Grain weight and the concentrations of phenylpropanoid glycosides and γ-oryzanol in response to heat stress during ripening in rice

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Background and objectives: Grain weight decreases by heat stress during ripening in rice. Phenylpropanoid glycosides and γ-oryzanol are biomarkers for heat stress. The relationships between grain weight and the concentrations of these compounds should be understood in order to use biomarkers to improve the heat tolerance of rice. In the present study, we aimed to determine the relationships between grain weight and the concentrations of these compounds in the japonica cultivar Koshihikari and the indica cultivar Takanari.

Findings: In Koshihikari, the concentrations of 3',6-di-O-sinapoylsucrose, 24-methylenecycloartanyl ferulate, and total γ-oryzanol had strong negative correlations with grain weight. Conversely, in Takanari, the concentrations of 3',6-di-O-sinapoylsucrose and 3'-O-sinapoyl-6-O-feruloylsucrose had negative correlations with grain weight, whereas those of 3',6-di-O-feruloylsucrose and cycloartenyl ferulate had positive correlations with grain weight. Interestingly, the relationships between grain weight and the concentrations of 3',6-di-O-sinapoylsucrose, 24-methylenecycloartanyl ferulate, and total γ-oryzanol appeared to be stronger in Koshihikari than in Takanari.

Conclusions: The metabolisms of 3',6-di-O-sinapoylsucrose, 24-methylenecycloartanyl ferulate, and total γ-oryzanol may be powerful tools for improving the heat tolerance of japonica cultivars.
1 | INTRODUCTION

Global average temperatures increased by 0.85°C between 1880 and 2012 (IPCC, 2014). According to the Representative Concentration Pathway RCP 2.6 scenario, the amount of CO₂ emissions is relatively low and the global average temperature will increase by 0.3–1.7°C by the end of this century. Conversely, if using the extreme RCP 8.5 scenario, the global average temperature will increase by 2.6–4.8°C.

The world population is estimated to reach 9.8 billion people by 2050 (United Nations, 2017), and global crop production needs to increase accordingly to feed the substantially larger population. Since the availability of arable land for crop cultivation is limited worldwide (Alexandratos & Bruinsma, 2012), land for crop cultivation is limited worldwide. Since the availability of arable land for crop cultivation is limited worldwide (Alexandratos & Bruinsma, 2012), the crop yield per unit area should be enhanced to resolve the global food issue.

Rice (Oryza sativa L.) is a staple food that is eaten by nearly half the world’s inhabitants (GriSP, 2013). Rice cultivars have been classified into japonica and indica types based on their morphological and physiological features (Khush, 1997). Japonica rice was considered to have been first domesticated from a specific population of Oryza rufipogon around the middle area of the Pearl River in southern China, and indica rice was subsequently developed from crosses between japonica and local wild rice as the initial cultivars spread into South East Asia and South Asia (Huang et al., 2012).

The suitable air temperature for ripening is higher for indica cultivars than for japonica cultivars (Nagata et al., 2016; Yoshida & Hara, 1977). Therefore, japonica cultivars are adapted to temperate regions, and indica cultivars are adapted to tropical regions (GriSP, 2013). In Japan, which belongs to the temperate region, japonica cultivars have traditionally been grown in most of the paddy field of approximately 1.6 million ha. However, to enhance grain yield under global warming conditions by breeding, the favorable trait of indica cultivars should be used to improve heat tolerance in japonica cultivars.

In our previous study using three japonica cultivars, two phenylpropanoid glycosides, 3',6-di-O-sinapoylsucrose (2) and 3-O-sinapoyl-6-O-feruloylsucrose (3), and two steryl ferulates (i.e., γ-oryzanol), cycloartenyl ferulate (5) and 24-methylenecycloartenyl ferulate (6), were isolated as biomarkers for heat stress during ripening (Nakano et al., 2013). The concentrations of 2, 3, and 6 increased, but that of 5 decreased by high air temperature. To use these biomarkers (2, 3, 5, and 6) to improve the heat tolerance of japonica cultivars, the relationships between grain weight and the concentrations of compounds (2, 3, 5, and 6) should be elucidated.

Phenylpropanoid glycosides exert several biomedical effects, such as anti-viral (Kernan et al., 1998), anti-bacterial (Didry et al., 1999), anti-inflammatory (Díaz et al., 2004), and anti-obesity activities (Yang et al., 2015). Similarly, γ-oryzanol exerts several biomedical effects, such as anti-hyperlipidemic (Ghatak & Panchal, 2012a), anti-diabetic (Ghatak & Panchal, 2012b), anti-inflammatory (Rao et al., 2016), and anticancer activities (Doello et al., 2018). The concentrations of phenylpropanoid glycosides were higher in japonica cultivars than in indica cultivars, and the quantitative trait loci (QTLs) for the concentrations of phenylpropanoid glycosides were detected (Nakano et al., 2019).

