation of the grain filling rate and number of days to 50% heading with weather parameters during three growth stages.

| Weather parameter                              | Growth stage | Grain filling rate | Number of days to 50% heading |
|------------------------------------------------|--------------|--------------------|------------------------------|
| Cumulative solar radiation during a growth stage | Vegetative   | 0.342              | 0.349                        |
|                                                 | Reproductive | 0.789***           | −0.310                       |
|                                                 | Ripening     | 0.544              | −0.869***                    |
| Average daily maximum temperature during a growth stage | Vegetative   | 0.583***           | −0.530                       |
|                                                 | Reproductive | 0.725***           | −0.281                       |
|                                                 | Ripening     | 0.509*             | −0.876***                    |
| Average daily mean temperature during a growth stage | Vegetative   | 0.414*             | −0.415*                      |
|                                                 | Reproductive | 0.707***           | −0.395*                      |
|                                                 | Ripening     | 0.607***           | −0.530                       |
| Average daily minimum temperature during a growth stage | Vegetative   | −0.105             | −0.566**                     |
|                                                 | Reproductive | 0.356              | −0.530                       |
|                                                 | Ripening     | 0.582**            | −0.566**                     |

Significance at the 0.05, 0.01 and 0.001 probability levels is indicated by *, **, and ***, respectively. – indicates no data because the ripening stage is after heading.

The cumulative solar radiation, and average daily maximum and mean temperatures during the reproductive stage of Basmati 370 sown on 15 June 2016 (455 MJ m$^{-2}$, 28.4°C, and 22.8°C, respectively) was within the range of parameters for the variety sown between September 2015 and February 2016 and between July 2016 and August 2016 (420–563 MJ m$^{-2}$, 26.3–31.2°C, and 21.9–24.5°C, respectively; Table 1). However, low temperature during the vegetative stage exacerbates sterility (Shimono, Okada, Kanda & Arakawa, 2007), which would have affected (and likely have reduced the yield of) Basmati 370 sown on June 15.

Mwea is located in the tropical highlands and has a mean temperature from 23°C to 25°C (Kihoro et al., 2013a, 2013b; Matii et al., 2011). However, we showed that there was a period with low temperature and low solar radiation, which are low enough to cause poor grain yield of Basmati 370, during and after the long rains. Unless cold-tolerant varieties, which produce good grain yield even under such conditions, are available, sowing between March and June with the intent of using seasonal rainwater for irrigation should be avoided in Mwea. In other words, the whole year cropping of Basmati 370 is impossible in Mwea currently because of the period with poor water availability and limited temperature and solar radiation levels.

Although the average daily minimum temperature during the reproductive stage did not significantly correlate with the filled grain rate, it cannot be denied that the minimum temperature induces sterility. The critical temperatures for cold-induced sterility are 15–17°C in cold-tolerant rice varieties and between 17°C and 19°C in susceptible ones (Satake, 1969). In this study, Basmati 370 sown between 1 September 2015 and 1 December 2015 and between 15 March 2016 and 1 June 2016 experienced the average daily minimum temperature below 17°C during the reproductive stage. The cold-induced sterility was observed only in the latter period. In the former period,
the adverse effects of the low minimum temperature would be alleviated by the high maximum temperature (Satake, 1969). However, cold-induced sterility is irreversible under extremely low minimum temperature even if the maximum temperature is high (Farrell, Fox, Williams & Fukai, 2006). These findings suggest that minimum or maximum temperature alone is insufficient as an indicator of the degree of cold stress for rice, and both should be used as the maximum and minimum temperatures do not always change simultaneously under the conditions of tropical highlands.

**Appropriate calendar options for single rice cropping**

The current cropping calendar from July or August to December or January (Abdullahi et al., 2003; Ngige, 2004) is acceptable under a secured water supply with adequate blast control, but there are also other calendar options in Mwea. The grain yields of Basmati 370 sown between July and February were almost always within the reported range of grain yield in most farmers’ fields in Mwea (2.5–6.5 t ha\(^{-1}\)) (Muhunyu, 2012). Muhunyu (2012) reported that grain yield of >7.5 t ha\(^{-1}\) was possible in farmers’ field in Mwea. The highest grain yield in this experiment (8.2 t ha\(^{-1}\)) confirmed it, although the cultivation methods in this study were not identical to the farmers’ practice. Grain yield of the variety sown in July and August was not necessarily higher than that sown in other months, except for March, April, May, and June. There was no sign of suboptimal yield due to the high temperature before and after January, which was reported in Moshi, Tanzania, located at a lower altitude (720–730 m) than that of Mwea (Sekiya et al., 2015). This finding indicates that temperature and solar radiation in Mwea are acceptable for the sowing of Basmati 370 between July and February.