A similar difference in subspecies was observed in the concentration of γ-oryzanol (Heinemann et al., 2008; Kato et al., 2017; Nakano et al., 2018), and the QTLs for the concentration of γ-oryzanol were detected (Kato et al., 2017; Nakano et al., 2018). In indica cultivars, which are more widely grown globally than japonica cultivars, the concentrations of phenylpropanoid glycosides response to air temperature are unclear. To produce rice grains with highly biomedical activities, the responses of these compounds to air temperature should be elucidated.

In the present study, we aimed to determine the effect of air temperature during ripening on grain weight and the concentrations of phenylpropanoid glycosides and γ-oryzanol in both the japonica cultivar Koshihikari and the indica cultivar Takanari and to analyze the relationships between grain weight and the concentrations of these compounds in each cultivar.

2 | MATERIALS AND METHODS

2.1 | Plant materials

Rice plants were grown at the Institute of Crop Science, National Agriculture and Food Research Organization (NARO) (36°03′N, 140°09′E, 22 m above sea level) in Tsukuba, Ibaraki, Japan. Treatments included two cultivars (Koshihikari and Takanari) and three air temperatures during the ripening stage (normal, moderately high, and high), arranged as a randomized complete block design with three replicates (each replicate has two pots) before heading. Koshihikari is a leading japonica cultivar with good eating quality (Kobayashi et al., 2018) and Takanari is a high-yielding indica cultivar (Imbe et al., 2004), both released and grown in Japan.

Germinated seeds were sown in nursery boxes in late April. Seedlings were then transplanted by hand into 1/5,000 a Wagner pot filled with paddy soil at a density of two seedlings per pot in late May. The plants received 0.5 g pot/N, 0.5 g pot/P<sub>2</sub>O<sub>5</sub>, and 0.5 g/pot K<sub>2</sub>O at transplanting in the form of synthetic fertilizer and 0.5 g pot/N both approximately 4 and 2 weeks before heading in the form of LP40 (Jcam Agri, Co., Ltd.), which release 80% of the total N content at
a uniform rate up to 40 days after application, were grown outside and then moved to phytotrons (Espec Mic Co., Ltd.) after heading (early August).

The air temperature in each phytotron was set to 26.0/20.0°C (14/10 hr, day/night) as the normal temperature, 29.0/23.0°C (14/10 hr, day/night) as the moderately high temperature, and 32.0/26.0°C (14/10 hr, day/night) as the high temperature treatments. The actual air temperatures recorded in the phytotrons were 25.2/19.1°C (14/10 hr, day/night) for the normal temperature, 29.7/23.2°C (14/10 hr, day/night) for the moderately high temperature, and 32.7/26.7°C (14/10 hr, day/night) for the high temperature treatments.

At maturity (September), the panicles were harvested by hand. The air-dried panicles were hand-threshed, and the rough rice grains were dehusked. The grain weight was corrected to a 15% moisture content basis.

### 2.2 Determination of compounds

Powdered grains (50 seeds) were extracted with aqueous acetone (acetone/H2O, 1:1 [v/v]) or acetone (20 ml) at 25°C for 1 day in the dark. The aqueous acetone extracts were subjected to C18 high-performance liquid chromatography (HPLC; TSKgel ODS-80Ts, Tosoh, 4.6 × 250 mm; eluent, CH3CN/H2O/TFA, 5:95:0.05 to 35:65:0.05 [v/v] for 60 min by liner gradient; flow rate, 0.8 ml/min; UV detection at 320 nm) to determine the 6-O-feruloylsucrose (1) (tR 28.6 min), 3’,6-di-O-sinapoylsucrose (2) (tR 44.1 min), 3’-O-sinapoyl-6-O-feruloylsucrose (3) (tR 45.3 min), and 3’,6-di-O-feruloylsucrose (4) (tR 46.2 min) concentrations. The acetone extracts were subjected to C18 HPLC (Sunfire, Waters, 4.6 × 250 mm; eluent, CH3CN/H2O, 15:85 [v/v]; flow rate, 0.8 ml/min; UV detection at 320 nm) to determine the cycloartenyl ferulate (5) (tR 32.0 min), 24-methylene cycloartenyl ferulate (6) (tR 34.8 min), and total γ-oryzanol (sum of 5, 6, campesterol ferulate and epi-campesterol ferulate [7a and b, respectively] [tR 37.0 min], and β-sitosteryl ferulate [8] [tR 41.7 min]) concentrations. The identities of peaks 5, 6, 7, and 8 for γ-oryzanol were confirmed with commercially available γ-oryzanol (Wako Chemicals) and by comparison with literature data (Bao et al., 2013; Tuncel & Yılmaz, 2011). The amounts of 1–6 and total γ-oryzanol were calculated using standard curves based on peak areas. This experiment was replicated three times.

### 2.3 Statistical analysis

Statistical analyses were performed using a general linear model in SPSS (version 17.0, SPSS Inc.). An analysis of variance was conducted to test the effect of air temperature during ripening and cultivar on concentrations of compounds of 6-O-feruloylsucrose (1). At a high air temperature, the

![FIGURE 1 Relationships between grain weight of rice and air temperature during ripening. Bars represent ± SE](Colour figure can be viewed at wileyonlinelibrary.com)
concentration of 1 did not differ between cultivars. However, at normal and moderately high temperatures, the concentration of 1 was higher in Koshihikari than in Takanari. In Koshihikari, the concentration of 1 decreased with increasing air temperature. However, in Takanari, the concentration of 1 did not differ among air temperatures. Hence, there could be a clear difference in the response of concentration of 1 to air temperature between the two cultivars. In our previous study using three japonica cultivars, the concentration of 1 did not differ between two air temperatures (Nakano et al., 2013). This means that the concentration of 1 may be highly sensitive to the growth conditions.

The concentrations of 3',6-di-O-sinapoylsucrose (2), 3'-O-sinapoyl-6-O-feruloylsucrose (3), and 3',6-di-O-feruloylsucrose (4) were higher in Koshihikari than in Takanari (Table 1, Figure 2). The concentration of 2 increased with increasing air temperature. In Koshihikari, the concentration of 2 was 2.3 times higher in high temperature than in normal temperature. This response was similar to that in our previous study that used three japonica cultivars (Nakano et al., 2013). However, in Takanari, the concentration of 2 was 4.2 times higher in high temperature than in normal temperature (Table 1). Therefore, the response of concentration of 2 to air temperature may appear to be more sensitive in Takanari than in Koshihikari. Additionally, the concentration of 3 did not differ among the three air temperatures. Conversely, the concentration of 4 decreased with increasing air temperature.

Similarly, the responses of concentrations of γ-oryzanol (5–8) to air temperature were examined in two cultivars (Table 1, Figure 2). The concentrations of cycloartenyl ferulate (5) and 24-methylene cycloartanyl ferulate (6) were higher in Koshihikari than in Takanari. Although the concentration of 5 decreased with increasing with air temperature, the concentration of 6 increased with increasing with air temperature. Conversely, the concentration of total γ-oryzanol (5–8) did not differ between two cultivars and among the three air temperatures. In our previous studies, total γ-oryzanol (5–8) was higher in Koshihikari than in Takanari and increased with increasing air temperature (Nakano et al., 2013, 2018).
In the present study, although a similar trend was observed, the dispersion of data was large, and the statistical significance was not detected.

The concentration of 3’,6-di-O-sinapoylsucrose (2) with two sinapoyl moieties increased by heat stress (Table 1, Figure 2). However, the concentration of 6-O-feruloylsucrose (1) with one feruloyl moiety and 3’,6-di-O-feruloylsucrose (4) with two feruloyl moieties decreased by heat stress. Additionally, 24-methylene-cycloartenyl ferulate (6), a main γ-oryzanol compound, with one feruloyl moiety increased by heat stress. This means that there may be a competitive relationship between the esterifications with ferulic acids in glycoside and steroid under heat stress condition.

**FIGURE 2** Chemical structures of 6-O-feruloylsucrose (1), 3’,6-di-O-sinapoylsucrose (2), 3’-O-sinapoyl-6-O-feruloylsucrose (3), 3’,6-di-O-feruloylsucrose (4), cycloartenyl ferulate (5), 24-methylene-cycloartenyl ferulate (6), campesteryl ferulate and ep-campesteryl ferulate (7a and 7b, respectively), and β-sitosteryl ferulate (8). Sinapoyl and feruloyl moieties represent red and blue atoms and bonds, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]
The concentration of cycloartenyl ferulate (5) decreased, but that of 24-methylene cycloartanyl ferulate (6) increased by heat stress (Table 1, Figure 2). 24-Methylenecycloartenol, a sterol moiety of 6, is generated from squalene via cycloartenol, a sterol moiety of 5 (Piironen et al., 2000). Therefore, the reaction of cycloartenol to 24-methylene cycloartanol may be enhanced by heat stress.