Compared with the current crop yield, higher yield may be possible by sowing between October and February. In this region, solar radiation and daily maximum temperatures during the reproductive stage correlated significantly and positively with the grain filling rate and grain yield. Thus, the high solar radiation (around 18 MJ m\(^{-2}\) d\(^{-1}\)) and high daily maximum temperature (around 30°C) with low daily minimum temperature (around 15°C) from January to March may be advantageous to rice production in Mwea. This is in line with the generally accepted idea that rice growth and grain yield increase under high solar radiation with large differences in day–night temperatures (Katsura et al., 2008). The grain yields of Basmati 370 sown between October and February were similar to or higher than those sown in the current cropping calendar. Therefore, sowing Basmati 370 between October and February is a good alternative sowing period for single rice cropping under a secured water supply, with adequate blast control. To narrow the yield gap in farmers’ field and to reach the yield potential of high-yielding varieties, utilization of the climatic advantage from January to March should be considered in Mwea.

Within each calendar option, optimal management is required to increase grain yield. Optimizing fertilizer practice is a key component of management. In this study, we followed the current standard N fertilizer practice in the region, which was 75 kg N ha\(^{-1}\) applied in three splits at fixed timing, at basal fertilization and fertilization at 21 and 45 days after transplanting (Ninju et al., 2018). This practice meant the variety received N topdressing at different development stages in each cultivation due to variation in the days to heading. Changes in day length are unlikely to cause variation in days to heading for Basmati 370 in Mwea because the day length differences over the year are negligible. Days to heading changed along with the maximum and mean temperatures during the vegetative stage in Mwea. Modification of N fertilizer management requires further study, considering the variation in days to heading in each cropping calendar.

**Appropriate calendar options for double rice cropping**

The feasibility of double cropping Basmati 370 in Mwea was supported by the results of this study. The appropriate cropping calendar is a combination of January–May and July–December, or February–June and August–January cultivations, considering the low temperature and low solar radiation period around July. For these options, the second cultivation in each year is carried out within the current cropping calendar. The second cultivation requires longer growth duration due to delayed heading caused by the low maximum and mean temperatures during the vegetative stage. Enabling double cropping is a key target for the technical support provided by the Japanese Government in Mwea (FAO, 2010). However, double cropping is still in the process of realization. According to this study, an increase of more than 100% rice production per year can be expected through the introduction of double cropping because grain yield in the additional cultivation (beginning January or February) is comparable to that of the current cropping calendar.

Improving cold tolerance in Basmati 370 or adopting good substitute varieties may enable more intensive rice cropping, such as double cropping plus ratoon cropping (2.5 times cropping), in Mwea. The lowest monthly averages of daily maximum and minimum temperatures were 24.5°C and 15.7°C, respectively, during the cold period from May to September in Mwea, whereas the average mean...
temperature seldom decreased to below 20°C (Figure 1). There are rice varieties that are tolerant to a mean temperature of 20°C, example, WAB 56–104, a japonica parent variety of many New Rice for Africa (NERICA) varieties, can maintain grain filling rate (>65%) under cold water irrigation at less than 20°C (Wainaina et al., 2015). Adaptability of these and other cold-tolerant varieties to the temperature conditions during the cold period in Mwea should be studied in the future. The varieties for more intensive rice cropping should be tolerant to low temperature in terms of not only grain filling rate but also the length of growth period. If the days to heading of the cold-tolerant Basmati 370 are not susceptible to low temperature, days to heading may be fixed at 60–70 days (Table 1). This suggests that the realization of cold-tolerant Basmati 370 will widen flexibility in the cropping calendar and more intensive – even triple – cropping may be possible in Mwea.

Conclusions
In this study, we explored the grain yield of Basmati 370 under a secured water supply with adequate blast control throughout the year in Mwea, Kenya, as a representative of tropical highlands in equatorial East Africa. The changes in grain yield were attributable to the changes in the grain filling rate, and then the rate had strong positive correlations with cumulative solar radiation, and average daily maximum and mean temperatures during the reproductive stage. The grain yield of the variety sown during the long rains is very poor because of low temperature and solar radiation during this stage. The current cropping calendar for single rice cropping in Mwea is acceptable even under sufficiently abundant year-round water supply but sowing between October and February is a good alternative sowing period according to the climatic conditions during the reproductive stage. Increases of more than 100% rice production per year can be expected by introducing double cropping because grain yield in an additional cultivation (starting in January or February) is similar to or higher than that of the current cropping calendar. These data are helpful for determining the appropriate calendar options for single and double cropping of rice in tropical highlands in equatorial East Africa.

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ORCID
Hiroaki Samejima http://orcid.org/0000-0001-9463-6066
Keisuke Katsura http://orcid.org/0000-0002-8856-8500
Daigo Makihara http://orcid.org/0000-0001-8932-4690

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