**FIGURE 3** Relationships between grain weight and the concentrations of phenylpropanoid glycosides (1–4) and γ-oryzanol (5–8) in the *japonica* cultivar Koshihikari. Compounds 1–6 are 6-O-feruloylsucrose (1), 3',6-di-O-sinapoylsucrose (2), 3'-O-sinapoyl-6-O-feruloylsucrose (3), 3',6-di-O-feruloylsucrose (4), cycloartenyl ferulate (5), and 24-methylenecycloartanyl ferulate (6) and compound 5–8 is total γ-oryzanol (5–8). * and *** are significant at the .05 and .001 probability levels, respectively.

**FIGURE 4** Relationships between grain weight and the concentrations of phenylpropanoid glycosides (1–4) and γ-oryzanol (5–8) in the *indica* cultivar Takanari. Compounds 1–6 are 6-O-feruloylsucrose (1), 3',6-di-O-sinapoylsucrose (2), 3'-O-sinapoyl-6-O-feruloylsucrose (3), 3',6-di-O-feruloylsucrose (4), cycloartenyl ferulate (5), and 24-methylenecycloartanyl ferulate (6) and compound 5–8 is total γ-oryzanol (5–8). * and ** are significant at the 0.05 and 0.01 probability levels, respectively.
Phenylpropanoid glycoside and γ-oryzanol exert biomedical effects, such as anti-inflammatory activities (Diaz et al., 2004; Rao et al., 2016). In the present study, the responses of concentrations of phenylpropanoid glycosides (1–4) and γ-oryzanol (5–8) to air temperature were revealed in two cultivars (Table 1, Figure 2). Thus, this information could be available for the selection of cultivars, growing seasons, and sites for the production of rice with biomedical effects.

3.3 | Relationships between grain weight and the concentrations of phenylpropanoid glycosides and γ-oryzanol

Although 3',6-di-O-sinapoylsucrose (2), 3'-O-sinapoyl-6-O-ferloylsucrose (3), cycloartenyl ferulate (5), and 24-methylene cycloartanyl ferulate (6) were isolated and identified as heat stress biomarkers in rice (Nakano et al., 2013), the relationships between grain weight and the concentrations of 2, 3, 5, and 6 have not yet been revealed. In the present study, a correlation analysis was conducted on the grain weight and the concentrations of compounds (1–6) and total γ-oryzanol (5–8) in each cultivar (Figures 2, 3 and 4). In Koshihikari, the concentrations of 2, 6 and 5–8 had strong negative correlations with grain weight (Figure 3). Additionally, the concentration of 3 had a negative correlation with grain weight. However, there was no correlation between grain weight and the concentrations of 1, 4, and 5. Conversely, in Takanari, the concentrations of 2 and 3 had negative correlations with grain weight, whereas that of 4 and 5 had positive correlations with grain weight. However, there was no correlation between grain weight and the concentrations of 1, 6, and 5–8. Interestingly, the relationships between grain weight and the concentrations of 2, 6, and 5–8 appeared to be higher in Koshihikari than in Takanari. The difference of relationship between grain weight and the concentration of 5–8 in the two cultivars was considered to be caused by those between grain weight and the concentration of 5 and between grain weight and the concentration of 6. Since there are numerous cultivars with genetic variations in the world, these relationships should be examined in several other cultivars including japonica and indica types.

Since global average temperatures will increase by 0.3–4.8°C by the end of this century and the world population is estimated to reach 9.8 billion people by 2050, enhancing the grain yield of rice, which is one of the most important crops, under climate change conditions is essential to resolve the global food issue. In the present study, the relationships between grain weight and the concentrations of phenylpropanoid glycosides and γ-oryzanol were analyzed for the japonica cultivar Koshihikari and the indica cultivar Takanari grown under various air temperature conditions. In Koshihikari, the concentration of 3',6-di-O-sinapoylsucrose (2), 24-methylene cycloartanyl ferulate (6), and total γ-oryzanol (5–8) had strong negative correlations with grain weight. Conversely, in Takanari, the concentration of 2 and 3 had negative correlations with grain weight, whereas that of 4 and 5 had positive correlations with grain weight. Interestingly, the relationships between grain weight and the concentrations of 2, 6, and 5–8 were appeared to be higher in Koshihikari than in Takanari. Therefore, the metabolisms of 2, 6, and 5–8 could have important relationships with the grain weight reduction caused by heat stress in Koshihikari and the concentrations of 2, 6, and 5–8 may be powerful tools to improve the heat tolerance of japonica cultivars. Additionally, the relationships between grain weight reduction caused by other stress, such as low solar radiation, and the concentrations of these compounds (1–8) should be examined.

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